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Dpt. de Ingeniería Eléctrica

Análisis de la teoría de ondículas orientada a las aplicaciones en ingeniería eléctrica:

Protección diferencial del transformador con discriminación por ondículas

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Índice

Capítulo 1

MODELO DE LA PROTECCIÓN DIFERENCIAL

1.1. Introducción

En el campo de las aplicaciones de la transformada wavelet en los sistemas eléctricos de potencia, se ha observado que en el área de las protecciones es donde más esfuerzos se han realizado para conseguir nuevos medios de discriminación y localización de faltas que sean más rápidos y precisos.

Este trabajo se ha centrado en el diseño de un algoritmo basado en “wavelet” para la protección diferencial de un transformador de potencia, la principal ventaja de este algoritmo es su capacidad para discriminar de manera rápida y eficiente entre faltas internas y externas con o sin “inrush”.

En este trabajo se demuestra que utilizando “wavelet” es posible diseñar un relé que discrimina de mejor forma la ocurrencia o no de una falta, gracias a que la transformada wavelet permite una buena caracterización de la señal en el dominio tiempo-frecuencia.

En este capítulo, se presenta el desarrollo de un modelo en ATP para la simulación de la protección diferencial de un transformador de potencia, a partir de este modelo se obtiene la corriente diferencial que posteriormente será utilizada como señal de entrada al relé.

1.2. Protección diferencial de transformadores

Los transformadores de potencia son dispositivos que juegan un papel importante en los sistemas eléctricos de potencia dado que intervienen de manera significativa en la seguridad y estabilidad de la red, por lo cual la protección de estos equipos es crítica para garantizar su operación segura. Actualmente, el problema principal en la protección del transformador es la detección de la corriente de energización (“inrush”), debido a que esta corriente puede alcanzar valores del orden 10 veces la corriente de plena carga y por lo tanto causar una incorrecta operación de los relés de protección, ya que esta no es una situación de falta sino un fenómeno transitorio que ocurre en el instante de energización del transformador. Esto significa que el sistema de protecciones debe permanecer sin actuar durante ese periodo transitorio, hecho que dificulta el diseño de la protección.

Hasta la fecha el sistema de protecciones más utilizado en el transformador es la protección diferencial con retención de segundo armónico. Este método bloquea la operación del relé cuando existe “inrush”, discriminado esta condición a partir del contenido de segundo armónico de la corriente diferencial medida; sin embargo, a medida que los sistemas de trasmisión crecen tanto en capacidad como en nivel de tensión y se incrementa el uso de cables subterráneos se pueden producir corrientes de faltas con un importante contenido de segundo armónico comparable al de la corriente “inrush”, de tal manera que el esquema diferencial de segundo armónico no siempre garantiza la correcta discriminación de la protección.

De este modo, la discriminación exacta entre corriente “inrush” y corrientes originadas por faltas internas es un desafío para la ingeniería de protecciones.

En este capítulo se presenta un esquema de protecciones basado en la transformada wavelet para discriminar entre faltas (internas y externas) o “inrush”, para ello se estudia la aplicación de la transformada wavelet a la forma de onda originada por la perturbación, ya que permite la localización en el dominio tiempo-frecuencia de las características de la señal lo que la hace más conveniente para el análisis de señales de naturaleza transitoria, especialmente aquellas señales que presentan cambios bruscos en su forma de onda tal como ocurre en el caso de la protección diferencial del transformador.

1.3. Simulación de "inrush" y faltas en un transformador de potencia

En esta sección se modela la protección diferencial de un transformador a fin de contar con un modelo para la simulación de diferentes casos de interés para el estudio de faltas internas, externas e "inrush". El modelo de la protección diferencial de un transformador se muestra en la Fig 1.1.

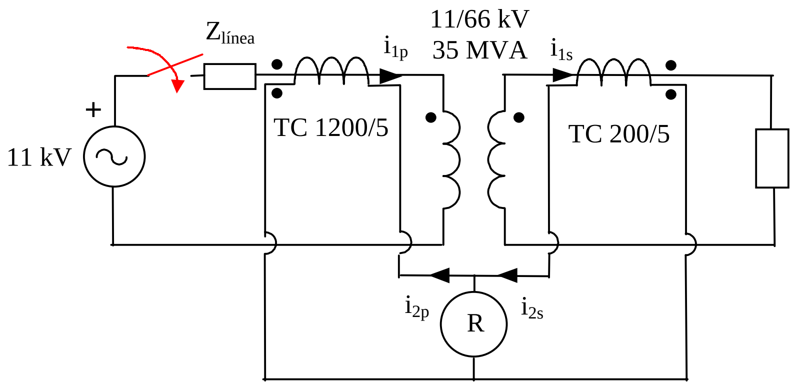


Fig. 1.1.- Protección diferencial del transformador.

Como se pretende aplicar la transformada wavelet al análisis de la protección diferencial del transformador, se requiere obtener la señal transitoria correspondiente a la corriente diferencial originada por algún tipo de perturbación (falta, inrush, desconexión, etc.) para descomponer esta señal en una serie de componentes wavelets, cada una de los cuales representa en el dominio del tiempo una banda específica de frecuencias (escalas). Posteriormente será posible caracterizar cada uno de los casos de interés para finalmente proponer un algoritmo que discrimine de manera rápida y confiable entre una condición de falta y una condición de "inrush".

Para llevar a cabo el estudio correspondiente al análisis transitorio de la corriente diferencial se ha simulado el circuito de la Fig. 1.1 en el programa de análisis de transitorios (ATP), para ello se ha modelado (ATPDraw) la protección diferencial del transformador tal como se muestra en la Fig.1.2.

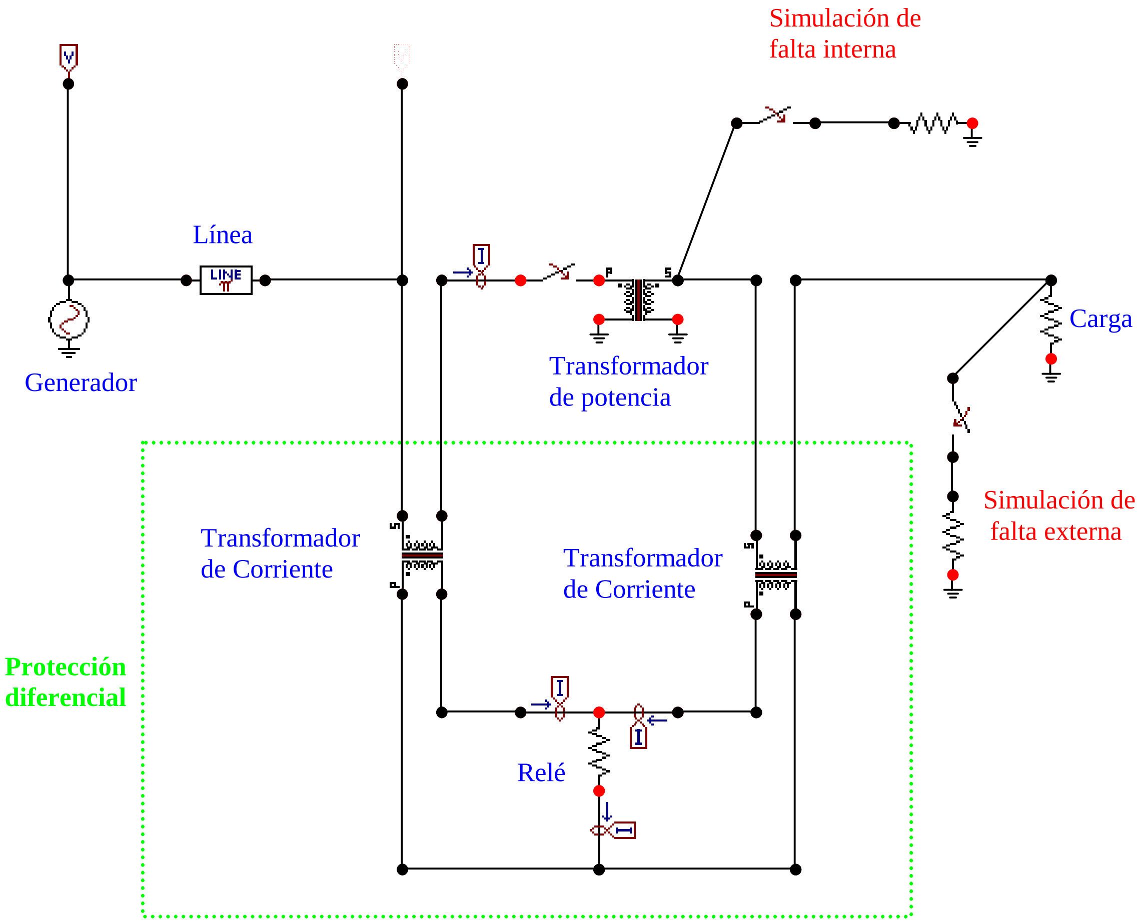
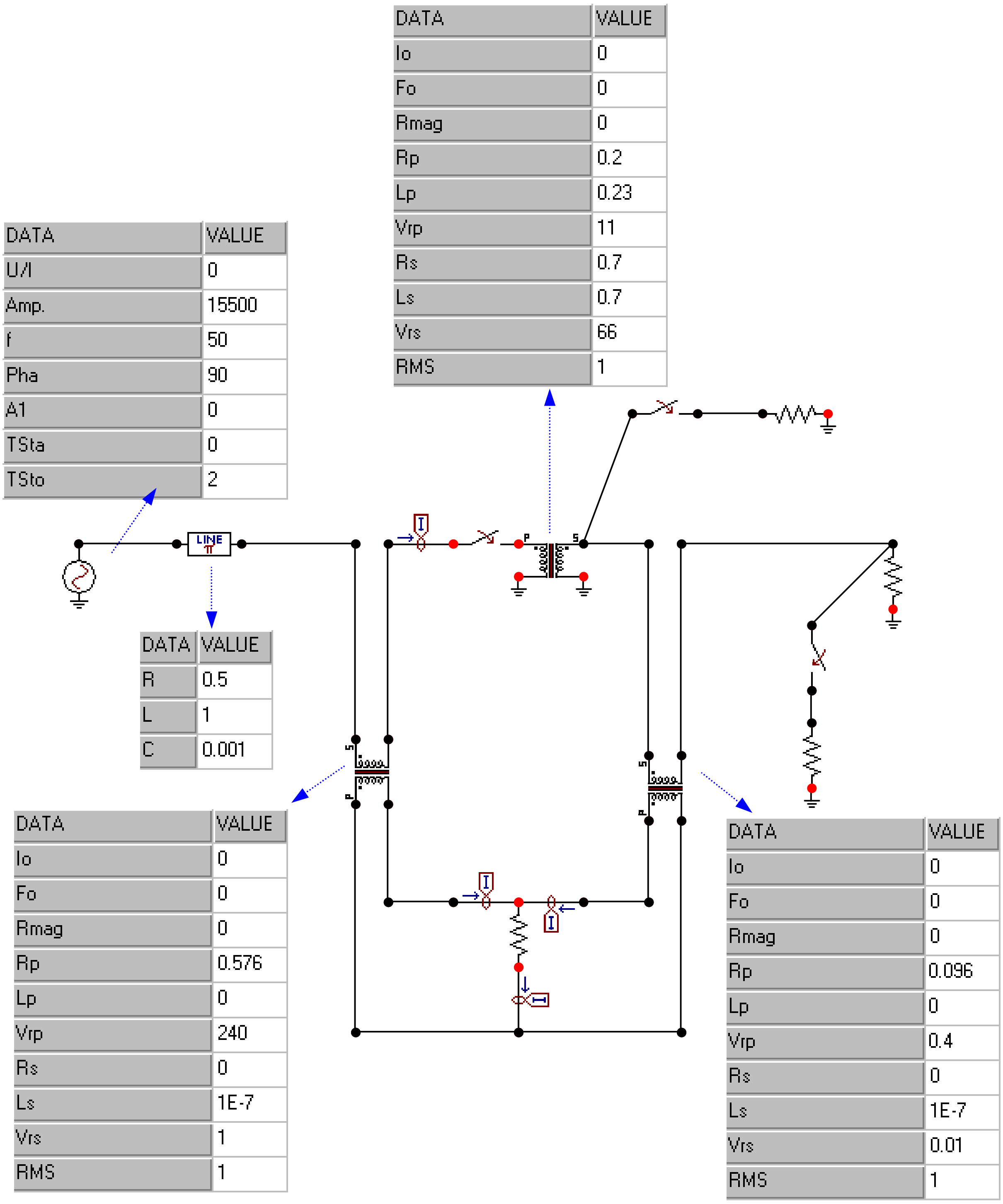


Fig. 1.2.- Modelo en ATP de la protección diferencial de un transformador.

1.3.1. Parámetros de los elementos

Los parámetros de los elementos del circuito de la Fig.1.2 utilizados en ATP son los que se muestran en detalle en la Fig. 1.3. Otras características de los elementos como curvas de saturación se indican en las páginas siguientes.



DATA	VALUE
Io	0
Fo	0
Rmag	0
Rp	0.2
Lp	0.23
Vrp	11
Rs	0.7
Ls	0.7
Vrs	66
RMS	1

DATA	VALUE
U/I	0
Amp.	15500
f	50
Pha	90
A1	0
TSta	0
TSto	2

DATA	VALUE
R	0.5
L	1
C	0.001

DATA	VALUE
Io	0
Fo	0
Rmag	0
Rp	0.576
Lp	0
Vrp	240
Rs	0
Ls	1E-7
Vrs	1
RMS	1

DATA	VALUE
Io	0
Fo	0
Rmag	0
Rp	0.096
Lp	0
Vrp	0.4
Rs	0
Ls	1E-7
Vrs	0.01
RMS	1

Fig. 1.3.- Parámetros en el programa ATP del circuito de estudio mostrado en la Fig. 1.2.

Los transformadores fueron modelados considerando la saturación del núcleo, lo cual es importante para el análisis de la corriente “inrush”.

1.3.1.1. Transformador de potencia

$$S_T = 35 \text{ MVA}$$
$$V_1 = 11 \text{ kV}$$
$$V_2 = 66 \text{ kV}$$

Tabla 1.1.- Curva de saturación

Vrms [V]	110	140	180	251	700	1000	4000	8700	10300	11000	13000
Irms [A]	1.2	1.5	1.8	2.1	2.8	3.3	8	15	20	30	10000

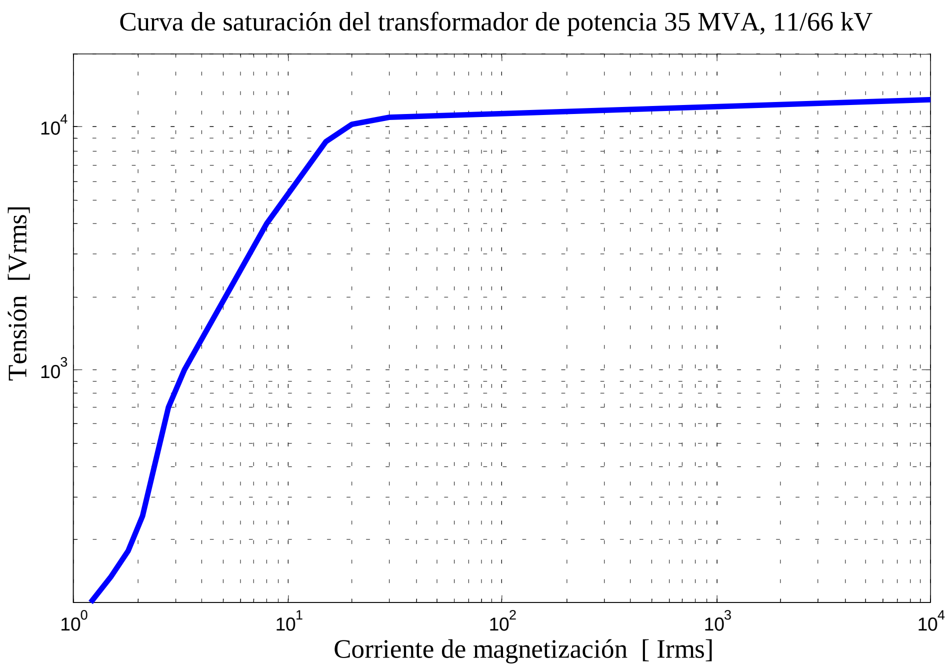


Fig. 1.4.- Curva de saturación del transformador de potencia de 35 MVA, 11/66 kV.

1.3.1.2. Transformadores de corriente

El modelo utilizado en ATP para los transformadores de corriente fue obtenido a partir de la referencia mostrada en el anexo 3, para ello se hace uso del modelo clásico del transformador con saturación disponible en ATP , pero considerando lo siguiente :

1. El secundario del transformador de corriente se modela como enrollado primario en el modelo de transformador saturable del ATP.

2. En el enrollado secundario se ajusta Rs = 0 (resistencia del primario del TT/CC despreciable) , la inductancia Ls deber ser distinta de cero, se ha elegido Ls=1e-7.

3. La inductancia Lp se ajusta a cero, puesto que en los TT/CC la inductancia del primario es despreciable.

4. La Resistencia Rp se ajusta al valor de la resistencia del secundario del TT/CC.

5. La resistencia de magnetización Rmag se ajusta a infinito, pues es usualmente un valor muy grande. En ATP esto se hace colocando un cero como valor de Rmag.

6. La curva de saturación se seleccionó de referencias y de estándares de TT/CC, utilizándose los datos mostrados en las tablas 1.2 y 1.3.

Tabla 1.2. Característica de saturación del transformador de corriente: 1200/5

Vrms[V]	9	90	428	500	600	700	780	800	927
Irms[A]	0.01	0.04	0.1	0.12	0.14	0.20	0.30	0.40	40

Tabla 1.3. Característica de saturación del Transformador de corriente: 200/5

Vrms [V]	0.09	1.1
Irms [A]	0.1	7

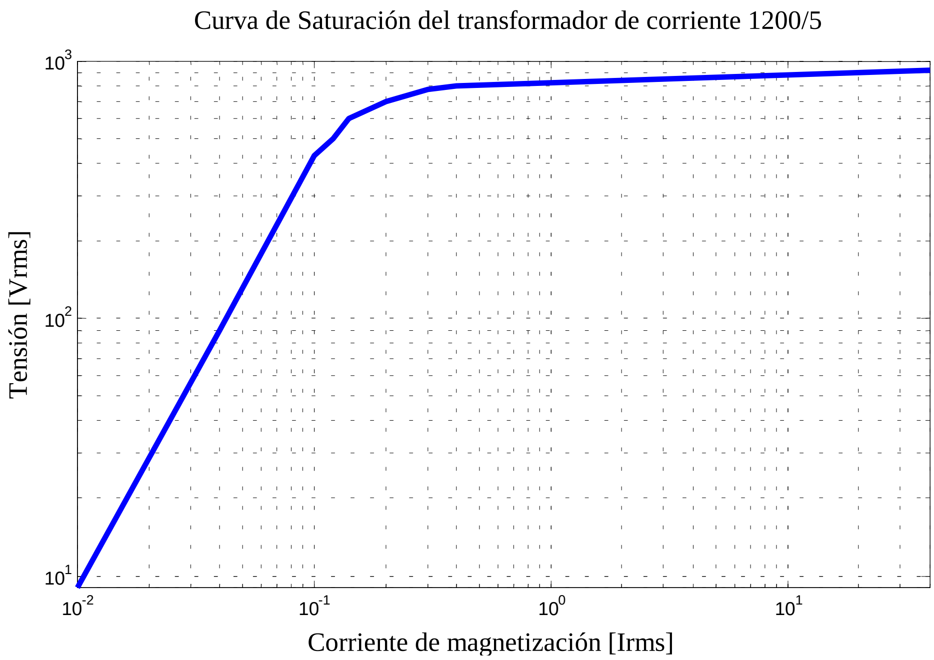
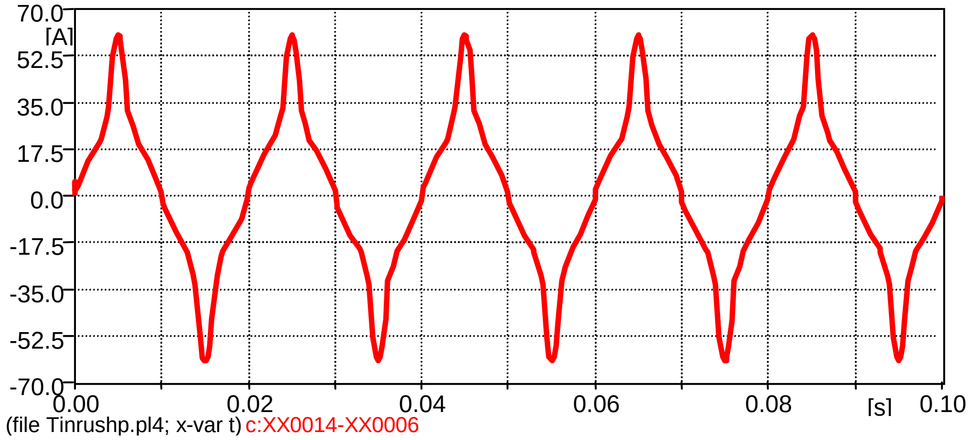


Fig. 1.5.- Curva de saturación del transformador de corriente 1200/5.

Para comprobar la validez del modelo propuesto para los transformadores de corriente en la Fig. 1.6 y Fig. 1.7 se muestran las corrientes primaria y secundaria del transformador 1200/5 y 200/5 para dos ejemplos cualquiera, donde puede observarse que satisfacen la las relaciones de transformación correspondientes.

Corriente del primario



Corriente del secundario

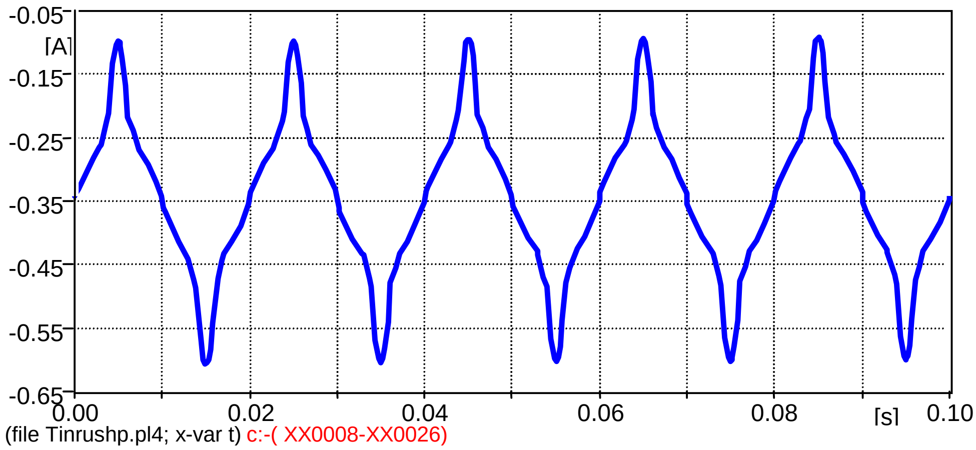
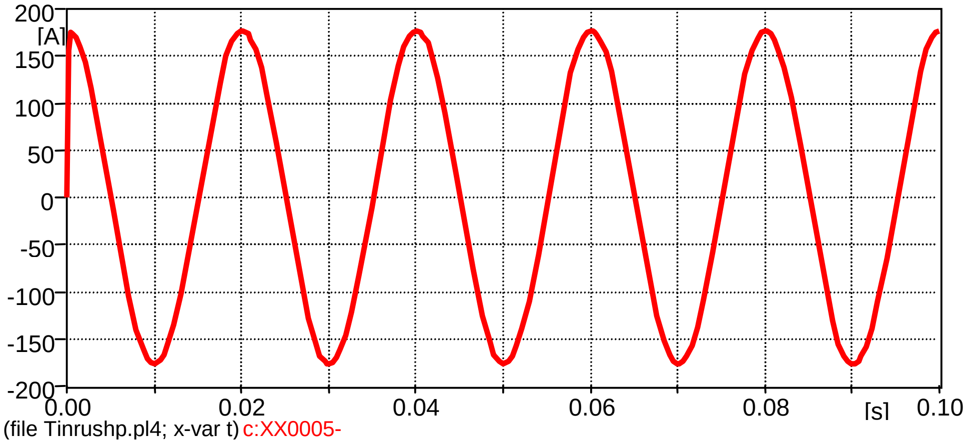


Fig. 1.6.- Ejemplo de corrientes que circulan por el primario y el secundario del transformador de corriente 1200/5.

Corriente del primario



Corriente del secundario

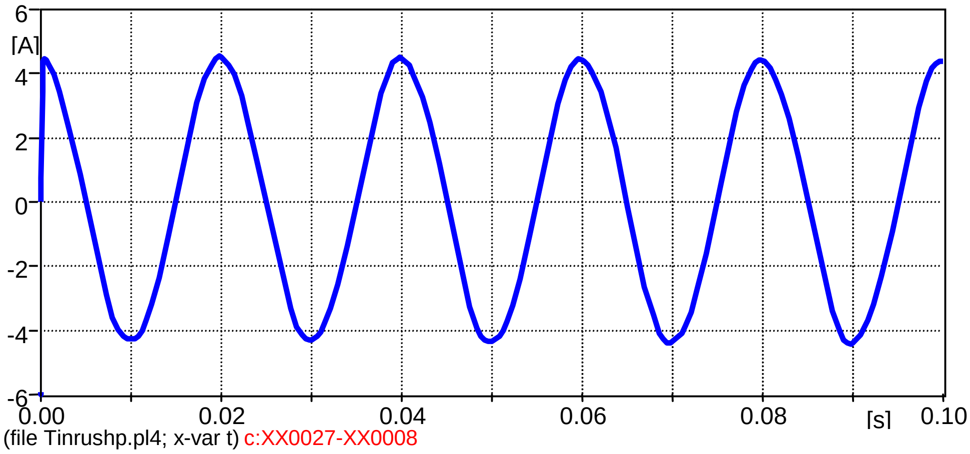


Fig. 1.7.- Ejemplo de circulación de corrientes por el primario y por el secundario del transformador de corriente 200/5.

Capítulo 2

RELÉ NUMÉRICO BASADO EN ONDÍCULAS

2.1. Introducción

En este capítulo se propone un modelo de relé numérico basado en ondículas para la protección diferencial de un transformador de potencia. Se analizan los diferentes bloques que constituyen la arquitectura del relé y se describe la metodología de discriminación que emplea, para ello se estudian diferentes casos de interés (falta, interna, falta externa, "inrush", etc.) considerando la señal transitoria correspondiente a la corriente diferencial producida por la perturbación y utilizando como herramienta de análisis la transformada wavelet discreta (DWT) con diferentes posibilidades de wavelets madre. Finalmente a partir de la comparación de las características del detalle 1 de la DWT de cada uno de los casos estudiados se demuestra que la transformada wavelet puede utilizarse para discriminar entre una condición de falta y una condición de operación normal de un transformador de potencia.

2.2. Modelo del relé propuesto

Con el objeto de proteger eficientemente el transformador de potencia, se propone el diseño de un relé que sea capaz de identificar eficientemente faltas internas en el transformador a partir del análisis de la señal correspondiente a la corriente diferencial. El diagrama en bloque del relé propuesto se presenta en la Fig. 2.1.

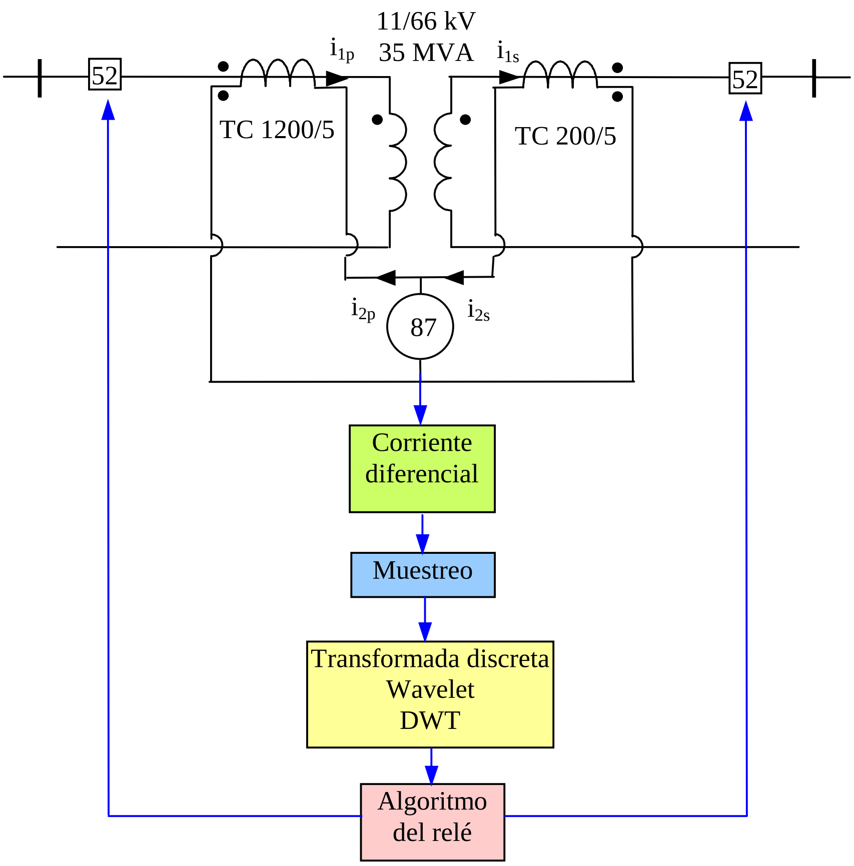


Fig. 2.1.- Diagrama en bloques del relé diferencial numérico con discriminación por ondículas.

Como se observa en la Fig. 2.1 la señal de entrada al relé son las corrientes diferenciales muestreadas a una frecuencia de 25 kHz, posteriormente se obtiene la transformada wavelet discreta de esta señal, con la estructura mostrada en la Fig. 2.2, donde x[n] es la señal original, h[n] y g[n] son los filtros paso bajo y paso alto respectivamente. En una primera etapa, la señal se divide en dos partes que corresponden a la mitad del ancho de banda de la frecuencia de muestreo, posteriormente la señal de salida del filtro paso alto se vuelve a dividir a la mitad de su frecuencia de entrada y así sucesivamente hasta un número de niveles determinados. De esta manera se obtiene un conjunto de señales que representan la señal original, pero cada una de ellas corresponde a un ancho de bandas diferentes. En la Fig. 2.2 pueden observarse tres niveles de detalle compuestos por las siguientes bandas de frecuencia:

Detalle 1: 12.5- 6.25 kHz

Detalle 2: 6.25 – 3.125 kHz

Detalle 3: 3.125 – 1.562 kHz.

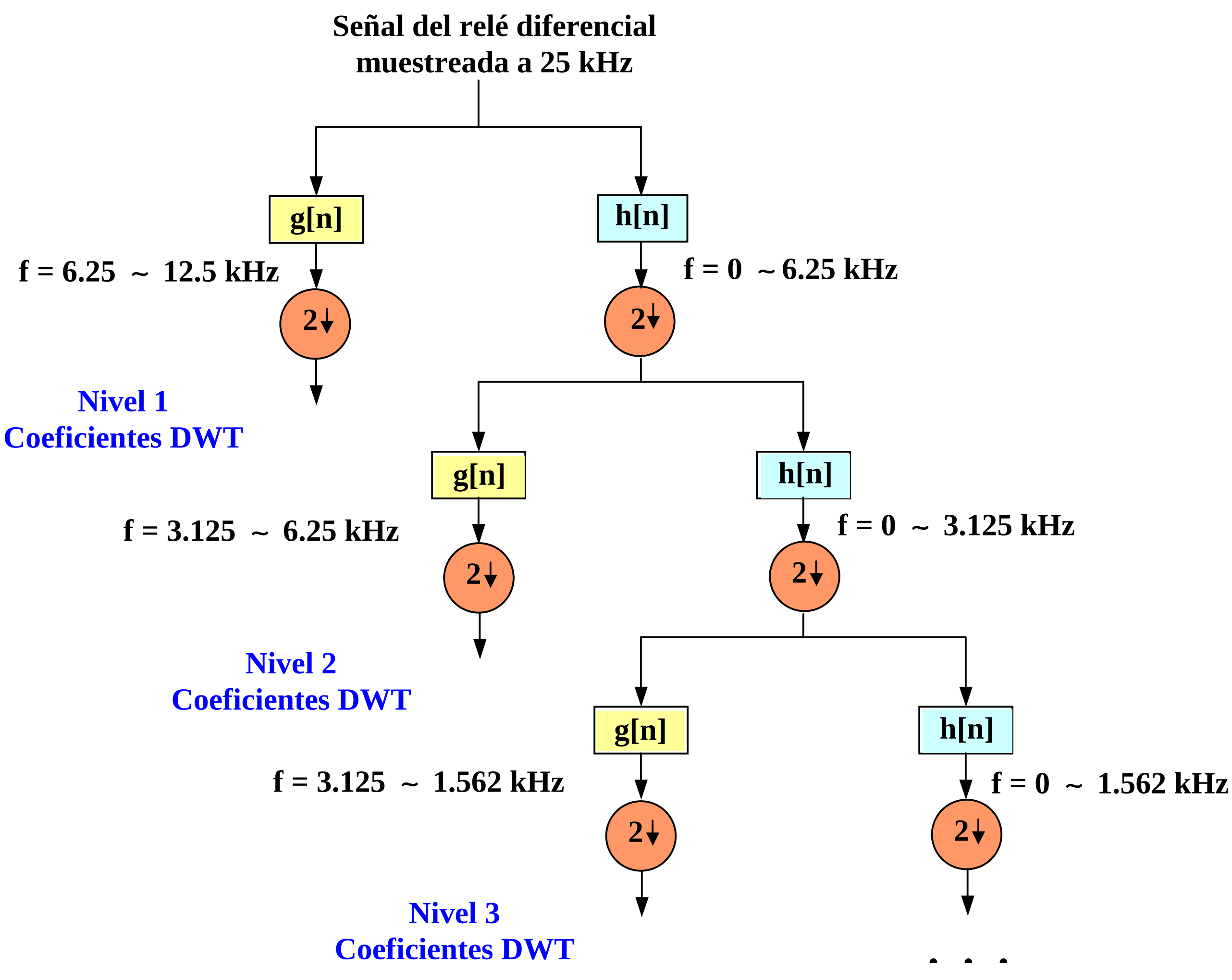


Fig. 2.2.- Esquema de interpretación de la transformada discreta (DWT) wavelet considerando una frecuencia de muestreo de 25 kHz.

La técnica que se ha desarrollado se basa en el análisis de alta frecuencia de los fenómenos asociados con el transformador de potencia. Por lo tanto es necesario el empleo de una frecuencia de muestreo lo más alta posible, por ejemplo de 25 kHz. o más. En la práctica, esta alta tasa de muestreo no debiera representar mucha dificultad en el hardware necesario para la implementación de esta técnica en vista que los procesadores digitales modernos son capaces de muestrear a tasas incluso superiores a los 200 kHz.

2.2.1. Análisis de las características de las señales transitorias del transformador empleando wavelet

Como se ha señalado el principio de discriminación del relé propuesto estará basado en el análisis de las características de la señal correspondiente a la corriente diferencial en el dominio wavelet. Por lo cual para crear un criterio de discriminación resulta de importancia el análisis del resultado de la DWT de los siguientes casos que tienen influencia en la actuación de la protección:

- Análisis de corriente "Inrush"
- Análisis de faltas internas
- Análisis de faltas externas

2.2.1.1. Análisis de corriente "Inrush"

En la Fig. 2.3 se muestra el resultado de la DWT de la corriente de magnetización "inrush" obtenida por simulación utilizando ATP, la señal que se muestra corresponde a la corriente diferencial medida por el relé cuando el transformador se conecta a la red y no existe ningún tipo de falta. Como puede observarse, la forma de onda de las corrientes correspondientes a cada uno de los detalles muestran que existen intervalos muy pequeños en los cuales existe una respuesta de tipo impulso, donde la señal alcanza un valor diferente de cero, mientras que para otros instantes de tiempo la señal es prácticamente nula. Esto se puede explicar por el hecho que el cambio repentino de la señal de entrada de un estado a otro produce un pequeño rizado, el cual no se aprecia a la frecuencia fundamental como se observa en la Fig. 2.3 (curva en rojo), pero que sin embargo es claramente demostrable empleando la transformada wavelet (curvas en azul).

Para el estudio que se realiza resulta de interés la velocidad del algoritmo y el análisis de una componente del dominio wavelet que esté bien localizada en el tiempo, ambos requisitos se pueden cumplir si se elige el análisis del detalle d1, que es el que tiene la menor resolución en frecuencia pero la mayor resolución en el tiempo, a la vez que es el que más rápido se puede determinar, puesto que se obtiene directamente después del primer filtrado (Fig. 2.2).

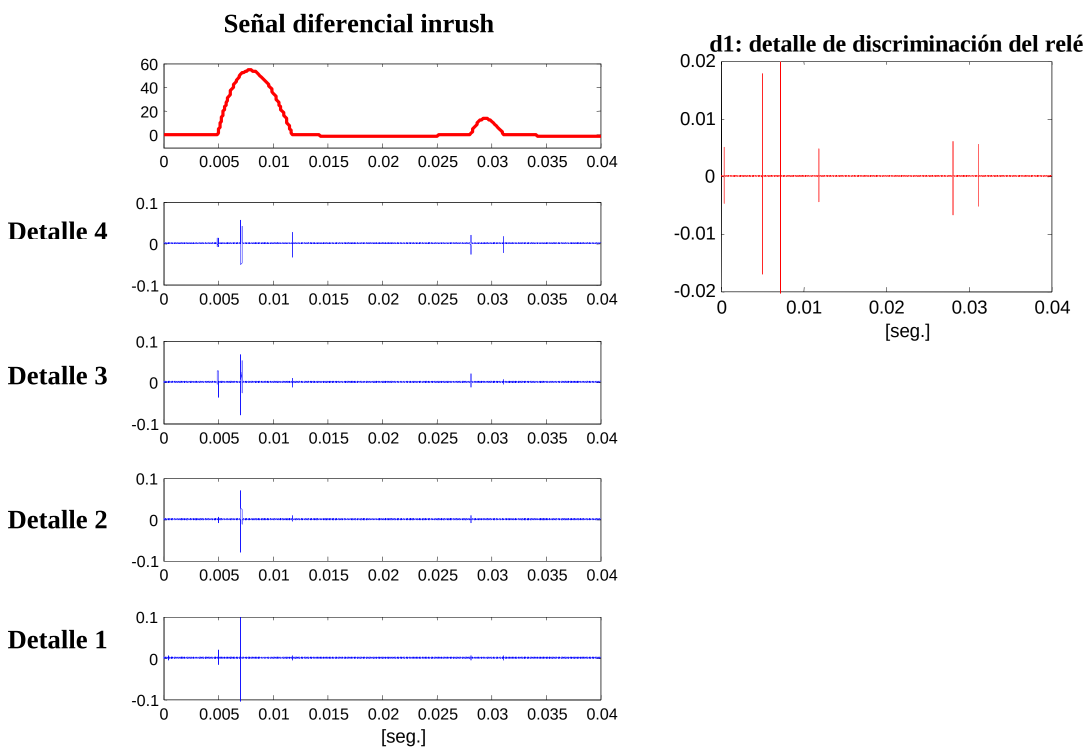


Fig. 2.3.- Corriente diferencial “inrush” y su descomposición empleando la transformada wavelet discreta (DWT) tipo Daubechies 4 con cuatro niveles de descomposición.

2.2.1.2.- Análisis de corrientes de falta interna

La Fig. 2.4, muestra el resultado de la DWT de la corriente diferencial originada por una corriente de falta interna en el transformador.

A partir del análisis del detalle 1 (12.5 - 6.25 kHz) se observa que existe una distorsión de la señal en altas frecuencias, esto es posiblemente una consecuencia de los efectos de la capacitancia e inductancia de la línea de transmisión, lo cual puede producir una significativa segunda armónica en la corriente de falta, dificultando la discriminación exacta entre corriente "inrush" y corriente de falta interna por el método convencional de retención de segundo armónico.

También es posible observar en el detalle 1 que el máximo de la señal corresponde al instante en que se produce la falta, el cual va progresivamente disminuyendo. No existen en este caso impulsos en determinados instantes de tiempo.

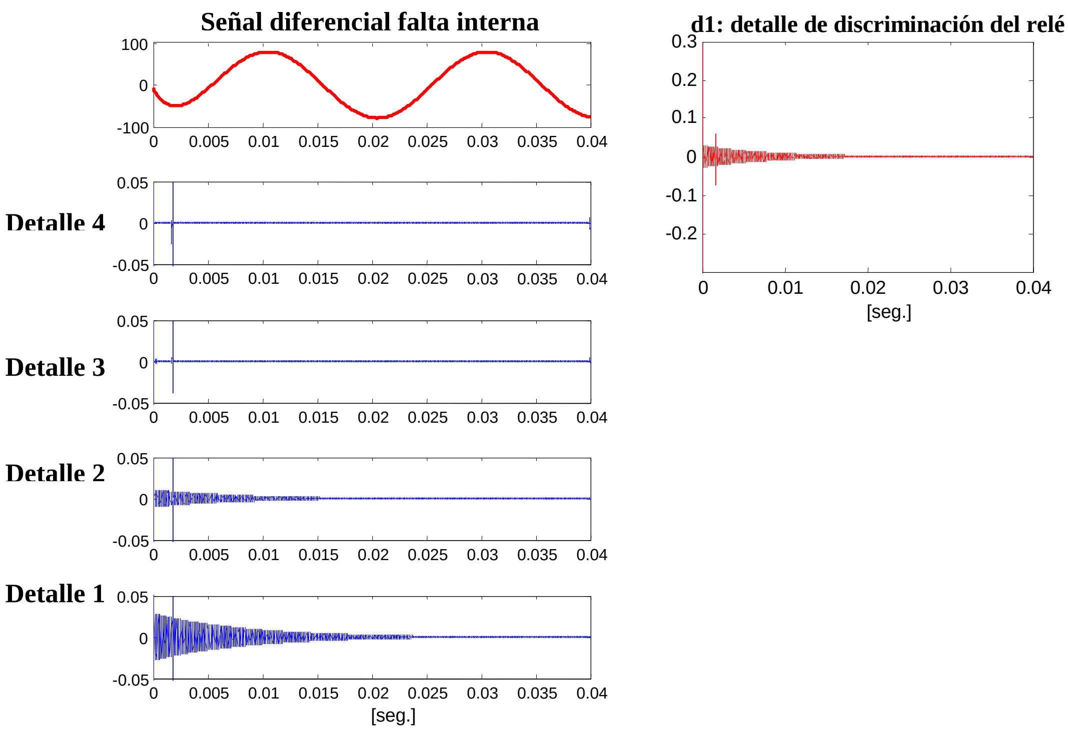


Fig. 2.4.- Corriente diferencial ante una falta interna y su descomposición empleando la transformada wavelet tipo Daubechies 4 con cuatro niveles de descomposición.

2.2.1.3. Análisis de corrientes de falta externa

La Fig. 2.5 muestra el resultado de la DWT de la corriente diferencial originada por una corriente de falta externa al transformador. En el detalle 1 puede observarse que igual que en los otros casos también existen componentes de altas frecuencias, de hecho la forma de la señal es similar al caso del análisis con “inrush”, sin embargo, los impulsos que aparecen en el detalle 1 tienen una distribución diferente que permite diferenciarlos del caso del “inrush”, puesto que sus magnitudes relativas son prácticamente iguales.

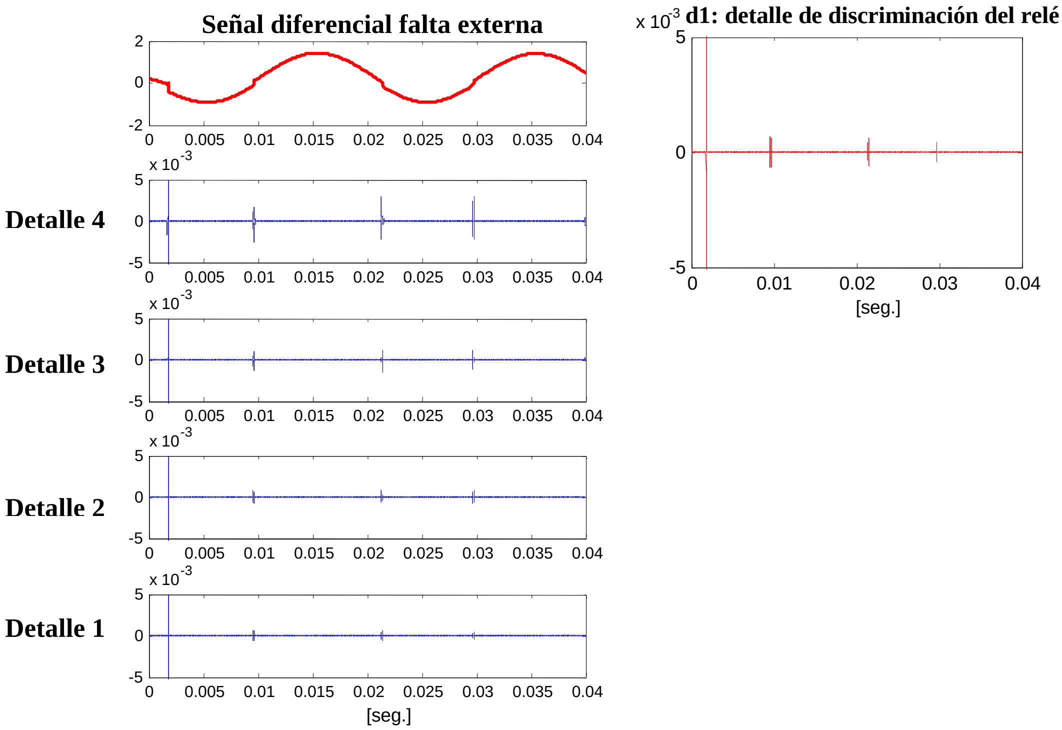


Fig. 2.5.- Corriente diferencial ante una falta externa y su descomposición empleando la transformada wavelet tipo Daubechies 4 con cuatro niveles de descomposición.

2.2.2. Selección de la wavelet madre

Para evaluar el efecto de la wavelet madre en el problema de estudio, se han analizado los casos anteriores de “inrush”, falta interna, falta externa considerando la wavelet madre Sym 4 y Haar. Las Fig. 2.6 a Fig. 2.11, muestran los resultados obtenidos.

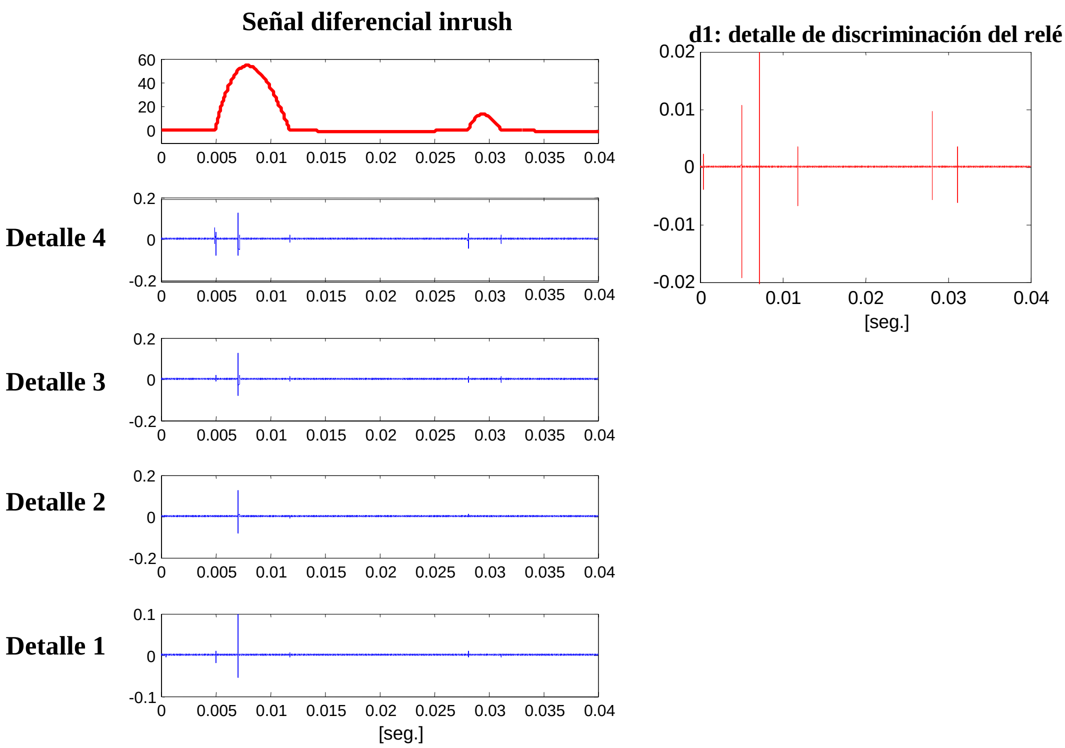


Fig. 2.6.- Corriente diferencial "inrush" y su descomposición empleando la transformada wavelet tipo Symlet 4 y cuatro niveles de descomposición.

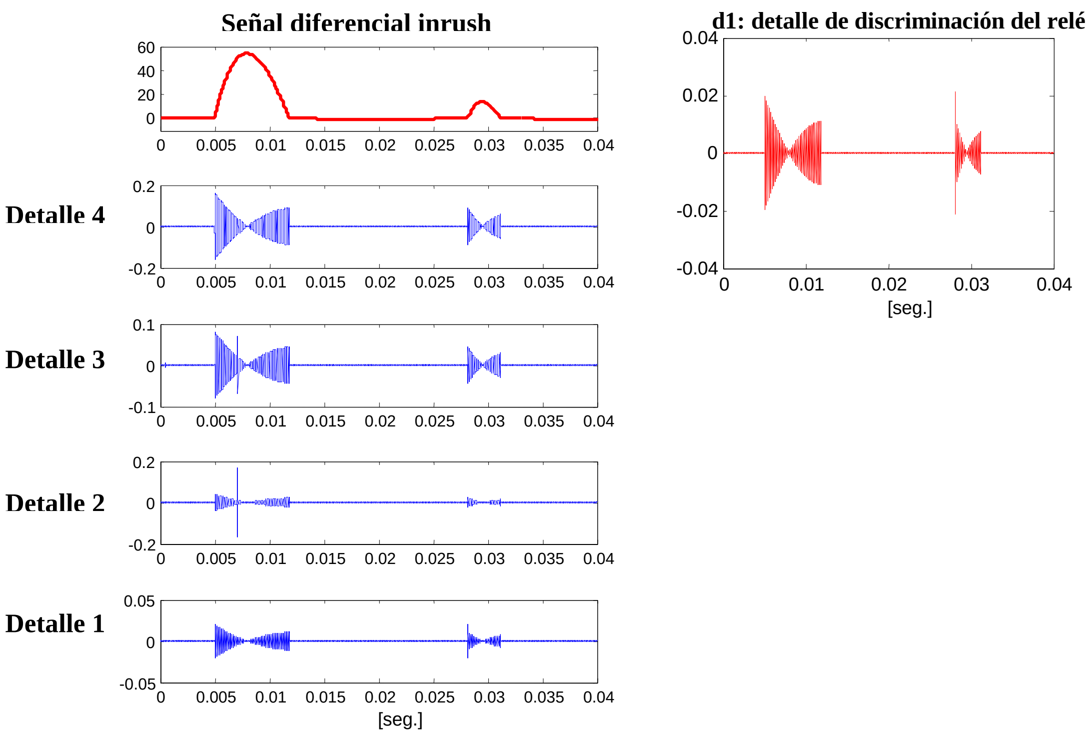


Fig. 2.7.- Corriente diferencial "inrush" y su descomposición empleando la transformada wavelet tipo Haar y cuatro niveles de descomposición.

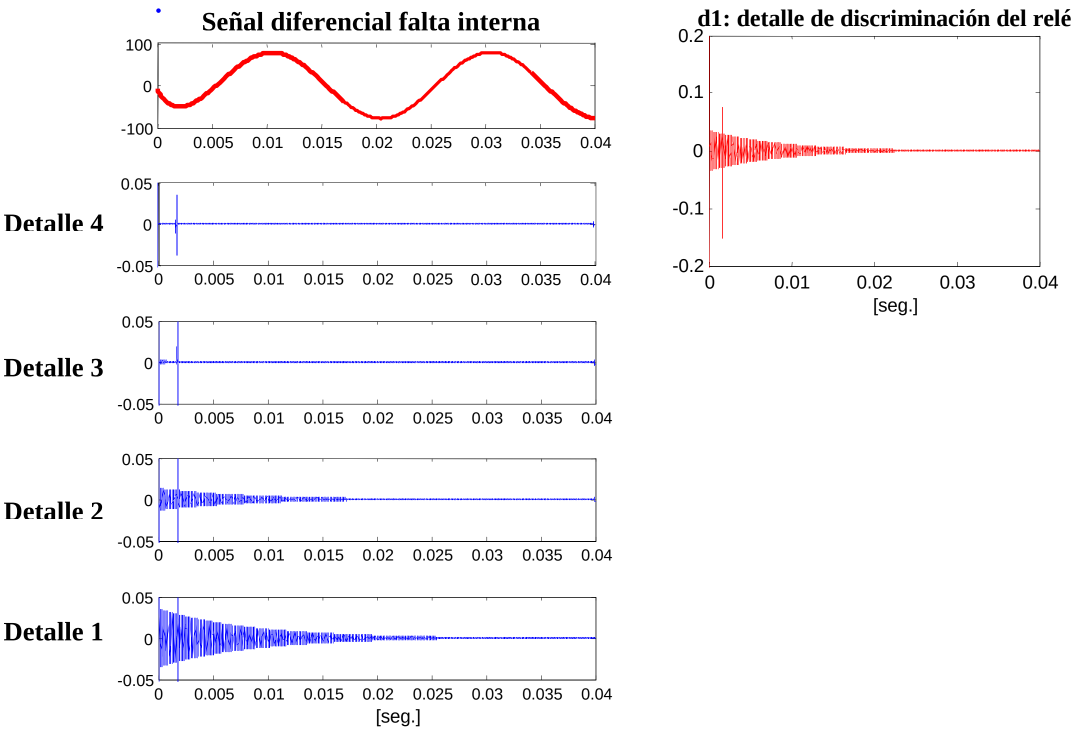


Fig. 2.8.- Corriente diferencial ante falta interna y su descomposición empleando la transformada wavelet tipo Symlet 4 con cuatro niveles de descomposición.

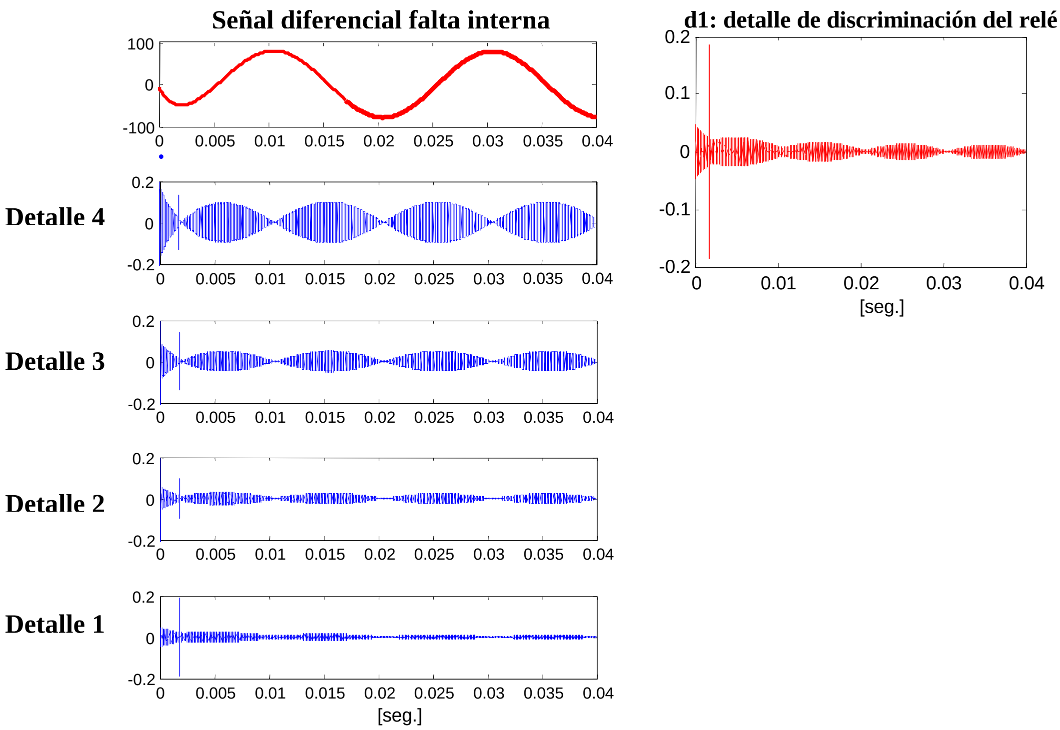


Fig. 2.9.- Corriente diferencial ante falta interna y su descomposición empleando la transformada wavelet tipo Haar con cuatro niveles de descomposición.

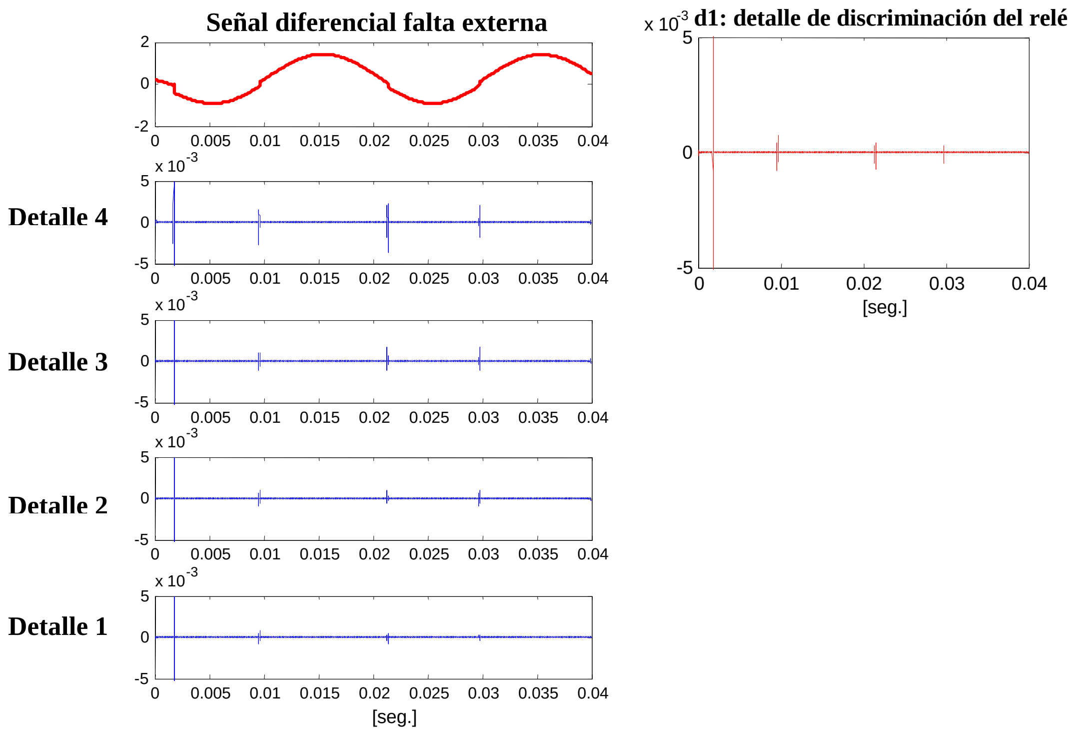


Fig. 2.10.- Corriente diferencial ante falta externa y su descomposición empleando la transformada wavelet tipo Symlet 4 con cuatro niveles de descomposición.

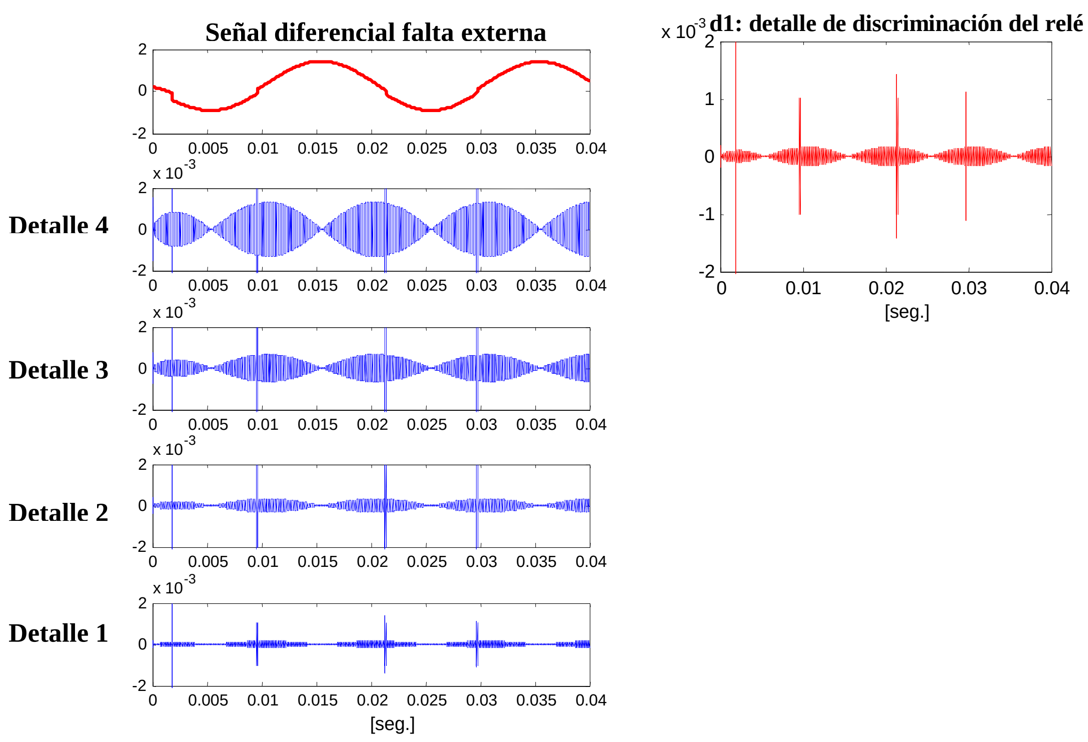


Fig. 2.11.- Corriente diferencial ante falta externa y su descomposición empleando la transformada wavelet tipo Haar con cuatro niveles de descomposición.

En cualquiera de los casos puede observarse de la Fig. 2.6 a la Fig. 2.11 que en este problema el tipo de wavelet que debe utilizarse no es un parámetro muy crítico, puesto que cualquier wavelet de la familia Daubechies o symlet resulta apropiada, excepto la wavelet básica Haar que no muestra diferencias importantes entre los diferentes casos de interés estudiados.

2.2.3. Comparación de las características de las señales analizadas

A partir del análisis de la simulación de los distintos casos de interés presentados y bajo distintas condiciones (ángulo de conexión, resistencia de falta, etc), puede identificarse que las corrientes diferenciales presentan las siguientes características :

- Para el caso de faltas internas (Fig. 2.4) se observa que la principal diferencia con los otros casos es la fuerte presencia de una envolvente de alta frecuencias en el detalle 1 que tiende a decaer a cero.

- En el caso del "inrush" se observa que las componentes de alta frecuencia sólo aparecen en determinados instantes de tiempo como un impulso que rápidamente se hace cero y cuyas magnitudes relativas son muy diferentes entre su antecesor y predecesor.

- En el caso de falta interna al observar el detalle 1 puede verse la aparición de componentes de altas frecuencias que también se presentan como impulsos de corta duración, pero que tienen magnitudes relativamente iguales entre sí.

Capítulo 3

DISEÑO DEL ALGORITMO DEL RELÉ

3.1. Introducción

En este capítulo se propone un criterio de operación del relé para discriminar si existe o no una condición de falta en el transformador a partir de un índice que cuantifica las características del detalle 1 de la transformada wavelet (Daubechies 8) de la corriente diferencial del transformador. A partir de este criterio se diseña un algoritmo para el funcionamiento del relé diferencial con discriminación por ondículas el que ha sido implementado en Matlab 6.0.

Finalmente se muestran diferentes casos críticos a fin de evaluar la correcta operación del relé.

3.2. Detección y discriminación del relé

A partir de los resultados de la simulación de diferentes casos de interés se ha demostrado que la transformada wavelet puede utilizarse para discriminar entre una condición de falta y una condición de operación normal de un transformador de potencia.

El criterio que se ha desarrollado para discriminar si existe o no una condición de falta en el transformador está basado en un índice que cuantifica las características del detalle 1 de la transformada wavelet (Daubechies 8) de la corriente diferencial del transformador. Este índice se muestra en la siguiente ecuación:

$$I_{ratio} = 2 \cdot \frac{I_{d1,max}}{\sum_{k=1}^{n} \left| I_{d1}^{(k)} \right|} \tag{1}$$

donde :

$I_{d1,max}$: Máxima componente del detalle 1 de la corriente diferencial.

$I_{d1}^{(k)}$: k-ésima componente del detalle 1 de la corriente diferencial.

n : Número de puntos de la señal muestreada.

El índice I_{ratio} se calcula en una ventana de muestreo con una longitud predefinida, para los estudios realizados se ajustó esta longitud a medio ciclo (10 ms a 50 Hz). A fin de garantizar una correcta detección de la perturbación ésta ventana se desplaza cada cuarto de ciclo (5 ms a 50 Hz).

De esta forma el criterio de discriminación entre falla interna, externa e “inrush” se hace en función del valor que alcanza este índice en una determinada ventana, de modo que si este es valor es superior a un umbral prefijado (threshold) entonces se está ante la presencia de una falta interna, en cualquier otro caso no existe falta interna. El umbral utilizado fue de threshold = 0.25

La expresión analítica de Iratio, así como el valor threshold se obtuvieron experimentalmente a partir de sucesivos ensayos con el sistema de prueba propuesto haciendo uso de un programa de cálculo implementado en Matlab y que se detallará en el capítulo 4.

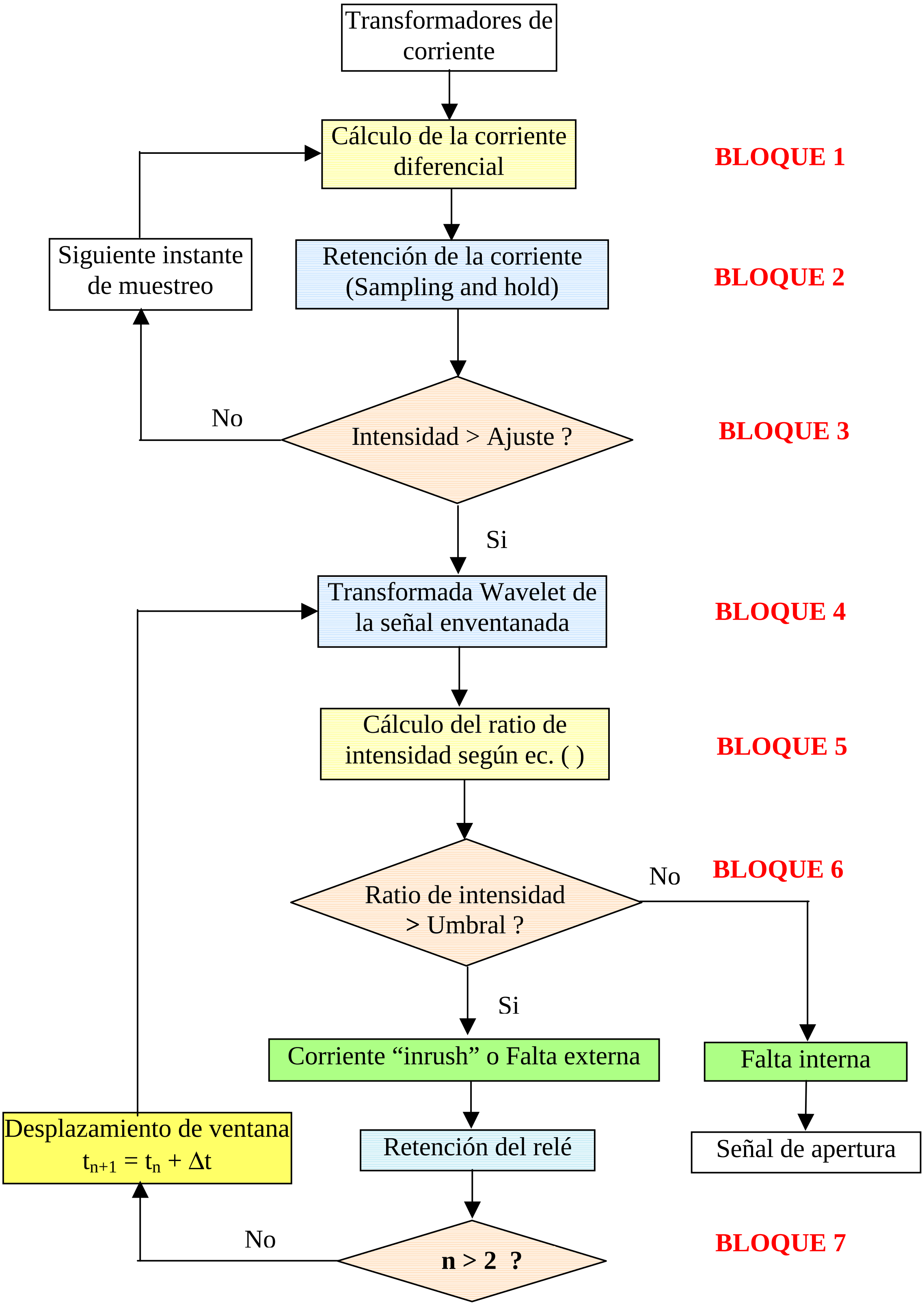


Fig. 3.1.- Diagrama de flujo del funcionamiento del relé diferencial con discriminación por ondículas.

En la Fig. 3.1 se muestra el diagrama de flujo de la lógica de decisión implementada. En el bloque (1) se recibe la señal correspondiente a la corriente diferencial y en el bloque (2) se almacena en un buffer durante medio ciclo (10 ms).

Luego, en el bloque (3) se realiza una comparación entre las corrientes diferenciales medidas y el ajuste de la corriente de retención (porcentaje del relé). Este ajuste es necesario para evitar falsas operaciones debido por ejemplo a errores en los transformadores de corriente y cambio de tomas. El relé se activa si la corriente diferencial es mayor que la corriente de retención; si este es el caso, en el bloque (4) se procede a calcular el detalle d1 de la transformada wavelet discreta utilizando Daubechies 8 y una ventana de anchura de 10 ms.

Finalmente para discriminar la existencia o no de una falta interna se evalúa el índice Iratio, bloque (5); si éste índice es mayor que un umbral, el relé enviará una orden de apertura, en caso contrario el relé no actuará y se seguirán registrando valores de la intensidad diferencial.

La forma de discriminación del relé se realiza a partir de la información obtenida del detalle 1 de la transformada wavelet discreta aplicada a una ventana de amplitud 10 ms de la corriente diferencial. El primer análisis wavelet después de detectada la perturbación se realiza considerando la ventana de 10 ms de la información “histórica” almacenada en el buffer, por lo tanto la primera ventana puede contener poca información de la señal originada por la falta, en consecuencia el relé no discriminaría de manera correcta; por esta razón, se considera una segunda ventana de 10 ms desfasada 5 ms respecto de la primera, cuya amplitud estará compuesta por 5 ms de información de pre-detección de falta más 5 ms de información de post detección falta, con lo cual, ya en este caso, al menos el 50% de la información analizada corresponde a la señal originada por la falta. Las pruebas realizadas muestran que para discriminar faltas externas e “inrush” es suficiente la primera ventana, sin embargo, para algunos casos de faltas internas el relé necesita el uso de la segunda ventana.

En consecuencia, para asegurar siempre la correcta actuación del relé se considera la segunda ventana como discriminante, es decir el valor de Iratio proporcionado en esta ventana determina la actuación o no del relé (bloque 6 y 7 de la Fig. 3.1).

Como la discriminación se realiza a partir de la segunda ventana, el tiempo para tomar la decisión es de al menos :

$$t_{\text{decisión}} = t_2 - t_1 \tag{2}$$

donde t_2 es el instante de tiempo correspondiente al término de la segunda ventana y t_1 es el instante de tiempo de término de la primera ventana (activación del relé). Por lo tanto el tiempo de actuación en el esquema propuesto de relé diferencial estaría dentro de los 10 ms (medio ciclo).

3.3. Evaluación de resultados.

Con la finalidad de evaluar la exactitud del modelo de protección propuesto se han estudiado tres casos típicos de posibles operaciones del relé: corriente “inrush”, falta interna, falta externa.

3.3.1. Caso corriente “inrush”

En la Fig. 3.2, se muestra un ejemplo del algoritmo de discriminación del relé al existir una corriente “inrush”. Tal como se aprecia en la Fig. 3.2 a) esta corriente produce un alto valor de la corriente diferencial, mucho mayor que la admisible (ajuste: área rayada) por lo cual se activa el algoritmo de discriminación, evaluándose en una ventana de muestreo de 10 ms. el detalle d1 (Fig. 3.2 b)) y el valor del índice Iratio, que tal como se aprecia en la Fig. 3.2 c) es mayor que el umbral de 0.25, lo que significa que no se está en presencia de una condición de falta interna, por lo cual el relé no actúa. La segunda ventana de muestreo que se muestra en la Fig. 3.2 corrobora que el relé también discrimina apropiadamente en este intervalo de tiempo.

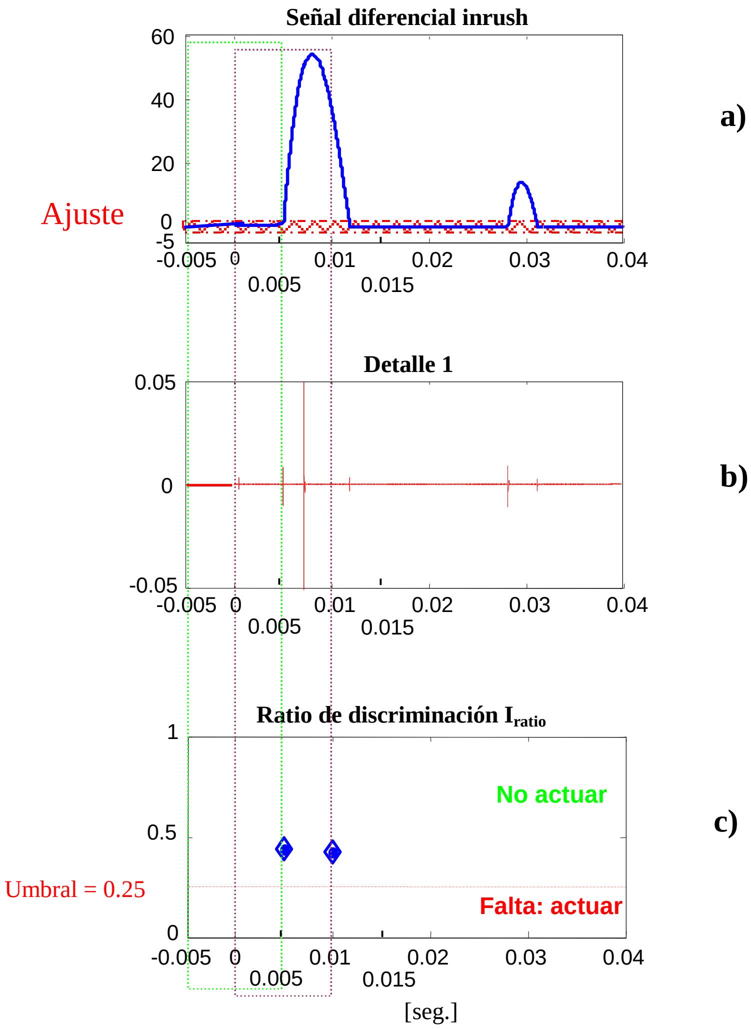


Fig. 3.2.- Ejemplo de operación del relé diferencial con discriminación por wavelet ante una energización (corriente "inrush").

3.3.2. Caso falta externa

En el caso de una falta externa puede producirse un incremento de la corriente diferencial, Fig. 3.3, debido a la posible saturación de los transformadores de corriente. Este hecho puede producir que se supere el límite de corriente diferencial permisible (ajuste: área rayada) con lo cual se activa el algoritmo de discriminación del relé. Sin embargo, tal como se aprecia en la Fig. 3.3 c), el relé no detecta esta situación como falta, demostrando una adecuada selectividad. También puede observarse en la Fig. 3.3 que la operación del relé es correcta ya sea en la primera o en la segunda ventana de muestreo.

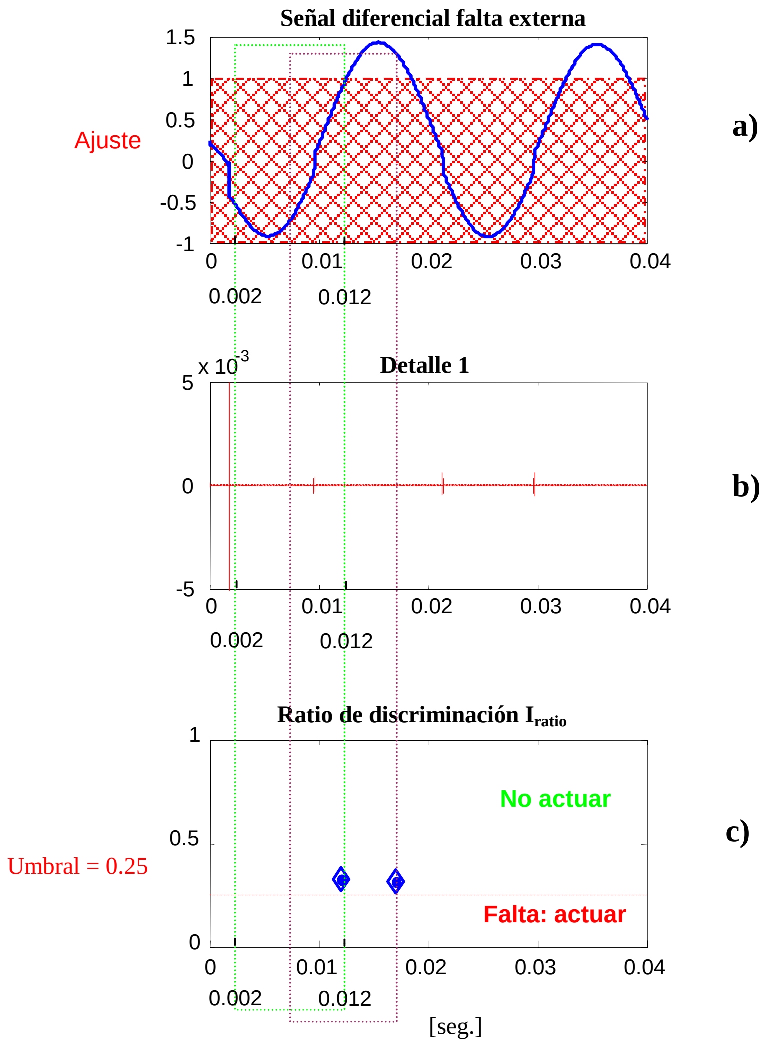


Fig. 3.3.- Ejemplo de operación del relé diferencial con discriminación por wavelet ante una falta externa.

3.3.3. Caso falta interna

En este caso se ha simulado una falta interna en el secundario del transformador de potencia originada por un cortocircuito franco a tierra. En la Fig. 3.4 puede observarse como opera el relé para este caso.

En la Fig. 3.4 a), se observa la corriente diferencial de falta medida en los secundarios de los transformadores de corriente de la protección diferencial (curva en azul) y el porcentaje de ajuste del réle (área rayada), que determinan si debe o no ejecutarse el algoritmo de discriminación para establecer que tipo de perturbación existe en el transformador.

Cuando se detecta que la corriente diferencial es mayor que el ajuste (t = 0 o instante de la perturbación) se calcula el detalle d1 de la DWT de esta señal (Fig. 3.4 b)) considerando una ventana que abarca un intervalo de tiempo de 10 ms, que comienza en el instante t = -10 ms (datos históricos) y termina en t = 0 ms. (ventana verde).

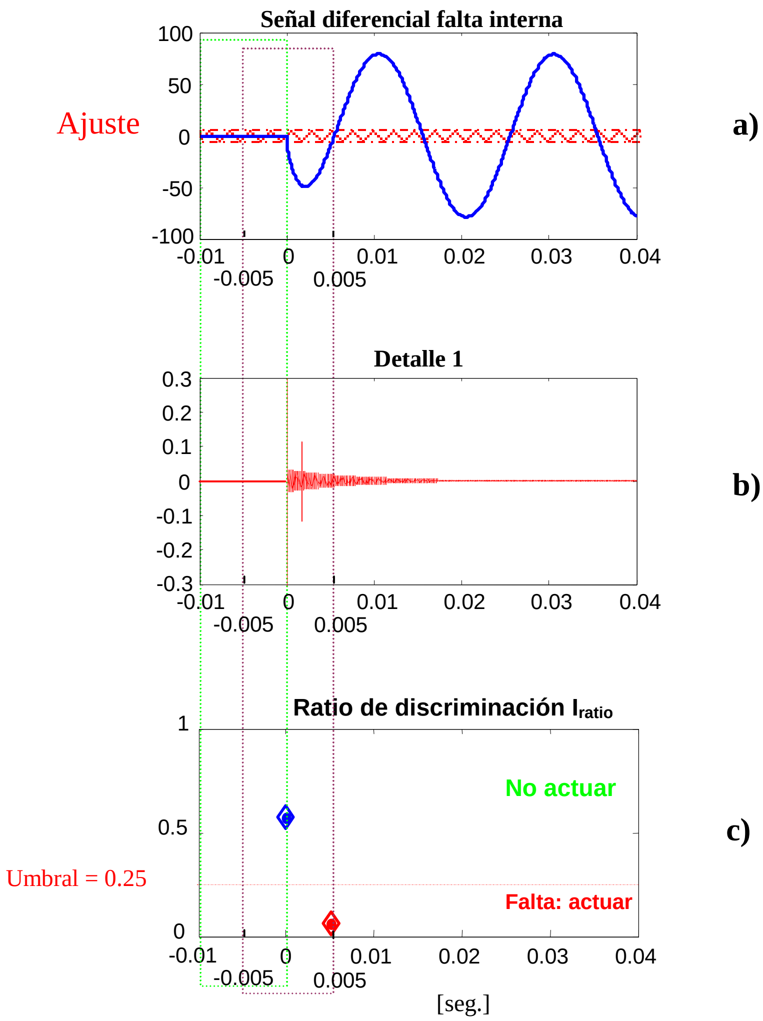


Fig. 3.4.- Ejemplo de operación del relé diferencial con discriminación por wavelet ante una falta interna.

El resultado de la operación del relé (evaluación del Iratio) se puede observar en la Fig. 3.4 c), donde se aprecia que Iratio en la ventana de color verde es mayor que el umbral de 0.25 (punto de color azul), lo que indicaría que el relé no actuaría; sin embargo, debería hacerlo puesto que se está en presencia de una falta interna, la razón de esta aparente insensibilidad se debe al hecho que en este caso la señal que evalúa el algoritmo corresponde a información histórica (-10 ms antes de la perturbación) donde aún no aparece la falta. Por este motivo se toma una segunda ventana (ventana magenta) de 10 ms. desfasada 5 ms. con respecto a la primera, de este modo al menos el 50% de la información corresponde a la falta. Como se aprecia en la Fig. 3.4 c) el Iratio para esta segunda ventana es menor que el umbral y por lo tanto el relé discrimina apropiadamente la existencia de la falta interna.

El caso comentado corresponde a la peor situación factible y corrobora que la segunda ventana es la que sirve para discriminar la existencia de una falta en cualquiera de los casos.

Capítulo 4

IMPLEMENTACIÓN DEL ESQUEMA PROPUESTO

4.1. Introducción

En este capítulo se presenta el programa desarrollado en Matlab 6.0 para simular la operación de la protección diferencial de un transformador en base a un relé numérico que discrimina por un análisis de wavelets, se explica el funcionamiento del programa a través de la descripción de cada uno de los bloques que constituyen la interfaz gráfica diseñada.

Con el esquema de protecciones propuesto se han analizado 44 casos que consideran diferentes perturbaciones, "inrush", falta externa, falta interna así como diferentes variables de interés (instante de la falta, resistencia de falta, etc.). Los resultados demuestran la correcta discriminación del relé en el 100% de los casos estudiados.

4.2. Programa realizado

La evaluación del algoritmo del relé diferencial propuesto se hizo a través de un programa de ordenador utilizando Matlab 6.0 (Anexo I), para una mejor presentación del algoritmo propuesto se realizó una interfaz gráfica que permite seleccionar de manera eficiente y sencilla los diversos casos de interés (Fig. 4.8). Básicamente esta interfaz está estructurada con los siguientes bloques:

4.2.1. Bloque I: Representación esquemática del caso a analizar

Contiene una representación gráfica esquemática del caso de estudio.

4.2.2. Bloque II: Selección de perturbación

Tal como se aprecia en la Fig. 4.1 en este bloque es posible seleccionar una señal que represente una determinada perturbación, para ello basta con especificar si se desea evaluar un condición de "inrush" para un cierto ángulo de conexión (0º, 30º, 60º o 90º) y si se considerará una falta interna o externa con una determinada resistencia de falta (0, 0.01, 1.0 o 100 ohm).

A partir de la información anterior el programa determina el tipo específico de perturbación que se evaluará y obtiene la señal correspondiente, la que previamente ha sido calculada con el programa ATP.

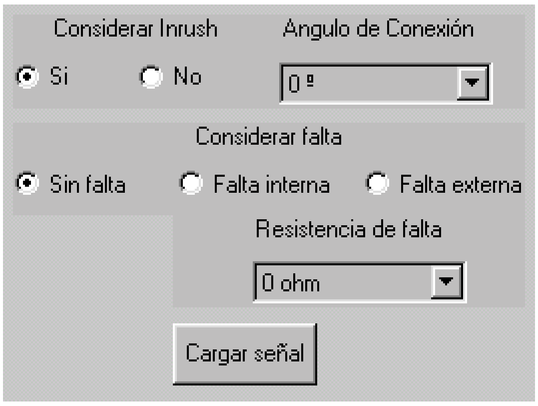


Fig. 4.1.- Bloque de selección de perturbación.

4.2.3. Bloque III: Presentación de la señal de estudio

En este bloque (Fig. 4.2) se muestra la señal obtenida por simulación en ATP, la cual representa la corriente diferencial medida para la perturbación especificada en el bloque I a partir de los secundarios de los transformadores de medida ubicados en cada lado del transformador de potencia.

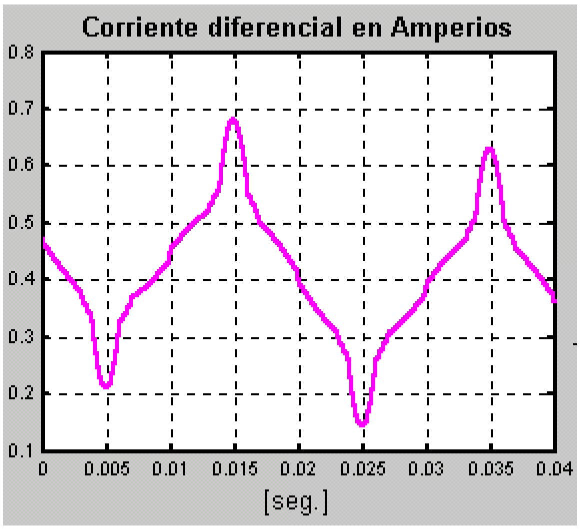


Fig. 4.2.- Bloque que muestra la señal correspondiente a la corriente diferencial originada por una perturbación.

4.2.4. Bloque IV : Selección de Wavelet

En este bloque (Fig. 4.3) es posible seleccionar la wavelet madre (Daubechies, Haar, Symlet), su tipo (1, 2, 3..) y su nivel de descomposición (1, 2, 3....). De esta manera se especifica completamente la wavelet que se empleará para el análisis.

El cálculo de la transformada wavelet se realiza utilizando el toolbox de wavelet disponible en Matlab 6.0.

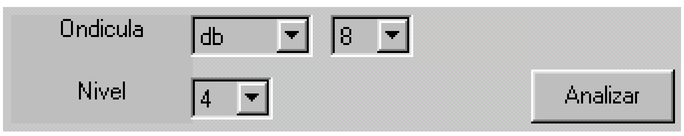


Fig. 4.3.- Bloque de selección de la wavelet madre que se utilizará para el análisis.

4.2.5. Bloque V : Presentación de la transformada wavelet, detalles y aproximación

En este bloque (Fig. 4.4) se presenta el resultado de la evaluación de la transformada wavelet, en él se muestran cada uno de los k-niveles de descomposición con sus respectivos detalles (d_i) , así como la aproximación (a_k)

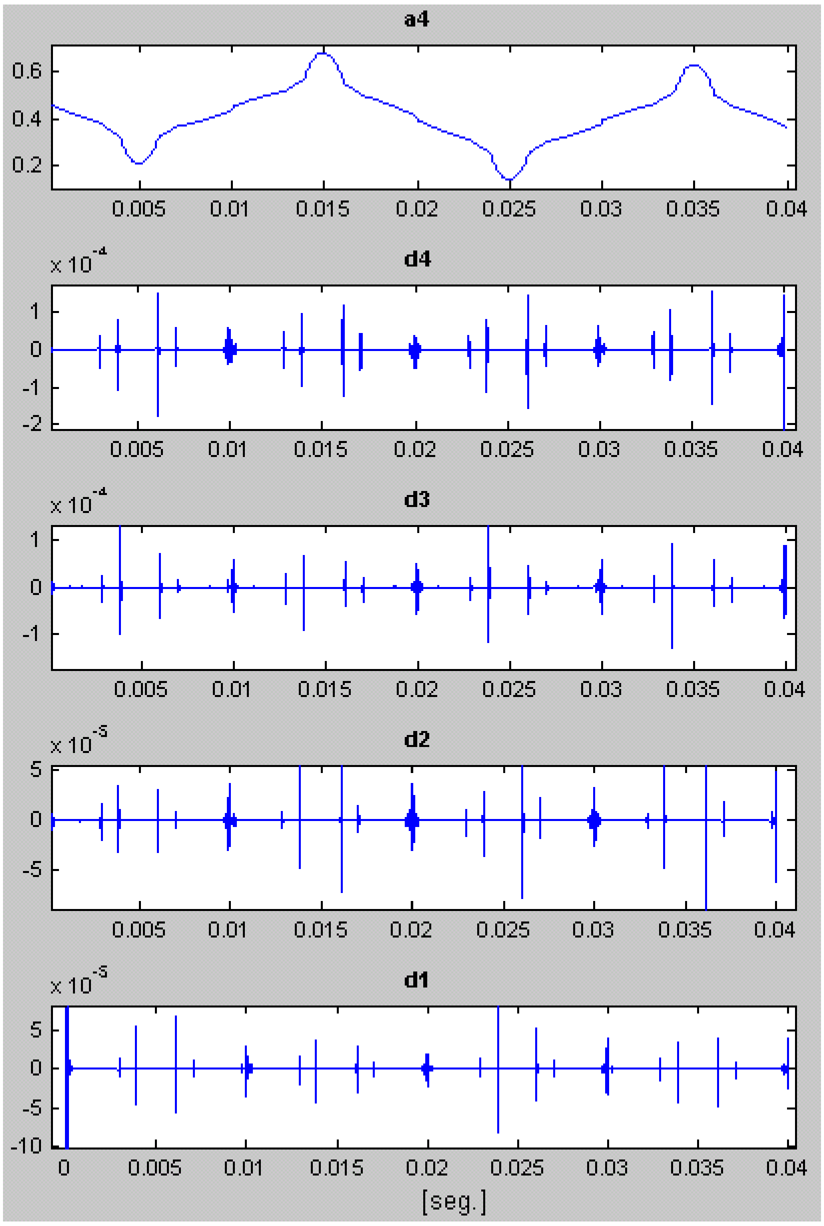


Fig. 4.4.- Bloque de presentación del resultado de la transformada wavelet de la señal de entrada.

4.2.6. Bloque VI : Presentación del detalle d1 de la transformada wavelet de la corriente diferencial y ejecución del algoritmo del relé

El objetivo de este bloque (Fig. 4.5) es mostrar de mejor forma el detalle d1 de la transformada wavelet de la corriente diferencial, pues a partir de la información que contiene se discrimina la existencia o no de una falta interna en el transformador. El análisis de esta situación se realiza mediante el botón “ejecutar”.

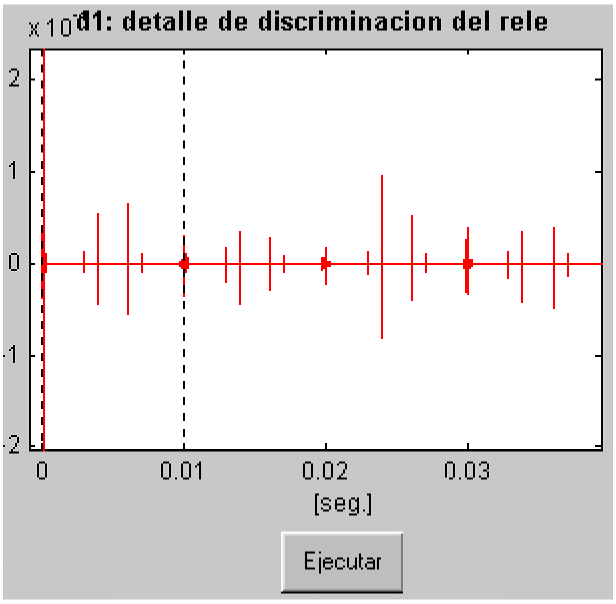


Fig. 4.5.- Bloque de presentación del detalle d1 de la transformada wavelet de la corriente diferencial y ejecución del algoritmo del relé.

4.2.7. Bloque VII: Presentación del resultado del análisis de la perturbación

En este bloque se muestra el resultado del análisis de la perturbación, es decir la discriminación que realiza el relé para determinar si existe o no falta interna.

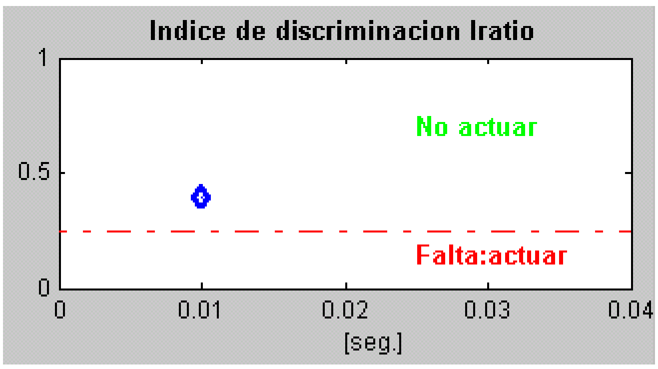


Fig. 4.6.- Bloque de presentación del índice de discriminación Iratio.

4.2.8. Bloque VIII : Análisis de Fourier

En este bloque (Fig. 4.7) se realiza el análisis de Fourier considerando dos periodos de la señal correspondiente a las corrientes diferenciales. El objetivo de este análisis es demostrar la importancia del contenido de segundo armónico, que muchas veces, en los esquemas tradicionales de protecciones, se utiliza como criterio para discriminar la existencia o no de falta interna en el transformador.

El esquema de protección basado en este criterio de discriminación evalúa el contenido relativo del segundo armónico con respecto al fundamental. En el caso de "inrush" el contenido de segundo armónico es mayor que el de la componente fundamental y esto es lo que se utiliza como criterio de discriminación; sin embargo, en el caso de falta interna no siempre el contenido de segundo armónico es menor que la fundamental, por lo cual el relé perdería selectividad.

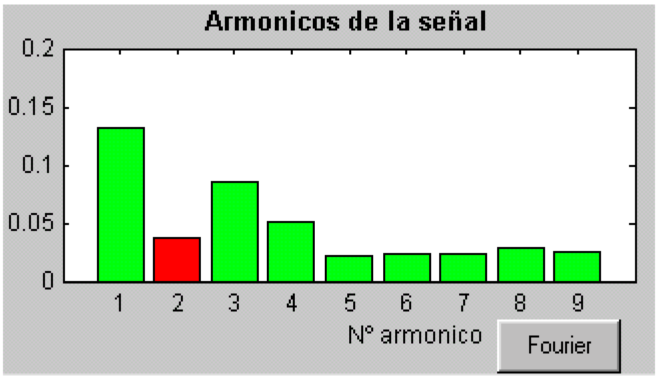


Fig. 4.7.- Bloque de presentación del resultado del análisis de Fourier de la señal correspondiente a la corriente diferencial.

En la Fig. 4.8, se muestra la interfaz gráfica del programa realizado que contiene los bloques anteriormente descritos.

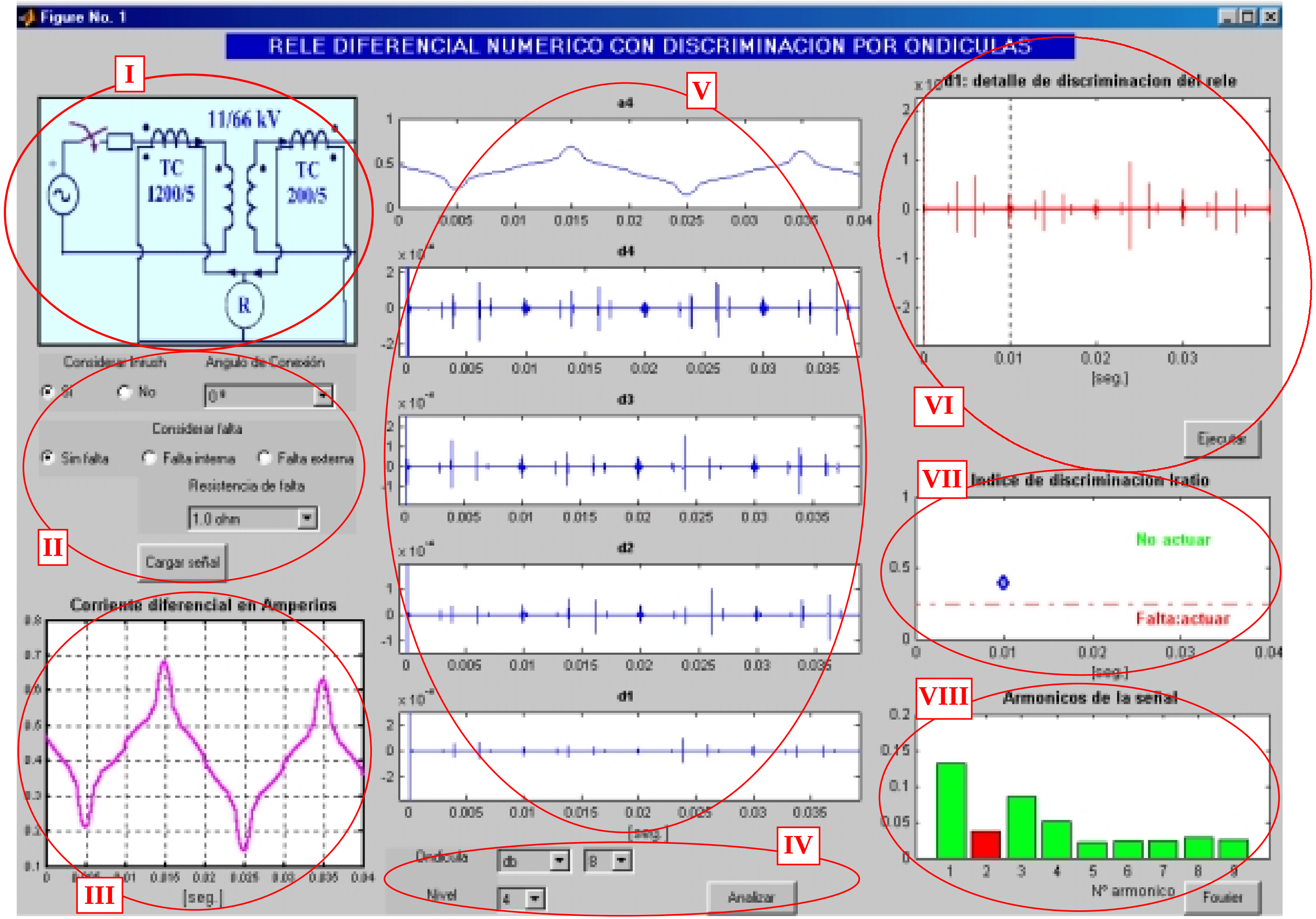


Fig. 4.8.- Interfaz gráfica del programa realizado en Matlab. [ondiculas.m]

4.3. Evaluación de resultados

Con el esquema de protecciones propuesto se han analizado 44 casos que consideran diferentes perturbaciones, “inrush”, falta externa, falta interna y combinaciones entre ellas, así como el efecto del instante de ocurrencia de la falta y su resistencia. Los resultados se muestran en la tabla 4.1 y demuestran la correcta discriminación del relé en el 100% de los casos estudiados.

A modo de ejemplo en las Fig. 4.9 a Fig. 4.13 se muestran los resultados de los siguientes casos:

a) Inrush con ángulo de conexión de 90º.

b) Falta interna con resistencia de falta de 100 Ω.

c) Falta externa con resistencia de falta de 0 Ω.

d) Inrush con ángulo de conexión de 90º y falta interna con resistencia de falta de 100 Ω.

e) Inrush con ángulo de conexión de 90º y falta externa con resistencia de falta de 0 Ω.

Tabla 4.1.- Resultados de los casos analizados.

Tipo de pertubación	Características de la perturbación		Discriminación del relé
INRUSH	Angulo de conexión		**Correcta/Incorrecta**
	0º		Correcta
	30º		Correcta
	60º		Correcta
	90º		Correcta
FALTA INTERNA	Resistencia de falta		**Correcta/Incorrecta**
	0.00 Ω		Correcta
	0.01 Ω		Correcta
	1.00 Ω		Correcta
	100 Ω		Correcta
FALTA EXTERNA	Resistencia de falta		**Correcta/Incorrecta**
	0.00 Ω		Correcta
	0.01 Ω		Correcta
	1.00 Ω		Correcta
	100 Ω		Correcta
INRUSH + FALTA INTERNA	Angulo	Resistencia	**Correcta/Incorrecta**
	0º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
	30º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
	60º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
	90º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
INRUSH + FALTA EXTERNA	Angulo	Resistencia	**Correcta/Incorrecta**
	0º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
	30º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
	60º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta
	90º	0.00 Ω	Correcta
		0.01 Ω	Correcta
		1.00 Ω	Correcta
		100 Ω	Correcta

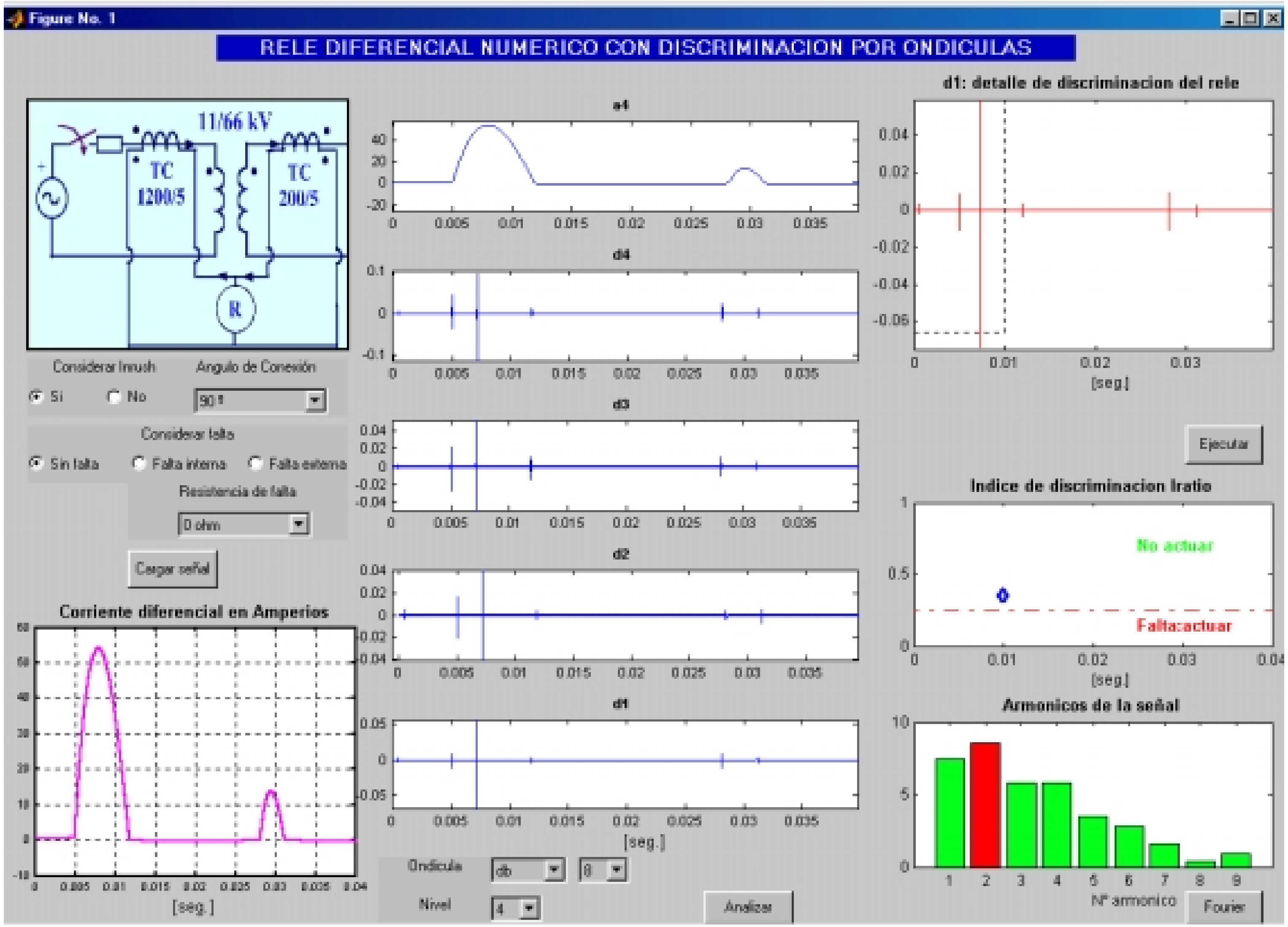


Fig. 4.9.- Resultado del análisis de operación del relé producto de la conexión del transformador ("inrush"), considerando un ángulo de conexión de 90 º. [ondiculas.m]

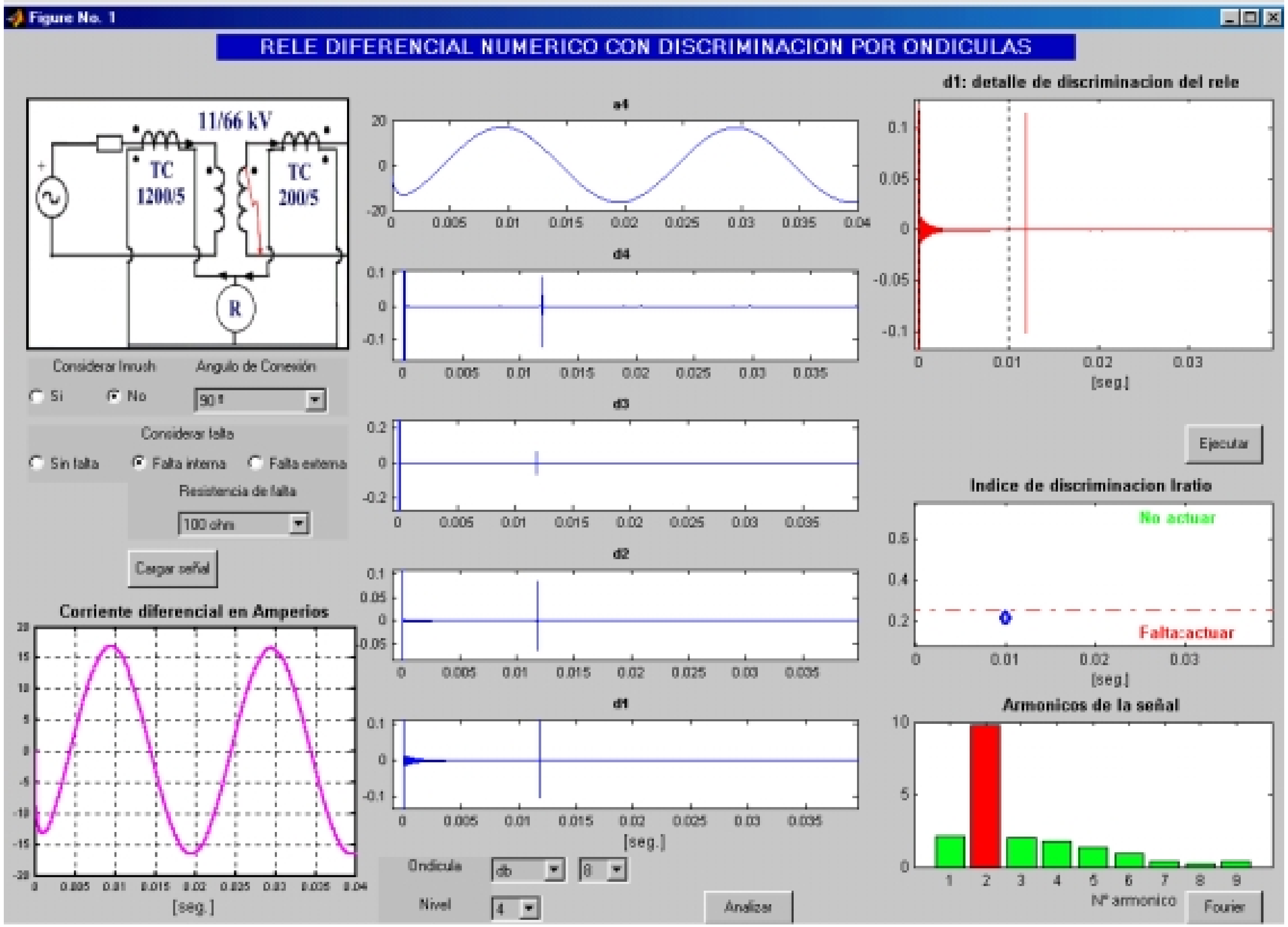


Fig. 4.10.- Resultado del análisis de operación del relé producto de una falta interna considerando una resistencia de falta de 100 Ω. [ondiculas.m]

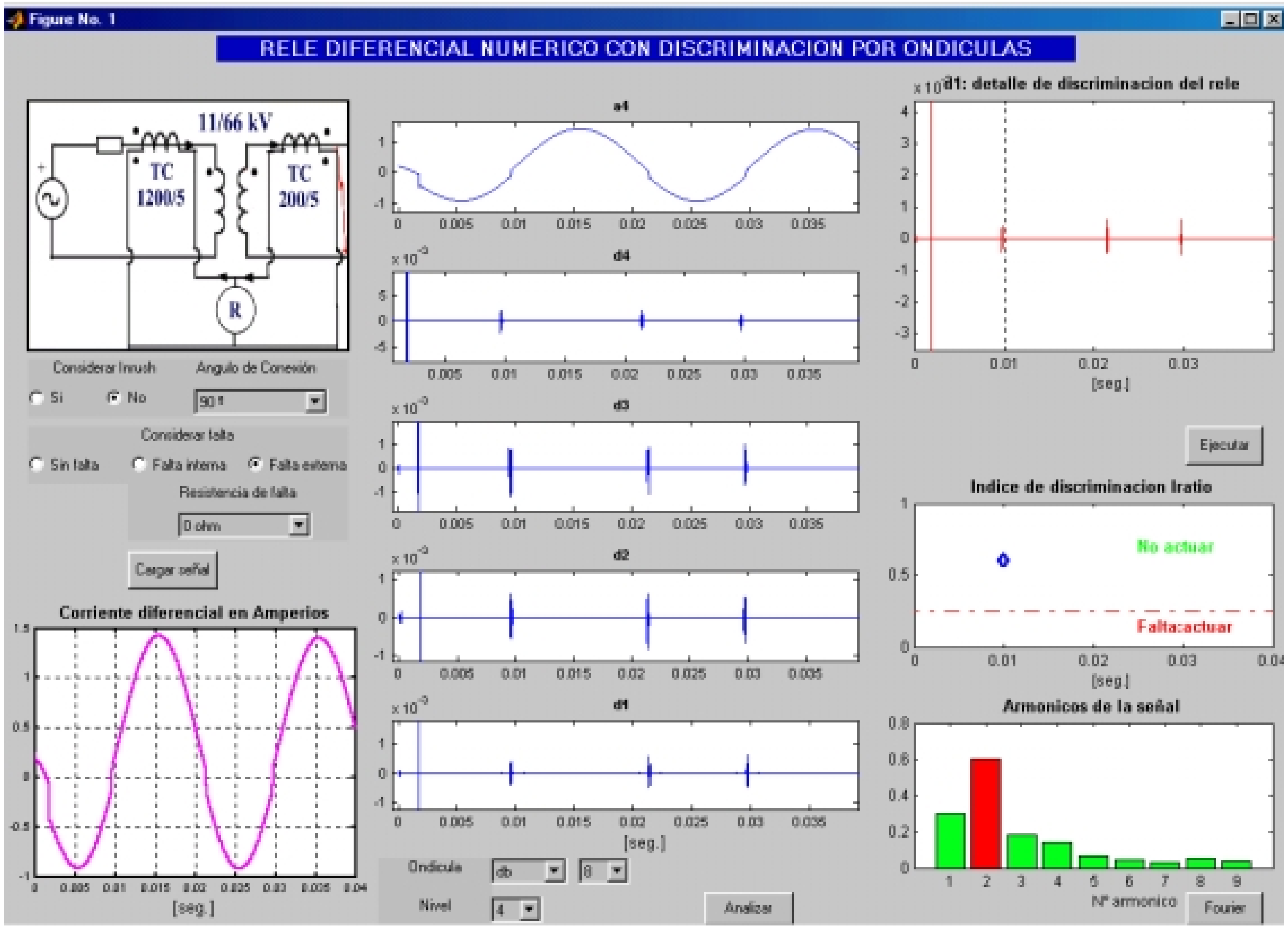


Fig. 4.11.- Resultado del análisis de operación del relé producto de una falta externa considerando una resistencia de falta de 0 Ω. [ondiculas.m]

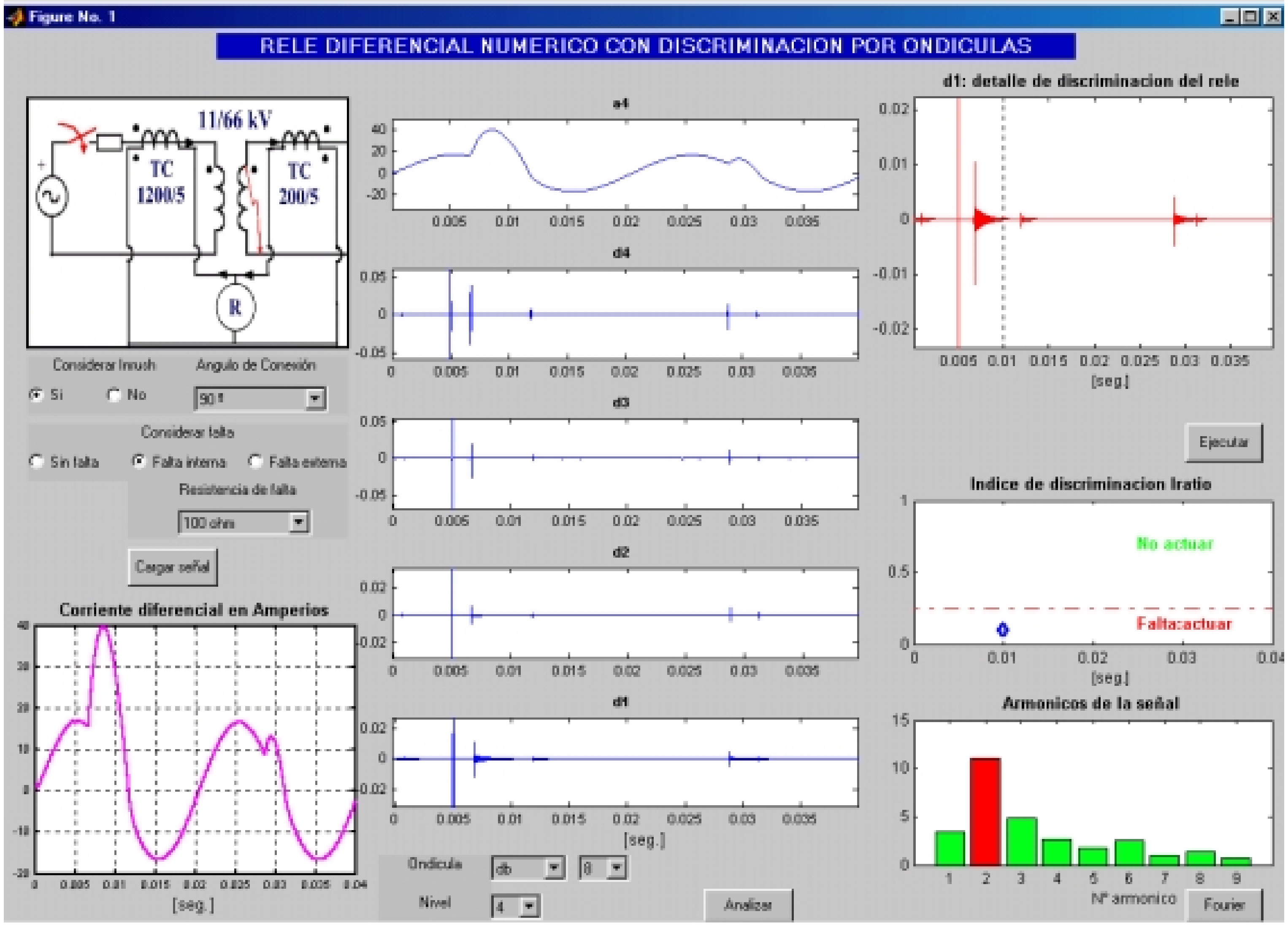


Fig. 4.12.- Resultado del análisis de operación del relé producto de una falta interna considerando una resistencia de falta de 100 Ω en el instante de energización del transformador (“inrush”) considerando un ángulo de conexión de 90º. [ondiculas.m]

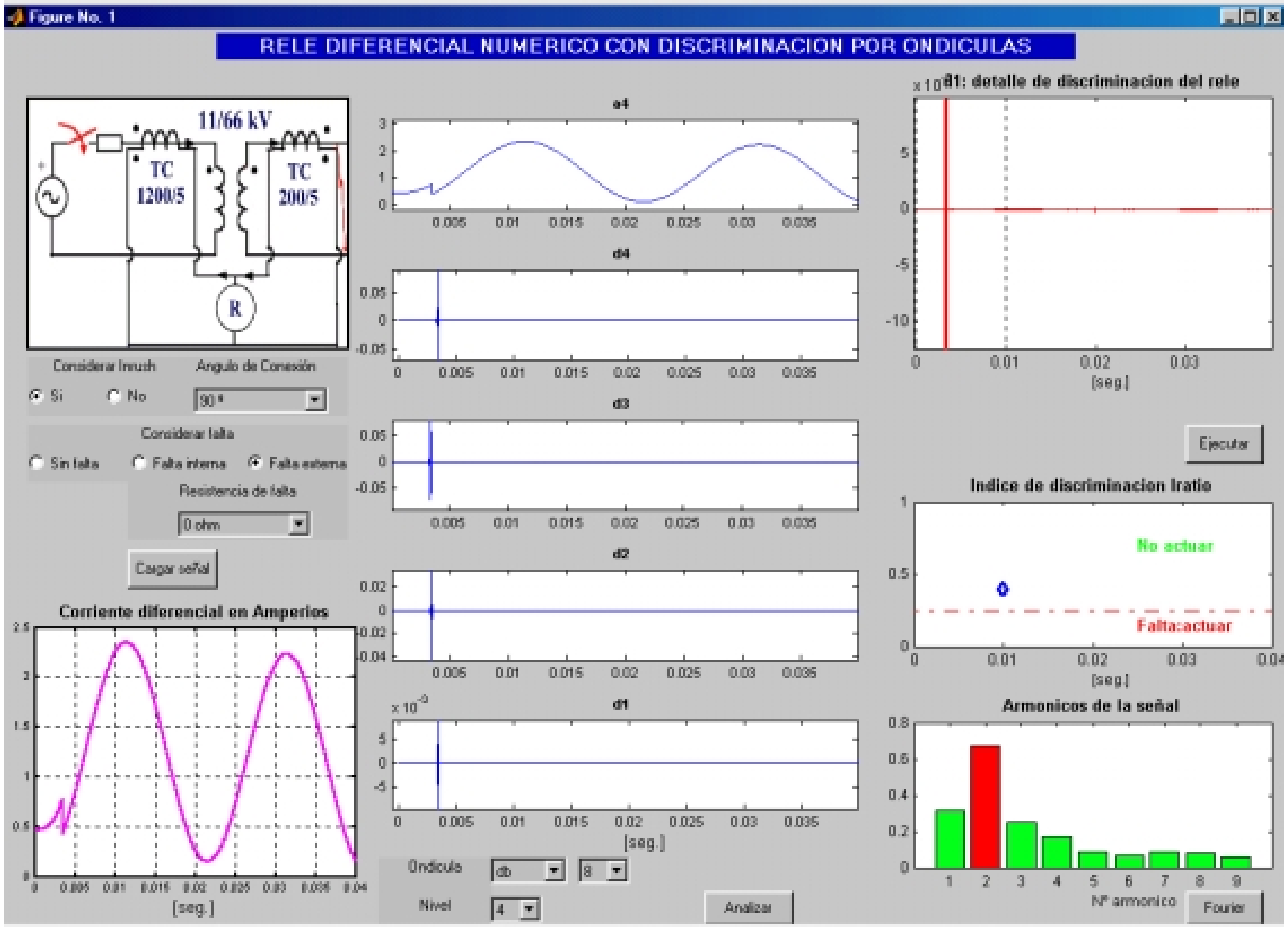


Fig. 4.13.- Resultado del análisis de operación del relé producto de una falta externa considerando una resistencia de falta de 0 Ω en el instante de energización del transformador ("inrush") considerando un ángulo de conexión de 90º. [ondiculas.m]

Capítulo 5

APLICACIÓN DE LAS WAVELETS EN SISTEMAS DE POTENCIA

5.1. Introducción

Este capítulo presenta una visión descriptiva de las aplicaciones de la transformada Wavelet en los sistemas eléctricos de potencia, mostrando las líneas de investigación que hasta el momento se han llevado a cabo, así como la evolución de los trabajos publicados en los últimos años.

La aparición de la transformada Wavelet (WT) como herramienta matemática ha sido bastante reciente, aunque las ideas esenciales en las que se basa han sido objeto de análisis durante bastante tiempo antes de que se plasmaran de forma analítica. Básicamente, se trata de una transformación lineal, al igual que la transformada de Fourier (FT), sin embargo a diferencia de la anterior, proporciona la localización en el dominio del tiempo de las diferentes componentes en frecuencia presentes en una señal dada. La transformada de Fourier enventanada (STFT) consigue parcialmente la identificación frecuencia-tiempo, pero la anchura fija de la función ventana que emplea supone una limitación. En el caso de la WT, las funciones de análisis llamadas wavelets, realizan la correlación tiempo-frecuencia de tal forma que las wavelets de alta frecuencia serán más estrechas y las de baja frecuencia serán más anchas.

El empleo de esta herramienta se ha utilizado en varios trabajos que cubren áreas diversas, y sobre todo en los últimos diez años se han logrado beneficios en la aplicación de esta transformada a los sistemas eléctricos de potencia, sobre todo, entre otras cosas, debido al interés en el análisis y procesado de señales tensión-corriente para realizar una identificación de fenómenos transitorios en tiempo real de forma rápida y exacta.

Las principales publicaciones existentes en este campo han sido analizadas y clasificadas por áreas destacando las contribuciones realizadas por sus autores o indicando la línea de investigación que siguen.

Se detallan en este capítulo las siguientes áreas de estudio:

- Descargas parciales
- Protecciones en los sistemas de potencia
- Transitorios en los sistemas de potencia

Para disponer de la información del resto de áreas de estudio remitirse al informe "Análisis de la teoría wavelet orientada a las aplicaciones en ingeniería eléctrica: Fundamentos".

En el anexo II se recogen las referencias bibliográficas de todas las publicaciones estudiadas incluyendo un resumen de las mismas. También se proporciona un cd- rom que contiene una base de datos de todas las referencias bibliográficas que se han estudiado.

Por lo tanto el objetivo de este capítulo es proporcionar una visión descriptiva de las aplicaciones de la transformada Wavelet en los sistemas de potencia a aquellos que deseen introducirse por primera vez en este tema. Para lo cual, las principales publicaciones existentes en este campo han sido analizadas y clasificadas por áreas.

5.2. Aplicación de las wavelets en los Sistemas Eléctricos de Potencia

Las wavelets se aplicaron por primera vez a los sistemas de potencia eléctricos en 1994 por Robertson y Ribeiro. A partir de este año el número de publicaciones en esta área han mostrado una tendencia creciente tal como muestra la Fig. 5.1.

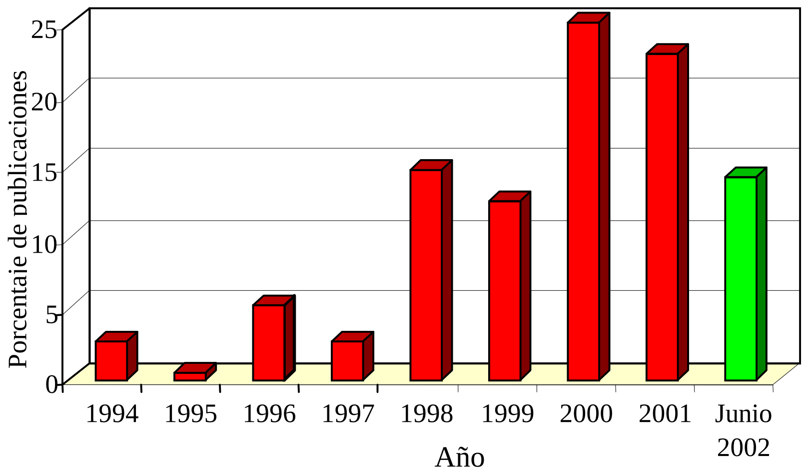


Fig. 5.1.- Evolución de los trabajos publicados que consideran la aplicación de la transformada wavelet en los sistemas eléctricos de potencia.

La mayor parte de los trabajos publicados se centran en el análisis de métodos de identificación y clasificación de las señales medidas, sin embargo, hasta ahora pocos estudios emplean la transformada wavelet como técnica de análisis de fenómenos transitorios para resolver el problema de evaluar las tensiones e intensidades que se propagan a lo largo del sistema.

Las aplicaciones más relevantes de la transformada Wavelet a los sistemas eléctricos de potencia se han centrado en las siguientes áreas de estudio:

- Protección de sistemas eléctricos de potencia
- Calidad del servicio
- Transitorios en sistemas eléctricos de potencia
- Descargas parciales
- Estimación de la demanda
- Medida de potencia

La Fig. 5.2 muestra el porcentaje de publicaciones que existen en cada una de las áreas indicadas anteriormente, donde se observa que el área de las protecciones y de la calidad de servicio son los campos donde se han realizado más estudios.

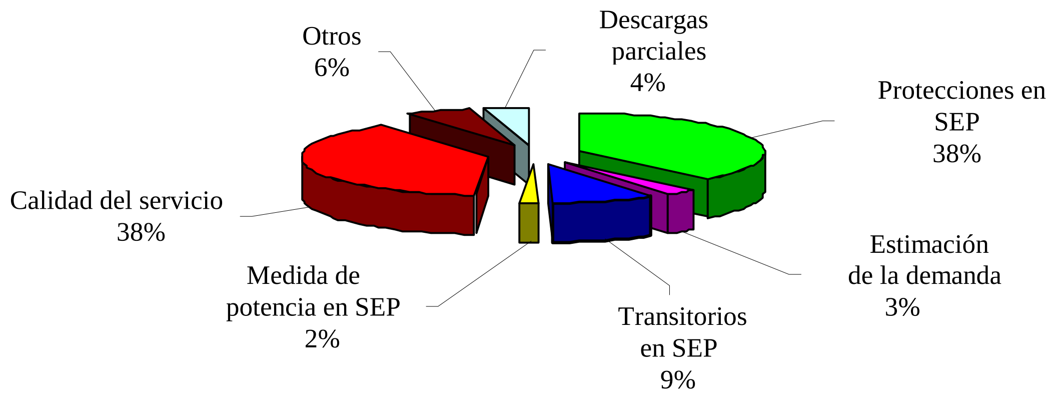


Fig. 5.2.- Porcentaje de las publicaciones que emplean la transformada Wavelet agrupadas en diferentes áreas de los sistemas eléctricos de potencia.

Las próximas secciones presentan una descripción general de la aplicación de las wavelets a las áreas de Descargas parciales, Protecciones en los sistemas eléctricos de potencia y Transitorios en los sistemas eléctricos de potencia, antes mencionadas.

5.2.1. Descargas parciales

Las descargas parciales son señales difíciles de detectar debido a su corta duración, alta frecuencia y baja amplitud, pero la capacidad de la transformada wavelet para ampliar en el tiempo las señales con discontinuidades en clara ventaja respecto a la transformada de Fourier, permite la identificación de variaciones locales de una señal. Los trabajos presentados en [26-32] aplican estos principios para detectar descargas parciales en los devanados de transformadores, cables y subestaciones aisladas con gas (GIS).

5.2.2. Protecciones en los sistemas eléctricos de potencia

Las ventajas en la aplicación de la transformada wavelet para la mejora en el funcionamiento de los relés de protección ha sido destacada en los últimos años, como muestran los trabajos [33-97]. En 1996, Chaari et al. [77] introducen la técnica wavelet para el campo de las protecciones de los sistemas eléctricos de distribución para analizar las señales transitorias producidas en faltas a tierra en una red resonante con neutro a tierra de 20 kV generada a partir del programa EMTP. En el mismo año Momoh et al presentan un algoritmo para desarrollar un extractor de características adecuado para el entrenamiento de una red neuronal artificial para la diagnosis de faltas empleando la transformada wavelet, en este caso los datos del caso se obtuvieron de forma experimental.

En 1998 Magnago y Abur desarrollan una nueva línea de investigación en el área de la localización de faltas empleando las wavelets, para lo cual la onda viajera asociada a la falta generada se procesa con la transformada wavelet para mostrar los tiempos que existen entre el instante en que se produce la falta y la localización de la misma por los relés. Para comprobar y validar el método de localización de faltas propuesto emplean simulaciones en el programa EMTP. En 1999 los mismos autores extienden el método a la identificación de faltas laterales en sistemas radiales de distribución [63] y en 2000 presentan un método mejorado para sus anteriores trabajos [60].

Métodos similares al anterior para la localización de faltas se pueden encontrar en los trabajos presentados en [55] y [76].

La identificación de faltas de alta impedancia [80]-[89]-[91] es otra área de aplicación de la transformada wavelet, así Charytoniuk presenta en [91] un análisis comparativo para la localización de las faltas con arco en el dominio del tiempo, frecuencia y tiempo-frecuencia (wavelet), el autor concluye que la alternativa wavelet es fuertemente dependiente de la familia wavelet escogida, nivel de descomposición, velocidad de muestreo y del comportamiento de la falta con arco.

El empleo de las wavelets en el área de la reconexión automática [92]-[97] se desarrolla para acelerar la apertura de las líneas de transmisión. La transformada wavelet se emplea para analizar los transitorios asociados a la falta generados por segundo arco, así como, las faltas permanentes; los resultados numéricos revelan que ciertos componentes de la wavelet pueden ser usados para detectar e identificar de forma eficiente las características relevantes de la falta en los sistemas eléctricos de transmisión, como también para la distinción entre faltas transitorias y permanentes.

La transformada wavelet también se ha aplicado a la protección de barras [33], de motores [38-43], de generadores [36]-[37] y de transformadores [44-54], en la mayoría de estos casos, el espectro de las señales se analiza con la transformada wavelet para desarrollar un algoritmo en línea para la detección de la degradación del aislante, corriente de conexión ("inrush") y para una precisa discriminación entre faltas internas y externas.

5.2.3. Transitorios en sistemas eléctricos de potencia

Las wavelets fueron por primera vez aplicadas al estudio de los transitorios de los sistemas eléctricos de potencia en 1994. En este trabajo, los autores presentan una metodología para desarrollar un software que clasifica las perturbaciones en los sistemas de potencia a partir de la forma de la onda transitoria originada por la perturbación. La forma de la onda se analiza mediante la transformada wavelet aplicada a la señal transitoria.

En 1996, Robertson et. al. [101] aplican las wavelets para el análisis de los transitorios derivados de la conexión de bancos de condensadores. Los autores realizan una implementación digital de la transformada wavelet mediante un análisis a partir de un conjunto de filtros, poniendo de manifiesto que cualquier wavelet válida puede ser empleada en esta implementación.

Hasta este momento, los estudios se han centrado en métodos de identificación de transitorios, es decir, identificar una perturbación transitoria y en algunos casos clasificarla de acuerdo a su espectro wavelet. En [102]-[103], Heydt y Galli proponen el empleo de la wavelet Morlet como técnica de análisis de los transitorios en los sistemas eléctricos de potencia como herramienta de solución analítica. Pero en este caso el término análisis se refiere a encontrar la solución de tensiones y corrientes que se propagan a lo largo del sistema debido a una perturbación transitoria.

En 2000, Meliopoulos [107], presenta un método alternativo para el análisis de los transitorios en los sistemas eléctricos de potencia. Esta alternativa se basa en las serie wavelets de expansión y reconstrucción. La matriz del sistema se desarrolla a partir del empleo de las series wavelets de expansión en las ecuaciones integro-diferenciales del sistema de potencia. El procedimiento da como resultado un conjunto de ecuaciones algebraicas para la red entera. La solución se presenta en función de los coeficientes wavelets de expansión para la tensión en los nudos de la red. Las tensiones además, pueden ser reconstruidas a partir de las series wavelets de reconstrucción.

La identificación de la corriente de conexión en los transformadores ("inrush") [109]-[111], basada en wavelet, tiene la ventaja que las corrientes de conexión en estos equipos pueden ser correctamente identificadas frente a faltas internas en el mismo; además, las faltas externas en transformadores pueden distinguirse de las faltas internas.

Aparte de la aplicación de las wavelets para el desarrollo de métodos de identificación, clasificación y análisis como los presentados anteriormente, en este momento se está estudiando la aplicación de las wavelets para el desarrollo de nuevos modelos para componentes. Así, en 2001, Abur el al [116] extienden los resultados de trabajos previos [115] y describen un modelo para línea de transmisión basado en la transformada wavelet teniendo en cuenta la dependencia con la frecuencia de las matrices de transformación modales en la simulación de transitorios. Se presenta un enfoque diferente para la simulación de la dependencia de la frecuencia de los transitorios en las líneas de transmisión no transpuestas. El efecto de la fuerte dependencia con la frecuencia de las matrices modales de transformación en los transitorios de las líneas de transmisión se tiene en cuenta para la simulación en el dominio del tiempo mediante el empleo de la transformada wavelet aplicada a las señales. Esto permite el uso de matrices modales de transformación exactas que varían con la frecuencia y que todavía se mantienen en el dominio del tiempo durante las simulaciones.

5.3. Resultado del análisis del estado del arte

En este capítulo se presentó una descripción de la aplicación de la transformada Wavelet a los sistemas eléctricos de potencia a fin de determinar el impacto que ha tenido el empleo de esta transformada en esta área. Para ello, se han revisado las últimas publicaciones que existen en este campo y se ha realizado una clasificación de las aplicaciones. Se ha incluido una breve descripción para tres áreas: Calidad del servicio, Estimación de la demanda y Medida de potencia, para mostrar la forma en la que se ha empleado la transformada wavelet para resolver problemas típicos.

Como resultado del análisis de la documentación analizada de la aplicación de las wavelets a los sistemas eléctricos de potencia se puede concluir lo siguiente:

- La mayor parte de las aplicaciones desarrolladas en esta área emplean datos de señales obtenidas a partir de programas de análisis de transitorios como el EMTP/ATP y programas específicos de manejo de wavelets como el wavelet toolbox de Matlab.

- Uno de los desarrollos más prometedores en esta área es el realizado en el campo de las protecciones para la detección y localización de faltas de alta rapidez.

- El futuro de la aplicación de la teoría wavelet a los sistemas eléctricos de potencia se encuentra en el desarrollo de nuevos modelos para el análisis de los transitorios en los sistemas de potencia.

- Los desarrollos teóricos necesarios para adentrarse y mejorar en este campo se encaminarán hacia la elección adecuada de la transformada wavelet para cada aplicación específica.

- El empleo de las multiwavelets y las wavelets de segunda generación deberían ser el nuevo camino a desarrollar para mejorar las aplicaciones actuales y futuras.

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Antecedentes Matemáticos

1989

[1] **A theory for multiresolution signal decomposition: the wavelet representation**
S. Mallat
IEEE Transactions on Pattern Analysis and Machine Intelligence Vol 11, Nr0. 7, 198Jul. 1989
Page(s):674-693
Abstract :
Multiresolution representations are effective for analysing the information content of images. The properties of the operator which approximates a signal at a given resolution were studied. It is shown that the difference of information between the approximation of a signal at the resolutions 2/sup j+1/ and 2/sup j/ (where j is an integer) can be extracted by decomposing this signal on a wavelet orthonormal basis of L/sup 2/(R/sup n/), the vector space of measurable, square-integrable n-dimensional functions. In L/sup 2/(R), a wavelet orthonormal basis is a family of functions which is built by dilating and translating a unique function psi (x). This decomposition defines an orthogonal multiresolution representation called a wavelet representation. It is computed with a pyramidal algorithm based on convolutions with quadrature mirror filters. Wavelet representation lies between the spatial and Fourier domains. For images, the wavelet representation differentiates several spatial orientations. The application of this representation to data compression in image coding, texture discrimination and fractal analysis is discussed.

1992

[2] **Ten Lectures on wavelets**
Daubechies, I.
Capital City Press, 1992

1996

[3] **Special No. on wavelets**

Proceedings of the IEEE , Apr. 1996,
Pages(s): 507-688

Tutorial

General

1991

[4] **Wavelet for kids**

Brani Vidakovic; Peter Muller
Duke University
Abstract :
26 páginas que presentan un tutorial general sobre wavelet.
Se incluye el desarrollo del concepto de wavelet, los diferentes tipos y aparece un ejemplo "sencillo" basado en la wavelet más fundamental, también existe un programa de wavelet disponible via ftp.El tutorial no muestra ni discute nada con respecto a wavelet en sistemas de potencia.

1994

[5] **Wavelets and wideband correlation processing**

Weiss, L.G.
IEEE Signal Processing Magazine , Volume: 11 Issue: 1 , Jan. 1994
Page(s): 13 -32
Abstract :
This tutorial presents the application of wavelet transforms to wideband correlation processing. One major difference between most applications of wavelets and the work presented is the choice of mother wavelet. It focuses on non-orthogonal, continuous mother wavelets, whereas most applications use the orthogonal mother wavelets that were advanced by Daubechies (1988). The continuous wavelet transform then provides an additional tool for studying and gaining insight into wideband correlation processing. In order to understand when wideband processing may be required, its counterpart, narrowband processing, is presented and its limitations are discussed. Identifying those applications requiring wideband processing and presenting techniques to implement the processing are two of the goals of this tutorial article. The underlying tool is the wavelet transform.

1995

[6] **An introduction to wavelets**

Graps, A.
IEEE Computational Science and Engineering , Volume: 2 Issue: 2 , Summer 1995
Page(s): 50 -61
Abstract :
Wavelets were developed independently by mathematicians, quantum physicists, electrical engineers and geologists, but collaborations among these fields during the last decade have led to new and varied applications. What are wavelets, and why might they be useful to you? The fundamental idea behind wavelets is to analyse according to scale. Indeed, some researchers feel that using wavelets means adopting a whole new mind-set or perspective in processing data. Wavelets are functions that satisfy certain mathematical requirements and are used in representing data or other functions. Most of the basic wavelet theory has now been done. The mathematics have been worked out in excruciating detail, and

wavelet theory is now in the refinement stage. This involves generalizing and extending wavelets, such as in extending wavelet packet techniques. The future of wavelets lies in the as-yet uncharted territory of applications. Wavelet techniques have not been thoroughly worked out in such applications as practical data analysis, where, for example, discretely sampled time-series data might need to be analysed. Such applications offer exciting avenues for exploration.

1996

[7] **Wavelets and time-frequency analysis**
Hess-Nielsen, N.; Wickerhauser, M.V.
Proceedings of the IEEE , Volume: 84 Issue: 4 , April 1996
Page(s): 523 -540
Abstract :
We present a selective overview of time-frequency analysis and some of its key problems. In particular we motivate the introduction of wavelet and wavelet packet analysis. Different types of decompositions of an idealized time-frequency plane provide the basis for understanding the performance of the numerical algorithms and their corresponding interpretations within the continuous models. As examples we show how to control the frequency spreading of wavelet packets at high frequencies using non-stationary filtering and study some properties of periodic wavelet packets. Furthermore we derive a formula to compute the time localization of a wavelet packet from its indexes which is exact for linear phase filters, and show how this estimate deteriorates with deviation from linear phase.

[8] **Wavelets: What next?**
Sweldens, W.
Proceedings of the IEEE , Volume: 84 Issue: 4 , April 1996
Page(s): 680 -685
Abstract :
The author looks ahead to see what the future can bring to wavelet research. He tries to find a common denominator for "wavelets" and identifies promising research directions and challenging problems.

[9] **Where do wavelets come from? A personal point of view**
Daubechies, I.
Proceedings of the IEEE , Volume: 84 Issue: 4 , April 1996
Page(s): 510 -513
Abstract :
The development of wavelets is an example where ideas from many different fields combined to merge into a whole that is more than the sum of its parts. The subject area of wavelets, developed mostly over the last 15 years, is connected to older ideas in many other fields, including pure and applied mathematics, physics, computer science, and engineering. The history of wavelets can therefore be represented as a tree with roots reaching deeply and in many directions. In this picture, the trunk would correspond to the rapid development of "wavelet tools" in the second half of the 1980's, with shared efforts by researchers from many different fields; the crown of the tree, with its many branches, would correspond to different directions and applications in which wavelets are now becoming a standard part of the mathematical tool kit, alongside other more established techniques. The author gives here a highly personal version of the development of wavelets.

1997

[10] **Wavelet based signal processing: where are we and where are we going?**
Burrus, C.S.
Digital Signal Processing Proceedings, 1997. DSP 97., 1997 13th International Conference on , Volume: 1 , 1997
Page(s): 3 -5 vol.1
Abstract :
This article discusses the history of modern wavelet based signal processing and then reviews the present state of the art. It also speculates about the future of this exciting field. The history of wavelets and wavelet based signal processing is fairly recent. Its roots in signal expansion go back to early geophysical and image processing methods and in DSP to filter bank theory and sub-band coding.

1998

[11] **A Friendly Guide To Wavelets**
Kilmer, W.
Proceedings of the IEEE , Volume: 86 Issue: 11 , Nov. 1998
Page(s): 2387 -2387
Abstract :
Un comentario sobre el libro a friendly guide to wavelet

[12] **A tutorial on wavelets from an electrical engineering perspective .2. The continuous case**
Sarkar, T.K.; Su, C.
IEEE Antennas and Propagation Magazine , Volume: 40 Issue: 6 , Dec. 1998
Page(s): 36 -49
Abstract :
The wavelet transform is described from the perspective of a Fourier transform. The relationships among the Fourier transform, the Gabor (1946) transform (windowed Fourier transform), and the wavelet transform are described. The differences are also outlined, to bring out the characteristics of the wavelet transform. The limitations of the wavelets in localizing responses in various domains are also delineated. Finally, an adaptive window is presented that may be optimally tailored to suit one's needs, and hence, possibly, the scaling functions and the wavelets.

2000

[13] **Prolog to sampling-50 years after Shannon**
O'Donnell, R.
Proceedings of the IEEE , Volume: 88 Issue: 4 , April 2000
Page(s): 567 -568
Abstract :
Prólogo del paper de 50 años despues de Shannon

[14] **Sampling-50 years after Shannon**
Unser, M.
Proceedings of the IEEE , Volume: 88 Issue: 4 , April 2000

Page(s): 569 -587

Abstract :

This paper presents an account of the current state of sampling, 50 years after Shannon's formulation of the sampling theorem. The emphasis is on regular sampling, where the grid is uniform. This topic has benefited from a strong research revival during the past few years, thanks in part to the mathematical connections that were made with wavelet theory. To introduce the reader to the modern, Hilbert-space formulation, we reinterpret Shannon's sampling procedure as an orthogonal projection onto the subspace of band-limited functions. We then extend the standard sampling paradigm for a presentation of functions in the more general class of "shift-in-variant" function spaces, including splines and wavelets. Practically, this allows for simpler-and possibly more realistic-interpolation models, which can be used in conjunction with a much wider class of (anti-aliasing) prefilters that are not necessarily ideal low-pass. We summarize and discuss the results available for the determination of the approximation error and of the sampling rate when the input of the system is essentially arbitrary; e.g., nonbandlimited. We also review variations of sampling that can be understood from the same unifying perspective. These include wavelets, multiwavelets, Papoulis generalized sampling, finite elements, and frames. Irregular sampling and radial basis functions are briefly mentioned.

Potencia

1991

[15] **Wavelets and signal processing**

Rioul, O.; Vetterli, M.

IEEE Signal Processing Magazine , Volume: 8 Issue: 4 , Oct. 1991

Page(s): 14 -38

Abstract :

A simple, non-rigorous, synthetic view of wavelet theory is presented for both review and tutorial purposes. The discussion includes non-stationary signal analysis, scale versus frequency, wavelet analysis and synthesis, scalograms, wavelet frames and orthonormal bases, the discrete-time case, and applications of wavelets in signal processing. The main definitions and properties of wavelet transforms are covered, and connections among the various fields where results have been developed are shown.

1994

[16] **Power electronics, power quality and modern analytical tools: the impact on electrical engineering education**

Ribeiro, P.F.; Rogers, D.A.

Frontiers in Education Conference, 1994. Twenty-fourth Annual Conference. Proceedings , 1994

Page(s): 448 -451

Abstract :

The new power electronics context characterized by the proliferation of sensitive electronics equipment supplied by an electrical network with very high levels of distortion, which are in part generated by the massive utilization of power electronics applications, creates an environment in which traditional circuit modelling analysis and techniques cannot be applied straightforwardly. High harmonic distortion, voltage notches, high frequency noise, etc., are among the typical situations in which sensitive electronic devices are being operated. As a consequence of the new electrical environment, the currents and voltages on the electrical network substantially and randomly deviate from a sinusoidal form. Thus the state of the electrical system cannot be fully analysed by traditional methods. Due to the consequent dynamics of distortion generation, propagation and interaction with the system, one would need a more powerful technique to efficiently analyse the system performance in the presence of non-stationary distortions. This paper briefly presents the basic concepts for some of the new analytical tools for signal processing and identification, their similarities and differences with respect to traditional techniques, and underlines how these new techniques are changing engineering design and ultimately Specifically, wavelet theory, genetic algorithms, expert systems, fuzzy logic, and neural network concepts are reviewed for their potential applications in power quality analysis.

1996

[17] **Exploring the power of wavelet analysis**

Galli, A.W.; Heydt, G.T.; Ribeiro, P.F.
IEEE Computer Applications in Power , Volume: 9 Issue: 4 , Oct. 1996
Page(s): 37 -41
Abstract :
Wavelets are a recently developed mathematical tool for signal analysis. Informally, a wavelet is a short-term duration wave. Wavelets are used as a kernel function in an integral transform, much in the same way that sines and cosines are used in Fourier analysis or the Walsh functions in Walsh analysis. To date, the primary application of wavelets has been in the areas of signal processing, image compression, sub-band coding, medical imaging, data compression, seismic studies, denoising data, computer vision and sound synthesis. Here, the authors describe how wavelets may be used in the analysis of power system transients using computer implementation.

1998

[18] **A tutorial on wavelets from an electrical engineering perspective. I. Discrete wavelet techniques**

Sarkar, T.K.; Su, C.; Adve, R.; Salazar-Palma, M.; Garcia-Castillo, L.; Boix, R.R.
IEEE Antennas and Propagation Magazine , Volume: 40 Issue: 5 , Oct. 1998
Page(s): 49 -68
Abstract :
The objective of this paper is to present the subject of wavelets from a filter-theory perspective, which is quite familiar to electrical engineers. Such a presentation provides both physical and mathematical insights into the problem. It is shown that taking the discrete wavelet transform of a function is equivalent to filtering it by a bank of constant-Q filters, the non-overlapping bandwidths of which differ by an octave. The discrete wavelets are presented, and a recipe is provided for generating such entities. One of the goals of this tutorial is to illustrate how the wavelet decomposition is carried out, starting from the fundamentals, and how the scaling functions and wavelets are generated from the filter-theory perspective. Examples (including image compression) are presented to illustrate the class of problems for which the discrete wavelet techniques are ideally suited. It is interesting to note that it is not necessary to generate the wavelets or the scaling functions in order to

implement the discrete wavelet transform. Finally, it is shown how wavelet techniques can be used to solve operator/matrix equations. It is shown that the "orthogonal-transform property" of the discrete wavelet techniques does not hold in numerical computations.

1999

[19] **A literature survey of wavelets in power engineering applications**

CHIEN-HSING LEE , YAW-JUEN WANG *AND WEN-LIANG HUANG **
Proc. Natl. Sci. Counc. ROC(A),Vol. 24, No. 4, 2000.
Page(s): 249-258
Abstract :
The use of wavelet analysis is a new and rapidly growing area of research within mathematics, physics, and engineering. In this paper, we present a literature survey of the various applications of wavelets in power engineering. We start by describing the wavelet properties that are most important for power engineering applications and then review their uses in the analysis of non-stationary signals occurring in power systems. Next, we provide a literature survey of recent wavelet developments in power engineering applications. These include detection, localization, identification, classification, compression, storage, and network/system analysis of power disturbance signals. In each case, we provide the reader with some general background information and a brief explanation.

[20] **Wavelet analysis for power system transients**

Galli, A.W.; Nielsen, O.M.
IEEE Computer Applications in Power , Volume: 12 Issue: 1 , Jan. 1999
Page(s): 16, 18, 20, 22, 24 -25
Abstract :
The purpose of this tutorial is to introduce the basics of wavelet analysis and propose how this new mathematical tool may be applied in power engineering. Frequently, newcomers to wavelet analysis become discouraged due to the oftentimes elusive mathematical rigor of the subject and the variety of nomenclatures that are used in various arenas. This tutorial presents wavelet analysis in such a way that the reader can easily grasp the rudiments and begin investigating the use of this powerful tool in a variety of applications related to power engineering.

2000

[21] **Wavelet transforms in power systems. I. General introduction to the wavelet transforms**

Chul Hwan Kim; Raj Aggarwal
Power Engineering Journal , Volume: 14 Issue: 2 , April 2000
Page(s): 81 -87
Abstract :
This tutorial gives an introduction to the field of the wavelet transform. It is the first of two tutorials which are intended for engineers applying or considering to apply WTs to power systems. They show how the WT-a powerful new mathematical tool-can be employed as a fast and very effective means of analysing power system transient waveforms, as an alternative to the traditional Fourier transform. The focus of the tutorials is to present concepts of wavelet analysis and

to demonstrate the application of the WT to a variety of transient signals encountered in electrical power systems.

2001

[22] **Wavelet transforms in power systems. II. Examples of application to actual power system transients**

Chul Hwan Kim; Aggarwal, R.
Power Engineering Journal , Volume: 15 Issue: 4 , Aug. 2001
Page(s): 193 -202
Abstract :
This is the second in a series of two and illustrates some practical applications of the wavelet transform to power systems: protection/fault detection, detection of power quality disturbances and analysis of the partial discharge phenomenon in GIS (gas-insulated substations). Emphasis is placed on a number of practical issues.

General

1994

[23] **Multiresolution transient detection**

Abry, P.; Flandrin, P.
Time-Frequency and Time-Scale Analysis, 1994., Proceedings of the IEEE-SP International Symposium on , 1994
Page(s): 225 -228
Abstract :
Designs and studies the performance of a multiresolution-based transient detector. The transients the authors are interested in consist of wide-band, pulse-like, coherent structures in a turbulent flow. To take advantage of the fast pyramidal wavelet algorithm, an important point when processing large amounts of experimental data, the detector makes use of the discrete wavelet transform. The authors show how the lack of time-invariance drawback of the discrete transform can be efficiently overcome by using relevant analytic wavelets. They thus compare this detection technique with one based on a continuous wavelet transform, as well as with other standard methods and show that wavelets perform best when the transients are superimposed on a coloured 1/f background noise. This description is very close to that of turbulence and relevant also in many other situations.

1996

[24] **A fuzzy-logic-based threshold function for signal recovery using discrete wavelet transform**

Wenbo Mei; Lik-Kwan Shark
Signal Processing, 1996., 3rd International Conference on , Volume: 1 , 1996
Page(s): 283 -286 vol.1

Abstract :
In this paper, a novel threshold function based on fuzzy logic is proposed to achieve good signal recovery performance in the presence of noise using the discrete wavelet transform. The proposed threshold is shown to provide an alternative and flexible approach to solve the problems associated with the conventional hard-threshold approach. Some typical results, obtained from the computer simulations of recovering a transient signal embedded in additive white Gaussian noise in different signal-to-noise ratio settings, are presented to demonstrate the potential and the effectiveness of the proposed threshold function.

2001

[25] **Genetic algorithm wavelet design for signal classification**
Jones, E.; Runkle, P.; Dasgupta, N.; Couchman, L.; Carin, L.
Pattern Analysis and Machine Intelligence, IEEE Transactions on , Volume: 23 Issue: 8 , Aug. 2001
Page(s): 890 -895
Abstract :
Biorthogonal wavelets are applied to parse multiaspect transient scattering data in the context of signal classification. A language-based genetic algorithm is used to design wavelet filters that enhance classification performance. The biorthogonal wavelets are implemented via the lifting procedure and the optimisation is carried out using a classification-based cost function. Example results are presented for target classification using measured scattering data.

Descargas parciales

1990

[26] **Signal processing techniques for partial discharge site location in shielded cables**
Knapp, C.H.; Bansal, R.; Mashikian, M.S.; Northrop, R.B.
Power Delivery, IEEE Transactions on , Volume: 5 Issue: 2 , April 1990
Page(s): 859 -865
Abstract :
An instrumentation package capable of locating partial discharge sites in cables has been developed. The digitised partial discharge (PD) signals recorded from one cable end consist of a sequence of pulses whose separations contain information on the relative location of the PD site. The signals are often contaminated by noise and undergo substantial attenuation and phase change as they travel though the cable and the detection system. Moreover, overlap of two successive pulses is possible if the PD site is close to a cable end. The authors describe and illustrate two techniques-maximum likelihood (ML) estimation and deconvolution-for extracting pulse separation from such a time series of noisy and ambiguous signals. Both real and simulated measurements are used to demonstrate the potential of these methods. A procedure whereby knowledge of the combined cable-instrumentation transfer function can be incorporated into the maximum likelihood technique is also discussed. The ML method appears to be much more effective in the presence

of cable noise. The main disadvantage of the ML method is that the approximate width of the wavelet or basic PD pulse should be known to give the best compromise between noise smoothing and peak resolution. This width can be determined by an impulse response test or by knowledge of cable length and parameters.

1998

[27] **Wavelet analysis used in UHF partial discharge detection in GIS [gas insulated substations]**

Li, Z.M.; Feng, Y.P.; Chen, J.Q.; Zheng, X.G.
Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International, Conference on , Volume: 1 , 1998
Page(s): 163 -166
Abstract :
One of the most important subjects in monitoring GIS is PD detection. The issue is that the PD signal is weak and sensitive to external noise. In this paper, the experiments of detection PD in GIS using UHF technique is described. The results show that UHF method is effective in detecting PD in GIS and avoiding the disturbance of corona. Nevertheless very large corona, fluorescent tube or radio frequency noise nearby can still disturb the measurement. A method of signal processing by software is presented in this paper. Through the procedure of signal wavelet transform, signal noise extraction and signal reconstruction the signal is analysed to determine the magnitude of PD in GIS and avoid false alarm.

1999

[28] **Partial discharge mapping in high voltage (HV) cable networks**

Shim, I.; Soraghan, J.J.; Siew, W.H.; McPherson, F.; Sludden, K.; Gale, P.F.
Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, 1999. Proceedings , 1999
Page(s): 497 -500
Abstract :
This paper presents a new technique for locating partial discharges in HV cables. The method has been developed and used for on-line measurement of HV cable networks. When there is more than one PD site, the PD location procedure becomes intricate. The PD patterns are processed to detect the individual PD locations. An analogue model was built to verify and test the technique proposed. The results of the PD generated from the model are presented and discussed. Real data from the field are later compared to the results obtained from the model.

2000

[29] **Defect classification based on Weibull statistic of partial discharge height distribution with wavelet preprocessing**

Chia P.Y.; Liew A.C.
Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on , Volume: 2 , 2000
Page(s): 1035 -1040

Abstract :
The paper describes a stochastic analysis performed using two-parameter Weibull statistics involving a scheme whereby the PD signals are decomposed using discrete wavelet transform. In a high voltage experimental se-tup, artificial cylindrical voids were made in a Perspex column of 40 mm in length. The signals obtained from a corona detector were collected via an 8 bit oscilloscope with data storage capabilities. The signals were analysed using PD height distribution (PDHD). The scheme presents itself as a multi-level Weibull analysis to identify and quantify voids in solid dielectric insulations based on nonultra wide band detection and wavelet aided signal processing.

[30] **Detection of wide-band E-M signals emitted from partial discharge occurring in GIS using wavelet transform**

Kawada, M.; Tungkanawanich, A.; Kawasaki, Z.-I.; Matsu-Ura, K.
Power Delivery, IEEE Transactions on , Volume: 15 Issue: 2 , April 2000
Page(s): 467 -471
Abstract :
Recently, diagnostic techniques have been investigated to detect a partial discharge (PD) associated with a dielectric material defect in a high-voltage electrical apparatus. Gas insulated switchgear (GIS) is an important equipment in a substation, it is highly desirable to measure a partial discharge (PD) occurring in GIS which is a symptom of an insulation breakdown. As it is important to develop a noncontact method for detecting the insulation fault, this paper proposes a new method to detect the wide-band electromagnetic (E-M) wave emitted from PD using the Wavelet transform. The Wavelet transform provides a direct quantitative measure of spectral content, "dynamic spectrum", in the time-frequency domain. This paper experimentally shows the "dynamic spectrum" of the wide-band E-M wave emitted from PD in the time-frequency domain. This method is shown to be useful for detecting the symptom of the insulation breakdown occurring in GIS.

[31] **Robust partial discharge measurement in MV cable networks using discrete wavelet transforms**

Shim, I.; Soragan, J.J.; Siew, W.H.; Sludden, K.; Gale, P.F.
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 1 , 2000
Page(s): 718 -723
Abstract :
This paper describes the application of discrete wavelet transforms to partial discharge (PD) measurements. Real field data measured from an 11 kV cable online has been used to test the algorithm. When taking measurements online, inaccuracy occurs when the measurements are affected by internal low frequency disturbances. Results demonstrate that the use of this technique leads to accurate location of partial discharge.

2001

[32] **Analysis of VHF-wideband electromagnetic noises from partial discharge using discrete wavelet transform**

Tungkanawanich, A.; Hamid, E.Y.; Kawasaki, Z.-I.; Matsuura, K.
Power Engineering Society Winter Meeting, 2001 IEEE , Volume: 1 , 2001
Page(s): 263 -268

Abstract :

Protecciones

Detección y clasificación de faltas en componentes

Protección de barras

2001

[33] **Application of wavelet transform in transient protection-case study: busbar protection**

Jiang, F.; Bo, Z.Q.; Redfern, M.A.; Weller, G.; Chen, Z.; Dong Xinzhou
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 197 -200
Abstract :
This paper presents extensive studies of the application of wavelet transforms to detecting power system faults and describes a number of new protection principles and techniques based on the wavelet transform. These include a number of novel protection schemes for the protection of transmission lines, distribution feeders, generators and transformers. The significant advantages of these protection schemes are outlined in the paper. Finally the application of the proposed technique to busbar protection is presented to examine the feasibility of new protective algorithm.

Protección de ferrocarriles

2000

[34] **Remote short-circuit current determination in DC railway systems using wavelet transform**

Chang, C.S.; Feng, T.; Khambadkone, A.M.; Kumar, S.
Electric Power Applications, IEE Proceedings- , Volume: 147 Issue: 6 , Nov. 2000
Page(s): 520 -526
Abstract :
For effective protection of DC railway systems, it is important to discriminate the remote short-circuit current from the train starting current. Four methods for the discrimination are assessed. The first two methods apply the traditional heuristics by comparing the magnitude and the rate of change (di/dt) between the two currents. The remaining methods use the Fourier and wavelet transforms. It is shown that the first three methods do not provide consistent discrimination. The remote short-circuit current is determined mainly by the steel rail impedance,

which is time varying due to the skin effect. In contrast, impedances of the traction motor and the contact wires, and the change of operating mode during starting govern the train starting current. The wavelet transform identifies these salient features. The remote short-circuit current is simulated using EMTP, and a SIMULINK model is used to obtain the train starting current.

2001

[35] **Real-time detection using wavelet transform and neural network of short-circuit faults within a train in DC transit systems**

Chang, C.S.; Kumar, S.; Liu, B.; Khambadkone, A.
Electric Power Applications, IEE Proceedings- , Volume: 148 Issue: 3 , May 2001
Page(s): 251 -256
Abstract :
A method is proposed for the real-time detection of DC-link short-circuit faults in DC transit systems. The discrete wavelet transform is implemented to detect any surges in the DC third-rail current waveform. In the event of a surge the wavelet transform extracts a feature vector from the current waveform and feeds it to a self-organising neural network. The neural network determines whether the feature vector belongs to a normal or a fault current surge.

Protección de generadores

1998

[36] **Study on wavelet analysis and its application to numerical protection for large synchronous generator**

Lin Tao; Ying Xianggeng; Chen Deshu
Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 1121 -1129
Abstract :
The definition, applied characteristics as well as fast algorithm of wavelet transform (WT) are introduced in this paper. The designation of WT based high pass (HP), band pass (BP) filters and their applications to numerical protection for large generator against stator internal faults as well as stator earth fault are also presented. Research results based on EMTP simulation and laboratory micro machine experiments show that WT can effectively improve the sensitivity and selectivity of traditional numerical protection principles and criteria.

2000

[37] **A Novel method for large turbine generator protection based on wavelet transformation**

Wu Guopei; Guan, L.; Ren Zhen; Huang Qungu

Advances in Power System Control, Operation and Management, 2000. APSCOM-00. 2000 International Conference on , Volume: 1 , 2000
Page(s): 254 -258

Abstract :
The frequency property of wavelet transformation (WT) has been studied in depth in this paper with comparison with the discrete Fourier transform (DFT). The band overlapping and frequency leakage among different scales of WT is discussed. Several new wavelet functions with compact-supported property in frequency domain are constructed. A general process for selecting proper wavelet functions according to practical requirements is proposed. A novel WT based method is developed to detect generator inner faults. Comparing with the DFT method, the Wt based signal analysis requires no frequency tracking and is not affected by frequency deviation. No leakage frequency occur with the new methods applied. Simulation results probe the feasibility and advantages of the new method presented for the paper.

Protección de motores

1996

[38] **Wavelet transform analysis of arrester voltage in surge motor protection**

Islam, M.S.; Samra, A.H.; Andrian, J.
Southeastcon '96. Bringing Together Education, Science and Technology., Proceedings of the IEEE , 1996
Page(s): 305 -308

Abstract :
Studies showed that most motors stator winding failures result from the breakdown of the turn insulation during switching or lightning surges. Failure would be less frequent if motors were properly protected against such surges. Meaningful information is contained in the transient surge signals and should be used in the protection algorithm to increase their speed and accuracy. In this paper, the Electromagnetic Transient Program (EMTP) is used to simulate surge arrester behaviour during switching. The multiscale wavelet transform is then applied to the voltage waveform across the terminals of an induction motor. The instantaneous time-frequency information obtained may be useful for the design of a fast and accurate relay algorithm.

2000

[39] **Induction motor mechanical fault simulation and stator current signature analysis**

Zhongming Ye; Bin Wu
Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on , Volume: 2 , 2000
Page(s): 789 -794 vol.2

Abstract :
This paper addresses the simulation of induction machines with mechanical faults

and the fault signature analysis of stator current. Models for three-phase induction motors with broken rotor bars by winding function method are developed. Current waveforms of an induction motor under normal and faulty conditions are simulated. New feature coefficients for signature analysis of the stator current are proposed based on the wavelet packet decomposition. The feature coefficients are calculated for both normal and fault conditions. If is shown that for most load conditions the new feature coefficients for fault cases are distinctive from normal conditions at certain depth and nodes. The features proposed here can be used for induction motor fault detection and diagnosis.

[40] **Insulation fault detection in a PWM controlled induction motor-experimental design and preliminary results**

Wang, J.; McInerny, S.; Haskew, T.
Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on, Volume: 2 , 2000
Page(s): 487 -492
Abstract :
To investigate feature extraction methods for early detection of insulation degradation in low voltage (under 600 V), 3-phase, PWM controlled induction motors, a series of seeded fault tests was planned on a 50 HP, 440 V motor. In this paper, the background and rationale for the test plan are described. The instrumentation and test plan are then detailed. Finally, preliminary test experiences are related.

2001

[41] **A new project for motor fault detection and protection**

Zhang, X.H.; Cao, Y.N.; Li, Y.L.
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 145 -148
Abstract :
This paper discusses a project that is used for detection and protection of the electrical and mechanical faults of motors. Through extracting the characteristics of sequence currents under all kinds of the electrical faults, the authors proposed a simple and comprehensive protective scheme in protection units. At the same time, by analysing the spectrum of the stator currents with wavelet transforms, one can detect the mechanical faults of motors, such as broken rotor bars, etc.

[42] **Motor bearing damage detection via wavelet analysis of the starting current**

Eren, L.; Devaney, M.J.
Instrumentation and Measurement Technology Conference, 2001. IMTC 2001. Proceedings of the 18th IEEE , Volume: 3 , 2001
Page(s): 1797 -1800
Abstract :
Preventive maintenance of induction motors plays an important role in avoiding expensive shut-downs due to motor failures. Motor Current Signature Analysis, MCSA, provides a non-intrusive way to assess the health of a machine. In this paper, the starting current transient of an induction motor is analysed via discrete

wavelet transform to detect bearing faults. The frequency sub-bands for bearing pre-fault and post-fault conditions are compared to identify the effects of bearing/machine resonant frequencies as the motor starts.

[43] **Online rotor bar breakage detection of three phase induction motors by wavelet packet decomposition and artificial neural network**

Zhongming Ye; Bin Wu
Power Electronics Specialists Conference, 2001. PESC. 2001 IEEE 32nd Annual , Volume: 4 , 2001
Page(s): 2209 -2216
Abstract :
Online detection algorithm for induction motor rotor bar breakage is presented using multi-layer perception network (MLP) and wavelet packed decomposition (WPD). New features of rotor bar faults are obtained by wavelet packed decomposition of the stator current. These features are of multiple frequency resolutions and obviously differentiate the healthy and faulty condition. Features with different frequency resolution are used together with the speed slip and the input sets of a 4-layer perception network. The algorithm is evaluated on a small three-phase induction motor with experiments the laboratory results show that the proposed method is able to detect the faulty condition with high accuracy. This algorithm is also applicable to the detection other electrical faults of induction motors.

Protección de transformadores

1998

[44] **A new principle of discrimination between inrush current and internal short circuit of transformer based on fuzzy sets**

Shaohua Jiao; Wanshun Liu; Peipu Su; Qixun Yang; Zhenhua Zhang; Jianfei Liu
Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 1086 -1090
Abstract :
A criterion of extracting the dead angle characteristic of the power transformer based on the wavelet is presented in the paper. Another criterion of extracting the symmetry feature of the internal fault current waveform based on an integral algorithm is also proposed. The fuzzy math models and the integral principle used to discriminate the inrush current and the fault current are developed in the paper based on these criteria. All the conclusions are verified by the EMTP and the electric power system simulation lab of NCEPU and proved to be highly accurate and fast.

[45] **Multiresolution signal decomposition: a new tool for fault detection in power transformers during impulse tests**

Pandey, S.K.; Satish, L.

Power Delivery, IEEE Transactions on , Volume: 13 Issue: 4 , Oct. 1998 Page(s): 1194 -1200

Abstract :

Detection of major faults in power transformers during impulse tests has never been an issue, but is rather difficult when only a minor fault, say a spark over between adjacent coils or turns and lasting for a few microseconds, occurs. However, detection of such a type of fault is very important to avoid any catastrophic situation. In this paper, the authors propose a new and powerful method capable of detecting minor incipient faults. The approach is based on wavelet transform analysis, particularly the dyadic-orthonormal wavelet transform. The key idea underlying the approach is to decompose a given faulty neutral current response into other signals which represent a smoothed and detailed version of the original. The decomposition is performed by the multiresolution signal decomposition technique. Preliminary simulation work demonstrated here shows that the proposed method is robust and far superior to other existing methods to resolve such types of faults.

1999

[46] **A wavelet-based differential transformer protection**

Gomez-Morante, M.; Nicoletti, D.W.

Power Delivery, IEEE Transactions on , Volume: 14 Issue: 4 , Oct. 1999

Page(s): 1351 -1358

Abstract :

Transformer inrush currents were traditionally evaluated by means of Fourier analysis. Such an approach affects the design of transformer differential relays concerning their immunity to inrush currents. This paper presents a wavelet-based method, which seems to provide a reliable and computationally efficient tool for distinguishing between internal faults and inrush currents.

[47] **Detection of Transformer Winding Faults Using Wavelet Analysis and Neural Network**

Hang Wang, Karen L. Butler

Abstract :

This paper investigates the application of wavelet transform as a pre-processor for neural networks (NN) in identifying internal turn-to-turn faults in transformer windings.

2000

[48] **A new paradigm for impulse testing of power transformers**

Vanaja, R.; Udayakumar, K.

Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 3 , 2000

Page(s): 2206 -2210

Abstract :

Reliable methods for sensitive detection of internal defects in the insulation system of a power transformer during impulse test, are still an active area of research. A new impulse analysing system for a power transformer is discussed. It is based on recognising the possible nature of winding fault using the temporal records, transfer function and high frequency spectra. The neutral current, transferred surge current, capacitively transferred current, could be analysed using these approaches. But for the analysis of interterm discharges and occurrence of partial discharges which are fast decaying signals it has been observed that application of the wavelet transforms would be more appropriate. This paper discusses methods of analysing some of the winding faults using signal processing methods.

[49] **A wavelet transform based decision making logic method for discrimination between internal faults and inrush currents in power transformers**

P. L. Mao and R. K. Aggarwal

International Journal of Electrical Power & Energy Systems, Volume 22, Issue 6, August 2000

Page(s): 389-395

Abstract :

This paper describes a decision making logic method for discrimination between internal faults and inrush currents in power transformers using the wavelet transform based feature extraction technique. It is shown that the features extracted by the wavelet transform have a more distinctive property than those extracted by the fast Fourier transform due to the good time and frequency localisation characteristics of the wavelet transform. As a result, by quantifying the extracted features, the decision for distinguishing an internal fault from an inrush current in different power transformer systems can be accurately made. The extensive simulation studies have verified that the proposed method is more reliable and simpler, and is suitable for different power transformer systems.

[50] **A wavelet-based method to discriminate between inrush current and internal**

Sng Yeow Hong; Wang Qin

Power System Technology, 2000. Proceedings. PowerCon 2000. International Conference on , Volume: 2 , 2000

Page(s): 927 -931

Abstract :

With the development of power systems, the content of the second harmonic current can be comparable to that produced in the inrush current. The conventionally used second harmonic current restrained method becomes unreliable for transformer protection. To obtain some new approaches on discrimination between inrush current and internal fault, transformer models with enough precision of computing inrush current and short-circuit current are firstly described. After that, Daubechies family wavelets are selected as a mother wavelet to analyse the inrush current and short-circuit current. The results show that the characteristics of inrush current are significantly different from those of short-circuit current. Based on the analysing result, the back-propagation neural network is trained to discriminate the inrush current and short-circuit current. The training results presented in this paper show that wavelet based discrimination method is efficient with good performance and reliability.

[51] **Improved technique for fault detection sensitivity in transformer impulse test**

Karady, G.G.; Reta-Hernandez, M.; Amarh, F.; McCulla, G.

Power Engineering Society Summer Meeting, 2000. IEEE , Volume: 4 , 2000

Page(s): 2412 -2416

Abstract :

Insulation of transformer windings can be damaged by impulse voltages of high amplitude produced by lightning or switching transients. Testing of the windings insulation is performed by using the standard impulse test, generally applying the fast Fourier transform (FFT) algorithm to analyse the transformer 'fingerprint' in the frequency domain. However, FFT analysis is limited by the spectral leakage and degradation at spectral peaks. To obtain a better signature analysis, this paper investigates the use of power spectral density (PSD) and wavelets analysis techniques. Experimental results are shown from different tests with windings under normal and turn-to-turn short circuit conditions in a single phase transformer.

[52] **Power transformer protection based on transient detection using discrete wavelet transform (DWT)**

Jiang, F.; Bo, Z.Q.; Chin, P.S.M.; Redfern, M.A.; Chen, Z.
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 3 , 2000
Page(s): 1856 -1861
Abstract :
This paper addresses a new relaying scheme for power transformer protection. In principle, the new technique implements the wavelet transform to extract the transient components from the captured transform currents. The powerful function of a discrete wavelet transform (DWT) in analysing non-static signals is capable of extracting those predominant transient signals energised by transformer internal fault. With the aid of spectrum analysis of extracted transients, the high selectivity of the proposed relay can be achieved. The new relay possesses the advantages of high speed response, immunity to the CT saturation, ability of detecting low level internal faults and inrush current, etc. The study in this paper evaluates the performance of the proposed relaying scheme and proves its feasibility.

2001

[53] **A new technique for power transformer protection using discrete dyadic wavelet transform**

Zhonghao Yang; Liu, J.Z.; Dong Xinzhou; Jiang, F.; Bo, Z.Q.; Chin, N.F.
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 383 -386
Abstract :
As one of the most important elements in modern power system, the transformer is responsible for the successful power transmission and distribution. Any unscheduled repair work, especially replacement of a faulty transformer, is very expensive and time consuming. Starting from here, this paper discusses an approach to introduce a wavelet-based view to identify inrush and other transformer faults. Furthermore, by careful cataloguing and comparing, the authors found distinct characteristics corresponding to fault and inrush, on the basis of which they proposed a generalized new criterion for inrush identification, that can help to enhance protection reliability. The outcome of numerical simulation shows the effectiveness of the algorithm.

[54] **A novel approach to the classification of the transient phenomena in power transformers using combined wavelet transform and neural network**

Mao, P.L.; Aggarwal, R.K.
Power Delivery, IEEE Transactions on , Volume: 16 Issue: 4 , Oct 2001

Page(s): 654 -660

Abstract :

The wavelet transform is powerful tool in the power transformer transients phenomena because to extract information from the transients signal simultaneously in both the time and frequency domain. This paper presents a novel technique for accurate discrimination between an internal fault and a magnetizing inrush current in the power transformer by combining wavelet transform with neural network. The wavelet transform is firstly applied to the compose the differential current signals of the power transformer in to a series of detailed wavelets components. The spectral energies of wavelet components are calculated and then employ to train a neural network to discriminate and internal fault from the magnetizing inrush current. The simulate results presented clearly shown that the proposed technique can accurately discriminate between and internal fault and a magnetizing inrush current in power transformer protection.

Detección y clasificación de faltas en el sistema

Detección de faltas

1996

[55] **A new approach to fast fault detection in power systems**

Aravena, J.L.; Chowdhury, F.N.

Intelligent Systems Applications to Power Systems, 1996. Proceedings, ISAP '96., International Conference on , 1996

Page(s): 328 -332

Abstract :

This paper presents an integrated approach to the problem of power system fast fault detection and isolation. The idea is to use concepts from signal processing and wavelet theory to create fast and sensitive fault indicators. The indicators can then be analysed by standard statistical hypothesis testing or by artificial neural nets to create intelligent decision rules. The approach described in this paper does not depend on the availability of an accurate mathematical model. Hence it is expected to be robust and of wide applicability. Results of the analysis of computer simulated faulty transmission lines using filter banks is included.

[56] **Application of wavelet theory to power distribution systems for fault detection**

Momoh, J.; Rizy, T.

Intelligent Systems Applications to Power Systems, 1996. Proceedings, ISAP '96., International Conference on , 1996

Page(s): 345 -350

Abstract :

In this paper, an investigation of the wavelet transform as a means of creating a feature extractor for artificial neural network (ANN) training is presented for application to distribution network fault location. The study includes a terrestrial-based three-phase delta-delta power distribution system. Faults were injected into the system and data was obtained from experimentation. Graphical representations

of the feature extractors obtained in the time domain, the frequency domain and the wavelet domain are presented to ascertain the superiority of the wavelet transform feature extractor.

1997

[57] **A new technique using wavelet analysis for fault location**

Xia Yibin; David Chan Tat Wai; Keerthipala, W.W.L.

Developments in Power System Protection, Sixth International Conference on (Conf. Publ. No. 434) , 1997

Page(s): 231 -234

Abstract :

A new technique employing wavelet transform (WT) is proposed for fault location. Dyadic wavelet analysis is implemented by way of the multiresolution filter banks. A six-level filter bank is constructed to abstract the fundamental frequency voltage and current signals from the faulted transmission line. Fault location is then calculated using the clean sinusoidal waveform obtained. Fault simulations are performed using EMTP, and results demonstrated the WT method is more accurate as compared to the Fourier transform (FT).

1998

[58] **A wavelet multiresolution analysis approach to fault detection and classification in transmission lines**

J. Liang, S. Elangovan and J.B.X. Devotta

International Journal of Electrical Power and Energy Systems 20 6 (1998)

Page(s): 327¯332

Abstract :

A real-time wavelet multiresolution analysis (MRA)-based fault detection and classification algorithm is proposed in this paper. The first stage MRA detail signals extracted from the original signals are used as the criteria for this problem. By measuring the sharp variation values of the MRA detail signals, faults in the power system can be detected. The fault type is then identified by the comparison of the three-phase MRA sharp variations. The effects of the fault distance, fault inception angle and fault impedance are examined, and the fault classification routine is designed to overcome their effects. Simulation results show that this algorithm is effective and robust, and it is promising in high impedance fault detection.

[59] **Data smoothing by B-spline wavelets for digital distance protection**

Yuan Liao and S Elangovan

International Journal of Electrical Power & Energy Systems, Volume 20, Issue 4, May 1998

Page(s): 281-286

Abstract :

The multiresolution analysis generated by the compactly supported cardinal B-spline wavelets for data smoothing is introduced. It is shown that the proposed technique has the advantages of high accuracy and low delay and may be used instead of the traditional low-pass filters for power system protection. Its applications in digital distance protection are presented in detail. Simulation studies using EMTP have shown that the wavelets-based method can reduce the relaying time and may be suitable for digital distance protection.

[60] **Fault location using wavelets**

Magnago, F.H.; Abur, A.
Power Delivery, IEEE Transactions on , Volume: 13 Issue: 4 , Oct. 1998
Page(s): 1475 -1480
Abstract :
This paper describes the use of wavelet transforms for analysing power system fault transients in order to determine the fault location. Travelling wave theory is utilized in capturing the travel time of the transients along the monitored lines between the fault point and the relay. Time resolution for the high frequency components of the fault transients, is provided by the wavelet transform. This information is related to the travel time of the signals which are already decomposed into their modal components. The aerial mode is used for all fault types, whereas the ground mode is used to resolve problems associated with certain special cases. The wavelet transform is found to be an excellent discriminant for identifying the travelling wave reflections from the fault, irrespective of the fault type and impedance. EMTP simulations are used to test and validate the proposed fault location approach for typical power system faults.

[61] **Travelling wave fault location of transmission line using wavelet transform**

Qin Jian; Chen Xiangxun; Zheng Jianchao
Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on , Volume: 1 , 1998
Page(s): 533 -537 vol.1
Abstract :
This paper presents a new fault location principle based on the double terminal methods of travelling waves using continuous wavelet transform (CWT). Due to the attenuation and distortion of travelling wave propagation in a transmission line, a open problem is how to define the arrival time and the propagation velocity of the travelling wave correctly. Since CWT has much better resolution for locating a transient event in time-domain, the arrival time can be defined by a characteristic point of the travelling wave extracted by a suitable continuous wavelet with the optimal dilation parameters, and the propagation velocity depends on the physical configuration of a transmission line and the optimal dilation parameters. Extensive simulation results show that the new method has a location accuracy within /spl plusmn/ one tower span in the case of various grounding resistances, different fault positions and different line configurations.

1999

[62] **A fault location technique for two and three terminal lines using high frequency fault clearing transients**

Styvaktakis, E.; Bollen, M.H.J.; Gu, I.Y.H.
Electric Power Engineering, 1999. PowerTech Budapest 99. International Conference on , 1999
Page(s): 255
Abstract :
This paper suggests that a voltage recorder, placed next to a circuit breaker not as

usual on the side of the substation, but on the side of the transmission line, may reveal the location of permanent faults. Two different approaches on estimating the fault location are presented here: a frequency domain approach and a time domain approach. These methods are tested and compared with simulations of typical transmission systems using the Electromagnetic Transients Program (EMTP). Two typical line configurations are considered: two terminal lines and three terminal lines.

[63] **A new fault location technique for radial distribution systems based on high frequency signals**

Magnago, F.H.; Abur, A.
Power Engineering Society Summer Meeting, 1999. IEEE , Volume: 1 , 1999 Page(s): 426 -431
Abstract :
This paper presents a fault location method for distribution systems. The method is based on the travelling wave theory and uses the transient signals recorded during the fault, as a basis for the analysis. According to the travelling wave theory fault transients will have different signatures at the substation terminals depending on the number of network junctions they pass through as they travel towards the substation. Unfortunately, these signatures only show up at high frequency end of the spectrum and will be missed by most methods based on the power frequency signals. The proposed method takes advantage of the special properties of the wavelet transform to differentiate between faults occurring along different laterals of the same main feeder, equal distance away from the main substation. Once the faulted lateral is identified, exact location of the fault is determined by one of the conventional methods developed for strictly radial systems. Simulation results obtained by using ATP/EMTP for a sample distribution system, are included for demonstration of the proposed method.

[64] **A non communication transmission line protection using wavelet transform and transients protection technique**

F. Jiang; Z.Q. Beo, Philips S. M. Chin, G. Weller
PSCC 1999
Abstract :
This paper describes a new a strategic in with wavelet transform and transients protection technique are utilised to protect transmission lines. The presented relaying technique is principally based on the detection of fault generates transient signals with has wideband of high frequency components. The simulation studies is carry out extentensively by use of EMPT and wavelet transform, with source that the proposed algorithm provides the possibilities of high-speed and accurate fault detection. In addition the algorithm provides simple and economic designs for power protection system.

[65] **An approach using wavelet transform for fault type identification in digital**

Silveira, P.M.; Seara, R.; Zurn, H.H.
Power Engineering Society Summer Meeting, 1999. IEEE , Volume: 2 , 1999
Page(s): 937 -942
Abstract :
This paper proposes the use of wavelet transform (WT) in power transmission lines for identifying fault types. WT multiresolution properties are quite adequate for detection of fast changes contained in the disturbed signal. Wavelet decomposition associated with modal components have shown to be an excellent alternative for

quick identification of faulted phases. Digitised phase voltage and/or current signals are fed to wavelet filters. The coefficients obtained are then transformed by a modified modal transformation matrix. From the resulting signals, the energy is measured with short time intervals. With an appropriately chosen threshold the fault type is identified. EMTP simulations are used to test and validate the proposed methodology. The obtained results are encouraging and the proposed technique requires a low computational complexity, allowing it to be used as part of a high speed protective relay.

2000

[66] **A B-Spline Wavelet Based Fault Classification Scheme for High Speed Protection Relaying**

CHENG HONG; S. ELANGOVAN;
Electric Machines and Power Systems, 28:313–324, 2000
Copyright c s2000 Taylor & Francis
Abstract :
This paper presents a new fault detection and classification algorithm based on the wavelet transform. The B-spline wavelet transforms of three phase currents on transmission lines are employed. By comparing the moving average of these transforms, fault types are classified easily. Effects of the fault inception angle, fault distance, and fault impedance are examined. Simulation studies using EMTP show that the wavelet-based algorithm is simple, effective, and robust. Without any modification, the proposed algorithm can be applied to power systems of any voltage level. It is suitable for the high-speed protection relaying.

[67] **Application of wavelet transform in travelling wave protection**

J. Liang, S. Elangovan and J. B. X. Devotta
International Journal of Electrical Power & Energy Systems, Volume 22, Issue 8, 1 November 2000
Page(s): 537-542
Abstract :
In this paper, the correlation function-based travelling wave protection algorithm is analysed from the viewpoint of wavelet transform (WT), and a wavelet correlation function (WCF) algorithm is proposed to replace it. In the new algorithm, the multi-scale spline WT is used to detect the edges of the travelling wave signal, and the WCF is then employed to fulfil the correlation operation in the WT domain instead of the time domain. This enhances the peak intensity and the noise rejection ability of the algorithm. The performance of this algorithm is illustrated by simulation results.

[68] **Effective transmission line fault detection during power swing with wavelet**

Xiangning Lin; Pei Liu; Shijie Cheng
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 3 , 2000
Page(s): 1950 -1955
Abstract :
A new scheme for fault identification during power swings is proposed in this paper. The new scheme is based on the orthonormal wavelet transform algorithm. The main advantage of the proposed scheme is that fault occurring in the transmission line can be correctly identified during different kinds of power swings. Details of applying the proposed scheme in the distance protection are

discussed in the paper. The effectiveness of the proposed scheme was verified with the data sampled from an EMTP based simulator. Furthermore. As only limited number of real value calculation is needed for the proposed scheme. It is easily realized in real-time applications.

[69] **Fault location of a teed-network with wavelet transform and neural networks**

Lai, L.L.; Vaseekar, E.; Subasinghe, H.; Rajkumar, N.; Carter, A.; Gwyn, B.J.
Electric Utility Deregulation and Restructuring and Power Technologies, 2000. Proceedings. DRPT 2000. International Conference on , 2000
Page(s): 505 -509

Abstract :

A new technique using wavelet transforms and neural networks for fault location in a tee-circuit is proposed in this paper. Fault simulation is carried out in EMTP96 using a frequency dependent transmission line model. Voltage and current signals are obtained for a single phase (phase-A) to ground fault at every 500 m distance on one of the branches, which is 64.09 km long. Simulation is carried out for 3 cycles (60 ms) with step size /spl Delta/t, of 2.5 /spl mu/s to abstract the high frequency component of the signal and every 100 points have been selected as output. Two cycles of waveform, covering pre-fault and post-fault information are abstracted for further analysis. These waveforms are then used in wavelet analysis to generate the training pattern. Two different mother wavelets have been used to decompose the signal, from which the statistical information is abstracted as the training pattern. RBF network was trained and cross-validated with unseen data.

[70] **Fault position relay based on current travelling waves and wavelets**

Dong Xinzhou; Ge Yaozhong; Xu Bingyin
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 3 , 2000
Page(s): 1997 -2004

Abstract :

The current travelling wave is utilized to detect the fault position in the transmission lines in this paper. How to identify the incident travelling waves and reflected ones from the fault point when noises exist is discussed and resolved. A fault position relay based on current travelling waves and wavelets theory is designed. The relay's principle is mainly on wavelet theory and modulus maxima of the wavelet transform. By analysing the distribution of the modulus maxima, different components in the current travelling waves can be distinguished and then the incident and reflected travelling waves are identified and finally useless components are filtered. The incident and reflected travelling wave's time difference arrival time difference indicates the fault position. An EMTP simulation example is illustrated. The relay is been proved correct and effective.

[71] **Use of time delays between modal components in wavelet based fault location**

A. Abur and F. H. Magnago
International Journal of Electrical Power & Energy Systems, Volume 22, Issue 6, August 2000
Page(s): 397-403

Abstract :

This paper presents an improved fault location method based on the travelling wave theory of the transmission lines. Fault transients recorded at one end of a transmission line are processed to determine the distance from the fault location. Wavelet transform is utilized for this purpose. The proposed method also takes advantage of the different travel times of the modal components in differentiating between close-in and remote end faults. The approach has the advantages of being independent of the fault impedance, mutual coupling effects and series compensation capacitors. The method's performance for typical faults is illustrated using transient simulations obtained by an electromagnetic transients program.

[72] **Wavelet analysis based scheme for fault detection and classification in underground power cable systems**

Zhao, Y.H. Song and Y. Min
Electric Power Systems Research 53 1 (2000), pp. 23-30
Abstract :
This paper presents a new method for detecting and classifying fault transients in underground cable systems based on the use of discrete wavelet transform. A 400 kV underground cable system is simulated by ATP/EMTP (electro-magnetic transients program) under various system and fault conditions. Daubechies eight wavelet transform is employed to analyse fault transients for the development of a novel fault detection and classification scheme. Simulation results show that this scheme is effective and robust.

[73] **Wavelet transform based accurate fault location and protection technique for cable circuits**

Chen, Z.; Bo, Z.Q.; Jiang, F.; Dong, X.Z.; Weller, G.; Chin, N.F.
Advances in Power System Control, Operation and Management, 2000. APSCOM-00. 2000 International Conference on , Volume: 1 , 2000
Page(s): 59 -63
Abstract :
This paper presents a new fault location technique applicable to power cable circuits. The proposed fault locator consists of a transients detection device install yield at the busbar to detect the high frequency voltage transient signals. The initial and subsequent reflected travelling waves cause by the fault are recorded. The wavelet transform (WT) is used as a filter bank to decompose the fault signals. The travelling times of fault transients and consequently the location of the faults are calculated using the extracted signals. The simulation studies shown that the WT is effective to extract the transients component from the complicate fault signals.

2001

[74] **A new approach to high-speed protection for transmission line based on transient signal analysis using wavelets**

Shang, L.; Herold, G.; Jaeger, J.
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 173 -176
Abstract :
This paper describes new criterions for high-speed transmission line protection using the wavelet technique. Based on the representation of the travelling waves through wavelet modulus maxima, the identification criteria for similar transients, such as switch onto unloaded lines and onto faulted lines, are proposed. Simulations are carried out for testing the criteria and the influences of fault location and noise are discussed.

[75] **A new principle of fault line selection for distribution**

Su Qianli; Dong Xinzhou; Shi Shenxing; Su Bin; He Jiali
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 379 -382
Abstract :
Fault line selection is important to maintenance and normal operation of power distribution system. If a fault does not disappear for a long time, it could develop into a phase to phase fault. Then the fault line should be found out as quickly as possible and the fault should be removed. Thus, to select a good method of fault line selection is necessary. A transient signal may be a selection for fault line selection. A travelling wave is a transient signal. It will be more suitable to analysing the single phase to ground fault because the fault itself is a transient process. But there are two problems to effect the use of the travelling wave signal: first, it is a high frequency signal, so it is hard to distinguish from noise; and secondly there is lack of a proper method to detect and describe the travelling wave signal. Traditional power signals analysis tools are limited in the presence of non-steady signals. The travelling wave signal possesses a mutant property. In mathematics, it is the function of not only time but also frequency. These problems are solved with the wavelet transform. The new principle of fault line selection based on travelling waves and wavelet transform is presented.

[76] **Improved GPS travelling wave fault locator for power cables by using wavelet analysis**

W. Zhao, Y. H. Song and W. R. Chen
International Journal of Electrical Power & Energy Systems, Volume 23, Issue 5, June 2001
Page(s) 403-411
Abstract :
The paper proposes an improved approach to cable-fault location, which is essentially based on synchronised sampling technique, wavelet analysis and travelling wave principle. After an outline of the new scheme and brief introduction to the three major techniques, wavelet analysis of faulty transient waveforms is conducted in details to determine the best wavelet levels for this particular application. Then a 400 kV underground cable system simulated by the Alternative Transient Program (ATP) under various system and fault conditions is used to fully evaluate the approach. Numerical results show that this scheme is reliable and accurate with errors of less than 2% of the length of the cable line.

Faltas a tierra

1994

[77] **A recursive wavelet transform analysis of earth fault currents in Petersen-coil-protected power distribution networks**

Chaari, O.; Meunier, M.
Time-Frequency and Time-Scale Analysis, 1994., Proceedings of the IEEE-SP International Symposium on , 1994
Page(s): 162 -165

Abstract :
Earth-phase faults are the most frequent faults likely to occur in a power distribution network. In the case of Petersen-coil-protected power networks, meaningful information is contained in the transient fault signals and should be used in the protections to increase their speed and accuracy. An earth-phase fault is simulated with EMTP (ElectroMagnetic Transient Program). Then, a recursive wavelet transform is applied on two kinds of fault currents that are the zero-sequence currents in the faulty feeder and in the healthy one. The instantaneous time-frequency information obtained may be useful for the design of a fast relay algorithm.

1996

[78] **Classification of power distribution system fault currents using wavelets associated to artificial neural networks**
Assef, Y.; Chaari, O.; Meunier, M.
Time-Frequency and Time-Scale Analysis, 1996., Proceedings of the IEEE-SP International Symposium on , 1996
Page(s): 421 -424
Abstract :
In a power distribution system with a resonant neutral grounding, traditional protection algorithms based on a steady state analysis are no longer adapted. Hence a good use of transients becomes essential. This paper deals with the possibility of using wavelet transform as a pre-process for artificial neural networks (ANN) in the algorithm of power system relays. The ANN decides, after training, if the measured signal is faulty or sound. The inputs of the ANN are the arguments of wavelet coefficients obtained after applying a recursive wavelet transform on faulty signals generated with EMTP (ElectroMagnetic Transient Program). A comparison between the wavelets and fast Fourier transform has been made.

[79] **Wavelets: a new tool for the resonant grounded power distribution systems**
Chaari, O.; Meunier, M.; Brouaye, F.
Power Delivery, IEEE Transactions on , Volume: 11 Issue: 3 , July 1996 Page(s): 1301 -1308
Abstract :
This paper introduces wavelets and shows that they may be efficient and useful for power distribution relaying. The wavelet transform of a signal consists in measuring the "similarity" between the signal and a set of translated and scaled versions of a "mother wavelet". The "mother wavelet" is a chosen fast decaying oscillation function. Wavelets are used to analyse transient earth faults in a 20 kV resonant grounded network as generated by EMTP. It is shown that wavelets may be employed for analysing records to study efficiently the faulted network. Moreover, this new technique can actually be implemented in real time for protection devices. Thus, it is suitable for application to protective relays.

1998

[80] **A novel technique for high impedance fault identification**
David Chan Tat Wai; Xia Yibin

Power Delivery, IEEE Transactions on , Volume: 13 Issue: 3 , July 1998
Page(s): 738 -744
Abstract :
A novel technique using wavelet analysis filter banks (WAFB) to identify distribution high impedance faults (HIFs) is presented. A new model of HIF is used. HIFs and capacitor bank switching operations are simulated by the Electromagnetic Transients Program (EMTP) and their current signals are studied. High frequency components with the time localization information of both HIFs and capacitor bank switching operations are obtained using WAFB and their behaviour is differentiated clearly. Results demonstrate that WAFB can be used as an element in a HIF detector for fast and accurate identification of distribution HIFs.

[81] **Application of discrete wavelet transform to high impedance fault identification**
Lai, L.L.; Styvaktakis, E.; Sichanie, A.G.
Energy Management and Power Delivery, 1998. Proceedings of EMPD '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 689 -693
Abstract :
This paper describes the application of discrete wavelet transforms to power system high-impedance fault identification. Fault simulation is carried out with the EMTP96 software package. Results demonstrate that there is a high potential in the use of this technique to distance relaying.

[82] **DSP implementation of a wavelet analysis filter bank for high impedance fault detection**
Xia Yibin; Qi Li; Chan, D.T.W.
Energy Management and Power Delivery, 1998. Proceedings of EMPD '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 417 -421
Abstract :
The real-time digital signal processing (DSP) implementation of a wavelet analysis filter bank (WAFB) to identify a high impedance fault (HIF) is presented. HIFs and capacitor bank switching events are simulated by using the Electromagnetic Transients Program (EMTP). The simulation results are used as the input signal for the implementation of a wavelet analysis filter bank. Results demonstrate that the wavelet analysis filter can be used as an element in a real-time HIF detector for fast and accurate identification of distribution HIFs.

1999

[83] **Comparison of wavelet and differential equation algorithms in earth fault distance computation**
S. Hanninen, M. Lehtonen, T. Hakola, R. Rantanen
PSCC 1999
Abstract :
This paper gives a comparison between wavelet analysis and a differential equation algorithm in transient based earth fault location in the 20 kV radial distribution networks. The items discussed are earth fault transients, signal pre-processing and the performance of the proposed distance estimation algorithms. The networks considered are either unearthed or resonant earthed. The comparison showed that

both algorithms were equal. The mean error in fault location was 12% in the field tests using staged faults which were recorded in real power systems.

[84] **Experimental study for transient phenomena of ground faults on distribution lines based on various fault causes**

Tungkanawanich, A.; Kawasaki, Z.-I.; Matsuura, K.; Kuno, H.

Electric Power Engineering, 1999. PowerTech Budapest 99. International Conference on, 1999

Page(s): 146

Abstract :

Transients normally contain information that is helpful to diagnose the cause and aspect of the fault. This experiment is conducted with the objective of studying the basic knowledge of fault features and hopefully useful to get more precise in discriminating fault causes. Ground faults are concentrated in this paper because they are known as the most frequent ones occurring on distribution lines. The results are compared with those from actual fault and computer simulation. The authors also conduct the time-frequency analysis of dynamic spectrum of transients of various fault causes by means of wavelet transform for explaining fault phenomena.

[85] **High-impedance fault detection utilizing a Morlet wavelet transform approach**

Shyh-Jier Huang; Cheng-Tao Hsieh

Power Delivery, IEEE Transactions on , Volume: 14 Issue: 4 , Oct. 1999

Page(s): 1401 -1410

Abstract :

An application of Morlet wavelets to the analysis of high-impedance fault generated signals is proposed in this paper. With the time-frequency localization characteristics embedded in wavelets, the time and frequency information of a waveform can be presented as a visualized scheme. Different from the fast Fourier transform, the wavelet transform approach is more efficient in monitoring fault signals as time varies. The proposed method has been applied to discriminate the high-impedance faults from the normal switching events, and to examine the faults under various grounds including Portland cement, wet soil and grass. Testing results have demonstrated the practicality and advantages of the proposed method for the applications.

[86] **Wavelet transforms for distance protection**

H. J. Koglin, T. Lobos, J. Rezner

PSCC 1999

Abstract :

When a ground fault occurs, the measured voltage waveform contain significant oscillatory transient components. The basis component of short circuit current can be distorted by and exponential dc component. In some situation, time constants of the decaying higher frequency components may reach values up to 100 ms. It is difficult to filter out such components with out delay the filter response. In the paper application of complex wavelets are investigated. First, phasor of distorted currents and voltages are estimated. Transients responses of the wavelet algorithms are compared to that of the Fourier ones. Front the phasor, the impedance of the protected line is calculated. Monotonous transients behaviour of the estimated impedance makes it possible to predict the desired parameters of a protected line even during a transient state.

2000

[87] **A new approach to high impedance fault detection using wavelet packet analysis**
Lazkano, A.; Ruiz, J.; Aramendi, E.; Leturiondo, L.A.
Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on, Volume: 3 , 2000
Page(s): 1005 -1010
Abstract :
The paper presents a new approach to high impedance fault detection based on wavelet packet analysis. The nature and dynamics of the arc phenomenon related to high impedance faults are analysed. A background is reported about wavelet transform and wavelet packet decomposition. Then, detecting criteria are proposed and assessing parameters calculated. Finally, in order to evaluate the procedure, the approach is applied to power system signals in normal conditions.

[88] **Comparison of artificial neural networks and conventional algorithms in ground fault distance computation**
Eberl, G.; Hanninen, S.; Lehtonen, M.; Schegner, P.
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 3 , 2000
Page(s): 1991 -1996
Abstract :
This paper gives a comparison between an artificial neural network method and a differential equation algorithm and wavelet algorithm in transient based earth fault location in the 20 kV radial power distribution networks. The items discussed are earth fault transients. Signal pre-processing and the performance of the proposed distance estimation methods. The networks considered are either unearthed or resonant earthed. The comparison showed that the neural network algorithm was better than the conventional algorithms in the case of very low fault resistance. The mean error in fault location was about 1 km in the field tests using staged faults, which were recorded in real power systems. With higher fault resistances, the conventional algorithms worked better.

2001

[89] **Transient protection of transmission line using wavelet transform**
Solanki, M.; Song, Y.H.; Potts, S.; Perks, A.
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 299 -302
Abstract :
This paper presents a new approach to developing protection techniques for EHV overhead transmission lines. When a fault occurs, the fault current and voltage waveforms contain significant high frequency transient signals. The presented method is based on the detection of fault generated transient signals using wavelet analysis. The simulation study is carried out, using ATP-EMTP and wavelet analysis, which indicates that the proposed approach has the potential of developing high speed protection relays with accurate fault detection and classification.

[90] **Wavelet transform in the accurate detection of high impedance arcing faults in high voltage transmission lines**

Kim, C.H.; Kim, H.; Aggarwal, R.K.; Johns, A.T.
Developments in Power System Protection, 2001, Seventh International Conference on (IEE)On 9-12 April 2001
Page(s): 422 - 425
Abstract :
This paper describes a new fault detection technique which involves capturing the current signals generated in a transmission line under high impedance faults (HIFs). Its main thrust lies in the utilisation of the absolute sum value of signal components based on the discrete wavelet transform (DWT). A sophisticated decision logic is also designed for the determination of a trip decision. The results presented relate to a typical 154 kV Korean transmission system, the faulted signals for which are attained using the well known Electromagnetic Transients Program (EMTP) software. The simulation also includes an embodiment of a realistic nonlinear HIF mode.

Faltas con arco

2000

[91] **Arcing fault detection in underground distribution networks-feasibility study**

Charytoniuk, W.; Wei-Jen Lee; Mo-Shing Chen; Cultrera, J.; Theodore Maffetone
Industry Applications, IEEE Transactions on , Volume: 36 Issue: 6 , Nov.-Dec. 2000
Page(s): 1756 -1761
Abstract :
In some circumstances, arcing faults on insulated low-voltage conductors can sustain or reignite intermittently for several or even several dozen minutes, generating large amounts of heat and gases. In underground secondary distribution cables in ducts, the decomposition gases escape to the ends of the duct, typically manholes, where they can ignite fire or explode, throwing out the manhole cover. Detection of arcing faults may be difficult using standard overcurrent protections because some arcing faults generate relatively low currents. To study the feasibility of detecting arcing faults in underground networks, personnel from Consolidated Edison Company of New York, Inc., New York, NY, conducted an experiment in one secondary network by staging arcing faults and collecting data at the fault location and several nearby vaults. The data were analysed to examine the feasibility of developing a detection algorithm. This paper presents some results of this analysis in time, frequency, and time-frequency domains.

Autoreclosure

1998

[92] **Development of novel adaptive single-pole autoreclosure schemes for extra high voltage transmission systems using wavelet transform analysis**

I. K. Yu and Y. H. Song

Electric Power Systems Research, Volume 47, Issue 1, October 1998
Page(s):11-19
Abstract :
A novel wavelet transform analysis-based adaptive single-pole autoreclosure (SPAR) scheme of extra high voltage (EHV) transmission systems is presented in this paper. The discrete wavelet transform is adopted to analyse the fault transients caused by the secondary arc and permanent faults and the numerical results reveal that certain wavelet components can be effectively used to detect and identify the fault relevant characteristics in transmission systems. A threshold-based decision logic for the wavelet analysis coefficients is used to distinguish the transient and permanent faults, and in the case of a transient fault, to determine the secondary arc extinction time. The outcome of the study clearly indicates that the wavelet transform analysis technique can be used as an attractive and effective means of developing an adaptive autoreclosing scheme.

[93] **The wavelet transform applied to distinguish between transient and permanent**
Jiang, F.; Bo, Z.Q.; Yang, Q.X.
Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 1116 -1120
Abstract :
This paper addresses the application of wavelet transform in the identification of transient and permanent faults by processing the fault generated high frequency current transient. The presented method can be utilised to achieve adaptive reclosure which means only the transient fault can activate the reclosing operation. An identification unit is designed to capture the high frequency component generated by a fault arc and the wavelet transform is used to extract the high frequency noise generated by the fault arc and distinguish between the transient and permanent fault.

[94] **Wavelet analysis and neural networks based adaptive single-pole autoreclosure scheme for EHV transmission systems**
I.K. Yu and Y.H. Song
International Journal of Electrical Power and Energy Systems 20 7 (1998)
Pages(s): 465-474
Abstract :
This paper proposes a wavelet analysis and neural network based adaptive single-pole autoreclosure scheme for Extra High Voltage (EHV) transmission systems. First, the fault transients generated by the secondary arc and permanent faults are analysed using discrete wavelet transform with particular reference to the development of the adaptive autoreclosure scheme. Daubechies D4 wavelet transform is adopted and the numerical analyses reveal that certain wavelet components can be effectively used as the features to detect and identify the fault relevant characteristics in transmission systems. Several results of wavelet analysis are used as the feature vectors of artificial neural network which is designed to distinguish between transient and permanent faults, and to determine the secondary arc extinction point. The outcome of the study clearly indicates that the wavelet analysis combined with neural network approach can be used as an attractive and effective means of realising an adaptive autoreclosing scheme.

[95] **Wavelet transform and neural network approach to developing adaptive single-pole auto-reclosing schemes for EHV transmission systems**

Yu, I.K.; Song, Y.H.
IEEE Power Engineering Review , Volume: 18 Issue: 11 , Nov. 1998
Page(s): 62 -64
Abstract :
The authors adopt the wavelet transform to detect and identify relevant electrical fault characteristics in power transmission systems. They use several components of wavelet analysis as input features to a forward neural network to distinguish transient, permanent faults and the secondary arc extinction point.

2000

[96] **Accelerated trip of power transmission line based on biorthogonal wavelet**

Shi, T.H.; Zhang, H.; Liu, P.; Zhang, D.J.; Wu, Q.H.
Power Engineering Society Summer Meeting, 2000. IEEE , Volume: 3 , 2000
Page(s): 1333 -1337
Abstract :
This paper presents a novel approach to accelerated trip of power transmission lines using biorthogonal wavelet transform to improve the performance of protection relays. The existing principle derived from the second abrupt changes of the sequence currents to accelerate trip has been widely applied, while a fault occurs in the second zone of the distance protection. However, a lower sensitivity has been observed for some specific system parameters and fault types for which the second abrupt changes of sequence currents are particularly faint. The wavelet analysis has an outstanding characteristics to extract signal components, by contrast to the conventional Fourier analysis which is inefficient to detect the faint abrupt signal. A fourth-order biorthogonal wavelet decomposition algorithm is proposed in this paper, which possesses the capability of fast calculation, partitioning the higher frequency band and linear phase. This algorithm, provided an accelerated trip scheme, can efficiently extract the faint second abrupt changes of the sequence currents and is able to deal with the dead-zone problem of conventional protection techniques. The simulation result obtained using MATLAB/SIMULINK shows the feasibility and efficiency of the proposed approach.

2001

[97] **Adaptive reclosure using high frequency fault transients**

Li Youyi; Dong Xinzhou; Bo, Z.Q.; Chin, N.F.; Ge Yaozhang
Developments in Power System Protection, 2001, Seventh International Conference on (IEE) , 2001
Page(s): 375 -378
Abstract :
A new signal processing algorithm for arcing faults detection based on the high frequency current transient is presented in this paper. In transient faults, arc current extinguishes and then ignites, and this periodically disturbs fault current. After several cycles, when transient signals by the fault decay a lot, the arc disturbance can be identified by the wavelet transform. The feasibility of this algorithm has been tested by computer simulation.

Transitorios

Conexión de condensadores

2000

[98] **Classification of power system transients: synchronised switching**

Styvaktakis, E.; Bollen, M.H.J.; Gu, I.Y.H.
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 4 , 2000
Page(s): 2681 -2686
Abstract :

This paper presents a new method for the identification and classification of transients due to synchronised capacitor switching in three-phase systems. Signal processing techniques are introduced to detect the switching actions in the individual phases. Synchronised switching methods for capacitor energization are considered. The proposed method enables detection and classification of synchronised capacitor switching events. This in turn will lead to a reduction in the amount of data to be reported from a power quality survey.

Test de onda impulso

2001

[99] **Wavelet analysis for estimation of mean-curve of impulse waveforms superimposed by noise, oscillations and overshoot**

Satish, L.; Gururaj, B.J.
Power Delivery, IEEE Transactions on , Volume: 16 Issue: 1 , Jan. 2001
Page(s): 116 -121
Abstract :

This paper describes a novel approach to estimate the mean-curve of impulse voltage waveforms that are recorded during impulse tests. These waveforms in practice are superposed by noise, oscillations, and overshoot. The approach is based on multiresolution signal decomposition (a kind of wavelet transform) and has many advantages over existing methods, since it does not assume any model for estimating the mean-curve, is interactive in nature, suitable for full and chopped impulses, does not introduce distortions due to its application, is easy to implement and does not call for changes to existing standards. Results presented show its applicability.

Análisis de transitorios en general

1996

[100] **Discrete wavelet analysis of power system transients**

Wilkinson, W.A.; Cox, M.D.

Power Systems, IEEE Transactions on , Volume: 11 Issue: 4 , Nov. 1996
Page(s): 2038 -2044

Abstract :

Wavelet analysis is a new method for studying power system transients. Through wavelet analysis, transients are decomposed into a series of wavelet components, each of which is a time-domain signal that covers a specific octave frequency band. This paper presents the basic ideas of discrete wavelet analysis. A variety of actual and simulated transient signals are then analysed using the discrete wavelet transform that help demonstrate the power of wavelet analysis.

[101] **Wavelets and electromagnetic power system transients**

Robertson, D.C.; Camps, O.I.; Mayer, J.S.; Gish, W.B.
Power Delivery, IEEE Transactions on , Volume: 11 Issue: 2 , April 1996
Page(s): 1050 -1058

Abstract :

The wavelet transform is introduced as a method for analysing electromagnetic transients associated with power system faults and switching. This method, like the Fourier transform, provides information related to the frequency composition of a waveform, but it is more appropriate than the familiar Fourier methods for the non-periodic, wide-band signals associated with electromagnetic transients. It appears that the frequency domain data produced by the wavelet transform may be useful for analysing the sources of transients through manual or automated feature detection schemes. The basic principles of wavelet analysis are set forth, and examples showing the application of the wavelet transform to actual power system transients are presented.

1997

[102] **Analysis of electrical transients in power systems via a novel wavelet recursion method**

Galli, Anthony Wayne, Gerald T. Heydt.
Purdue University graduate School

Abstract :

This work utilizes wavelet analysis, a relatively new mathematical tool, to develop a new method of analysis for electrical transients in electric power systems. Techniques which are currently employed fall into two main categories: time domain or the integral transform domain. Time domain methods include the mathematical solution of differential equations and companion circuit techniques. The integral transform domain methods include Laplace transform and frequency (e.g., Fourier transform) analysis. Both of the aforementioned categories can be stressed when solving systems of equations with a wide eigenspectrum or when a system of equations is subjected to a non-stationary forcing function. One of the benefits of wavelet analysis, however, is the ability to easily resolve signals of a non-stationary nature. In this thesis, four wavelet recursion formulae the Right Formula Backward Difference (RFBD), the Left Formula Backward Difference (LFBD), the Right Formula Forward Difference (RFFD), and the Left Formula Forward Difference (LFFD) are derived for the solution of the differential equations that are germane to the analysis of electric power systems. The convergence properties of the formulae are discussed and several examples are presented. It is shown by these examples, that the method developed in this work is a viable and sometimes preferred alternative to the current methods of electrical transient analysis of power systems.

[103] **Transient power quality problems analyzed using wavelets**

Heydt, G.T.; Galli, A.W.
Power Delivery, IEEE Transactions on , Volume: 12 Issue: 2 , April 1997
Page(s): 908 -915
Abstract :
In the literature, wavelet techniques have been proposed for the identification of power system transient signals (e.g., lightning impulse, and capacitor switching transients). In this paper, the wavelet technique is proposed for the analysis of the propagation of transients in power systems. The advantages and disadvantages of the method are discussed and the way in which these analysis methods complement previously reported identification methods is described. An example based on the discretized solution of a differential equation is given.

[104] **Wavelet modelling of transients in power systems**

Mo, F.; Kinsner, W.
WESCANEX 97: Communications, Power and Computing. Conference Proceedings., IEEE , 1997
Page(s): 132 -137
Abstract :
This paper presents a new scheme to model transients in power systems. Since transients are non-stationary both in time and space, their analysis and characterization are difficult, and the traditional method of Fourier transform and short-time Fourier transform have their limitations in transient analysis. Here, the authors propose the use of a new time-frequency multiresolution wavelet analysis of transients in power systems. The final objective is to build an intelligent transient recorder, which is capable of detecting and classifying power system transients by type from the transient waveform signature based on an effective and efficient wavelet modelling and characterization.

1998

[105] **Power System Transients Characterization and Classification using Wavelets and Neural Networks**

Fan Mo
http://citeseer.nj.nec.com/mo98power.html
Abstract :
This paper presents a framework for transients classification using wavelet transform and two specific artificial neural networks, probabilistic neural networks (PNN) and resource allocating neural networks (RAN). One significant feature of wavelet for transients characterization is its time-scale two dimensional but compact representation. One distinguishing feature of PNN and RAN is the ability to adjust their architecture automatically to adapt to new environment quickly and accurately, which makes them the promising candidates for transients classification in power system. Some experimental results have indicated the suitability of this framework for transients classification.

1999

[106] **Wavelet Analysis of Power Systems Transients Using Scalograms and Multiresolution Analysis**

J. LIU ; P. PILLAY; P. RIBEIRO
Electric Machines and Power Systems, 27, 1999 Copyright c 1999 Taylor & Francis, Inc.
Page(S): :1331–1341
Abstract :
The Wavelet Transform has attracted considerable attention in the field of power quality analysis recently. It has proved to be a powerful tool to study those transients that have time-localized information. In this paper, the insight to be gained from using multiresolution analysis and scalograms is presented. With multiresolution analysis, the original signal is transformed into coefficients in different octave levels. From the scalogram of the respective coefficients at each level, the special features of the original signals become distinctive. Advantages of the wavelet transform over the Fourier transform are also presented. Typical power transients are used to test the method to illustrate its applicability in the analysis of power transients.

2000

[107] **An alternative method for transient analysis via wavelets**

Meliopoulos, A.P.S.; Chien-Hsing Lee
Power Delivery, IEEE Transactions on , Volume: 15 Issue: 1 , Jan. 2000
Page(s): 114 -121
Abstract :
This paper presents an alternative method for the transient analysis of dynamical systems. The method consists of the traditional frequency domain analysis to capture the steady state operation of the system and a wavelet-based transient analysis which captures the disturbance. The total solution is obtained from the superposition of the steady state and disturbance solutions. This paper focuses on the second part of the solution method. The authors have named this method WBTA (wavelet-based transient analysis). It can be implemented using any set of orthogonal wavelets. In this paper, they present an implementation with Daubechies wavelets. The results obtained using this method are compared and verified with a numerical time-domain analysis method. A concise description of the method is presented followed by examples.

[108] **Electric power transient disturbance classification using wavelet-based hidden Markov models**

Jaehak Chung; Powers, E.J.; Grady, W.M.; Bhatt, S.C.
Acoustics, Speech, and Signal Processing, 2000. ICASSP '00. Proceedings. 2000 IEEE International Conference on , Volume: 6 , 2000
Page(s): 3662 -3665
Abstract :
We utilize wavelet-based hidden Markov models (HMM) to classify electric power transient disturbances associated with degradation of power quality. Since the wavelet transform extracts power transient disturbance characteristics very well, this wavelet-based HMM classifier illustrates high classification correctness rates. The power transient disturbance is decomposed into multi-resolution wavelet

domains, and the wavelet coefficients are modelled by a HMM. Based on this modelling, the maximum likelihood classification is applied to classify actual power quality transient disturbance data recorded on a 7200 V distribution line, and the result is tuned by post-processing. Of 507 power quality events experimentally observed by an electrical utility, 95.5% are correctly classified.

Corriente de connexion en transformadores

1998

[109] **A new approach to detect transformer inrush current by applying wavelet**

Zhang Chuanli; Huang Yizhuang; Ma Xiaoxu; Lu Wenzhe; Wang GuoXing
Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 1040 -1044

Abstract :

In this paper, a mother wavelet suitable for processing transient signal in power system is constructed according to the theory of wavelet analysis and the Improve Recursive Wavelet Transform (IRWT) is presented in order to meet the real time demands of analysing power system signals. At the same time, research work are carried out to detect transformer inrush current. IRWT has been used to analyse transformer inrush current generated by PSCAD and it proved both effective and feasible.

[110] **Investigation of transformer inrush current using a dyadic wavelet**

Qi Li; Chan, D.T.W.
Energy Management and Power Delivery, 1998. Proceedings of EMPD '98. 1998 International Conference on , Volume: 2 , 1998
Page(s): 426 -429

Abstract :

This paper presents the application of a dyadic wavelet to investigate transformer inrush current. Inrush currents are simulated using the Electromagnetic Transient Program (EMTP). Different values of remnant flux and point of voltage switch-on are chosen to produce various inrush current waveforms. The dyadic wavelet is applied to analyse the signature of the simulated inrush waveforms. Preliminary results are presented.

2000

[111] **A wavelet transform based scheme for power transformer inrush identification**

Xianguing Liu; Pei Liu; Shijie Cheng
Power Engineering Society Winter Meeting, 2000. IEEE , Volume: 3 , 2000
Page(s): 1862 -1867

Abstract :

A new scheme for transformer inrush identification is proposed in this paper. The new scheme is based on the wavelet packet transform algorithm. The main advantage of the proposed scheme is that different kinds of inrush of the transformers can be correctly identified from different types of the internal faults of

the transformers. Also, the external fault of the transformers can also be identified from the internal fault with the proposed scheme. Test results with the sampled data from a prototype device on a dynamic power system model verify the effectiveness of the proposed scheme. Furthermore, another advantage of thus algorithm is that it can be realized in real time applications.

Líneas de transmisión

1999

[112] **Wavelet transform solution of multiconductor transmission line transients**

Raugi, M.
Magnetics, IEEE Transactions on , Volume: 35 Issue: 3 Part: 1 , May 1999
Page(s): 1554 -1557

Abstract :

In this paper a wavelet transform approach is used to solve multiconductor transmission line equations. By using wavelets on the interval, differential and integral operators are represented by sparse matrices. Then the time domain differential equations of multiconductor transmission lines are reduced to algebraic ones. The unknowns of the algebraic system are the coefficients of the wavelet basis functions. Therefore a Fourier-type approach is obtained for transient analysis of transmission lines. The procedure reduces the CPU times with respect to the usual transient analysis obtained by time stepping methods. An initial analysis of the numerical characteristics and performances of the method is carried out considering constant RLCG multiconductor lines.

2000

[113] **Hybrid F.E.-wavelet method for nonlinear analysis of nonuniform MTL**

Barmada, S.; Musolino, A.; Raugi, M.
Magnetics, IEEE Transactions on , Volume: 36 Issue: 4 Part: 1 , July 2000
Page(s): 977 -981

Abstract :

This paper deals with the numerical solution of non-uniform Transmission Lines (TL) with non-linear loads. The method presented here is based on the combination of wavelet expansion and Finite Elements (FE) in space and time domain. By expanding voltages, currents and operators by means of wavelet functions, the TL equations are transformed into algebraic equations where the differential operator is represented by a matrix and the unknowns are the coefficients of the wavelet expansion of voltages and currents. The numerical efficiency of the method is tested by analysing uniform, non-uniform lines and non-linear loads. The results are compared with results obtained by means of different methods.

[114] **Visualizing wavelet transformed travelling waves on power transmission line using JAVA**

Kit Po Wong; Lee, K.
Advances in Power System Control, Operation and Management, 2000. APSCOM-00. 2000 International Conference on , Volume: 2 , 2000
Page(s): 349 -353

Abstract :

The paper reports work on analysis travelling waves, with make occur on power transmission lines using Bewley Lattice Diagram (BLD) and wavelet transform (WT). It also reports the development work on a visualizing system, which implements the BLD an WT methods for visualizing the travelling wavelets using the Java computer programming languages. The paper describes the BLD and WT techniques for the analysis of the electromagnetic transients on power lines. Analysis of electromagnetic transients is important in the area of transmission lines protection since the high frequency components of the transients can be utilized for the identification of the location of disturbances of line. The structure of the visualization system is then described. The usefulness of the system is demonstrated by applying it to the fault distance identification problem on a 330 kV transmission line. The java visualization system reporter in this paper provides and excellent tool to dynamically so the complicated formation of travelling waves along the lines initiated by large disturbance. It is useful to system planning and protection engineers. It is also a valuable tool for the teaching of electromagnetic transients analysis

[115] **Wavelet-based simulation of transients along transmission lines with frequency dependent parameters**

Magnago, F.H.; Abur, A.
Power Engineering Society Summer Meeting, 2000. IEEE , Volume: 2 , 2000
Page(s): 689 -694
Abstract :
This paper describes a transmission line model which is based on wavelet transform, and takes into account frequency dependence of its parameters. Multiresolution decomposition of time domain signals is used to view the transient at different sub-bands, solving each sub-band using the corresponding values of frequency dependent parameters. Open line energization transients computed using this model are presented as an illustration, of the proposed method of modelling and simulation.

2001

[116] **Accurate modelling and simulation of transmission line transients using frequency dependent modal transformations**

Abur, A.; Ozgun, O.; Magnago, F.H.
Power Engineering Society Winter Meeting, 2001 IEEE , Volume: 3 , 2001
Page(s): 1443 -1448
Abstract :
The frequency dependent line model (also known as the J. Marti model) which is currently used in most electromagnetic transient programs, is very efficient and accurate for most simulation cases. However, it makes an approximation in choosing the modal transformation matrix that is used to switch variables between the phase and modal domains at each simulation time step. This approximation may not hold true for certain tower configurations and/or conductor types where line parameters vary drastically with frequency. In this paper, a wavelet based alternative solution, which incorporates frequency dependence of transformation matrices into the simulation process.

Otros

Máquinas eléctricas

2001

[117] **A unified wavelet-based approach to electrical machine modeling**
Fedrigo, S.; Gandelli, A.; Monti, A.; Ponci, F.
Electric Machines and Drives Conference, 2000. IEMDC 2001. IEEE International , 2001
Page(s): 765 -769
Abstract :
The paper presents an original approach to electrical machine modelling based on wavelet transformation. The main purpose of the approach is to give a more detailed description of the field in the airgap removing the hypothesis of sinusoidal field distribution typical of a traditional space-phasor approach. As a result, a more detailed closed-form analysis is possible including torque ripple evaluation.

Motores

1999

[118] **End effect analysis of linear induction motor based on the wavelet transform technique**
Mori, Y.; Torii, S.; Ebihara, D.
Magnetics, IEEE Transactions on , Volume: 35 Issue: 5 Part: 2 , Sept. 1999
Page(s): 3739 -3741
Abstract :
The performance of LIM is degraded due to the influence of the end effects. LIM is analysed using the Fourier series expansion to throw light on this problem. However, when we want to obtain the high-accuracy in this technique, the number of times for calculation is increased. In the case of the wavelet transform technique, as the wavelet coefficients converge rapidly to zero, this technique has been applied to analyse the end effects of LIM. In this paper, we investigated the method for determining mother wavelet.

Potencia

2000

[119] **Some notes on wavelet analysis of time-variant electrical networks**
Gandelli, A.; Leva, S.
Circuits and Systems, 2000. Proceedings of the 43rd IEEE Midwest Symposium on , Volume: 3 , 2000
Page(s): 1166 -1169
Abstract :

After presenting a new approach for the analysis and the resolution of linear time variant circuits base on wavelets functions the author are introducing some specific consideration relates to matrix properties associated to such methodology. The simple recursive algorithm for the construction of the integral and convolution matrixes and the topological matrix are evaluated more in depth in order to outcome the most interesting features proposal for numerical optimisations are also given. And example including a three phase inverter study using such technique is presented

Transformadores

2001

[120] **Condition assessment of power transformer on-load tap-changers using wavelet analysis**

Pengju Kang; Birtwhistle, D.
Power Delivery, IEEE Transactions on , Volume: 16 Issue: 3 , July 2001
Page(s): 394 -400

Abstract :
The operation of a power transformer on-load tap-changer (OLTC) produces a well-defined series of vibration bursts as its signature. Due to the harmonic and non-stationary nature of the transient vibration signal, traditional frequency and time-frequency techniques are on longer effective for characterization of this type of vibration signals, as the localized time domain features, such as delays between bursts, the number of bursts, and the strengths of bursts, are essential for the condition assessment of OLTC. A wavelet transform based technique is developed in this paper to characterize the OLTC vibration signals. This technique gives a simplified format for displaying and representing the essential features of the OLTC vibration signatures. Application results from a selector type OLTC demonstrate that the features extracted in the wavelet domain can be utilized to provide reliable indications of the actual heath of an OLTC.

Web

General

1997

[121] **Wavelets and Filter Banks**

Gilbert Strang and Truong Q. Nguyen
Web http://saigon.ece.wisc.edu/~waveweb/Tutorials/book.html

Abstract :
This new textbook by Gilbert Strang and Truong Nguyen offers a clear and easy-to-understand introduction to two central ideas -- filter banks for discrete signals, and wavelets. The connections are fully explained -- the wavelet is determined by a choice of filter coefficients. All important wavelet properties (orthogonality or biorthogonality, symmetry, accuracy of approximation, and smoothness) come from specific properties of the filters. The text shows how to construct those filters

and wavelets. The applications are very widespread -- and they continue to develop rapidly. The book gives a direct approach to signal processing and image processing through filter banks that iterate on the lowpass filter (this is the wavelet idea). Blocking and ringing artefacts are analysed, along with many MATLAB applications. Wavelets and Filter Banks is written for the very broad audience that uses these ideas

2000

[122] **Applied Wavelet Analysis Courses**

Web http://www.wavelets.com/
Abstract :
Información general de wavelets, aparece índice de libros en el área.

[123] **Applying the Haar Wavelet Transform to Time Series Information**

Web http://www.bearcave.com/misl/misl_tech/wavelets/haar.html
Abstract :
Tutorial general

2001

[124] **Pagina web de Shyh-Jier Huang**
Shyh-Jier Huang
Web http://www.ee.ncku.edu.tw/chinese/professor/teac53.html
Abstract :
Este autor tiene más de 10 publicaciones en nuestra B.D.

[125] **UC Berkeley Wavelet Group**

Web http://gabor.eecs.berkeley.edu/
Abstract :
Documentación general sobre wavelet.

[126] **Wavelet Resources**

Web http://www.ee.umanitoba.ca/~ferens/wavelets.html
Abstract :
Web con archivos .pdf sobre información general y especifica de wavelets, pero no aparecen aplicaciones en SEP. Aparecen algoritmos y mucho mas.

Matlab

2000

[127] **Mathematica Activities Matlab**

Web
Abstract :
Un conjunto de programas de matlab

2001

[128] **Kevin S. Amaratunga web page**
Kevin S. Amaratunga
Web http://wavelets.mit.edu/
Abstract :
Aparece un curso general de wavelets con aplicaciones en Matlab.

[129] **WAVELAB 802 for Matlab5.x**

Web http://www-stat.stanford.edu/~wavelab/
Abstract :
WaveLab is a collection of Matlab functions that have been used by the authors and collaborators to implement a variety of computational algorithms related to wavelet analysis. A partial list of the techniques made available:
orthogonal wavelet transforms,
biorthogonal wavelet transforms,
translation-invariant wavelets,
interpolating wavelet transforms,
cosine packets,
wavelet packets,
matching pursuit,
and a lot more... It includes more than 1100 Matlab files, datasets, and demonstration scripts. Some computationally expensive routines have been implemented as Matlab MEX functions.

[130] **Wavelet Sites**

Web http://epore.mit.edu/~tgowrish/tgowrish/wlet.html
Abstract :
Muchas referencias a sitios relacionados con wavelet de diferentes universidades.

Tutorial

1995

[131] **Tutorial on continuous wavelet analysis of experimental data**
Jacques Lewalle
Web Syracuse University
http://www.ecs.syr.edu/faculty/lewalle/tutor/tutor.html
Abstract :
Our purpose is to make the wavelet techniques approachable without unnecessary

mathematical sophistication. Therefore, graphics are more important than the formulae or analytical results, shown in small print. Also, with the expectation that the user wants to interrogate his or her data from the viewpoint of the underlying physics, only a few simple wavelets with readily interpretable transforms are used: the first two Gaussians and the Morlet wavelets. The examples range from cosines to modulated and intermittent data.

1996

[132] **The engineer's ultimate guide to wavelet analysis**
Robi Polikar
Web http://engineering.rowan.edu/~polikar/WAVELETS/WTtutorial.html
Abstract :
Un tutorial en el web sobre teoría de wavelet

1998

[133] **A wavelet tour of signal processing**
Stéphane Mallat
Academic Press, 1998
http://cas.ensmp.fr/~chaplais/Wavetour_presentation/Wavetour_presentation_US.html
Abstract :
Apunte

1999

[134] **Tutorial slides on wavelets**
Gregory Mc Garry
Signal Processing research centre
Abstract :
Transparencias muy básicas sobre wavelet

2000

[135] **Amara's wavelet page**

Web http://www.amara.com/current/wavelet.html
Abstract :
Pagina muy conocida entrega diversas información, incluyendo un curso detallado de wavelets.

Anexo I

PROGRAMAS EN MATLAB

ondiculas.m

```
% Relé diferencial numérico con discriminación por Ondículas
%
% Este programa simula la proteccion diferencial de un transformador
%mediante un rele diferencial numerico con discriminacion por ondiculas
%
% Funciones utilizadas:
%                          csenal.m
%                          ana_wave.m
%                          rele_cri.m
%                          calc_fft.m
%
clear all; close all; clc;
in_state=1;
falta_state=1;
an_f=1;
res_f=1;
tipo_w=1
nro_w=1
nro_nivel=1
irele=[];
d=[];
criterio=1;
%
%Definición de  interfaz gráfica
%
pantalla=get(0,'ScreenSize');
xw=pantalla(3);
yw=pantalla(4);
vent1=figure('Position', [0 -0.03*yw xw yw], 'Menubar','none');
titulo=uicontrol(gcf,...
   'Style','text',...
   'String','RELE DIFERENCIAL NUMERICO CON DISCRIMINACION POR
ONDICULAS',...
   'fontsize',11,...
   'foregroundcolor',[1 1 1],...
   'backgroundcolor',[0 0 0.78],...
   'fontweight','bold',...
   'Position',[xw/6 yw*0.95 0.67*xw 0.028*yw]);
set(titulo)
ejes_red = axes('units','pixels','Position',[xw/50 yw*0.65 0.25*xw
0.26*yw]);image(imread('trafo1.jpg'));   %Figura de la red
set(ejes_red,'linewidth',1.5,'TickLength',[0
0],'YTickLabel','','XTickLabel','')
ejes_senal=axes('units','pixels','Position',[xw/40 yw*0.1 0.25*xw
0.26*yw]);
set(ejes_senal,'Visible','off');

for i=1:(nro_nivel+1)
 ejes_wave(i)=axes('units','pixels','Position',[xw/40 yw*0.1 0.25*xw
0.26*yw]);
 set(ejes_wave(i),'Visible','off');
end
ejes_detalle = axes('units','pixels','Position',[xw/40 yw*0.1 0.25*xw
0.26*yw]);
set(ejes_detalle,'Visible','off');
ejes_cri = axes('units','pixels','Position',[xw/40 yw*0.1 0.25*xw
0.26*yw]);
```

```
set(ejes_cri,'Visible','off');
ejes_fourier = axes('units','pixels','Position',[xw/40 yw*0.1 0.25*xw
0.26*yw]);
set(ejes_fourier,'Visible','off');

%Ventanas para considerar el estudio de Inrush

   txt_inrush=uicontrol(gcf,...
   'Style','text',...
   'units','pixels','Position', [ xw/50 yw*0.6 0.12*xw 0.04*yw],...
   'string','Considerar Inrush');
       %Estudiar Inrush
       inrush_in=uicontrol(gcf,...
       'Style','radio',...
       'Position',[xw/50 yw*0.58 0.06*xw 0.04*yw] ,...
       'String','Si',...
       'Value',1,...
       'CallBack',[...
       'in_state= 1,'...
       'set(inrush_in,''Value'',1),'...
       'set(inrush_out,''Value'',0),']);

       %No estudiar Inrush
       inrush_out=uicontrol(gcf,...
       'Style','radio',...
       'Position', [0.08*xw yw*0.58 0.19*xw 0.04*yw],...
       'String','No',...
       'Value',0,...
       'CallBack',[...
       'in_state= 0,'...
       'set(inrush_out,''Value'',1),'...
       'set(inrush_in,''Value'',0),']);

 %Definicion menu pop-up para seleccionar ángulo de conexión de la
%fuente

 txt_popan=uicontrol(gcf,...
   'Style','text',...
   'units','pixels','Position', [ xw/50+110 yw*0.6 0.12*xw+23
0.04*yw],...
   'string','Angulo de Conexión');
 popan=uicontrol(vent1,...
    'Style','popup',...
    'String','0 º|30 º|60 º|90 º',...
    'Position',[0.14*xw+10 0.57*yw 0.07*xw+35 0.04*yw],...
    'CallBack', ['an_f = get(popan,''Value'')']);

%Menú para seleccionas el tipo de falta a estudiar

txt_falta=uicontrol(gcf,...
   'Style','text',...
   'units','pixels','Position', [ xw/50 yw*0.53 0.25*xw 0.04*yw],...
   'string','Considerar falta');
       %
       %No estudiar falta
       %
       sin_falta=uicontrol(gcf,...
       'Style','radio',...
       'Position',[xw/50 yw*0.51 0.08*xw 0.04*yw] ,...
       'String','Sin falta',...
       'Value',1,...
```

```
       'CallBack',[...
       'falta_state= 1,'...
       'set(sin_falta,''Value'',1),'...
       'set(falta_interna,''Value'',0),'...
       'set(falta_externa,''Value'',0),']);
       %
       %Estudiar falta interna
       %
       falta_interna=uicontrol(gcf,...
       'Style','radio',...
       'Position', [0.1*xw yw*0.51 0.09*xw 0.04*yw],...
       'String','Falta interna',...
       'Value',0,...
       'CallBack',[...
       'falta_state= 0,'...
       'set(sin_falta,''Value'',0),'...
       'set(falta_interna,''Value'',1),'...
       'set(falta_externa,''Value'',0),']);
       %
       %Estudiar falta externa
       %
       falta_externa=uicontrol(gcf,...
       'Style','radio',...
       'Position', [0.19*xw yw*0.51 0.08*xw 0.04*yw],...
       'String','Falta externa',...
       'Value',0,...
       'CallBack',[...
       'falta_state= -1,'...
       'set(sin_falta,''Value'',0),'...
       'set(falta_interna,''Value'',0),'...
       'set(falta_externa,''Value'',1),']);

 %Menú para seleccionar la resistencia de falta

 txt_popre=uicontrol(gcf,...
   'Style','text',...
   'units','pixels','Position', [ xw/50+80 yw*0.45 xw/50+155
0.06*yw],...
   'string','Resistencia de falta');
 popre=uicontrol(vent1,...
    'Style','popup',...
    'String','0 ohm|0.01 ohm|1.0 ohm|100 ohm',...
    'Position',[xw/50+120 0.44*yw 0.07*xw+35 0.04*yw],...
    'CallBack', ['res_f = get(popre,''Value'')']);

 %Texto para ventanas de elección de wavelet

 txt_wave=uicontrol(gcf,...
   'Style','text',...
   'units','pixels','Position', [ xw/50+280 yw*0.07 xw/50+70
0.05*yw],...
   'string','Ondicula');
 pop_wave=uicontrol(vent1,...
    'Style','popup',...
    'String','db|haar|sym',...
    'Position',[xw/50+370 0.07*yw xw/50+40 0.05*yw],...
    'CallBack', ['tipo_w = get(pop_wave,''Value'')']);
popwave_nro=uicontrol(vent1,...
    'Style','popup',...
    'String','1|2|3|4|5|6|7|8|9|10',...
    'Position',[xw/50+440 0.07*yw xw/50+20 0.05*yw],...
```

```
    'CallBack', ['nro_w = get(popwave_nro,''Value'')']);
txt_nivel=uicontrol(gcf,...
   'Style','text',...
   'units','pixels','Position', [ xw/50+280 yw*0.05 xw/50+70
0.03*yw],...
   'string','Nivel');
popwave_nivel=uicontrol(vent1,...
    'Style','popup',...
    'String','1|2|3|4|5|6|7|8|9|10',...
    'Position',[xw/50+370 0.04*yw xw/50+20 0.04*yw],...
    'CallBack', ['nro_nivel = get(popwave_nivel,''Value'')']);

%Botón tipo pushbutton para seleccionar la señal de estudio

senal=uicontrol(gcf,...
    'Style','push',...
    'Position',[xw/50+80 0.4*yw 0.07*xw 0.04*yw],...
    'String','Cargar señal',...

'CallBack','[irele,t]=csenal(vent1,ejes_red,ejes_senal,in_state,falta_
state,an_f,res_f,xw,yw,tipo_w,nro_nivel,nro_w,ejes_wave,ejes_detalle,e
jes_cri,ejes_fourier);');

%Botón tipo pushbutton para el análisis wavelet

analizar=uicontrol(gcf,...
    'Style','push',...
    'Position',[xw/50+540 0.05*yw 0.07*xw 0.035*yw],...
    'String','Analizar',...

'CallBack','[ejes_wave,ejes_detalle,ejes_cri,ejes_fourier,d]=ana_wave(
irele,ejes_wave,ejes_detalle,ejes_cri,ejes_fourier,tipo_w,nro_w,nro_ni
vel,xw,yw,t);');

%Botón tipo pushbutton para Ejecutar el algoritmo del relé

analizar=uicontrol(gcf,...
    'Style','push',...
    'Position',[xw/50+925 0.53*yw 0.06*xw 0.04*yw],...
    'String','Ejecutar',...
    'CallBack','[ejes_cri,
ejes_fourier]=rele_cri(d,ejes_cri,ejes_detalle,ejes_fourier,0,xw,yw,t)
;');

%Botón tipo pushbutton para evaluar la transformada rápida de Fourier
de la señal de estudio

Fourier=uicontrol(gcf,...
    'Style','push',...
    'Position',[xw/50+925 0.05*yw 0.06*xw 0.035*yw],...
    'String','Fourier',...
    'CallBack','[ejes_fourier]=calc_fft(irele,ejes_fourier,xw,yw);');
```

dibuja_mono.m

```
%
%dibuja_mono.m
%
%  Funcion para pintar una imagen en una ventana
%
% Parametros:
%        nombre_ejes  : Datos de los ejes de localizacion de la imegen
%        nombre_mono  : Nombre de la imagen a pintar.

function dibuja_mono(nombre_ejes,nombre_mono)
axes(nombre_ejes);
set(gcf,'currentaxes',nombre_ejes);
image(imread(nombre_mono));
set(nombre_ejes,'linewidth',1.5,'TickLength',[0
0],'YTickLabel','','XTickLabel','')
```

csenal.m

```
%
% csenal.m
%
%  Programa para la selección del caso de estudio
%  se considera:
%                falta interna o externa
%                Inrush
%                Instante de conexión del transformador
%                Resistencia de falta
%
function
[irele,t]=csenal(vent1,ejes_red,ejes_senal,in_state,falta_state,an_f,r
es_f,...
xw,yw,tipo_w,nro_nivel,nro_w,ejes_wave,ejes_detalle,ejes_cri,ejes_four
ier)

%Crea ejes para dibujar señal

set(ejes_senal,'Visible','off');
axes(ejes_senal);
cla;
for i=1:length(ejes_wave)
   set(ejes_wave(i),'Visible','off');
   axes(ejes_wave(i));
   cla;
end
set(ejes_detalle,'Visible','off');
   axes(ejes_detalle);
   cla;
set(ejes_cri,'Visible','off');
   axes(ejes_cri);
   cla;
set(ejes_fourier,'Visible','off');
axes(ejes_fourier);
cla;

if in_state==1
   switch an_f
      case 1                              % Inrush = 0º sin Fi,
sin Fe
         if falta_state==1
            disp('solo inrush')
            casos=1;
            dibuja_mono(ejes_red,'inrush.jpg');
              clear irele;
              load in0gr;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

         elseif falta_state==0
             dibuja_mono(ejes_red,'infalin.jpg');
         switch res_f
         case 1                              % Inrush= 0º y Fi con
Rf=0
            casos=2;
              clear irele;
              load in0f0;
```

```
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

         case 2                              % Inrush= 0º y Fi con
Rf=0.01
            casos=3;
              clear irele;
              load in0f001;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

         case 3                              % Inrush= 0º y Fi con
Rf=1.0
            casos=4;
              clear irele;
              load in0f1;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

         case 4                              % Inrush= 0º y Fi con
Rf=100
            casos=5;
              clear irele;
              load in0f100;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

         end
       disp('falta interna+in')
    else
         dibuja_mono(ejes_red,'infalex.jpg');
       switch res_f
       case 1                 %Rf = 0
          casos=6;
              clear irele;
              load i0fe0;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

       case 2                 %Rf = 0.01
          casos=7;
              clear irele;
              load i0fe001;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

       case 3                 %Rf = 1.0
          casos=8;
              clear irele;
              load i0fe1;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

       case 4
          casos=9;            %Rf = 100
              clear irele;
              load i0fe100;
              t=0:0.04/(length(irele)-1):0.04;
              dibuja_senal(ejes_senal,irele,7,'m',t);

         end
```

```
      disp('falta externa+ in')
   end
     case 2                          % Inrush para 30º
   if falta_state==1
      disp('solo inrush')
      casos=10;
      dibuja_mono(ejes_red,'inrush.jpg');
             clear irele;
             load in30gr;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

   elseif falta_state==0
    dibuja_mono(ejes_red,'infalin.jpg');
      switch res_f
      case 1
         casos=11;
             clear irele;
             load in30f0;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

      case 2
         casos=12;
             clear irele;
             load in30f001;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

      case 3
         casos=13;
             clear irele;
             load in30f1;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

      case 4
         casos=14;
             clear irele;
             load in30f100;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

        end
      disp('falta interna+in')
   else
       dibuja_mono(ejes_red,'infalex.jpg');
      switch res_f
      case 1
         casos=15;
             clear irele;
             load i30fe0;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

      case 2
         casos=16;
             clear irele;
             load i30fe001;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
```

```
   case 3
      casos=17;
          clear irele;
          load i30fe1;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);

   case 4
      casos=18;
          clear irele;
          load i30fe100;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);

     end
   disp('falta externa+ in')
end
   case 3                                 % Inrush para 60º
if falta_state==1
   disp('solo inrush')
   dibuja_mono(ejes_red,'inrush.jpg');
   casos=19;
          clear irele;
          load in60gr;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);
elseif falta_state==0
    dibuja_mono(ejes_red,'infalin.jpg');
   switch res_f
   case 1
      casos=20;
          clear irele;
          load in60f0;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);

   case 2
      casos=21;
          clear irele;
          load in60f001;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);

   case 3
      casos=22;
          clear irele;
          load in60f1;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);

   case 4
      casos=23;
          clear irele;
          load in60f100;
          t=0:0.04/(length(irele)-1):0.04;
          dibuja_senal(ejes_senal,irele,7,'m',t);

     end
   disp('falta interna+in')
else
```

```
        dibuja_mono(ejes_red,'infalex.jpg');
        switch res_f
        case 1
           casos=24;
               clear irele;
               load i60fe0;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);

        case 2
           casos=25;
               clear irele;
               load i60fe001;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);

        case 3
           casos=26;
               clear irele;
               load i60fe1;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);

        case 4
           casos=27;
               clear irele;
               load i60fe100;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);

          end
        disp('falta externa+ in')
     end
         case 4                          % Inrush para 90º
            if falta_state==1
               casos=28
               dibuja_mono(ejes_red,'inrush.jpg');
               disp('solo inrush')
               clear irele;
               load in90gr;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);
             elseif falta_state==0
         dibuja_mono(ejes_red,'infalin.jpg');
        switch res_f
        case 1
           casos=29;
               clear irele;
               load in90f0;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);

        case 2
           casos=30;
               clear irele;
               load in90f001;
               t=0:0.04/(length(irele)-1):0.04;
               dibuja_senal(ejes_senal,irele,7,'m',t);

        case 3
           casos=31;
```

```
            clear irele;
            load in90f1;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);

     case 4
        casos=32;
            clear irele;
            load in90f100;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);

       end
     disp('falta interna+in')
  else
      dibuja_mono(ejes_red,'infalex.jpg');
     switch res_f
     case 1
        casos=33;
            clear irele;
            load i90fe0;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);

     case 2
        casos=34;
            clear irele;
            load i90fe001;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);

     case 3
        casos=35;
            clear irele;
            load i90fe1;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);
        case 4
        casos=36;
            clear irele;
            load i90fe100;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);

       end
     disp('falta externa+ in')
  end
      end
else
  if falta_state==1
     disp('nada')
     casos=37;
     dibuja_mono(ejes_red,'trafo1.jpg');
            clear irele;
            load sinIsinF;
            t=0:0.04/(length(irele)-1):0.04;
            dibuja_senal(ejes_senal,irele,7,'m',t);
        elseif falta_state==0
      dibuja_mono(ejes_red,'falin.jpg');
     switch res_f
     case 1
```

```
         casos=38;
             clear irele;
             load fa0ohm;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
      case 2
         casos=39;
             clear irele;
             load fa001oh;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
      case 3
         casos=40;
             clear irele;
             load fa1ohm;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
      case 4
         casos=41;
             clear irele;
             load fa100ohm;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
        end
      disp('falta interna')
   else
       dibuja_mono(ejes_red,'falex.jpg');
      switch res_f
      case 1
         casos=42;
             clear irele;
             load sinIf0;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);

      case 2
         casos=43;
             clear irele;
             load sinIf001;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
      case 3
         casos=44;
             clear irele;
             load sinIf1;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
      case 4
         casos=45;
             clear irele;
             load sinIf100;
             t=0:0.04/(length(irele)-1):0.04;
             dibuja_senal(ejes_senal,irele,7,'m',t);
        end
      disp('falta externa')
   end
end
```

dibuja_senal.m

```
%
%dibuja_senal.m
%
% Función para pintar una señal
%
%Parámetros :
%        nombre_ejes    : Nombre de los ejes de la curva
%        nombre_senal   : Curva a pinar
%        tamano_letra   : Tamaño de letra
%        color_curva    : Color de la curva
%        t              : Intervalo de tiempo

function
dibuja_senal(nombre_ejes,nombre_senal,tamano_letra,color_curva,t)
axes(nombre_ejes);
set(gcf,'currentaxes',nombre_ejes);
plot(t,nombre_senal,color_curva,'linewidth',2);
grid on;
axis on;
set(nombre_ejes,'fontsize',tamano_letra,'linewidth',1.5);
xlabel('[seg.]','fontsize',10);
title('Corriente diferencial en
Amperios','fontweight','bold','fontsize',10);
zoom
```

ana_wave.m

```
%
%ana_wave.m
%
% Función para realizar la transformada wavelet de la señal de estudio
%
%Parámetros de entrada :
%          irele     : señal de estudio
%          ejes_wave, ejes_detalle,ejes_cri,ejes_fourier : ubicacion
% de ventanas
%          tipo_w    : nombre de wavelet
%          nro_w     : tipo de wavelet
%          nro_nivel : nivel de descomposicion
%          xw, yw    : ubicacion (x,y) de la ventana de resultados
%          t         : Intervalo de tiempo considerado
%
%Parametros de salida :
%ejes_wave, ejes_detalle, ejes_cri, ejes_fourier : ubicación de ventanas
%          d : Detalles del análisis wavelet
%
% obs:
%     Se utiliza el toolbox de wavelet de Matlab.
%
function [ejes_wave,
ejes_detalle,ejes_cri,ejes_fourier,d]=ana_wave(irele,ejes_wave,...

ejes_detalle,ejes_cri,ejes_fourier,tipo_w,nro_w,nro_nivel,xw,yw,t);

for i=1:length(ejes_wave)
   set(ejes_wave(i),'Visible','off');
   axes(ejes_wave(i));
   cla;
end
set(ejes_detalle,'Visible','off');
axes(ejes_detalle);
cla;
set(ejes_cri,'Visible','off');
axes(ejes_cri);
cla;
set(ejes_fourier,'Visible','off');
axes(ejes_fourier);
cla;

switch nro_nivel
case {1,2,3}
   tamano=10;
case {4,5,6}
   tamano=8;
case {7,8,9,10}
   tamano=7;
end

switch tipo_w
case 1
    tipo_w='db';
    tipo=[tipo_w,int2str(nro_w)];
case 2
    tipo_w='haar';
```

```
    tipo=tipo_w;
case 3
    tipo_w='sym';
    tipo=[tipo_w,int2str(nro_w)];
end
d=[];
[c,l] = wavedec(irele,nro_nivel,tipo);
for i=1:nro_nivel
 cd=wrcoef('d',c,l,tipo,i);
  d=[d;cd];
end
a=wrcoef('a',c,l,tipo,nro_nivel);
figura=[d;a];
altura_eje=0.78*yw/(nro_nivel+1);
Yeje=yw*0.17;
rotulod=char('d1','d2', 'd3','d4','d5','d6','d7','d8','d9','d10');
rotuloa=char('a1','a2','a3','a4','a5','a6','a7','a8','a9','a10');
%
%Pinta en pantalla el resultado del analisis de la DWT de la señal
%
for i=1:(nro_nivel+1)
 ejes_wave(i) = axes('units','pixels','Position',[xw/3-30 Yeje xw/3+30
altura_eje*0.6]);
 Yeje=Yeje+altura_eje;
 axes(ejes_wave(i));
 set(gcf,'currentaxes',ejes_wave(i));
 plot(t,figura(i,:),'b');
 if i==1
    xlabel('[seg.]','HorizontalAlignment','left');
 end
 axis on;
 set(ejes_wave(i),'fontsize',tamano,'linewidth',1);
 if i==nro_nivel+1
   title(rotuloa(i-1,:),'fontweight','bold');
 else
    title(rotulod(i,:),'fontweight','bold');
 end
 zoom
end
ejes_detalle = axes('units','pixels','Position',[(2/3)*xw+45 yw*0.65
0.28*xw 0.26*yw]);
axes(ejes_detalle);
set(gcf,'currentaxes',ejes_detalle);
plot(t,figura(1,:),'r');
hold on
set(ejes_detalle,'fontsize',9,'linewidth',1);
xlabel('[seg.]','HorizontalAlignment','left');
title('d1: detalle de discriminacion del
rele','fontweight','bold','fontsize',10);
```

rele_cri.m

```
%
%rele_cri.m
%
% Función para discriminar la operación del relé diferencial
%
%Parámetros de entrada :
%          ejes_cri,ejes_detalle,ejes_fourier    : Ubicación de ventanas
%          d         : Detalles del análisis wavelet
%          criterio : Criterio de operación del relé
%          xw, yw    : Ubicación de la ventana de resultados
%          t         : Intervalo de tiempo
%
%Parámetros de salida :
%          ejes_cri,ejes_fourier : Ubicación de ventanas
%
function
[ejes_cri,ejes_fourier]=rele_cri(d,ejes_cri,ejes_detalle,ejes_fourier,
criterio,xw,yw,t)
set(ejes_cri,'Visible','off');
axes(ejes_cri);
cla;
ttotal=0.04;
desfase=0.005;
tfinal=0.01;
tinicio=0;
npuntos=length(d(1,:));
thrvm=0.4;
thrvu=0.25;
axes(ejes_detalle);
set(gcf,'currentaxes',ejes_detalle);
cla;
plot(t,d(1,:),'r');
hold on

if criterio==1
    colores=['k' 'g' 'b' 'k' 'g' 'b' 'k'];
    for j=1:7
    tgrf(j)=tfinal;
   if tinicio==0
     puntoinicio=1;
  else
     puntoinicio=fix(npuntos*tinicio/ttotal)-1;
 end
    puntofinal=fix(npuntos*tfinal/ttotal);
    cs=d(1,puntoinicio:puntofinal);
    picomax(j)=max(cs);
    ratio(j)=picomax(j)/picomax(1);
    plot([tinicio tfinal tfinal tinicio tinicio],[-
(1+j*j/100)*picomax(1) -(1+j*j/100)*picomax(1)...
    (1+j*j/100)*picomax(1) (1+j*j/100)*picomax(1) -
(1+j*j/100)*picomax(1)],colores(j),'linestyle',':');
    hold on
    tinicio=tinicio+desfase;
    tfinal=tfinal+desfase;
    cs=[];
end
```

```
    ejes_cri = axes('units','pixels','Position',[(2/3)*xw+45 yw*0.34
0.28*xw 0.15*yw]);
    axes(ejes_cri);
    set(gcf,'currentaxes',ejes_cri);
    tgrf=[0 0.0099 tgrf];
    ratio=[0 0 ratio];
    x=[0;0.04];y=[thrvm;thrvm];
    plot([0 0.01 0.01 0 0],[-(1+1/100)*ratio(3) -(1+1/100)*ratio(3)...
    (1+1/100)*ratio(3) (1+1/100)*ratio(3) -
(1+1/100)*ratio(3)],colores(1),'linestyle',':');
    hold on
    plot([desfase desfase+0.01 desfase+0.01 desfase desfase],[-
(1+4/100)*ratio(3) -(1+1/100)*ratio(3)...
    (1+4/100)*ratio(3) (1+4/100)*ratio(3) -
(1+4/100)*ratio(3)],colores(2),'linestyle',':');
    hold on
    plot(tgrf,ratio,'linewidth',2,'marker','d');
    axis([0,0.04,-0.01,1.2]);
    lt=line(x,y);
    set(lt,'color','red','linewidth',2,'linestyle','-.');
    set(ejes_cri,'fontsize',9,'linewidth',1);
    xlabel('[seg.]','HorizontalAlignment','left');
    title('Ratio de discriminacion Ventanas
multiples','fontweight','bold','fontsize',10);
    in=text(0.025,0.7,'No actuar');
    set(in,'color','g','fontweight','bold');
    fa=text(0.025,0.14,'Falta:actuar');
    set(fa,'color','r','fontweight','bold');
else
    tcriterio=0.01;
    puntoinicio=1;
    plot([0 tcriterio tcriterio 0 0],[-1.1*max(d(1,:)) -
1.1*max(d(1,:))...
    1.1*max(d(1,:)) 1.1*max(d(1,:)) -
1.1*max(d(1,:))],'k','linestyle',':');
    hold on
    puntofinal=fix(npuntos*tcriterio/ttotal)
    cs=d(1,puntoinicio:puntofinal);
    indice=max(cs)/(sum(abs(cs))/2 );
    ejes_cri = axes('units','pixels','Position',[(2/3)*xw+45 yw*0.34
0.28*xw 0.15*yw]);
    axes(ejes_cri);
    set(gcf,'currentaxes',ejes_cri);
    x=[0;0.04];y=[thrvu;thrvu];
    plot(tcriterio,indice,'linewidth',2,'marker','d');
    axis([0,0.04,0,1]);
    lt=line(x,y);
    set(lt,'color','red','linewidth',2,'linestyle','-.');
    set(ejes_cri,'fontsize',9,'linewidth',1);
    xlabel('[seg.]','HorizontalAlignment','left');
    title('Indice de discriminacion
Iratio','fontweight','bold','fontsize',10);
    in=text(0.025,0.7,'No actuar');
    set(in,'color','g','fontweight','bold');
    fa=text(0.025,0.14,'Falta:actuar');
    set(fa,'color','r','fontweight','bold');
end
```

calc_fft.m

```
%
%calc_fft
%
%Función para evaluar la transformada rápida de Fourier
%
%Parámetros:
%           irele :Señal de estudio
%           ejes_fourier, xw, yw: Parámetros de localización gráfica
%……………………………………………………………………………………………..de la ventana
%
function [ejes_fourier]=calc_fft(irele,ejes_fourier,xw,yw)
set(ejes_fourier,'Visible','off');
axes(ejes_fourier);
cla;
amp=[];
Nt=10;
Npto=length(irele);
y=irele(1:2^15);
eval_f=fft(y,Npto)/(Npto/2);
for k=1:Nt
  amp(k)=(1/sqrt(2))*abs(eval_f(k));
end
x=1:Nt-1;
yf=amp(2:Nt);
ejes_fourier = axes('units','pixels','Position',[(2/3)*xw+45 yw*0.11
0.28*xw 0.15*yw]);
axes(ejes_fourier);
set(gcf,'currentaxes',ejes_fourier);
b=bar(x,yf);
set(b,'FaceColor',[0 1 0.1])
hold on
m=bar(x(2),yf(2));
set(m,'FaceColor','r')
set(ejes_fourier,'fontsize',9,'linewidth',1);
xlabel('Nº armonico','HorizontalAlignment','left');
title('Armonicos de la señal','fontweight','bold','fontsize',10);
```

Anexo II

"An overview of wavelet transform applications in power systems"

AN OVERVIEW OF WAVELET TRANSFORMS APPLICATION IN POWER SYSTEMS

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Abstract – Wavelet transform has received great attention in power community in the last years, because are better suited for the analysis of certain types of transient waveforms than the other transforms approach. This paper presents a descriptive overview of the wavelet transform applications in power systems. The main publications carried out in this field have been analyzed and classified by areas. A list of 116 references is also provided.

Keywords: Signal processing, wavelet transform, time-frequency analysis, power systems.

1 INTRODUCTION

Wavelet transform (WT) has been introduced rather recently in mathematics, even though the essential ideas that lead to this development have been around for a longer period of time. It is a linear transformation much like the Fourier transform, however it allows time localization of differences frequency components of a given signal; windowed Fourier transform (STFT) also partially achieves the same goal, but the fixed width windowing function is a limitation. In the case of the wavelet transform, the analyzing functions called wavelets, will adjust the time width to the frequency in such a way that high frequency wavelets will be very narrow and lower frequency ones will be broader. There are two main approaches to present wavelet theory: the integral transform approach (continuous time) and the multiresolution analysis (MRA)/filter bank approach (discrete time).

Several works have been developed in many areas with the aim of this tool, specially, in the last ten years have been met the potential benefits of applying WT to power systems due to, among other, the interest in analyzing and processing the voltage-current signals in order to make a real time identification of transients in a fast and accurate way.

The aim of this paper is to provide a descriptive overview of the wavelet transform applications in power systems to those who are novel in the study of this subject. For this purpose, the main publications carried out in this field have been analyzed and classified by areas. For space reasons, a group of 116 references have been selected by the authors of this paper's criteria, choosing those more representative of a certain area either for their contributions or continuity of a line of investigation.

2 APPLICATION OF WAVELETS IN POWER SYSTEMS

In the mainstream literature, wavelets were first applied to power system in 1994 by Robertson [17] and Ribeiro [4]. From this year the number of publications in this area has increased as Fig. 1 shows.

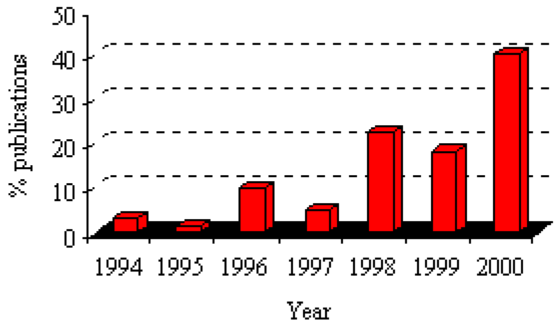

Fig. 1: Evolution of wavelet publications in power system.

The main focus in the literature has been on identification and classification methods from the analysis of measured signals, however, few works use wavelet transform as an analysis technique for the solution of voltages and currents which propagate throughout the system due, for example, a transient disturbance.

The most popular wavelet transform applications in power systems are the following:

- Power system protection
- Power quality
- Power system transients
- Partial discharges
- Load forecasting
- Power system measurement

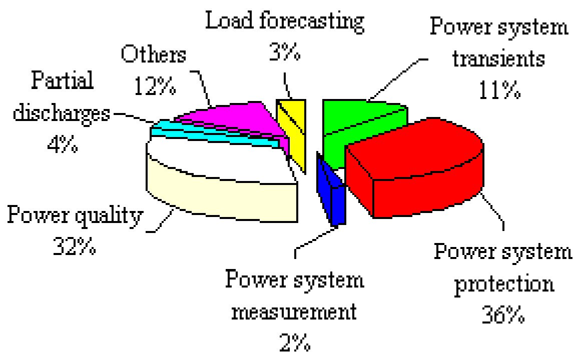

Fig. 2: Percentage of wavelet publications in different power system areas.

Fig 2 shows the percentage of publications in each area; the areas in which more works have been developed are the protection and power quality field. Next sections present a general description of wavelet applications in the selected areas of power systems.

2.1 Power quality

In the area of power quality, several studies have been carried out to detect and locate disturbances using the wavelet transform as an useful tool to analyze interferences, impulses, notches, glitches, interruptions, harmonics, flicker, etc. of non stationary signals.

There are two main approaches to the harmonics and flicker field. The first one, carries out a multiresolution analysis (MRA) using wavelet filter banks in a first step and the application of the continuous wavelet transform to the subbands in a second step; the second one, uses a complex wavelet transform analysis or continuous wavelet.

Accordingly to the first approach, in 1999 is presented a study [5] to evaluate harmonics, developing an algorithm to identify all of them, including integer, non integer and subharmonics. In the first step of this approach, the frequency spectrum of the waveform is decomposed in two subbands using discrete wavelet packet transform filter banks with orthogonal high order Daubechies function. In the second step, a continuos wavelet transform is applied to nonzero subbands, achieving satisfactory results from a real test system. In later works [6]-[7], is presented an improvement to eliminate the effect of imperfect frequency respond of the filters in WT filter banks, and to better analyze subharmonics. [9]-[14] present a similar approach for harmonics and flicker analysis, respectively. Other similar work using different mother wavelets is presented in [11]. Accordingly to the second approach, [8] describes an harmonic analysis with a trapezoid complex wavelet function and the associated trapezoid WT. [15]-[16] show a flicker analysis using the Morlet and Gaussian continuous WT.

However, the effectiveness of wavelet transform for voltage disturbances studies is questioned in [10], pointing out that the STFT is more appropriate for these analysis with a properly chosen window size.

In power system disturbances field, the first works make use of WT to detect and locate various types of power quality disturbances, decomposing a disturbance into its wavelet coefficients using a MRA analysis technique. Santoso et. al. set up an investigation line on this area with the work presented in [33], then the authors in [25] make the proposal that, based on uniqueness of squared WT coefficients at each scale of the power quality disturbance, a classification tool such as neural networks may be employed for the classification of disturbances [28]-[29]. Moreover, in [26] develop an application to compress power quality disturbances signals

Other similar publications have been developed in this area [30-32].

However, the application of WT is not always adequate for the analysis of all types of disturbances, such as the case of voltage sag, as [22] points out, because the wavelet filter does not detect the voltage sag depth.

2.2 Partial discharges

The partial discharges are difficult to detect due to their short duration, high frequency and low amplitude signals, but the capacity of the wavelet transform to zoom in time the signals with discontinuities unlike the Fourier transform, allows to identify local variations of the signal. [36-40] applies these principles to detect partial discharges in transformers winding, cables and GIS (gas insulated substations).

2.3 Load forecasting

Demand forecasting is key to the efficient management of electrical power systems. The works have been developed for short term electrical load forecasting by combining the wavelet transform and neural networks. As electrical load at any particular time is usually assumed to be a linear combination of different components, from the signal analysis point of view, load can be also considered as a linear combination of different frequencies. Every component of load can be represented by one or several frequencies. The process decomposes the historical load into an approximate part associated with low frequencies and several detailed parts associated with high frequencies through the wavelet transform. Then, the forecast of the part of future load is develop by means of a neural approximation [42]-[43] or adjusting the load by a regression method [44].

2.4 Power system measurements

The advantage of using the wavelet transform for the application of power/energy and rms measurements is that it provides the distribution of the power and energy with respect to the individual frequency bands associated with each level of the wavelet analysis. There has not been much work on applying wavelet transform for rms voltage and power measurements. The discrete wavelet transform (DWT) algorithm for rms value of voltage or current and active power measurements is first introduced in the literature to achieve frequency separation into the various wavelet levels using IIR filters, [47]-[48], however provides non-uniform frequency bands which cannot be used to measure the rms value of voltage or current and power of individual harmonic components. In [46] this problem is solved developing a wavelet packet that can decompose a waveform into uniform frequency bands, so that this WPT algorithm has a capability to measure the rms value of voltage or current and power of individual harmonic components.

2.5 Power system protection

The potential benefits of applying wavelet transform for improving the performance of protection relays have been recognized in recent years [49-80]. In 1996, Chaari et al [71] introduce wavelets for the power distribution relaying domain to analyse transient earth faults signals in a 20 kV resonant grounded network as generated by EMTP; in the same year J. Momoh et al present an algorithm to develop a feature extractor suitable for training an Artificial Neural Network for fault diagnosis using the wavelet transform, in this case data was obtained from experimentation. At 1998 Magnago and Abur set up the development of a new investigation line in the area of fault location using wavelets, for this purpose, the fault generated travelling wave is processed by the wavelet transform to reveal their travel times between the fault and the relay locations; EMTP simulations are used to test and validate the proposed fault location. In 1999 the same authors extend the method to the identification of the faulted lateral in a radial distribution systems [65] and in 2000 present an improved method for their earlier papers [67]. Similar methods for fault location can be found in [66], [68].

High impedance fault identification [72]-[73]-[75] is other application area of wavelet transform, for example, in [75] Charytoniuk presents a comparative analysis for arc fault time location, frequency and time-frequency (wavelet) domain, the author demonstrates that the wavelet approach is strongly affected by the choice of a wavelet family, decomposition level, sample rate and arcing fault behaviour.

The application of wavelets to autoreclosure schemes [76]-[77] is develop to accelerate trip of power transmission lines, wavelet transform is adopted to analyse the fault transients generated by the secondary arc and permanent faults and the numerical results reveal that certain wavelet components can effectively be used to detect and identify the fault relevant characteristics in transmission systems and then to distinguish between transients and permanent fault.

The wavelet transform is also applied for the bars [49] , motors [54-57], generators [52]-[53] and transformer protection [58-63], in most of this cases, the spectrum of signals is analysed with the wavelet transform to develop online detection algorithm to detect insulation degradation, inrush and to carry out the precise discrimination between internal and external faults

2.6 Power system transients

In the mainstream literature, wavelets are first applied to power system transients in 1994 [17]. In this paper, the authors present a methodology for the development of software for classifying power system disturbances by type from the transient waveform signature. The waveform signature is derived from the wavelet transform of the transient signal. In 1996, Robertson, et al. [83] apply wavelet for the analysis of capacitor switching transients. The authors give a digital implementation of the wavelet transform via filter bank analysis and make clear that any valid wavelet can be used in this implementation.

Up to this point, the focus in the literature has been on identification methods. That is, identifying a transient disturbance and perhaps classifying it according to its wavelet spectrum. In [84], [86], Heydt and Galli propose the use of the Morlet wavelet as an *analysis* technique for power systems transients. The term *analysis* denotes the solution of voltages and currents which propagate throughout the system due to a transient disturbance.

In 2000, Meliopoulos [87], presents an alternative method for transient analysis of power systems, the method is based on the wavelet series expansion and reconstruction. The system matrix is developed by applying wavelet series expansion on the integro-differential equations of the power system. The procedure results in a set of algebraic equations for the entire network. The solution is in terms of the wavelet expansion coefficients of the voltages at the nodes of the network. The actual voltages can be reconstructed via the wavelet series reconstruction.

The transformer inrush identification based on wavelet [89]-[90] have the advantages that different kinds of inrush of the transformers can be correctly identified from different types of internal transformer faults; external transformer faults can be also distinguished from the internal fault.

Apart from, the application of wavelets to introduce new identification, classification and analysis methods such as those presented previously, at the moment is also studied the application of wavelets to develop new components models; for example in 2001, Abur et al. [92] extend the results of previous works [91] and describe a transmission line model which is based on wavelet transform taking into account frequency dependence of modal transformation matrices into the transients simulation. A different approach to the simulation of frequency dependence, untransposed transmission line transients is introduced. The effect of strong frequency dependence of modal transformation matrices on the transmission line transients is accounted for the time domain simulations via the use of the wavelet transform applied to the signals. This allows the use of accurate modal transformation matrices that vary with frequency and yet still remain in the time domain during the simulations.

3 CONCLUSIONS

This work carries out an approach on the wavelet application in power systems in order to facilitate the search of information in this area. So, it has been revised the last literature that exists in this field and made a classification of the different fields of power system applications. A brief description is included for each area to show the way as wavelet has been applied to solve some typical problems of power system protections, power quality and others. According to the authors of this paper's criteria, only some of the publications are presented due to space reasons; however, the full literature analysed, including the abstract, may be freely downloaded from http://dinel.etsii.upm.es/~hdiaz.

Since the analysis of the literature in wavelets application to power systems it could be concluded the following:

- The most of the application developments in this area use signal data obtained from a transient analysis program such as EMTP/ATP and a specialized wavelet program such as wavelet Matlab toolbox.
- One of the most promising developments in this area is the system relaying for high speed fault detection and localization.
- The field of wavelet application to power system is moving to build new models to analyse power system transients.
- The theoretical developments needed to further push forward the field is a methodology to choose the adequate mother wavelet for a specific application.
- Multiwavelets and second generation wavelets should be new approach to improve the actual and future applications.

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An Overview of Wavelet Transform Applications in Power Systems

Power system disturbances

- Detection, localization and classification
  - fast voltage fluctuations
  - short and long durations
  - voltage variations
  - periodically disturbances

  ➡ The detection method is based in the decomposition of the power disturbance signal in to its wavelet coefficients using MRA technique

- Data compression of power quality disturbance signals
- Useful reference

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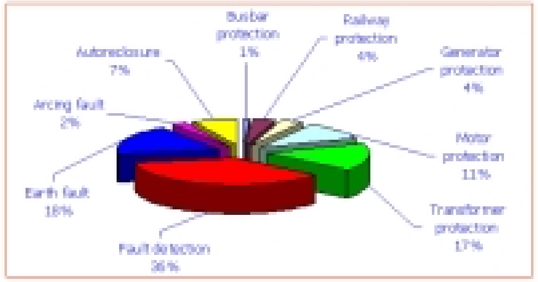
Wavelet in power system protection

Areas in power system protection

- Components fault detection and classification
- System fault detection and classification



Power system protection

- Digital signature discrimination of different perturbation types
- Advantage the ability of the wavelet transform to extract time domain information from the transient signal
  - Fault detection and identification ➡
  - Accurate transient/permanent, internal/external faults distinction

  Study of the travelling wave to reveal the travel times between the fault and the relay location

- Useful reference

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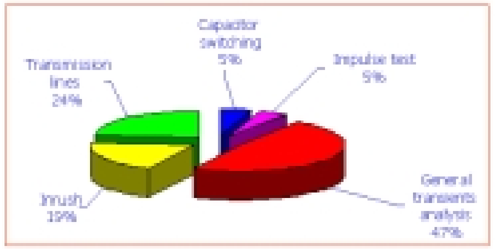
Wavelet in power system transients

Areas in power system transients

- General transients analysis
- Transmission lines
- Inrush
- Capacitor switching
- Impulse test



Power system transients

- Analysis techniques for the solution of voltages and current which propagate throughout the system

  Wavelet transform is apply to solve a set of integro-differential equations in terms of wavelet expansions coefficients of the voltages or currents

- New components models development

  Transmission line considering frequency dependent parameters

- Useful references

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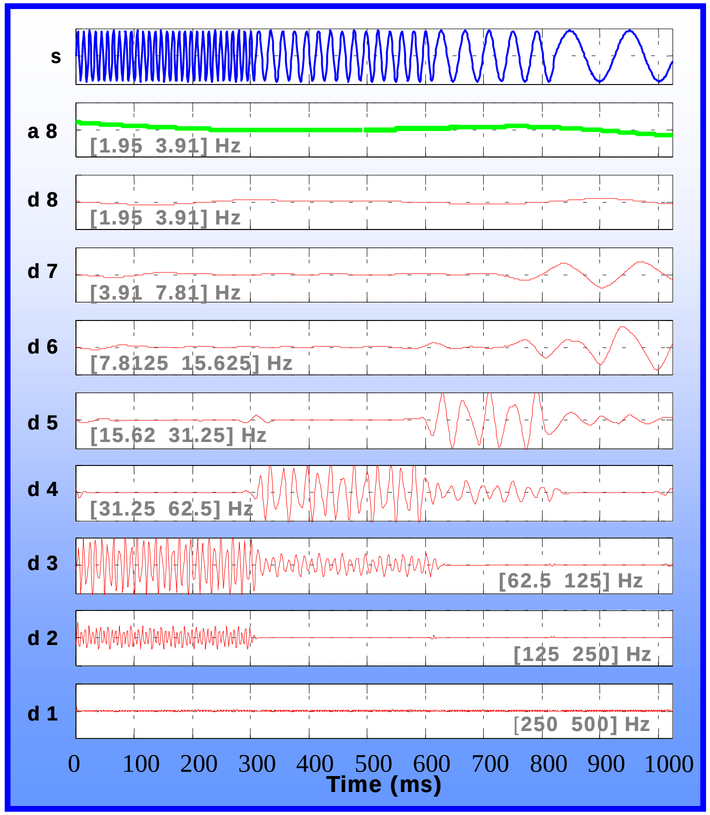
Conclusions

- The most of the application use signal data obtained from a transient analysis program
- One of the most promising developments is the system relaying for high speed fault detection and localization
- The application to power system is moving to build new models to analyse power system transients
- The theoretical developments needed to further push forward the field is a methodology to choose the adequate mother wavelet for a specific application



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14th PSCC, Sevilla, 24-28 June 2002

What are wavelets ?

WT of f(t) at scale s and translation τ

Mother wavelet

Translation

$$WT(\tau,s)=\frac{1}{\sqrt{|s|}}\cdot\int_{-\infty}^{\infty} f(t)\cdot\psi^{*}\left(\frac{t-\tau}{s}\right)dt$$

Normalization factor

Scaling: Changes the support of the wavelet based on the scale (frequency)

Why use wavelets ?

- Provide simultaneously time and frequency information of non-stationary signals

  Drawback: STFT achieved the same goal, but the fixes width windowing function is a limitation

- Time-frequency domain allows to obtain information about frequency composition of a signal at a particular time

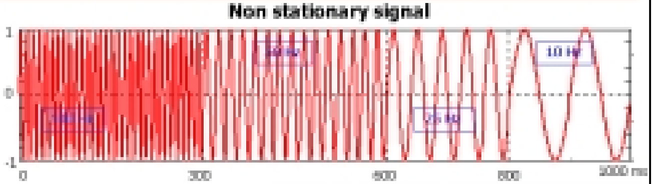
  Drawback: localization of abrupt changes such as spikes, notches, glitches, irregularities...

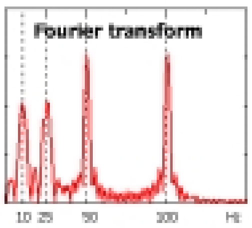
- Adjust the time width window with frequency

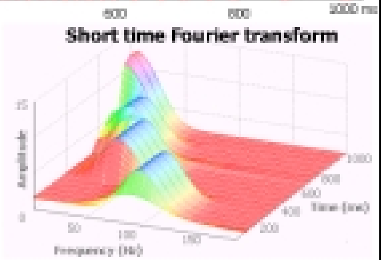
  High frequency (narrow window): Good time resolution and poor frequency resolution

  Low frequency (wide window) : Good frequency resolution and poor time resolution

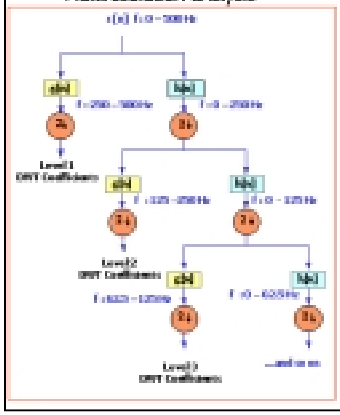
How do wavelets work ?

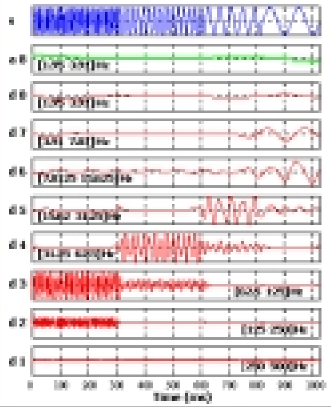






How do wavelets work ?

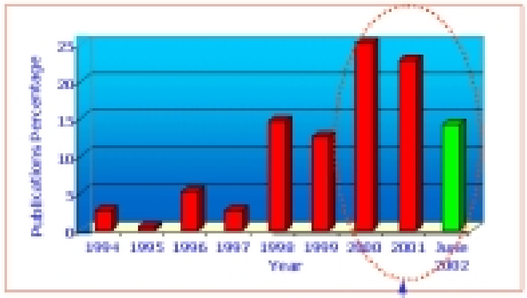




Wavelet in power systems

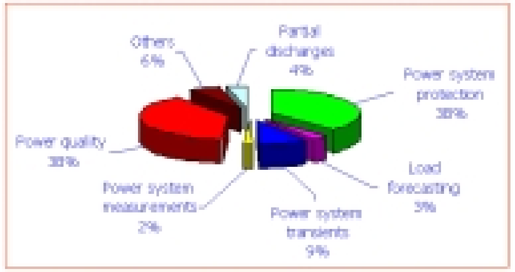
- The state of the art was analysed considering
  - IEEE, IEE
  - Electric power systems research
  - International Journal of Electrical Power and Energy Systems
  - Proceedings of international conferences
- The most popular areas in power systems
  - Power system protection
  - Power quality
  - Power system transients
  - Partial discharges
  - Load forecasting
  - Power system measurement
  - Other (prices estimation, condition assessment of components)

Evolution of wavelet publications in power system



Great publication amount in the last three years (62 %)

Percentage of wavelet publications in power system areas

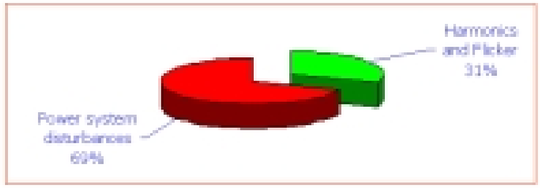


Others:
- Mechanical condition assesment
- Price estimation
- End effect analysis

Wavelet in power quality

Areas in power quality

- Harmonics and Flicker
- Power systems disturbances
  - voltage sag
  - monitoring
  - impulses
  - glitches
  - interferences
  - interruptions



Harmonics and Flicker

- Simultaneously evaluation and identification of harmonics
  - Integer
  - Non-integer
  - subharmonics

  ➡ decomposition of the frequency spectrum of the waveform in two sub-band using discrete wavelet packet and then use the CWT to the non zero sub-band

- In the analysis of time-varying harmonics, it is shown that the WT-based method is more accurate at measuring the harmonic amplitudes than DFT and STFT

- Useful reference
  - Pham, V.L.; Wong, K.P. "Wavelet-transform-based algorithm for harmonic analysis of power system waveforms", IEE Proceedings of Generation, Transmission and Distribution, Vol. 146, No. 3, May 1999, pp. 249 –254

Anexo III

"Determine current transformer suitability using EMTP models"

DETERMINE CURRENT TRANSFORMER SUITABILITY USING EMTP MODELS

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ABSTRACT

Current transformer (CT) and relay modeling are practical tools to evaluate protection equipment performance. This paper demonstrates the use of a set of software tools - Electromagnetic Transients Program (EMTP), The Output Processor (TOP), and Mathcad® - to model transient events in the power system, as well as relay response to those events. The paper provides step-by-step instructions for using these tools to better understand and protect power systems.

Specifically, in this paper we:

1. Model CTs using EMTP to visualize transient events.
2. Transfer EMTP output into Mathcad to examine CT accuracy, burden effects, saturation, and subsidence.
3. Model digital relays in Mathcad to show the effects of CT saturation on overcurrent, distance, and directional element operation, making relay response to transient events easier to understand.

INTRODUCTION

Older existing or spare equipment is often used in new construction or retrofit projects. Changing system conditions can cause existing and spare equipment to operate outside of its intended rating. To effectively evaluate equipment suitability, you must have the tools to determine power transformer or circuit breaker CT performance in a protection scheme.

The Alternative Transients Program (ATP) version of EMTP is an inexpensive, powerful tool for evaluating CT performance. This paper briefly describes ATP software, provides instructions for constructing a CT model using ATP, and presents a method of modeling relay response by using the CT model as input to digital relay models in Mathcad. The paper uses the CT and relay models to demonstrate:

- Secondary burden and connection effects on Ratio Correction Factor (RCF) and Phase Angle Connection Factor (PACF) to answer the question "When can a relay-accuracy class CT be used for metering?"
- The effects of X/R, CT class, and burden on CT saturation and recovery times
- Saturated secondary current reduction and its effects on overcurrent, inverse time-overcurrent, and breaker failure element pickup
- The effect of CT subsidence current on breaker failure element dropout time
- Saturated secondary current and its effects on distance and directional element performance.

Examples in this paper show methods of analysis rather than illustrating the performance of particular CTs or relays. Appendices A through E provide ATPDraw circuits and detailed Mathcad calculations used in these examples.

SOFTWARE

The choice of power system transient analysis software is a matter of suitability, cost, and individual preference. Cost can range from $0 to $15,000. We chose the four programs used in the following work for their power, availability, and reasonable price.

ATP

The ATP version of EMTP is the basic software tool for electric system transient modeling. Different computer operating systems use different versions of the program. Version *ATPMING* works very well with MS Windows® 95 and 98.

ATP is free to licensed users who meet the requirements of the ATP users group. Most utilities, consultants, and manufacturers easily meet these requirements. Licensing information is available on the World Wide Web at *http://www.ee.mtu.edu/atp/index.html.* Once licensed, simply download the program from a password-protected site on the World Wide Web.

ATPDraw

ATPDraw is a graphical, mouse-driven preprocessor to ATP on the MS Windows platform and uses a standard Windows layout. Users build a picture of an electric circuit by selecting components from menus and using dialog boxes to enter component values and ATP parameters. ATPDraw then creates the ATP input file and runs ATP.

Basic ATP model development is much easier in this environment, particularly for new users. You can download ATPDraw for Windows free of charge from the ftp server *ftp.ee.mtu.edu (user: anonymous; password: your e-mail address).* The Bonneville Power Administration, USA, and SINTEF Energy Research, Norway, own the proprietary rights.

TOP

TOP, written and supported by Electrotek Concepts, Inc., is a graphical postprocessor for transient data. TOP will graph ATP output files (*.pl4) and allow users to save the data in different formats, including COMTRADE and comma separated variable (CSV) text files. This program is the bridge between ATP and Mathcad.

You can download TOP free of charge from the Electrotek website at *http://www.electrotek.com/*.

Mathcad 7 Professional

Mathcad worksheets process the CT transient data generated by ATP. The Mathcad desktop interface uses mathematical equations similar to those seen in textbooks. Concepts are easy to see and understand, although the same results can be achieved in other programs such as MATLAB®. Mathcad 7 Professional is available from Mathsoft, Inc.

CONSTRUCTING A CT MODEL USING ATP

This section demonstrates CT modeling using the ATP Saturable Transformer Component, shown in Figure 1.

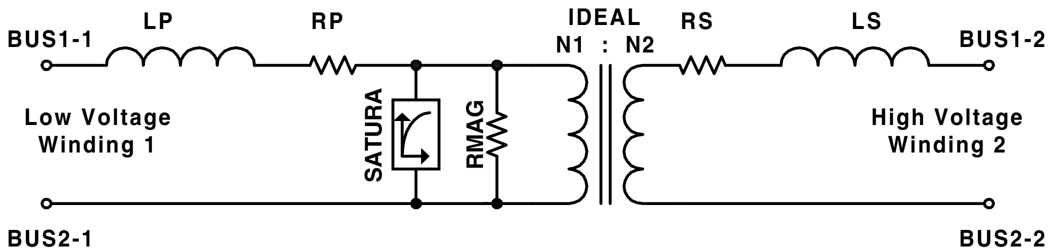

Figure 1: ATP Saturable Transformer Component

To model the CT, use the CT accuracy class, ratio, secondary winding resistance, and excitation curve. Some manufacturers provide the ratio and phase angle correction curves which are useful while testing the model.

Accuracy class "C" indicates the CT relay accuracy can be calculated adequately [9]. This paper considers only C-class CTs.

Using the step-by-step instructions in ***Appendix A: Develop a 1200/5 CT Model***, create the CT model in ATP as follows:

1. Model the CT secondary on Winding 1 of the saturable transformer component (Figure 1).
2. On Winding 2, set resistor RS equal to zero. Set inductor LS, which must have a value greater than zero, equal to 10E-6.
3. Set LP equal to zero, since a C-class CT secondary leakage reactance is very small.
4. Set resistor RP equal to the CT secondary winding resistance. Add separate circuit components to model lead resistance and burden resistance.
5. Set magnetizing resistance, RMAG, to infinity, since RMAG is very large. Enter a "0" in the ATP model for infinite RMAG.
6. Select seven to ten excitation-current versus voltage points from the CT excitation curve, to include saturation in the model.
7. Convert these current versus voltage points to current versus flux points using the ATP supporting routine SATURA.
8. Create the CT model in ATPDraw (Figure 2).
9. Test the model by recreating the CT excitation curve using the ATPDraw circuit shown in Figure 2.

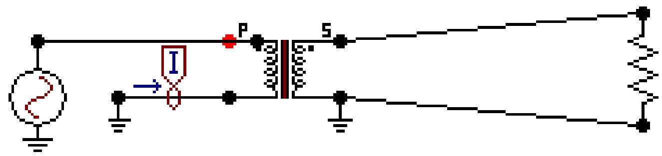

Figure 2: CT Excitation Test Circuit in ATPDraw

Figure 3 shows the results of three excitation curve tests using three, four, and nine points to model saturation. The nine-point model gives the best results of the three.

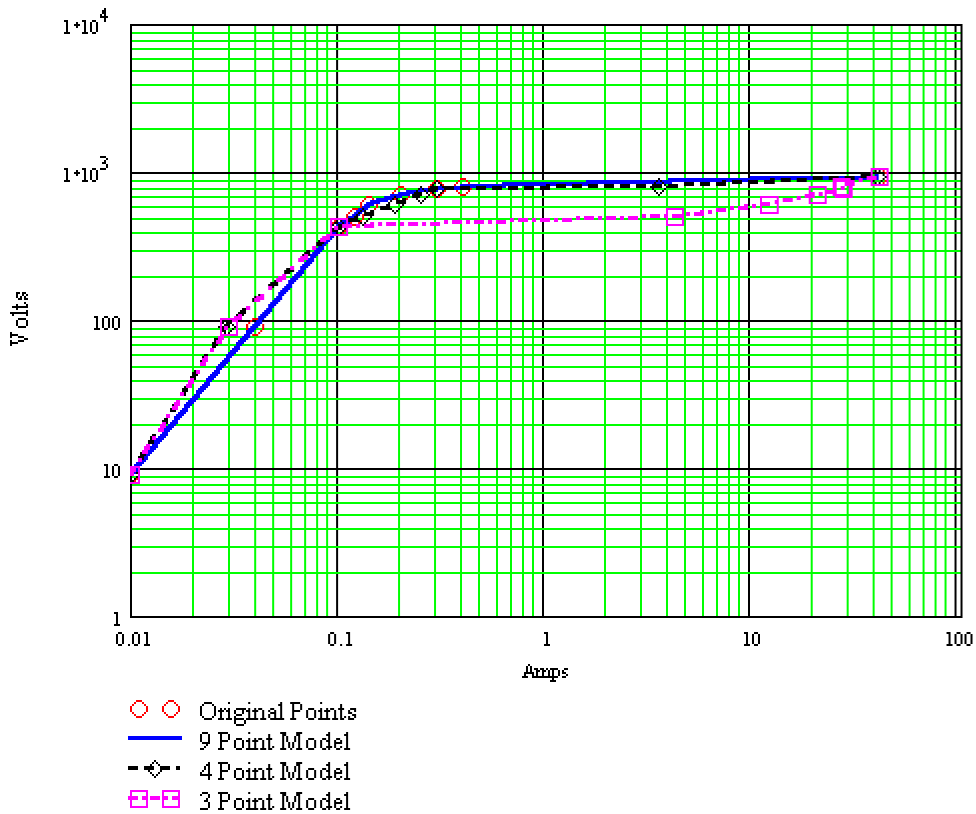

Figure 3: Comparison of CT Models with Different Numbers of Excitation Points

Always test the CT model. Mistakes appear as ratio errors and irregularities in the excitation curve. Use the model only after it has been tested.

In ATP, saturation is a piecewise linear model that can be unstable in certain conditions. Picking too many points on the excitation curve or selecting a time step that is too large can cause high frequency oscillations in the output.

Appendix A: Develop a 1200/5 CT Model describes the development of a 1200/5, C800 CT model using nine points from the excitation curve.

SECONDARY BURDEN AND CONNECTION EFFECTS ON RCF AND PACF

Increasing CT burden increases induced secondary voltage and exciting current, causing ratio and phase angle errors in a CT. Since C-class CT accuracy can be calculated accurately, use ATP to examine the effects of secondary burden at different primary current levels. ***Appendix B: Calculate CT Accuracy*** describes the ATPDraw circuit and Mathcad calculations in the following example:

This example uses a 1200/5, class C800, CT model in the ATPDraw circuit in Figure 4. The six sources turn on and off in sequence to apply 5%, 10%, 20%, 60%, 100%, and 150% rated current. Each source is on for three cycles.

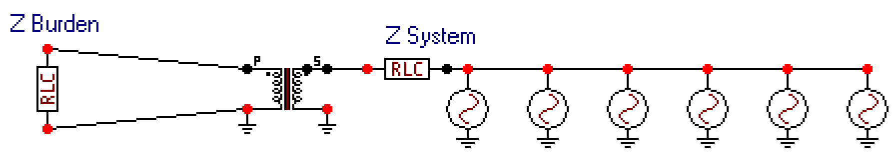

Figure 4: Accuracy Test Circuit in ATPDraw

The CT secondary resistor in Figure 4 is a standard burden, B-1.8 (1.62 + j0.784). This burden is equivalent to 1,800 feet of No. 10 AWG.

Figure 5 shows the ATP output of primary and secondary current in the graphical postprocessor, TOP. The secondary quantities appear very small because of the plot vertical scale. Notice the six increasing levels of primary current.

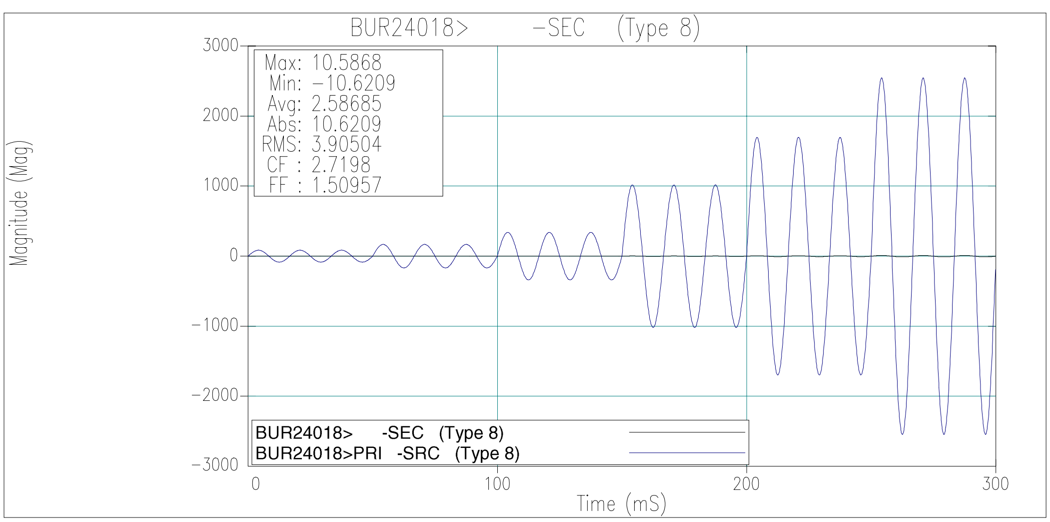

Figure 5: Primary and Secondary Current in TOP

Save the TOP active window containing the CT primary and secondary currents shown in Figure 5 as a CSV text file using the "File Save As" menu item. Read the CSV text file into Mathcad and calculate the RCF and PACF.

Figure 6 shows calculated RCF and PACF.

The maximum ratio error is 0.09 percent, indicating that this CT could be used in a metering application.

You can easily change the ATPDraw circuit to include other burdens and connections. For example, you could model wye-connected CTs under unbalanced load to see how the size of a common neutral wire affects accuracy.

Appendix B: Calculate CT Accuracy describes the ATPDraw circuit and Mathcad calculations used in this example.

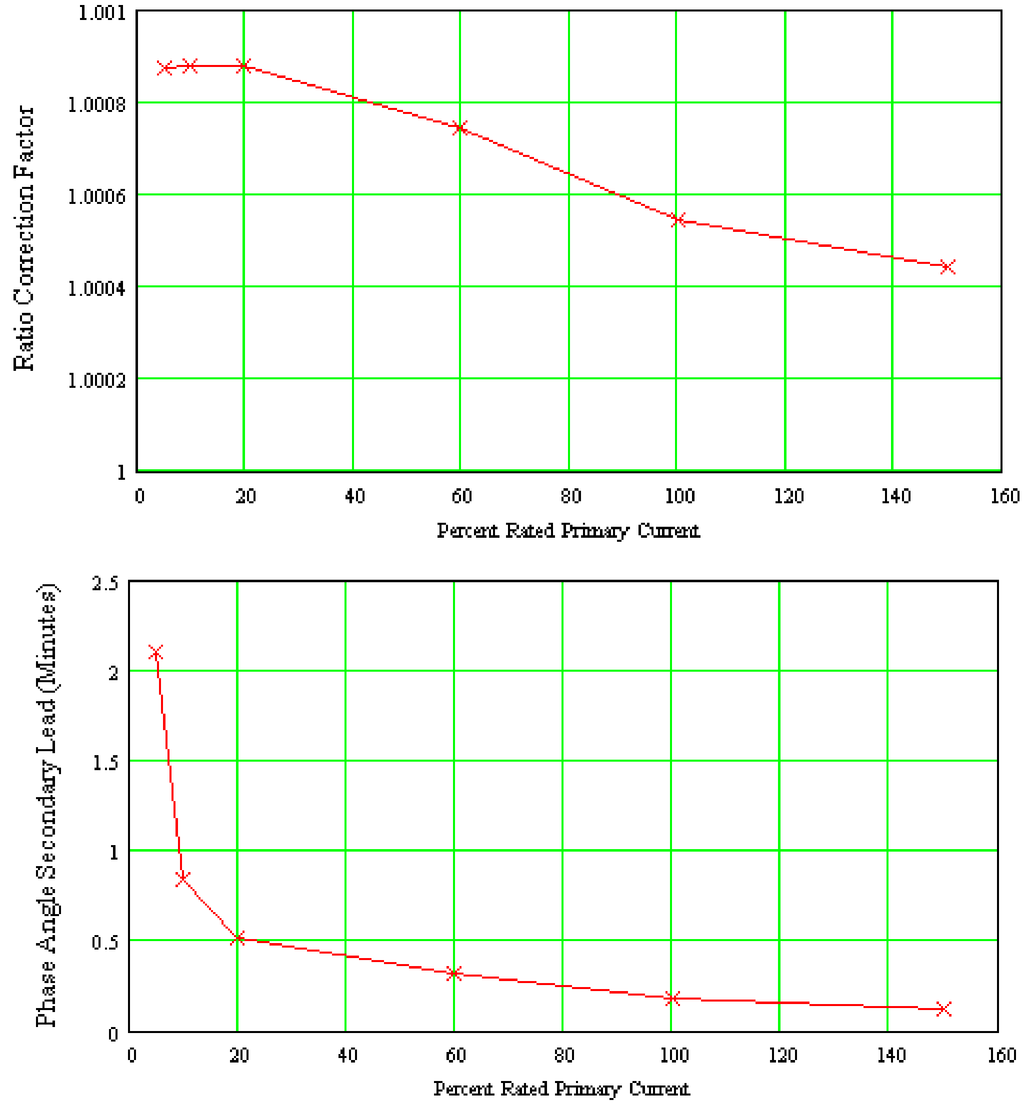

Figure 6: Calculated RCF and PACF

THE EFFECTS OF X/R, CT CLASS, AND BURDEN ON CT SATURATION AND RECOVERY TIMES

The criterion to avoid CT saturation [2] is:

$$20 \geq \left(\frac{X}{R}+1\right) \cdot I_f \cdot Z_b$$

Where:

X/R = the X/R ratio of the primary fault circuit.

I_f = the maximum fault current in per unit of CT rating.

Z_b = the CT burden in per unit of standard burden.

As an example, consider a transmission line with an impedance angle of 85.24° (X/R = 12) and a 1200/5, C800 CT. The maximum fault current is four times the rated CT current. The criterion is satisfied when Z_b is less than or equal to 0.38 per unit of the standard 8 Ohm burden, or 3.08 Ohms.

Use the circuit shown in Figure 7 to model this example.

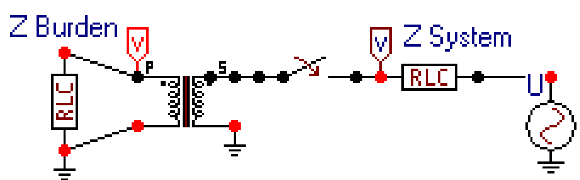

Figure 7: Test Circuit in ATPDraw

Figure 8 shows the voltage developed across the CT secondary during the simulation.

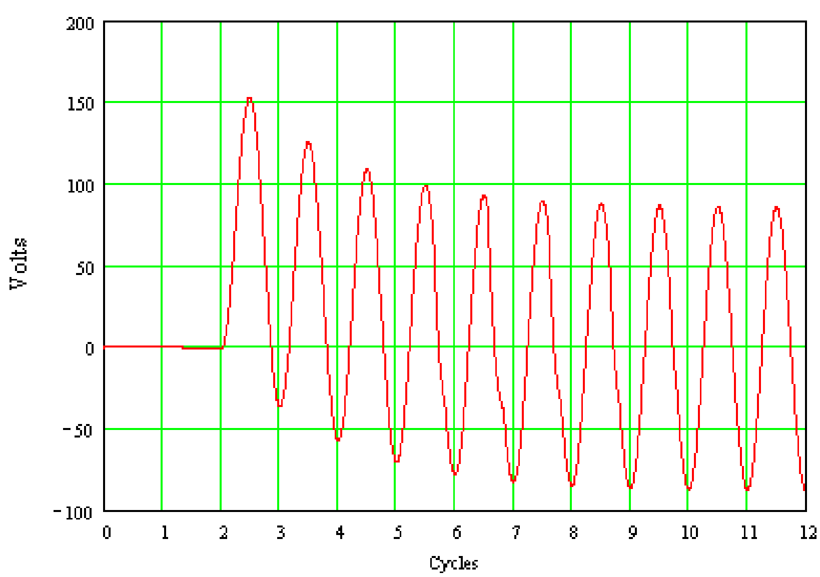

Figure 8: CT Burden Voltage During an Asymmetrical Fault

The equation that describes the volt-time area under the voltage wave produced by asymmetrical fault current is:

$$B_s \cdot N \cdot A \cdot \omega = I_F \cdot Z_B \left[-\frac{\omega \cdot L}{R} \int_0^t e^{-\frac{R}{L} \cdot t} \left(\frac{-R}{L} \right) dt - \int_0^t \cos(\omega t)(\omega dt) \right]$$

Where:

B_s	=	Saturated flux density
N	=	Number of turns
A	=	Core cross sectional area
ω	=	Power system frequency
I_F	=	Magnitude of secondary current
Z_B	=	Secondary burden impedance
L/R	=	Time constant of the primary fault circuit

The CT is at the point of saturation. The same quantity is calculated from the simulation voltage by:

$$VTA(n) = \omega \cdot \Delta t \cdot \sum_0^n V_B(n)$$

Where:

VTA(n)	=	Volt-time area at time step “n”
ω	=	Power system frequency
Δt	=	Simulation time-step duration
n	=	Number of the time-step in the simulation
$V_B(n)$	=	Burden voltage at time-step “n”

Plot VTA(n) as n changes from 0 to the end of the simulation and compare the result to the rating voltage of 800 volts for a C800 CT. The voltage in Figure 8 shows slight saturation after 5 cycles, when the accumulated volt-time area shown in Figure 9 approaches 1,000 volts. Recall that CT ratio accuracy will be within 10 percent at the CT rating voltage. The criterion to avoid CT saturation will maintain this accuracy.

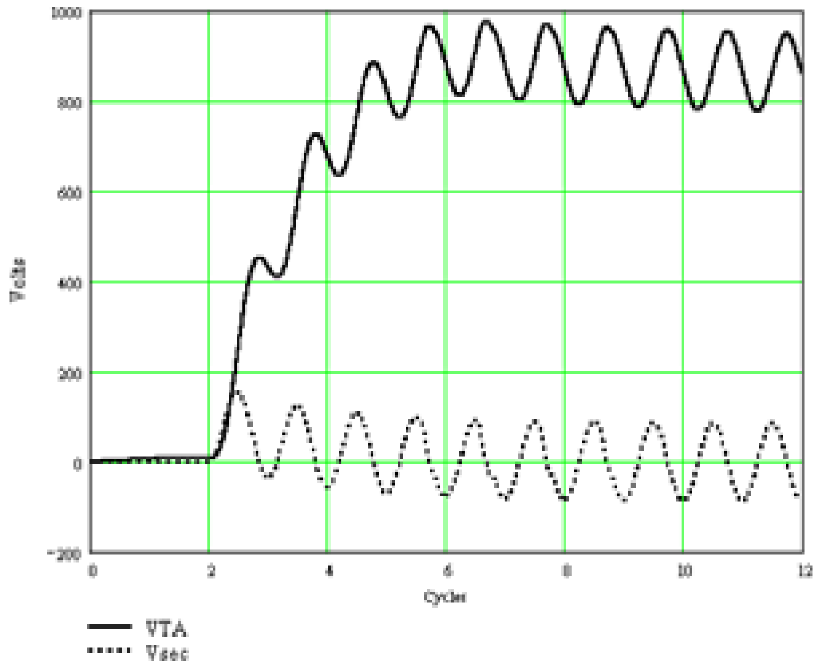

Figure 9: Accumulated Volt-Time Area

Now consider a C800 CT, Figure 7, operating at its rating voltage (100 amps secondary, 8 Ohm burden). Using the same technique, plot the secondary voltage and accumulated volt-time area in Figure 10.

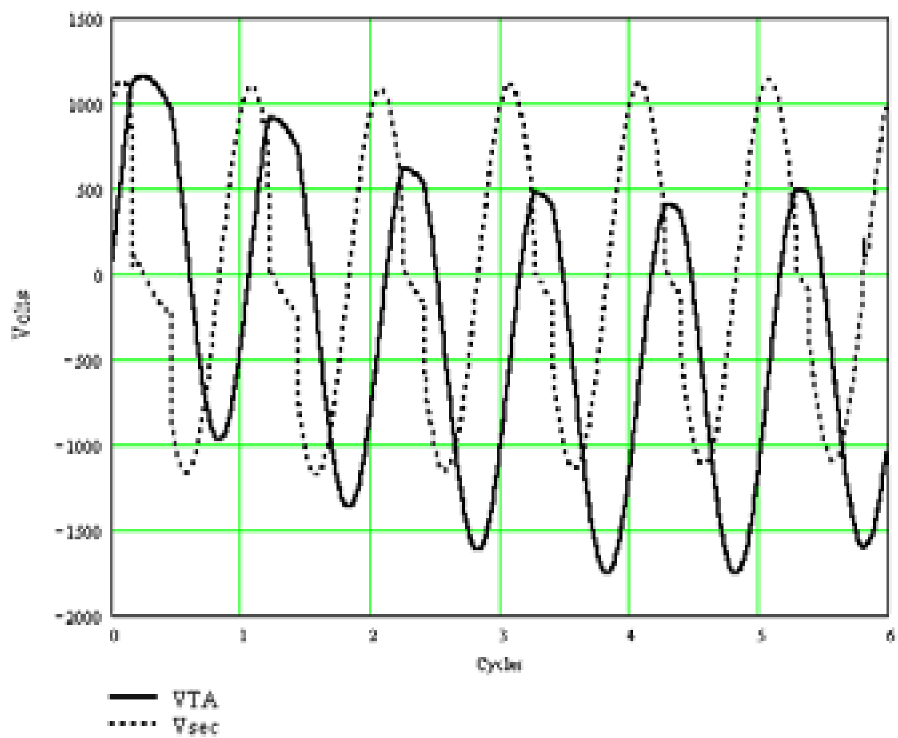

Figure 10: C800 CT at Rated Voltage

Note in Figure 10 that the CT is operating in saturation, but the ratio correction factor in Table 1 shows the CT accuracy is within its rating limits after one cycle, and below two percent error after four cycles.

Table 1: CT RCF at Rated Voltage

Cycle	1	2	3	4	5
RCF	1.136	1.057	1.030	1.019	1.013

Finally, consider the C800 CT in Figure 7, now with a secondary burden of 4 Ohms. The magnitude of the primary current is selected to give 65 amps secondary, operating the CT well below its rating voltage after the dc transient subsides. The dc offset in the primary current drives the CT into saturation.

In Figure 11, the CT recovers from saturation when the peak of the volt-time area drops below approximately 1000 volts.

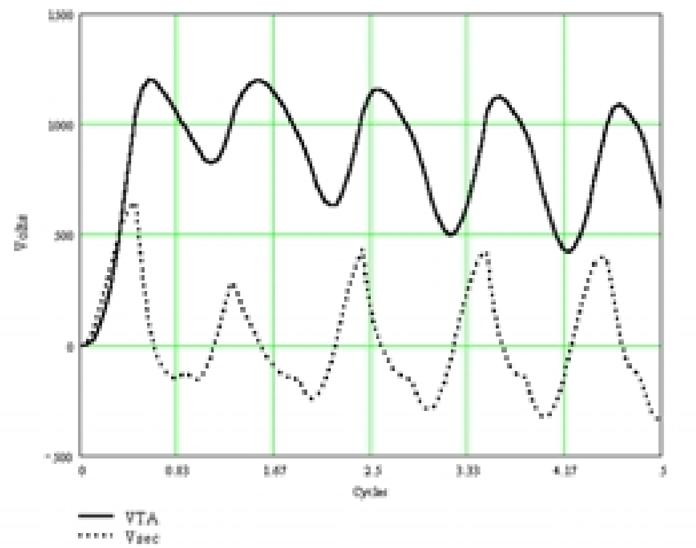

Figure 11: CT Recovery From Saturation

Use these techniques to calculate actual CT class and performance. For example, a C400 CT may actually be just below a C800 rating. Calculate the accuracy under different burdens or use ATP to model CT performance under load and offset fault current at a particular point in your system.

Appendix C: Examine X/R, Saturation, and Burden Effects describes the ATPDraw circuit and Mathcad calculations used in this example.

SATURATED SECONDARY CURRENT REDUCTION AND ITS EFFECTS ON OVERCURRENT ELEMENT PICKUP

Saturation reduces the magnitude of CT secondary current from its ideal value as shown in Figure 12.

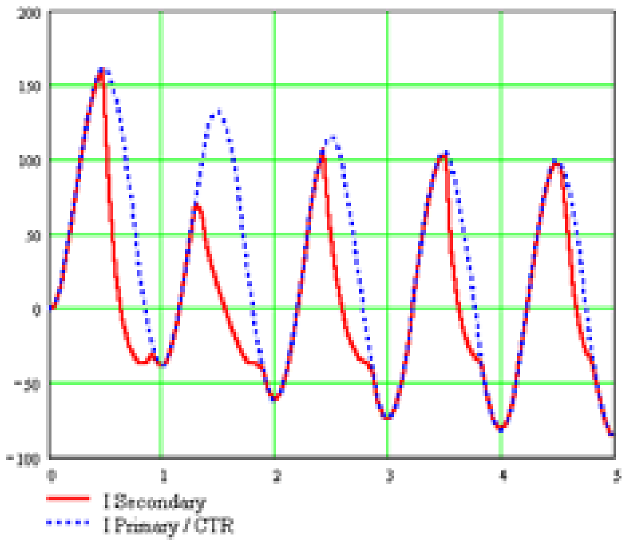

Figure 12: CT Primary and Secondary Current During Saturation

You can calculate the effect of this reduction on digital relay overcurrent elements if you know the relay parameters. Consider the digital relay block diagram in Figure 13.

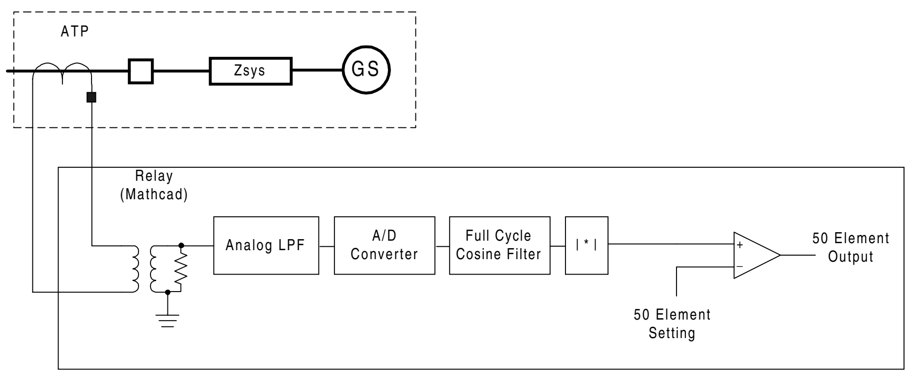

Figure 13: Digital Relay Block Diagram

The following example demonstrates a digital overcurrent relay response to saturated CT secondary current.

Assume a sample rate of 16 samples per cycle or 960 samples per second. The analog low-pass filter is set at a cutoff frequency of 540 Hz to limit signal aliasing. After sampling by the A/D converter, the relay converts the current samples to complex vectors by:

$$Icpx_s = I_s + j \cdot \left(I_{s-\frac{n}{4}} \right)$$

Where:

$Icpx_s$	=	the complex current at sample "s"
I_s	=	the most recent sample of current at sample "s"
n	=	the number of samples per cycle
$I_{s\text{-}n/4}$	=	the sample of current take 1/4 cycle in the past.

The relay then compares the absolute values of the complex currents to the 50 element setting to determine if the element should operate.

Figure 14 shows the relay response to the saturated current from Figure 12.

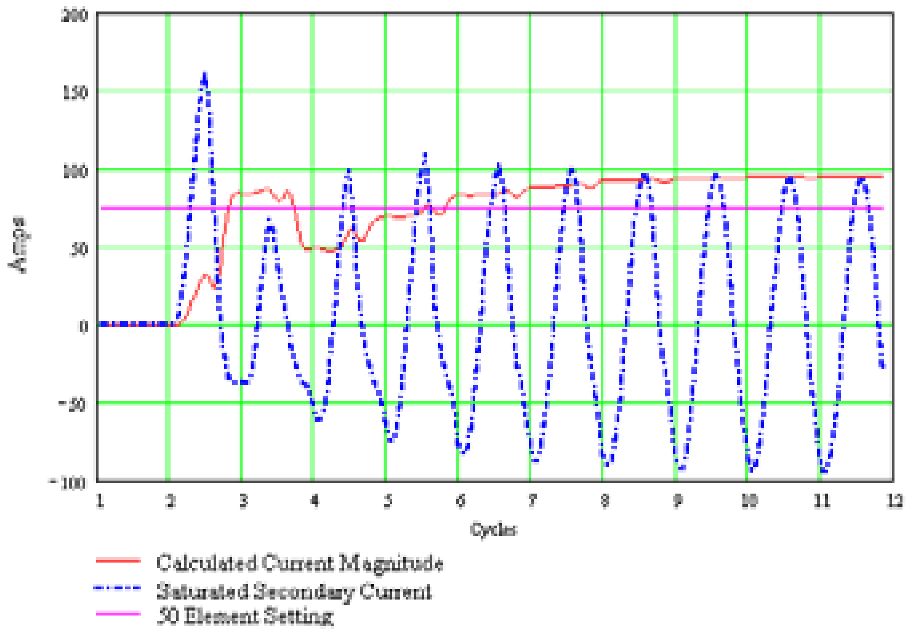

Figure 14: Relay Response to Saturated CT Secondary Current

In this example, saturation initially reduces the relay magnitude response by one half, a reduction that may affect relay performance in different ways. For example, a high-set instantaneous 50 element could pick up for one cycle and then drop out for one to two cycles. A time-delayed overcurrent element could respond up to three cycles late.

This example demonstrates that you can model saturated CTs and relay elements, to better understand relay performance during transient events.

Appendix D: Examine Overcurrent-Element Response to Saturated CT Secondary Current describes the ATPDraw circuit and Mathcad calculations in this example.

The Effect of CT Subsidence Current on Breaker Failure Element Dropout Time

Subsidence current is the current that flows through a CT burden after the line breaker opens. Subsidence current may affect the dropout time of breaker failure overcurrent element, 50BF. If the 50BF element is picked up beyond the breaker failure time delay, other breakers must trip to isolate the failed breaker. CT subsidence current keeps the 50BF element asserted longer than necessary and may contribute to a false breaker failure operation in tightly coordinated systems.

Model CT subsidence current with the relay elements shown in Figure 13. Since a fast dropout overcurrent element is used for breaker failure applications, replace the full-cycle cosine filter with a one-half-cycle cosine filter. Open the power system circuit breaker while the CT is saturated to see the most subsidence current.

Figure 15 shows the same system as in Figure 12, using a one-half-cycle cosine filter.

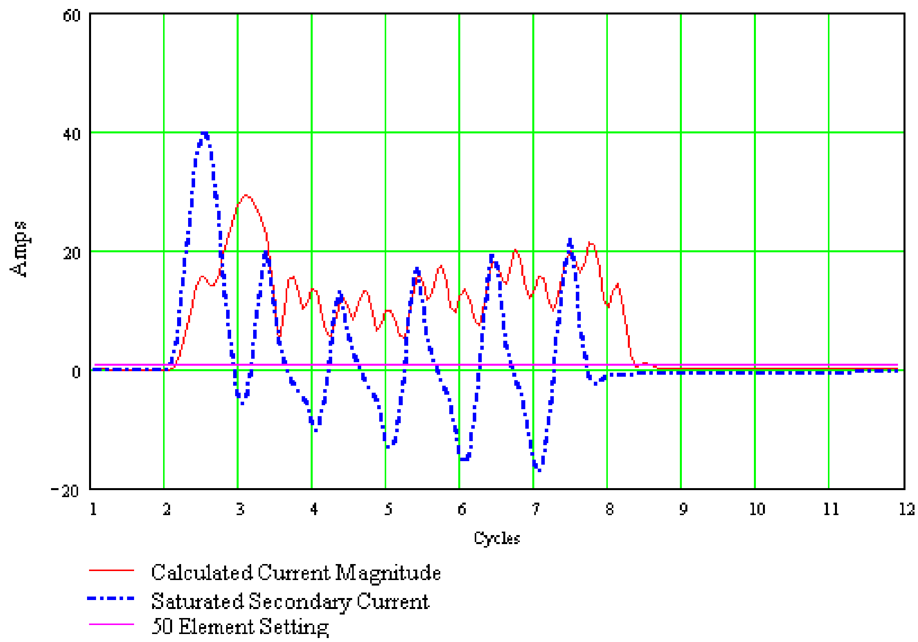

Figure 15: Subsidence Current

Figure 16 shows the model results between 7.5 and 10 cycles. Notice the subsidence current and the relay response.

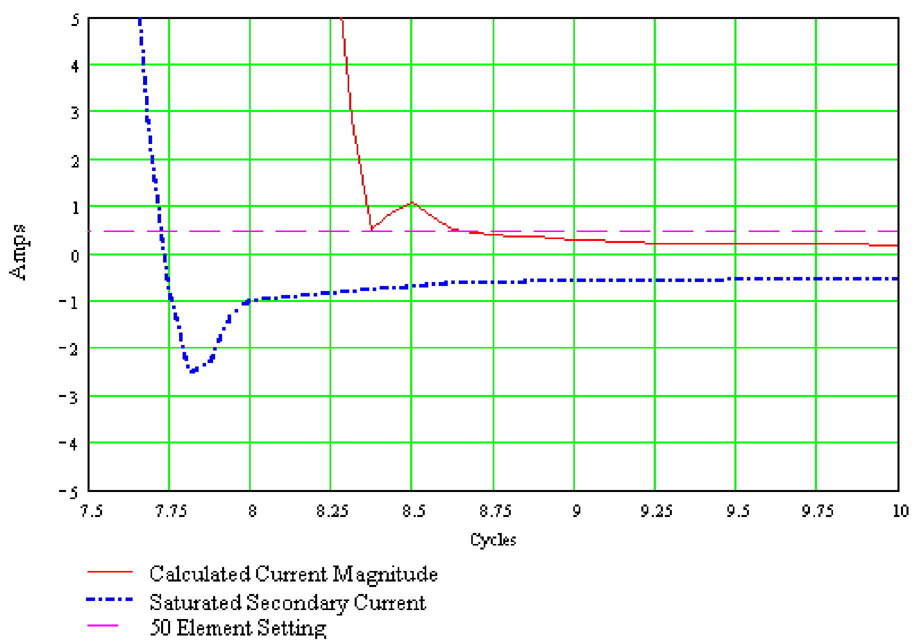

Figure 16: Subsidence Current – 7.5 to 10 Cycles

The one-half-cycle cosine filtered current drops below 0.5 amps at t = 8.6 cycles, or 0.75 cycles after the breaker opens. The unfiltered CT secondary current and low-pass filtered CT secondary current decay over time, dropping below 0.5 amps at approximately 10 cycles, or 3 cycles after the breaker opens. A low set 50BF relay that picks up on dc will have a very long dropout time. An induction-cup electromechanical relay designed for breaker failure applications will drop out in 1.25 cycles.

In this example, the CT secondary burden is resistive, to give the most subsidence current. Investigate subsidence by varying burden magnitude, burden angle, and circuit breaker opening time.

Appendix D: Examine Overcurrent Element Response to Saturated CT Secondary Current describes the ATPDraw circuit and Mathcad calculations used in this example.

SATURATED SECONDARY CURRENT AND ITS EFFECTS ON DISTANCE AND DIRECTIONAL ELEMENT PERFORMANCE

ATP Power System Model

Use a more detailed ATP system model to examine the effects of saturated CT secondary current on distance and directional elements. As a minimum, include the following elements in the ATP model, as shown in Figure E.1:

- Sending and receiving sources
- Source impedances
- Line circuit breakers
- Transmission line impedance on either side of the fault
- Fault switch
- Fault impedance
- Dampening resistance to prevent numerical oscillation
- Voltage transformers (resistor dividers)
- Current transformers
- CT secondary lead and burden impedances

Digital Relay Model

The digital relay model is derived from public information, conference papers, and manufacturer' instruction manuals. The digital relay model includes:

- Anti-alias low-pass filter (cutoff slightly above one-half sampling frequency)
- Sampling function
- Full-cycle cosine filter
- Sample-to-vector converter
- Sequence current and voltage calculation
- Polarizing voltage calculation
- Phase-distance calculation
- Ground-distance calculation

- Negative-sequence impedance calculation
- Zero-sequence impedance calculation

Appendix E: Power System and Digital Relay Models describes the ATPDraw circuit and Mathcad calculations used in this example.

Figure 17 shows the effects of CT saturation during a phase-to-phase-to-ground fault at 15 percent of the line length, applied at 7 cycles into the simulation. Force saturation by increasing CT burden to 4 Ohms. Open the line breaker after 5 cycles.

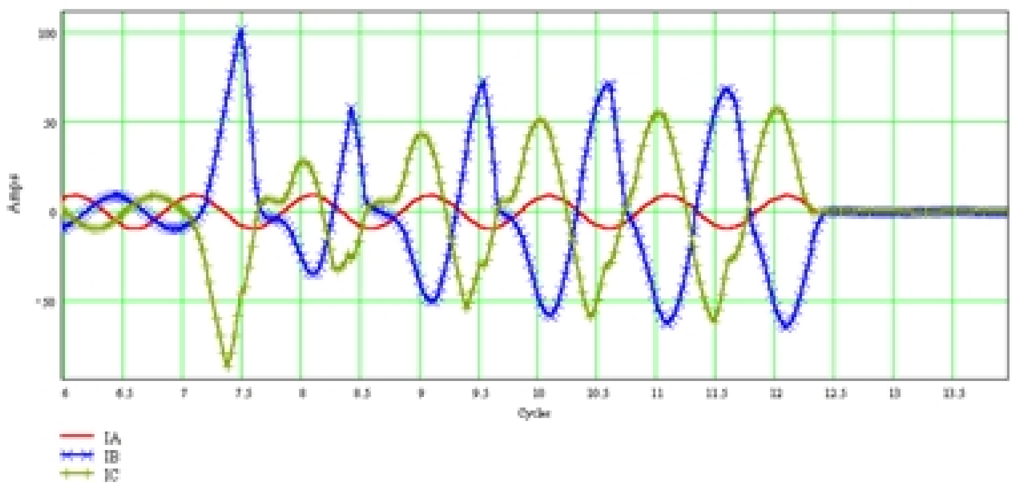

Figure 17: Saturated B- and C-Phase CT Secondary Current, Phase-to-Phase-to-Ground Fault

After analog filtering, sampling, and digital filtering, the CT secondary current appears as shown in Figure 18.

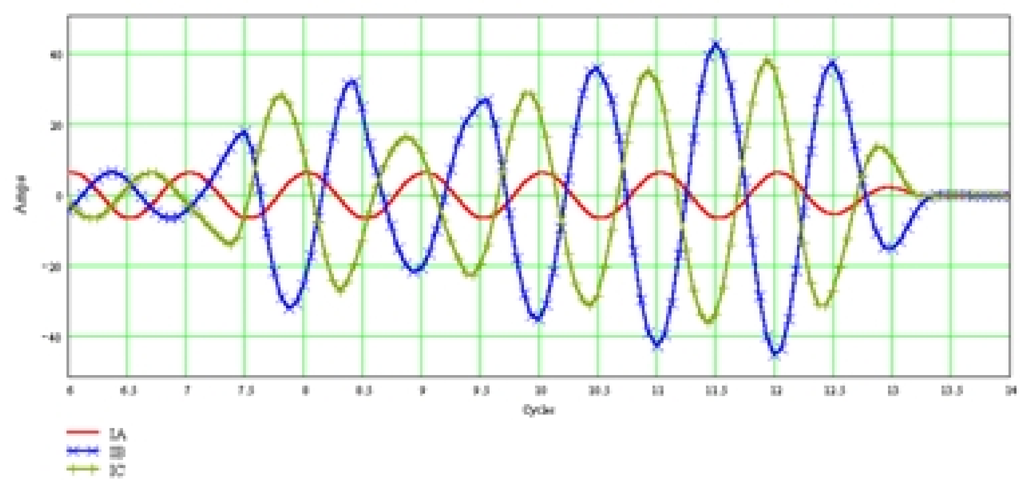

Figure 18: Filtered Secondary Current, Phase-to-Phase-to-Ground Fault

Saturation causes the relay to under-reach, as shown in Figure 19. Without saturation, the relay calculates the ideal B-phase to C-phase impedance (MBC) = 0.936 Ohm at 1.375 cycles after fault inception [4]. With saturation, the relay calculates MBC = 2.09 Ohms at 1.375 cycles after fault inception. At 5 cycles after fault inception, with the B- and C-phase CTs still slightly saturated, the relay calculates 1 Ohm.

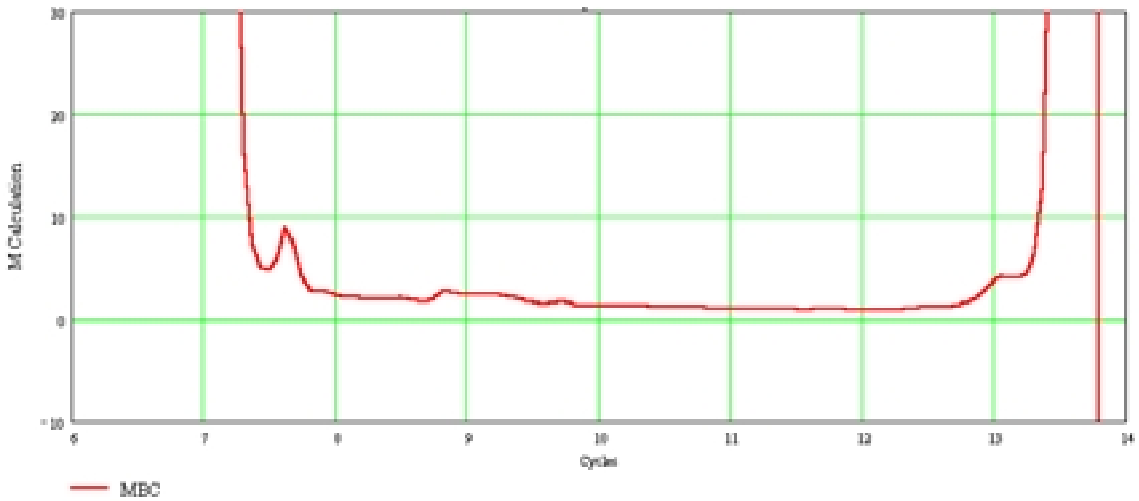

Figure 19: Phase-to-Phase Impedance Calculation During CT Saturation

The phase angle calculated by the relay remains close to the actual phase angle as the CT recovers from saturation, as shown in Figure 20.

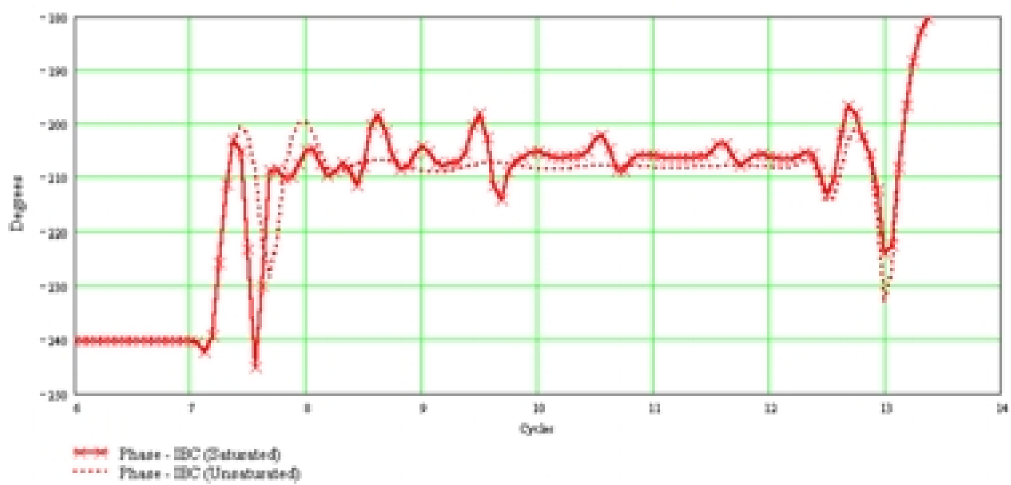

Figure 20: CT Phase Angle During Saturation

Figure 21 shows the effects of CT saturation on Z2 and Z0 calculations. These directional elements are very secure. Notice that Z0 has a brief positive excursion. Security counters in the directional logic ensure that the calculation has stabilized before allowing a directional determination.

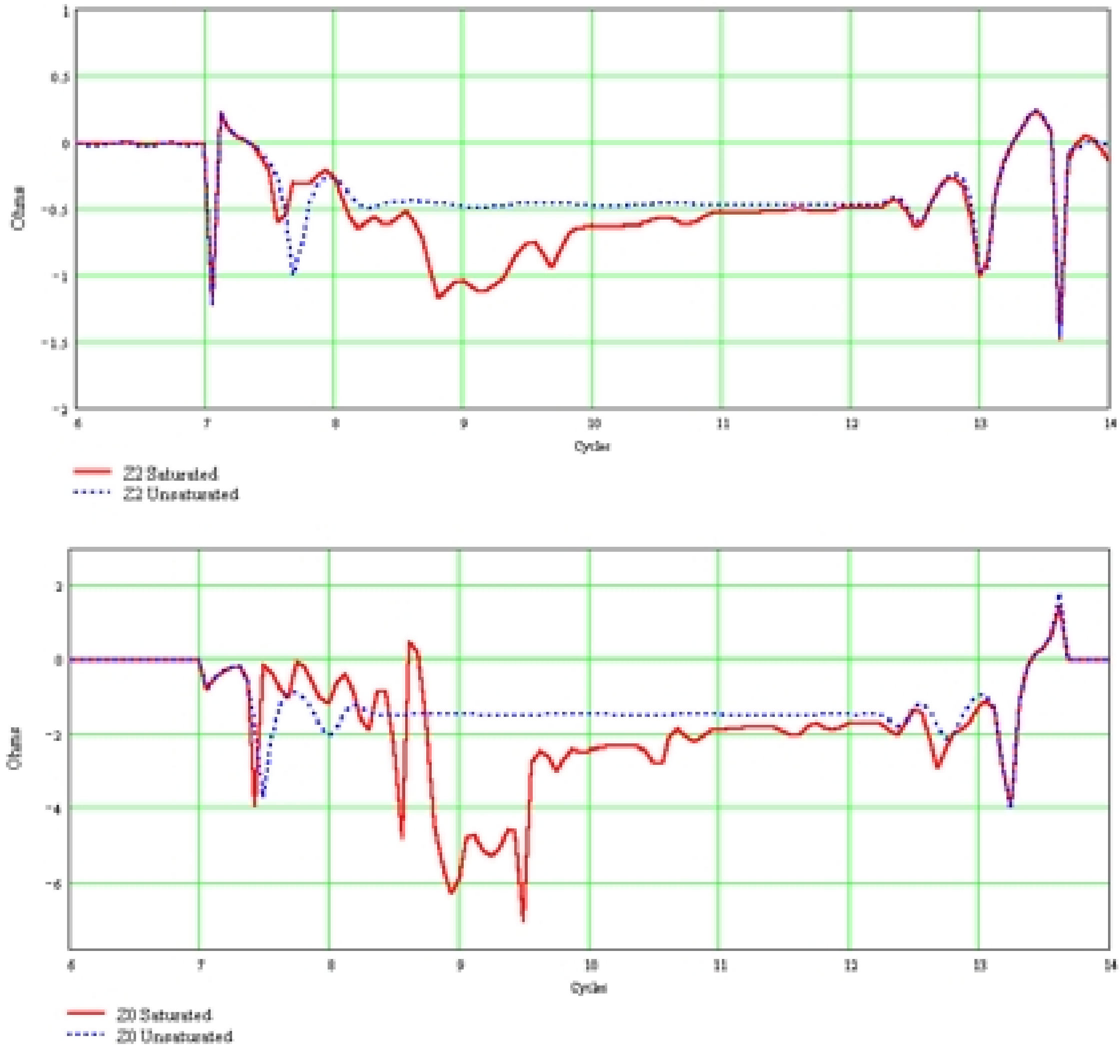

Figure 21: CT Saturation Effects on Z2 and Z0 Calculations

Appendix E: Power System and Digital Relay Models describes the ATPDraw circuit and Mathcad calculations used in this example.

CONCLUSIONS

1. ATP, ATPDraw, TOP, and Mathcad are effective, inexpensive tools for power system transient analysis and relay simulation. ATP is very effective for modeling particular power systems and equipment configurations.
2. You can construct an effective C-class CT model from excitation curve data. The model is limited to a frequency response of a few kilohertz and does not include hysteresis or remnant flux.

3. You can derive an accurate relay model from public information such as conference papers and instruction manuals. Use the model to understand relay transient performance in your system to improve applications and settings.

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[2] Stanley E. Zocholl, Jeff Roberts, and Gabriel Benmouyal, "Selecting CTs to Optimize Relay Performance," Proceedings of the 23rd Annual Western Protective Relay Conference, Spokane, WA, October 15 – 17, 1996.

[3] J. Esztergalyos, S. Sambasivan, J.P. Gosalia, and R. Ryan, "ATP Simulator of Low Impedance Bus Differential Protection," Proceedings of the 50th Annual Relay Engineers Conference, Texas A&M University, College Station Texas, April 7 – 9, 1997.

[4] E. O. Schweitzer, III and Jeff Roberts, "Distance Relay Element Design," Proceedings of the 46th Annual Relay Engineers Conference, Texas A&M University, College Station Texas, April 12 – 14, 1993.

[5] Stanley E. Zocholl and Gabriel Benmouyal, "How Microprocessor Relays Respond to Harmonics, Saturation, and Other Wave Distortions," Proceedings of the 24th Annual Western Protective Relay Conference, Spokane, WA, October 21 – 23, 1997.

[6] E. O. Schweitzer, III and Daqing Hou, "Filtering for Protective Relays," Proceedings of the 47th Annual Georgia Tech Protective Relay Conference, Atlanta, GA, April 28 – 30, 1993.

[7] Alternative Transients Program (ATP) Rule Book, Copyright© 1987 – 1988 by Canadian / American EMTP User Group.

[8] László Prikler and Hans Kr. Høidalen, ATPDraw for Windows 3.1x/95/NT version 1.0 User's Manual, SINTEF Energy Research, Trondheim, Norway, October 15, 1998.

[9] IEEE C57.13-1993 Standard Requirements for Instrument Transformers.

[10] Joseph B. Mooney, Charlie F. Henville, and Frank P. Plumptre, "Computer Based Relay Models Simplify Relay-Application Studies," Proceedings of the 20th Annual Western Protective Relay Conference, Spokane, WA, October 19 – 21, 1993.

BIOGRAPHY

Ralph W. Folkers received his B.S. and M.S. in Electrical Engineering from Iowa State University. He joined Iowa Public Service in 1978, specializing in substation operations and design, electric metering, and system protection. In 1998 he joined the Research and Development Group of Schweitzer Engineering Laboratories as a power engineer.

Mr. Folkers has been a registered Professional Engineer in the State of Iowa since 1979. He has authored several technical papers and presentations on power engineering.

Appendix A: Develop a 1200/5 CT Model

Use the data in Figure A.1 to develop and test a 1200/5 CT model in ATP.

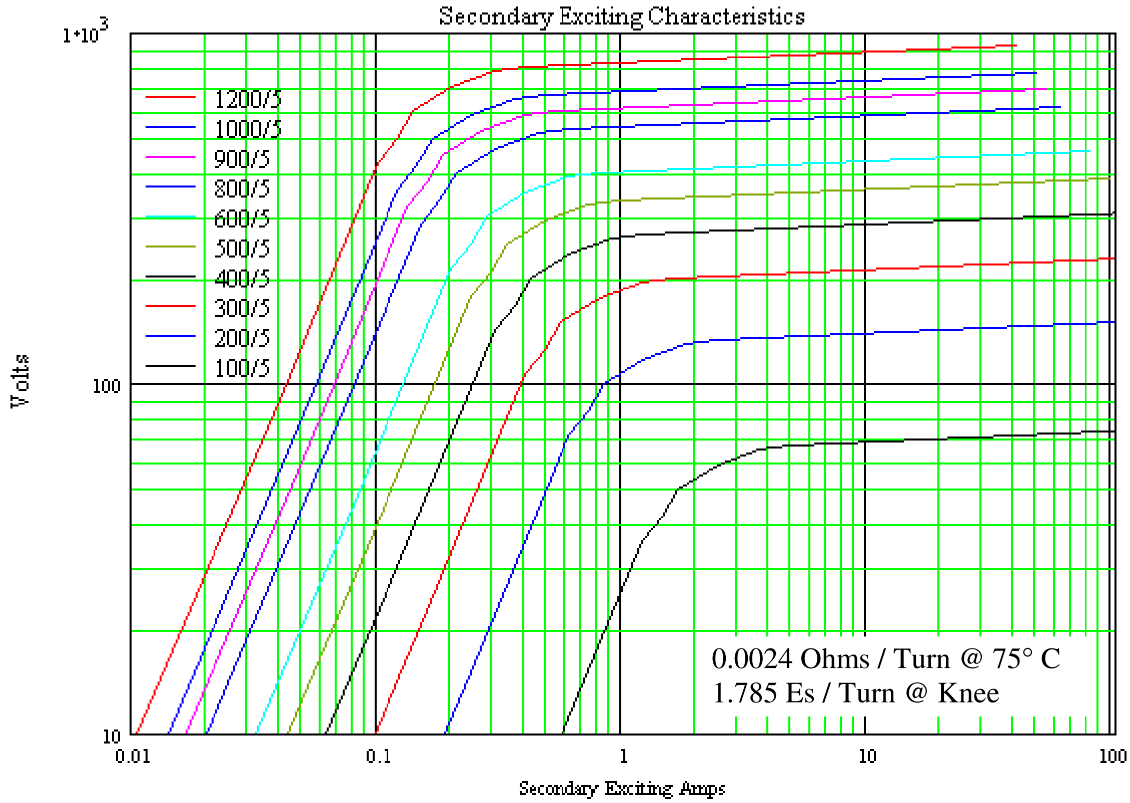


Figure A.1: CT Characteristics

Calculate secondary resistance, Rs:

$$Rs = 0.0024 \cdot 240$$
$$Rs = 0.576\ \Omega$$

Calculate secondary voltage, V, at the knee of the excitation curve:

$$V = 1.875 \cdot 240$$
$$V = 428.4\ \text{V}$$

Create a file *SAT240.atp* with current-voltage pairs selected from the 1200/5 secondary excitation curve. Select a point at the lower end of the curve, several points at, and just above the knee of the curve, and a point at the upper end of the curve.

```
BEGIN NEW DATA CASE
C        1         2         3         4         5
C 345678901234567890123456789012345678901234567890
SATURATION
60.     .001     1.E-6    1     0
             .01              9.
             .04             90.
             0.1            428.
             .12            500.
             .14            600.
             0.2            700.
             0.3            780
             0.4            800
            40.0            927
            9999
C
$PUNCH, SAT240.pch
BLANK LINE
BEGIN NEW DATA CASE
BLANK LINE ENDING ALL CASES
```

Send this file to ATP to create a punch file, *SAT240.pch,* containing the current-flux pairs that define the CT characteristic used in the transformer model saturation branch.

```
C  <++++++>  Cards punched by support routine on  14-Jun-99  15:37:55  <++++++>
C SATURATION
C 60.     .001     1.E-6    1     0
C              .01              9.
C              .04             90.
C              0.1            428.
C              .12            500.
C              .14            600.
C              0.2            700.
C              0.3            780
C              0.4            800
C             40.0            927
C             9999
  1.41421356E-02  3.37618619E-02
  5.36733089E-02  3.37618619E-01
  1.31694552E-01  1.60556410E+00
  1.75046597E-01  1.87565899E+00
  1.89134128E-01  2.25079079E+00
  3.41310866E-01  2.62592259E+00
  5.61072569E-01  2.92602803E+00
  9.75998771E-01  3.00105439E+00
  9.43968011E+01  3.47747177E+00
            9999
```

Use ATPDraw to create the circuit diagram (Figure A.2). The drawing is saved in a circuit (*.adp) file. Enter component values by clicking with the mouse on the component to open a dialog box.

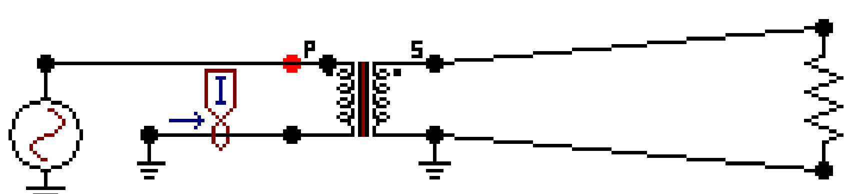


Figure A.2: CT Test Circuit in ATPDraw

The circuit has four components; a voltage source on the transformer secondary, a current probe, the saturable transformer model, and a primary resistor. Figure A.3 shows the saturable transformer model.

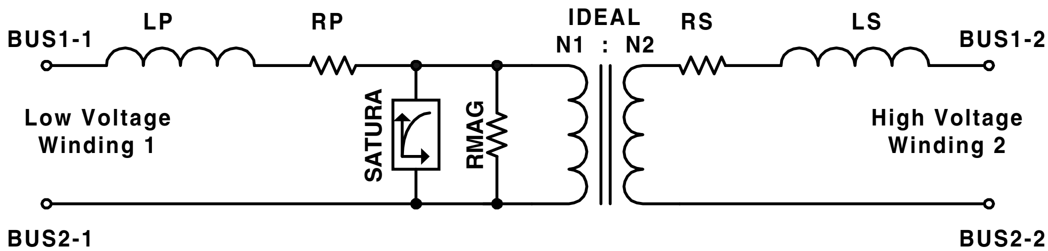


Figure A.3: ATP Saturable Transformer Model

Use the low voltage winding as the CT secondary. The values required by ATPDraw in the saturable transformer attributes dialog box are in Table A.1:

Table A.1: Saturable Transformer Attributes Values in ATPDraw

Value	Description
I0 = 0	Current [A] through magnetizing branch (MB) at steady state.
F0 = 0	Flux [Wb-turn] in MB at steady state.
RMAG = 0	Resistance in magnetizing branch in Ohm. 0 = infinite resistance.
RP = 0.576	Resistance in primary winding in Ohm.
LP = 0	Inductance in primary winding in Ohm if Xopt. = power freq.
VRP = 240	Rated voltage [kV] in primary winding (N1).
RS = 0	Resistance in secondary winding in Ohm.
LS = 1E-7	Inductance in secondary winding in Ohm if Xopt = power freq.
VRS = 1	Rated voltage [kV] in secondary winding (N2).
RMS = 0	Nonlinear characteristic flag. Current/Flux characteristic must be entered.

Figure A.4 shows how the saturation characteristic file, *SAT240.pch,* is entered as an "$INCLUDE" file in the component characteristic dialog box.

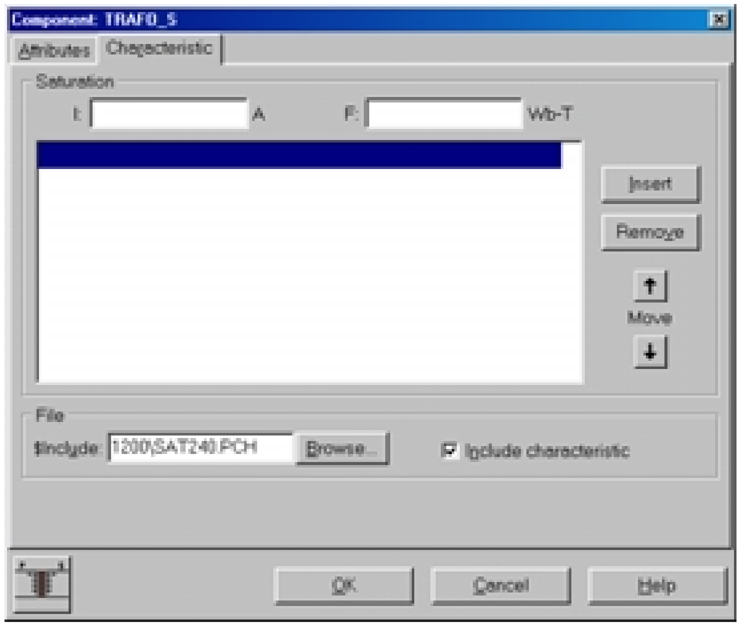


Figure A.4: Saturable Transformer Characteristic Dialog Box in ATPDraw

Enter all of the component data and review the ATP "Settings" command under the ATP menu item in ATPDraw. Use the "Make File" command under the ATP menu item to create the following text file for ATP input.

```
BEGIN NEW DATA CASE
C --------------------------------------------------------
C Generated by ATPDRAW  July, Monday 19, 1999
C A Bonneville Power Administration program
C Programmed by H. K. Høidalen at SEfAS - NORWAY  1994-98
C --------------------------------------------------------
ALLOW EVEN PLOT FREQUENCY
C Miscellaneous Data Card ....
C  dT  >< Tmax >< Xopt >< Copt >
 .000002     .05     60.     60.
     500      10       1       1       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
  TRANSFORMER                         TX0001                                   1
$INCLUDE, C:\WINDOWS\DESKTOP\WPRC\CT1200\SAT240RD.PCH
 1XX0001SEC1                .576        240.
 2PRI                           1.0E-7    1.
        PRI               1.00E7                                               0
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
        SEC1                                          MEASURING                1
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
14XX0001 0    707.1        60.                                     -1.        1.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Send the file to ATP with the "run ATP" command under the ATP menu in ATPDraw. Examine the output with the graphical postprocessor TOP and record the secondary excitation voltage versus the RMS excitation current. Repeat this process for every data point in the excitation curve. Plot the secondary excitation voltage versus the RMS excitation current to test the model.

Figure A.5 shows the ATP output *.pl4 file in TOP. The source in ATP was set for a peak of 707.1 V, or 500 V RMS. From the file *SAT240.atp,* at 500 V, the secondary excitation current should be 0.12 A RMS. TOP calculates the RMS current as 0.120022 A.

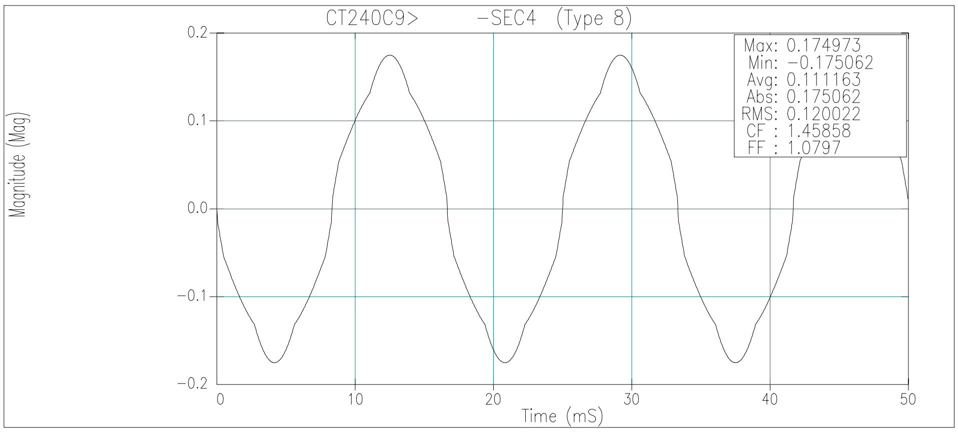


Figure A.5: ATP Output *.pl4 File in TOP

Figure A.6 shows the RMS secondary excitation current from ATP plotted along with the current-voltage points selected from the CT characteristic curve.

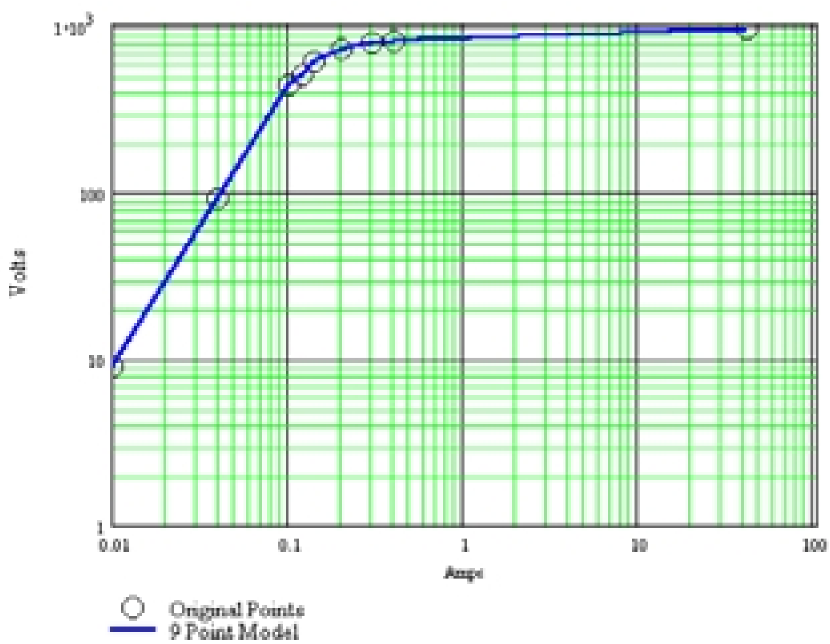


Figure A.6: Original and Calculated Secondary Excitation Current

APPENDIX B: CALCULATE CT ACCURACY

Use the 1200/5 CT model from Appendix A in the test circuit (Figure B.1) with a known burden, B-1.8 (1.62 + j0.784). ATPDraw supports Windows copy, cut, and paste functions. Copy the transformer graphical element in the circuit of Appendix A, and paste it into the new drawing. Transformer data (CTR, etc.) will be included in the operation.

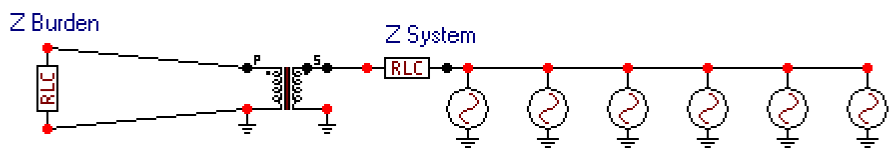


Figure B.1: CT Accuracy Test Circuit in ATPDraw

Table B.1 shows the setup of the current sources for the accuracy test. Each source is turned on for three cycles, and then turned off. The six sources operate in sequence. The data required by each source element also includes frequency (60 Hz) and phase angle (0 degrees).

Table B.1: Current Source Setup

Current Source	Percent Full Load	RMS Primary Current	Peak Primary Current	Source Start Time	Source End Time
1	5%	60	84.9	0.0	0.05
2	10%	120	169.7	0.05	0.10
3	20%	240	339.4	0.10	0.15
4	60%	720	1018.2	0.15	0.20
5	100%	1200	1697.1	0.20	0.25
6	150%	1800	2545.6	0.25	0.30

Figure B.2 shows the CT primary and secondary current in the graphical postprocessor, TOP. Notice that the secondary quantities appear very small because of the plot vertical scale. Save the TOP active window, containing the CT primary and secondary currents, as a CSV text file in TOP using the "File Save As" menu item.

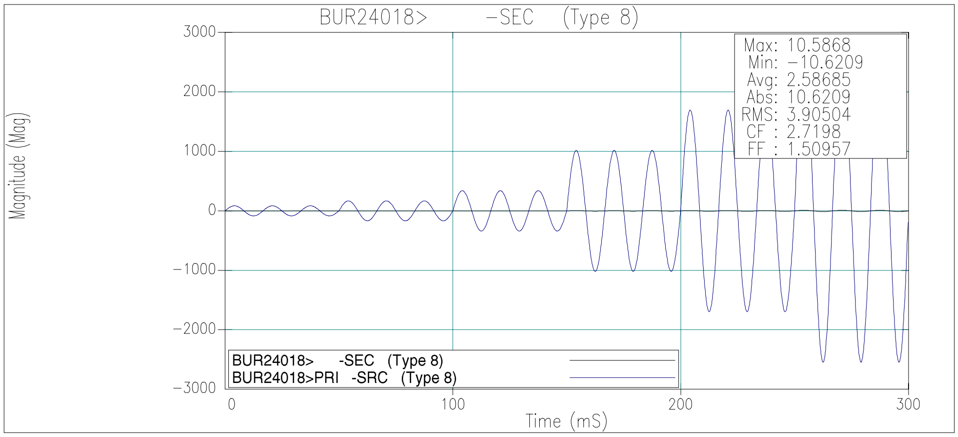


Figure B.2: Primary and Secondary Current in TOP

Figure B.3 shows the beginning of the CSV text file created by TOP. The file columns are listed in the first line as:

1. Time in seconds
2. CT secondary current
3. CT primary current

Delete the first text row so Mathcad can read the numerical data.

```
,"BUR24018>      -SEC   (Type 8)","BUR24018>PRI   -SRC   (Type 8)"
0,0.000181417,-5.20417e-15
0.0001,0.0141828,3.1999
0.0002,0.0274833,6.39525
0.0003,0.0407447,9.58151
0.0004,0.0539482,12.7542
0.0005,0.067075,15.9087
0.0006,0.0801065,19.0406
0.0007,0.0930242,22.1454
0.0008,0.10581,25.2188
0.0009,0.118445,28.2564
0.001,0.130912,31.2538
0.0011,0.143192,34.2068
0.0012,0.15527,37.1111
0.0013,0.167126,39.9628
0.0014,0.178746,42.7576
0.0015,0.190111,45.4917
0.0016,0.201206,48.1611
0.0017,0.212015,50.7621
0.0018,0.222523,53.291
0.0019,0.232714,55.7441
0.002,0.242575,58.118
0.0021,0.252091,60.4094
0.0022,0.261249,62.6149
```

Figure B.3: TOP CSV Text File Output

The Mathcad file that processes the primary and secondary data is listed below.

Import data from an external file into matrix "Data."

$Data := $

C:\..\BUR24018.CSV

Count rows of matrix "Data" and create an index "i" as a row pointer.

$i := 0 .. rows(Data) - 1$

Create time vector "t" and calculate the data time-step, Δt.

$t := Data^{<0>}$

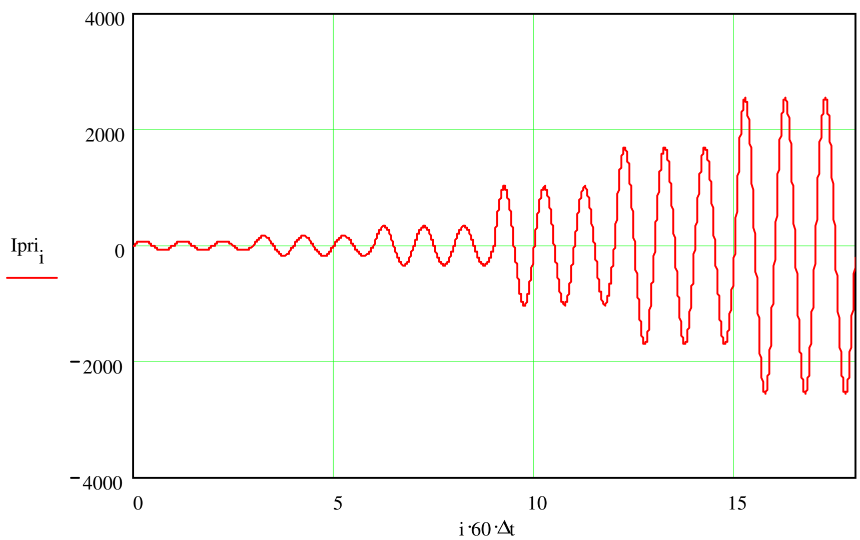
$\Delta t := t_1 - t_0$

Create current vector "Isec" and "Ipri" from imported data.

$Isec := Data^{<1>}$

$Ipri := Data^{<2>}$

Plot Ipri. The data from ATP consists of 3 cycles each at 5%, 10%, 20%, 60%, 100%, and 150% rated primary current. The functions below calculate RCF and PACF using the "middle" cycle of the 3-cycle tests.



Create an index of middle cycle endpoints.

$y := 2, 5 .. 17$

Create functions k(y) and g(y) to calculate the beginning and ending row index points of the middle cycle.

(continued on next page)

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$k(y) := \mathrm{ceil}\left[\frac{(y-1)}{60 \cdot \Delta t}\right]$

$g(y) := \mathrm{ceil}\left(\frac{y}{60 \cdot \Delta t}\right)$

Create function RMS to calculate the rms value of the middle cycle of current "I" determined by "Y."

$$
\begin{aligned}
RMS(I, Y) := \; & rms \leftarrow 0 \\
& \text{for } j \in k(Y) .. g(Y) \\
& \quad rms \leftarrow \left[60 \cdot \left(I_j\right)^2 \cdot \Delta t\right] + rms \\
& RMS \leftarrow \sqrt{rms}
\end{aligned}
$$

Calculate the number of data points per quarter cycle.

$r := \mathrm{ceil}\left(\frac{1}{4} \cdot \frac{1}{60} \cdot \frac{1}{\Delta t}\right)$

Create function PA to calculate the phase angle difference in seconds between Ipri and Isec at middle cycle points.

$$
\begin{aligned}
PA(Y) := \; & pa \leftarrow 0 \\
& \text{for } j \in k(Y), k(Y) + 2 .. g(Y) \\
& \quad Ipcc_j \leftarrow Ipri_{j+r} + j \cdot Ipri_j \\
& \quad Iscc_j \leftarrow Isec_{j+r} + j \cdot Isec_j \\
& \quad pa_j \leftarrow \arg\left(Ipcc_j\right) - \arg\left(Iscc_j\right) \\
& PA \leftarrow -\mathrm{mean}(pa) \cdot \frac{180 \cdot 60}{\pi}
\end{aligned}
$$

Calculate the rms value of secondary current, Isec at the middle cycle points, y.

$RMSsec_y := RMS(Isec, y)$

Calculate the rms value of primary current, Ipri at the middle cycle points, y.

$RMSpri_y := RMS(Ipri, y)$

Calculate the phase angle difference in seconds between Ipri and Isec at the middle cycle points, y.

$PA_y := PA(y)$

Calculate the ratio correction factor, RCF at each middle cycle point, y. The calculation assumes a 1200/5 CT.

$RCF_y := \frac{RMSpri_y}{RMSsec_y \cdot 240}$

(continued on next page)

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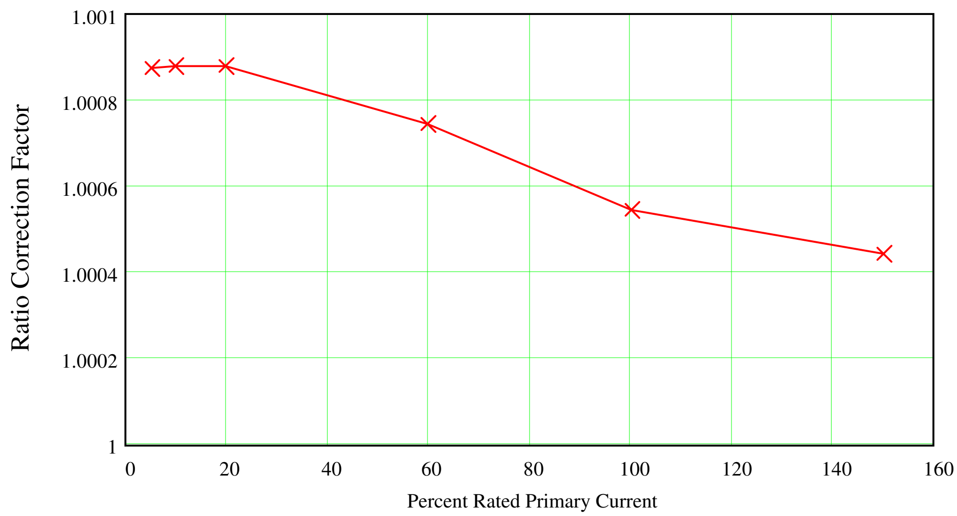
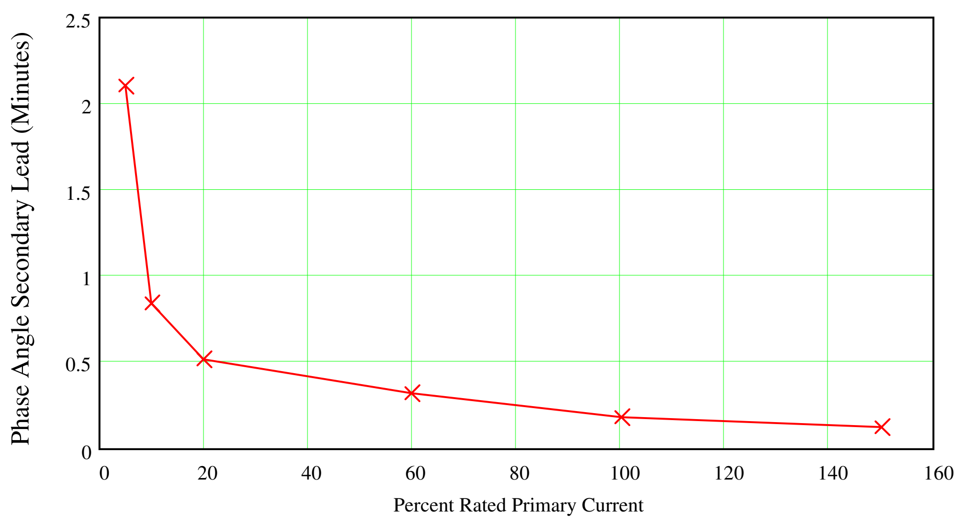
Calculate the percent primary current at each middle cycle point, y. The calculation assumes a 1200/5 CT. This quantity is used as the independent variable (x axis) for graphing.

$$PCTIpri_y := \frac{RMSpri_y \cdot 100}{1200}$$

Graph RCF and secondary phase angle (minutes).





APPENDIX C: EXAMINE X/R, SATURATION, AND BURDEN EFFECTS

Use the ATPDraw circuit shown in Figure C.1 to simulate CT response to changes in X/R, saturation, and burden. The source represents system voltage. Adjust X/R with the RLC element connected to the source. Appendix A describes the CT, which is modeled as a saturable transformer component. Set the CT secondary burden using the RLC element connected to the transformer.

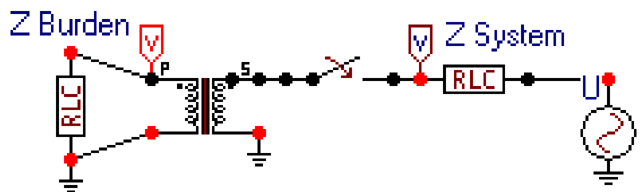


Figure C.1: Test Circuit in ATPDraw

Enter all of the component data and review the ATP "Settings" command under the ATP menu item in ATPDraw. Use the "Make File" command under the ATP menu item to create the following text file for ATP input.

```
BEGIN NEW DATA CASE
C --------------------------------------------------------
C Generated by ATPDRAW  August, Thursday 19, 1999
C A Bonneville Power Administration program
C Programmed by H. K. Høidalen at SEfAS - NORWAY  1994-98
C --------------------------------------------------------
ALLOW EVEN PLOT FREQUENCY
C Miscellaneous Data Card ....
C  dT  >< Tmax >< Xopt >< Copt >
 .000018     .09     60.     60.
     500      50       1       1       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
  TRANSFORMER                         TX0001                                   3
$INCLUDE, C:\WINDOWS\DESKTOP\WPRC\CT1200\SAT240.PCH
 1SEC                       .576        240.
 2SWI                           1.0E-6    1.
        SEC                   4.                                               3
  PRI   SRC                 .39   4.5                                          3
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
  SWI   PRI          -1.       10.    10000.                                   0
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
14SRC    0   100000.       60.     85.24                                     20.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
  SEC
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Send the file to ATP with the "run ATP" command under the ATP menu in ATPDraw.

Examine the output with the graphical postprocessor TOP and plot the secondary burden voltage, secondary burden current, and primary current as shown in Figure C.2. Notice that the secondary quantities appear very small because of the plot vertical scale.

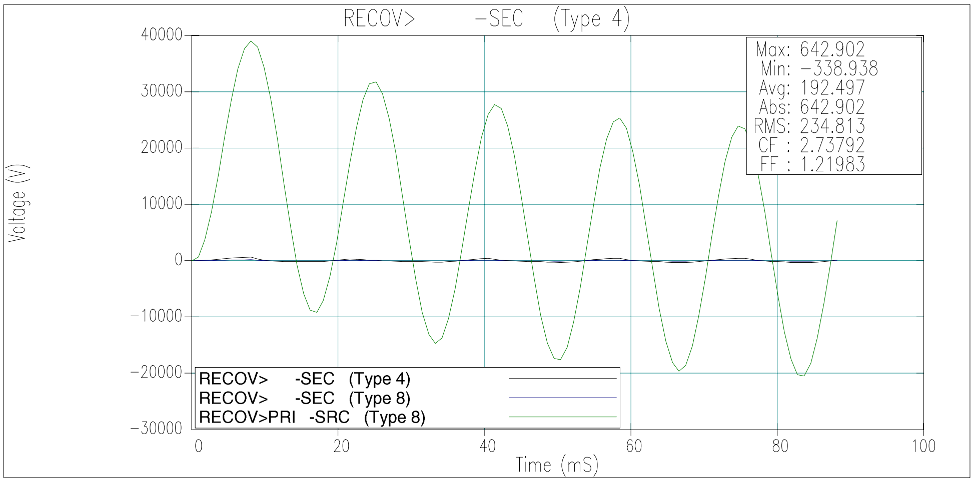


Figure C.2: Simulation Results in TOP

Save the TOP active window, containing the currents and voltage, as a CSV text file using the "File Save As" menu item.

Import the CSV text file into Mathcad. The Mathcad file that processes the data is listed below.

Import data from an external file into matrix "Data:"

data :=

C:\..\RECOV.CSV

Count rows of matrix "Data:"

$r := \mathrm{rows}(data)$

Create an index "I" as a row pointer:

$i := 0 .. r-1$

Create time vector "t", secondary Voltage vector "V_{sec}", current vectors "I_{sec}" and "I_{pri}" from imported data:

$t := data^{\langle 0\rangle}$

$V_{sec} := data^{\langle 1\rangle}$

$I_{sec} := data^{\langle 2\rangle}$

$I_{pri} := data^{\langle 3\rangle}$

Calculate the data time-step, Δt:

$\Delta t := t_1 - t_0$

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Create a function, VTA to calculate the Volt-Time-Area of the "V_{sec}" secondary voltage curve:

$$VTA(x) := \sum_{j=0}^{x} V_{sec_j} \cdot \Delta t$$

$$VT_i := VTA(i)$$

Create functions k(y) and g(y) to calculate the beginning and ending cycle index points for the RMS calculation:

$$k(y) := \text{ceil}\left[\frac{(y-1)}{60 \cdot \Delta t}\right]$$

$$g(y) := \text{ceil}\left(\frac{y}{60 \cdot \Delta t}\right)$$

Create function RMS to calculate the rms value of one cycle of current "I" determined by cycle count "Y:"

$$RMS(I, Y) := \left| \begin{array}{l} rms \leftarrow 0 \\ \text{for } j \in k(Y) .. g(Y) \\ \quad rms \leftarrow \left[60 \cdot \left(I_j\right)^2 \cdot \Delta t\right] + rms \\ RMS \leftarrow \sqrt{rms} \end{array} \right.$$

Create an index of simulation time in integer cycles:

$$ii := 1 .. \text{floor}(\max(t) \cdot 60)$$

Calculate the CT ratio correction factor.

$$RCF_{ii} := \left(\frac{RMS\left(I_{sec}, ii\right) \cdot 240}{RMS\left(I_{pri}, ii\right)}\right)^{-1}$$

Create a cycle pointer:

$$x_{ii} := ii$$

Ratio correction factor at the end of each cycle:

$$\text{stack}\left(x^T, RCF^T\right) = \begin{bmatrix} 0 & 1 & 2 & 3 & 4 & 5 \\ 0 & 1.2487 & 1.8881 & 1.3119 & 1.1109 & 1.0594 \end{bmatrix}$$

(continued on next page)

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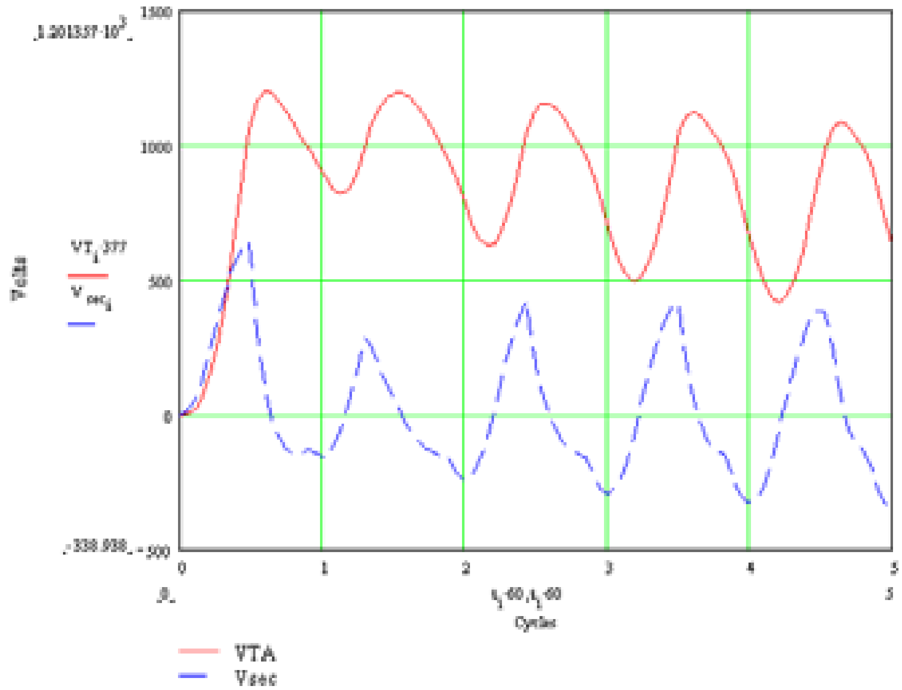

APPENDIX D: EXAMINE OVERCURRENT ELEMENT RESPONSE TO SATURATED CT SECONDARY CURRENT

Use the ATPDraw circuit shown in Figure D.1 to simulate CT response to changes in X/R, saturation, and burden. The source represents system voltage. Adjust X/R with the RLC element connected to the source. ***Appendix A: Develop A 1200/5 CT Model*** describes the CT, which is modeled as a saturable transformer component. Set the CT secondary burden using the RLC element connected to the transformer.

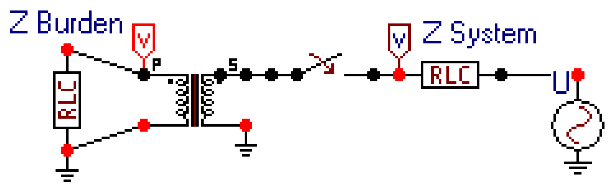

Figure D.1: Test Circuit in ATPDraw

Enter all of the component data and review the ATP “Settings” command under the ATP menu item in ATPDraw. Use the “Make File” command under the ATP menu item to create the following text file for ATP input.

```
BEGIN NEW DATA CASE
C --------------------------------------------------------
C Generated by ATPDRAW  August, Friday 20, 1999
C A Bonneville Power Administration program
C Programmed by H. K. Høidalen at SEfAS - NORWAY  1994-98
C --------------------------------------------------------
ALLOW EVEN PLOT FREQUENCY
C Miscellaneous Data Card ....
C  dT  >< Tmax >< Xopt >< Copt >
 .000018      .2     60.     60.
     500      50       1       1       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
  TRANSFORMER                         TX0001                                  3
$INCLUDE, C:\WINDOWS\DESKTOP\WPRC\CT1200\SAT240.PCH
 1SEC                      .576        240.
 2SWI                          1.0E-6    1.
       SEC                   5.                                               3
  PRI   SRC                .39   4.5                                          3
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
  SWI   PRI          -1.      100.    10000.                                  0
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
14SRC    0   120000.       60.     85.24                        .0333       20.
BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
  SEC
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Send the file to ATP with the "run ATP" command under the ATP menu in ATPDraw. Examine the output with the graphical postprocessor TOP and plot the secondary current as shown in Figure D.2.

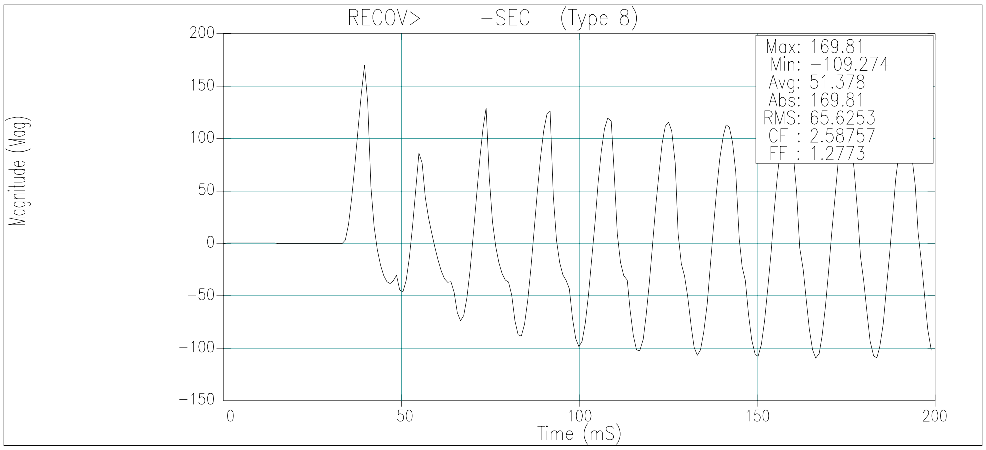

Figure D.2: Simulation Results in TOP

Save the TOP active window, containing the currents and voltage, as a CSV text file using the "File Save As" menu item.

Import the CSV text file into Mathcad. The Mathcad file that processes the data is listed below.

Import data from an external file into matrix "Data:"

Data :=

C:\..RECOV.CSV

Count rows of matrix "Data:"

$R := \text{rows}(\text{Data}) - 1$

Create an index "i" as a row pointer:

$i := 0..\,R$

Create time vector "t" and current vector "I" from imported data and calculate the data time-step, Δt:

$t := \text{Data}^{\langle 0 \rangle}$

$IR := \text{Data}^{\langle 2 \rangle}$

$\Delta t := t_1 - t_0$

Enter the number of samples per cycle of the relay:

$RS := 16$

Calculate the number of samples to create an averaging LP filter with a cutoff frequency at 1/2 the sampling frequency:

$$LPW := \text{floor}\left(\frac{2}{60 \cdot \Delta t \cdot RS}\right)$$

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Averaging filter:

$$LP(a) := \left(1 + \frac{1}{RS}\right) \cdot \sum_{k=0}^{LPW-1} \frac{IR_{a-LPW+k}}{LPW}$$

Calculate LP filtered current:

$$ii := LPW .. R$$

$$I_{ii} := LP(ii)$$

Calculate the number of relay samples available in the data and create an index “s” as a row pointer:

$$S := \mathrm{floor}\left(t_R \cdot 60 \cdot RS\right)$$

$$s := 0 .. S$$

Create a vector “Ia” representing the sampled relay values:

$$Ia_s := \mathrm{linterp}\left(t, I, \frac{s}{RS \cdot 60}\right)$$

Create a filter index “if” and apply a full-cycle cosine filter “IF” to vector “Ia:”

$$if := (RS - 1) .. S$$

$$IF_{if} := \frac{2}{RS} \cdot \sum_{k=0}^{RS-1} \cos\left(k \cdot \frac{2 \cdot \pi}{RS}\right) \cdot Ia_{(if-(RS-1))+k}$$

Create a vector index “iv” and form vector current “Icpx” from 90-degree-interval filtered quantities:

$$iv := (RS + 1) .. S$$

$$Icpx_{iv} := IF_{iv} + j \cdot IF_{iv - \frac{RS}{4}}$$

(continued on next page)

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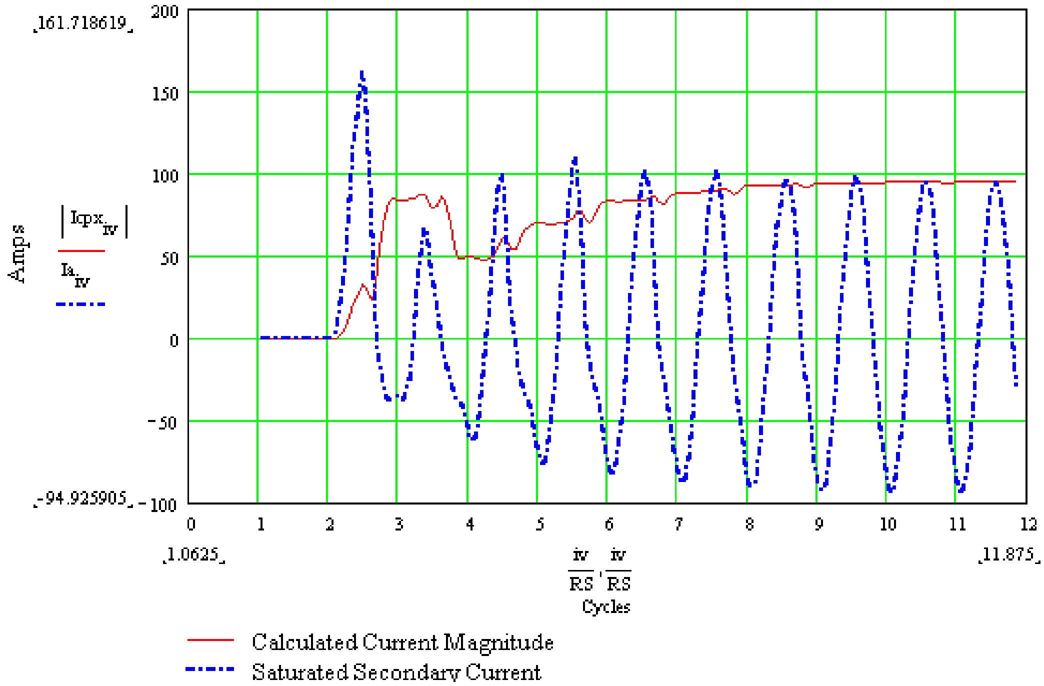
Graph the absolute value of the complex quantity, Icpx, and the value of the sampled current, Ia:



Appendix E: Power System and Digital Relay Models

Use the ATPDraw circuit shown in Figure E.1 to simulate CT response in a two-bus power system. The system quantities are:

Z_{1L} = 8.19 + j77.57	Positive-sequence line impedance
Z_{0L} = 36.81 + j245.15	Zero-sequence line impedance
Z_S = 0.1 Z_L	Positive- and zero-sequence source impedances
V_P = 189500	Peak source voltage. V_{Send} leads $V_{Receive}$ by 30°

This example uses mutually coupled RL elements for lines and sources, but you can use any ATP line model. Split the line into two elements, one on either side of the fault.

Appendix A: Develop A 1200/5 CT Model describes the CTs, which are modeled as saturable transformer components. The CT secondaries are wye-connected and grounded at the relay. The CT leads and relay elements are modeled as resistances, but you can change them to include reactances.

Attach shunt RLC elements to the circuit breakers to dampen numerical oscillation.

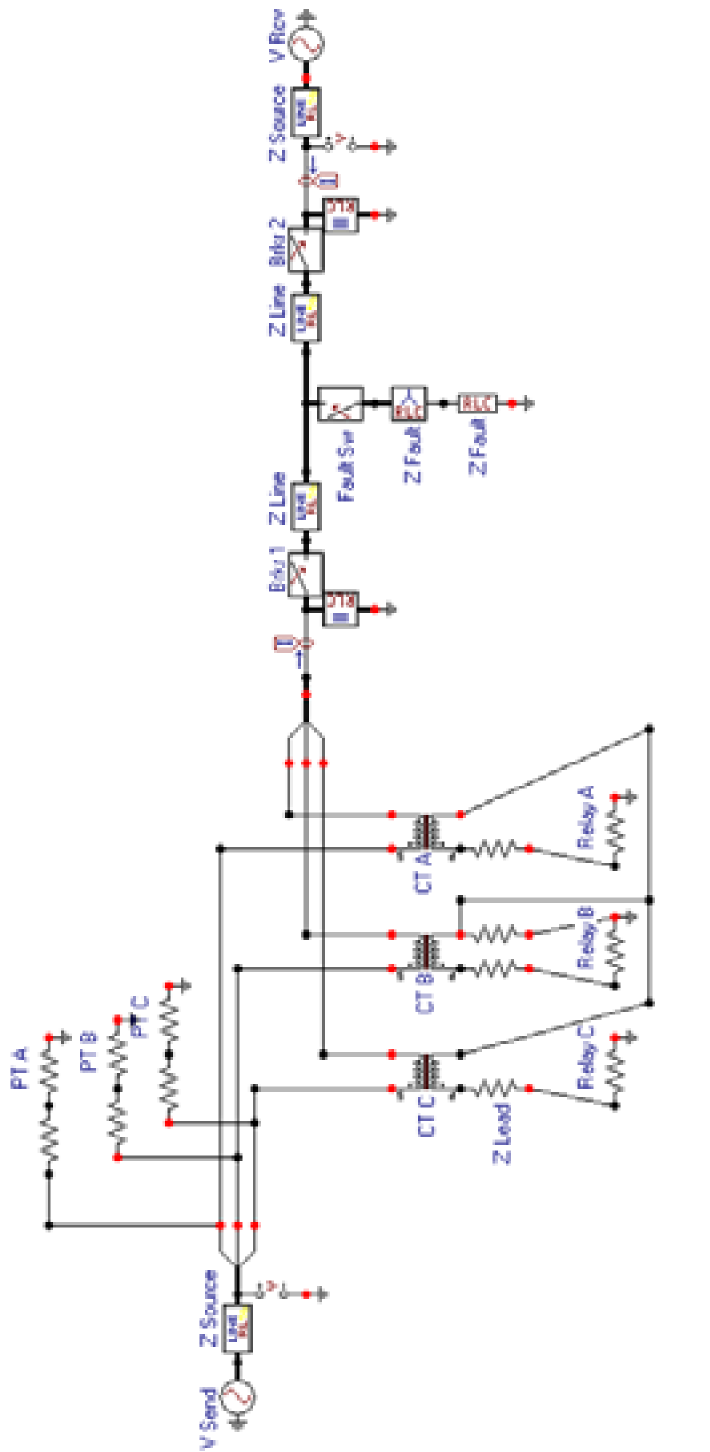


Figure E.1: Small System Model in ATPDraw

Enter all of the component data and review the ATP "Settings" command under the ATP menu item in ATPDraw. Use the "Make File" command under the ATP menu item to create the following text file for ATP input.

```
BEGIN NEW DATA CASE
C -----------------------------------------------------------
C Generated by ATPDRAW  September, Wednesday 1, 1999
C A Bonneville Power Administration program
C Programmed by H. K. Høidalen at SEfAS - NORWAY  1994-98
C -----------------------------------------------------------
ALLOW EVEN PLOT FREQUENCY
C Miscellaneous Data Card ....
C  dT  >< Tmax >< Xopt >< Copt >
 .000002   .2833     60.     60.
     500     250       1       1       1       0       0       1       0
C        1         2         3         4         5         6         7         8
C 345678901234567890123456789012345678901234567890123456789012345678901234567890
/BRANCH
C < n 1>< n 2><ref1><ref2>< R  >< L  >< C  >
C < n 1>< n 2><ref1><ref2>< R  >< A  >< B  ><Leng><><>0
C Sending Source Impedance
51VSA   VSBA               3.681      24.515
52VSB   VSBB                .819       7.757
53VSC   VSBC
C Line Impedance - Sending Side
51VSLA  FA                 7.363       49.03
52VSLB  FB                 1.639      15.514
53VSLC  FC
  VSBA                     1.E+9                                             2
  VSBB                     1.E+9                                             2
  VSBC                     1.E+9                                             2
C Three Phase Fault Impedance
  FSWA  FN                1.0E-6                                             3
  FSWB  FN                1.0E-6                                             3
  FSWC  FN                1.0E-6                                             3
C Line Impedance - Receiving Side
51FA    VRLA               29.45      196.21
52FB    VRLB               6.555      62.055
53FC    VRLC
C Ground Fault Impedance
  FN                      1.0E-6                                             0
C Receiving Source Impedance
51RBA   VRA                3.681      24.515
52RBB   VRB                 .819       7.757
53RBC   VRC
  RBA                      1.E+9                                             2
  RBB                      1.E+9                                             2
  RBC                      1.E+9                                             2
C Dampening Resistance
        VSSWA             4.00E5                                             0
        VSSWB             4.00E5                                             0
        VSSWC             4.00E5                                             0
C Dampening Resistance
        VRSWA             4.00E5                                             0
        VRSWB             4.00E5                                             0
        VRSWC             4.00E5                                             0
C Phase C Current Transformer
  TRANSFORMER                         TX0001                                 3

$INCLUDE, C:\WINDOWS\DESKTOP\WPRC\CT600\SAT120.PCH
 1SCC   SECN                .288        120.
 2VSBC  CTC                     1.0E-6    1.
C Phase B Current Transformer
  TRANSFORMER                         TX0002                                 3
$INCLUDE, C:\WINDOWS\DESKTOP\WPRC\CT600\SAT120.PCH
 1SCB   SECN                .288        120.
 2VSBB  CTB                     1.0E-6    1.
```

(continued on next page)

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```
C Phase A Current Transformer
  TRANSFORMER                        TX0003                                       3
$INCLUDE, C:\WINDOWS\DESKTOP\WPRC\CT600\SAT120.PCH
 1SCA   SECN               .288  .001  120.
 2VSBA  CTA                    1.0E-6    1.
  SECC  SCC                  .2                                                   0
  SECB  SCB                  .2                                                   0
        SECN                 .2                                                   1
  SECA  SCA                  .2                                                   0
C Phase C Relay Resistance
  SECC                       4.                                                   1
C Phase B Relay Resistance
  SECB                       4.                                                   1
C Phase A Relay Resistance
  SECA                       4.                                                   1
C Phase B Voltage Transformer
  VSECB                    100.                                                   2
  VSBB  VSECB            2.00E5                                                   0
C Phase A Voltage Transformer
  VSECA                    100.                                                   2
  VSBA  VSECA            2.00E5                                                   0
C Phase C Voltage Transformer
  VSECC                    100.                                                   2
  VSBC  VSECC            2.00E5                                                   0
/SWITCH
C < n 1>< n 2>< Tclose ><Top/Tde ><   Ie   ><Vf/CLOP ><  type  >
  CTA   VSSWA                                      MEASURING                      1
  CTB   VSSWB                                      MEASURING                      1
  CTC   VSSWC                                      MEASURING                      1
  RBA   VRSWA                                      MEASURING                      1
  RBB   VRSWB                                      MEASURING                      1
  RBC   VRSWC                                      MEASURING                      1
C Sending Circuit Breaker
  VSSWA VSLA        -1.        .2       .01                                       0
  VSSWB VSLB        -1.        .2       .01                                       0
  VSSWC VSLC        -1.        .2       .01                                       0
C Receiving Circuit Breaker
  VRLA  VRSWA       -1.        .2       .01                                       0
  VRLB  VRSWB       -1.        .2       .01                                       0
  VRLC  VRSWC       -1.        .2       .01                                       0
C Fault Switch
  FSWA  FA           1.       10.                                                 0
  FSWB  FB         .117        1.                                                 0
  FSWC  FC         .117        1.                                                 0
/SOURCE
C < n 1><>< Ampl.  >< Freq.  ><Phase/T0><   A1   ><   T1   >< TSTART >< TSTOP  >
C Sending Source
14VSA    0   189500.       60.                                   -1.        1.
14VSB    0   189500.       60.     -120.                         -1.        1.
14VSC    0   189500.       60.      120.                         -1.        1.
C Receiving Source
14VRA    0   189500.       60.      -30.                         -1.        1.
14VRB    0   189500.       60.     -150.                         -1.        1.
14VRC    0   189500.       60.       90.                         -1.        1.


BLANK BRANCH
BLANK SWITCH
BLANK SOURCE
BLANK OUTPUT
BLANK PLOT
BEGIN NEW DATA CASE
BLANK
```

Send the file to ATP with the "run ATP" command under the ATP menu in ATPDraw. Examine the output with the graphical postprocessor TOP and plot secondary currents and voltages from the sending end. Save the TOP active window, containing the currents and voltage, as a CSV text file using the "File Save As" menu item.

Import the CSV text file into Mathcad. The Mathcad file, shown below, processes the data and is a reference for the Mathcad file that displays the data.

Count rows of matrix "Data:"

$a := 1 \cdot e^{120j \cdot deg}$

$\angle(A, B) := A \cdot e^{j \cdot B \cdot deg}$

$R := rows(data) - 1$

Create an index, "i" as a row pointer:

$i := 0 .. rows(data) - 1$

Create time vector "t" from imported data and calculate the data time-step, Δt:

$t := data^{\langle 0 \rangle}$

$\Delta t := t_1 - t_0$

Calculate the number of samples to create an averaging LP filter with at cutoff frequency at 1/2 the sampling frequency, RS:

$$LPW := floor\left(\frac{2}{60 \cdot \Delta t \cdot RS}\right)$$

Averaging filter:

$$LP(C, a) := \left(1 + \frac{1}{RS}\right) \cdot \sum_{k=0}^{LPW-1} \frac{C_{a-LPW+k}}{LPW}$$

Create an index "ii" for the LP filtered quantities:

$ii := LPW .. R$

Calculate filtered quantities:

$ia_{ii} := LP\left(data^{\langle 1 \rangle}, ii\right)$ $va_{ii} := LP\left(data^{\langle 4 \rangle}, ii\right)$ $ib_{ii} := LP\left(data^{\langle 2 \rangle}, ii\right)$

$vb_{ii} := LP\left(data^{\langle 5 \rangle}, ii\right)$ $ic_{ii} := LP\left(data^{\langle 3 \rangle}, ii\right)$ $vc_{ii} := LP\left(data^{\langle 6 \rangle}, ii\right)$

Calculate the number of samples available in the data and create an index "s" as a row pointer:

$S := floor\left(t_R \cdot 60 \cdot RS\right)$

$s := 0 .. S$

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Create vectors representing sampled current and voltages in the relay:

$$Ia_s := \frac{\mathrm{linterp}\left(t, ia, \frac{s}{RS \cdot 60}\right)}{\sqrt{2}} \qquad Ib_s := \frac{\mathrm{linterp}\left(t, ib, \frac{s}{RS \cdot 60}\right)}{\sqrt{2}} \qquad Ic_s := \frac{\mathrm{linterp}\left(t, ic, \frac{s}{RS \cdot 60}\right)}{\sqrt{2}}$$

$$Va_s := \frac{\mathrm{linterp}\left(t, va, \frac{s}{RS \cdot 60}\right)}{\sqrt{2}} \qquad Vb_s := \frac{\mathrm{linterp}\left(t, vb, \frac{s}{RS \cdot 60}\right)}{\sqrt{2}} \qquad Vc_s := \frac{\mathrm{linterp}\left(t, vc, \frac{s}{RS \cdot 60}\right)}{\sqrt{2}}$$

Create a filter index, "if" and apply a full-cycle cosine filter, "CF" to current and voltage vectors:

$$if := (RS - 1) .. S$$

$$CF(A, q) := \frac{2}{RS} \cdot \sum_{k=0}^{RS-1} \cos\left(k \cdot \frac{2 \cdot \pi}{RS}\right) \cdot A_{(q-(RS-1))+k}$$

$$IA_{if} := CF(Ia, if) \qquad VA_{if} := CF(Va, if) \qquad IB_{if} := CF(Ib, if)$$

$$VB_{if} := CF(Vb, if) \qquad IC_{if} := CF(Ic, if) \qquad VC_{if} := CF(Vc, if)$$

Create a complex vector index, "iv" and form a complex vector, "__cpx" from filtered quantities at 90 degree intervals:

$$iv := (RS + 1) .. S$$

$$IAcpx_{iv} := IA_{iv} + j \cdot IA_{iv - \frac{RS}{4}} \qquad VAcpx_{iv} := VA_{iv} + j \cdot VA_{iv - \frac{RS}{4}} \qquad IBcpx_{iv} := \left(IB_{iv} + j \cdot IB_{iv - \frac{RS}{4}}\right)$$

$$VBcpx_{iv} := VB_{iv} + j \cdot VB_{iv - \frac{RS}{4}} \qquad ICcpx_{iv} := IC_{iv} + j \cdot IC_{iv - \frac{RS}{4}} \qquad VCcpx_{iv} := VC_{iv} + j \cdot VC_{iv - \frac{RS}{4}}$$

Calculate sequence currents and voltages:

$$ZERO(A, B, C) := \frac{A + B + C}{3} \quad ONE(A, B, C) := \frac{A + a \cdot B + a^2 \cdot C}{3} \quad TWO(A, B, C) := \frac{A + a^2 \cdot B + a \cdot C}{3}$$

$$I0_{iv} := ZERO\left(IAcpx_{iv}, IBcpx_{iv}, ICcpx_{iv}\right) \qquad V0_{iv} := ZERO\left(VAcpx_{iv}, VBcpx_{iv}, VCcpx_{iv}\right)$$

$$I1_{iv} := \left(ONE\left(IAcpx_{iv}, IBcpx_{iv}, ICcpx_{iv}\right)\right) \qquad V1_{iv} := \left(ONE\left(VAcpx_{iv}, VBcpx_{iv}, VCcpx_{iv}\right)\right)$$

$$I2_{iv} := \left(TWO\left(IAcpx_{iv}, IBcpx_{iv}, ICcpx_{iv}\right)\right) \qquad V2_{iv} := \left(TWO\left(VAcpx_{iv}, VBcpx_{iv}, VCcpx_{iv}\right)\right)$$

Create polarizing voltages for impedance calculations:

$$iii := RS + 1 .. RS + 17 \qquad ii := RS + 17 .. S$$

$$VPOLVa_{iii} := V1_{iii} \qquad VPOLVa_{ii} := \frac{V1_{ii}}{32} - \frac{31 \cdot VPOLVa_{ii - \frac{RS}{2}}}{32}$$

$$VPOLVb_{ii} := a^2 \cdot VPOLVa_{ii} \qquad VPOLVc_{ii} := a \cdot VPOLVa_{ii}$$

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Calculate phase-to-phase impedances:

$$MAB_{iv} := \frac{\mathrm{Re}\left[\left(VAcpx_{iv} - VBcpx_{iv}\right)\cdot\overline{\left(VPOLVa_{iv} - VPOLVb_{iv}\right)}\right]}{\left[\mathrm{Re}\left[\left((1 \angle \alpha 1L)\right)\cdot\left(\left(IAcpx_{iv} - IBcpx_{iv}\right)\right)\cdot\overline{\left(VPOLVa_{iv} - VPOLVb_{iv}\right)}\right]\right] + .00001}$$

$$MBC_{iv} := \frac{\mathrm{Re}\left[\left(VBcpx_{iv} - VCcpx_{iv}\right)\cdot\overline{\left(VPOLVb_{iv} - VPOLVc_{iv}\right)}\right]}{\left[\mathrm{Re}\left[\left((1 \angle \alpha 1L)\right)\cdot\left(\left(IBcpx_{iv} - ICcpx_{iv}\right)\right)\cdot\overline{\left(VPOLVb_{iv} - VPOLVc_{iv}\right)}\right]\right] + .00001}$$

$$MCA_{iv} := \frac{\mathrm{Re}\left[\left(VCcpx_{iv} - VAcpx_{iv}\right)\cdot\overline{\left(VPOLVc_{iv} - VPOLVa_{iv}\right)}\right]}{\left[\mathrm{Re}\left[\left((1 \angle \alpha 1L)\right)\cdot\left(\left(ICcpx_{iv} - IAcpx_{iv}\right)\right)\cdot\overline{\left(VPOLVc_{iv} - VPOLVa_{iv}\right)}\right]\right] + .00001}$$

Calculate phase-to-ground impedances:

$$MAG_{iv} := \frac{\mathrm{Re}\left(VAcpx_{iv}\cdot\overline{VPOLVa_{iv}}\right)}{\left[\mathrm{Re}\left[\left((1 \angle \alpha 1L)\right)\cdot\left(IAcpx_{iv} + 3\ k0\cdot I0_{iv}\right)\cdot\overline{VPOLVa_{iv}}\right]\right] + .00001}$$

$$MBG_{iv} := \frac{\mathrm{Re}\left(VBcpx_{iv}\cdot\overline{VPOLVb_{iv}}\right)}{\left[\mathrm{Re}\left[\left((1 \angle \alpha 1L)\right)\cdot\left(IBcpx_{iv} + 3\ k0\cdot I0_{iv}\right)\cdot\overline{VPOLVb_{iv}}\right]\right] + .00001}$$

$$MCG_{iv} := \frac{\mathrm{Re}\left(VCcpx_{iv}\cdot\overline{VPOLVc_{iv}}\right)}{\left[\mathrm{Re}\left[\left((1 \angle \alpha 1L)\right)\cdot\left(ICcpx_{iv} + 3\ k0\cdot I0_{iv}\right)\cdot\overline{VPOLVc_{iv}}\right]\right] + .00001}$$

Calculate negative-sequence impedance:

$$Z2_{iv} := \frac{\mathrm{Re}\left[V2_{iv}\cdot\left(\overline{\left[I2_{iv}\cdot(1 \angle \alpha 1L)\right]}\right)\right]}{\left(\left|I2_{iv}\right|\right)^{2} + .00001}$$

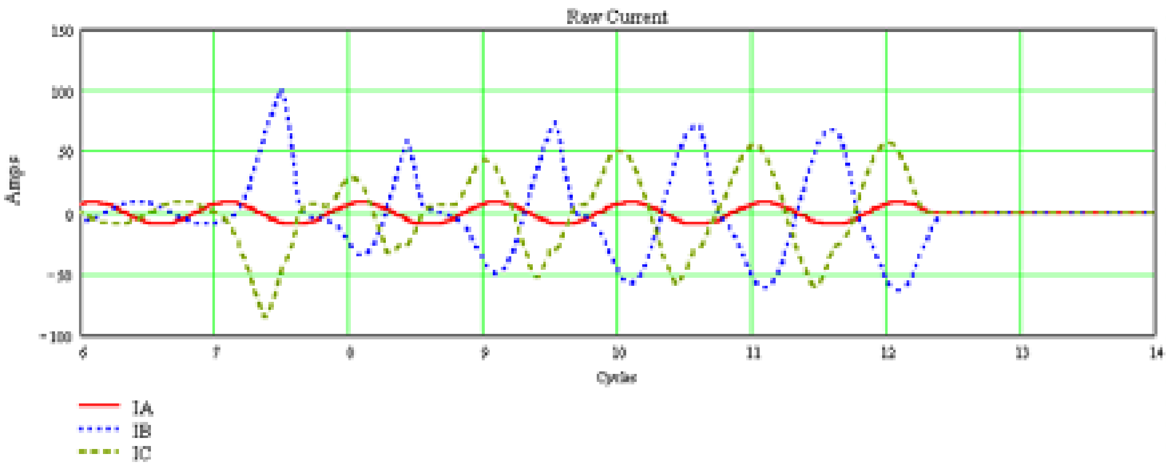
Calculate zero-sequence impedance:

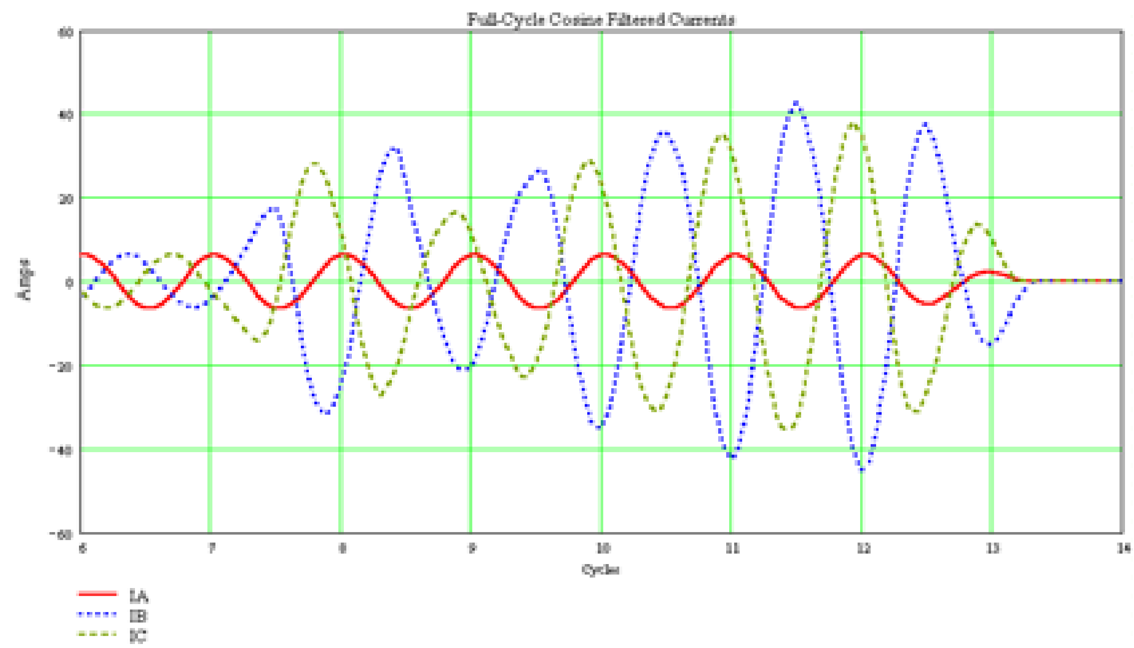
$$Z0_{iv} := \frac{\mathrm{Re}\left[V0_{iv}\cdot\left(\overline{\left[I0_{iv}\cdot(1 \angle \alpha 0L)\right]}\right)\right]}{\left(\left|I0_{iv}\right|\right)^{2} + .00001}$$

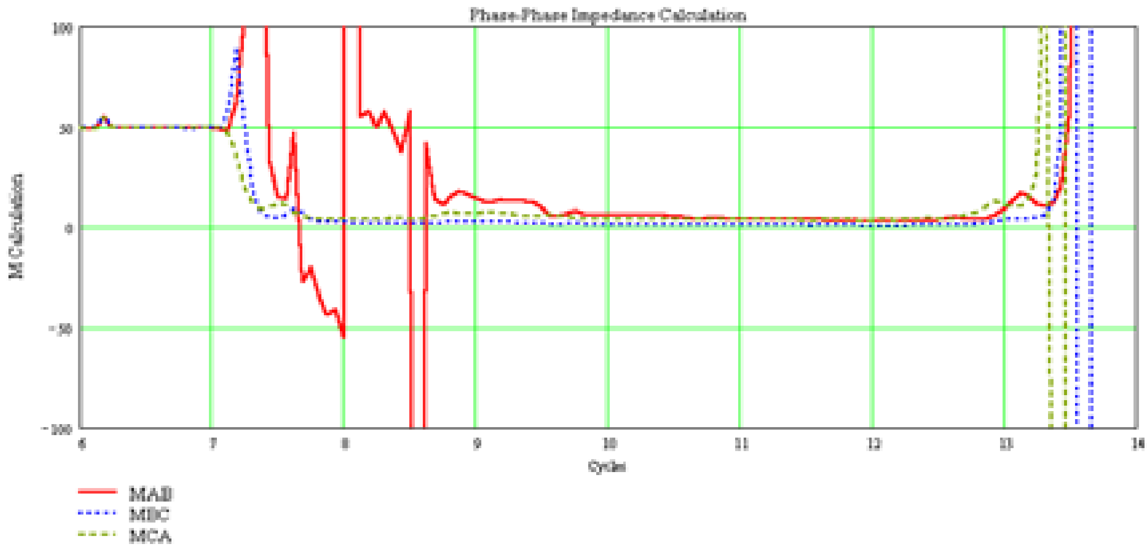
Figure E.2, below, which extends over several pages, shows a portion of the Mathcad display file. Example plots show simulated relay response to saturated CT secondary currents calculated by ATP.

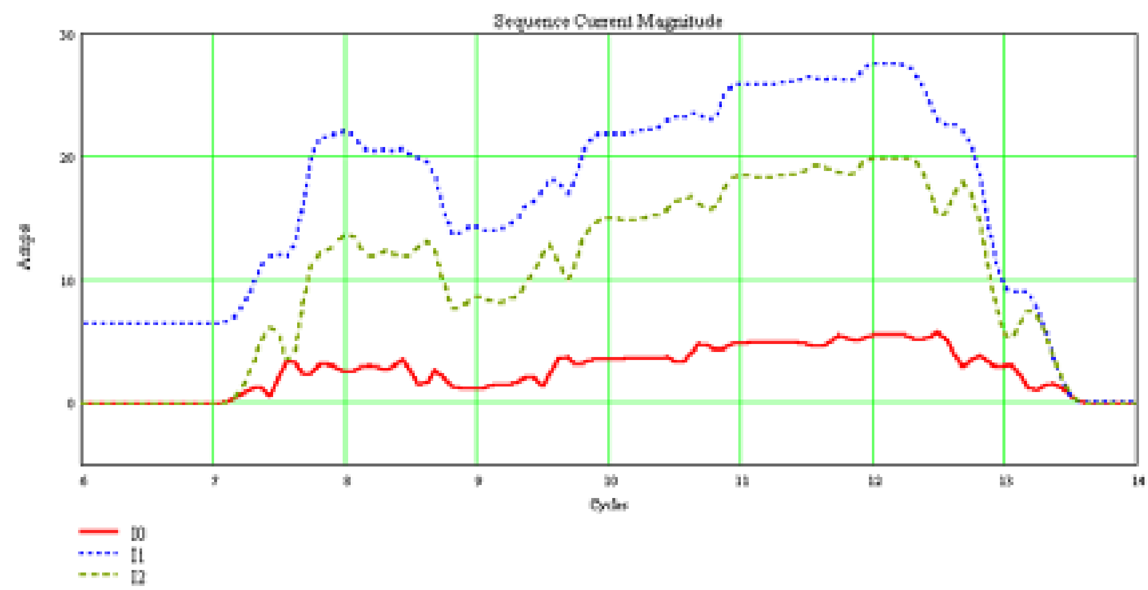
data := C:\1TBKSAT.CSV	Import data from an external file into matrix "data"
$\angle(A, B) := A \cdot e^{j \cdot B \cdot deg}$	Create a function to enter complex data in polar form.
$k0 := .726 \angle 3.69$	Enter the k0 value of the transmission line.
$\omega 1L := 83.97$	Enter the positive sequence line angle
$\omega 0L := 83.97$	Enter the zero sequence line angle
$RS := 16$	Enter the number of samples per cycle of the digital relay
	Call reference file for background calculations

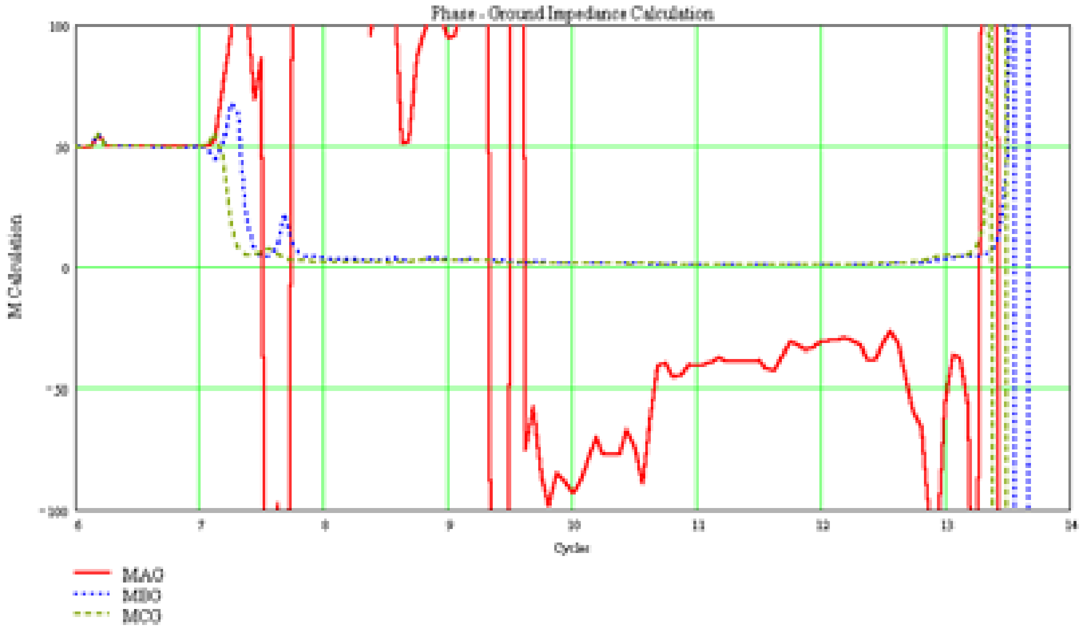
Reference:C:\WINDOWS\Desktop\WPRC\TwoBus\ATPref.mcd(R)






Phase-Phase Impedance Calculation
M Calculation
Cycles
MAB
MBC
MCA


Sequence Current Magnitude
Amps
Cycles
I0
I1
I2



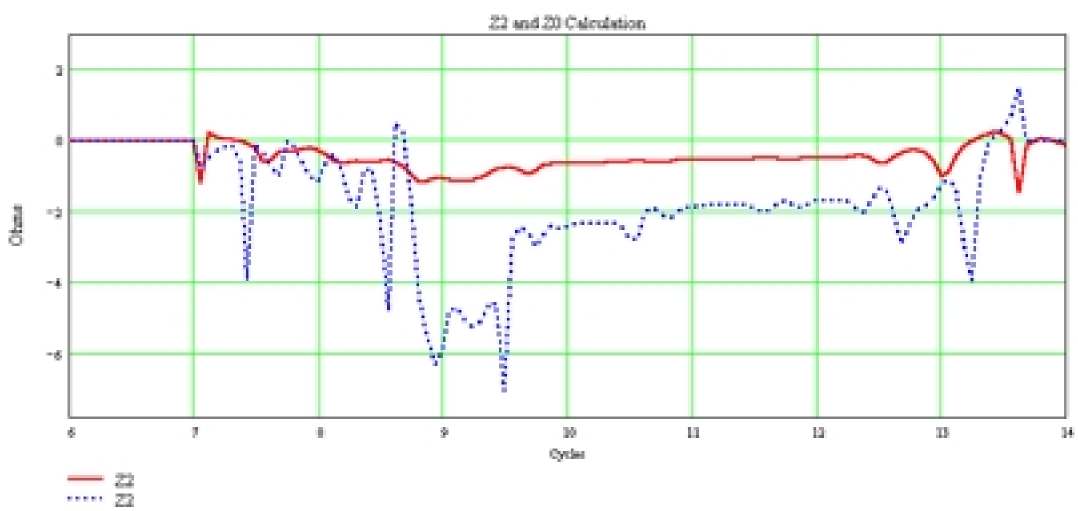


Figure E.2: A Portion of the Mathcad Display File