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Applying Wavelet Transform to Ferroresonance Detection and Protection

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***Abstract*—**Non-synchronous breakage or line failure in power systems with light or no loads can lead to core saturation in transformers or potential transformers. This can cause component and capacitance matching resulting in the formation of resonant circuits, which trigger ferroresonance. This study employed a wavelet transform for the detection of ferroresonance. Simulation results demonstrate the efficacy of the proposed method.

***Keywords*—**Ferroresonance, Wavelet Transform, Intelligent Electronic Device, Transformer.

I. Introduction

THE term "ferroresonance" was coined by Boucherot in 1920 [1], referring to the resonance that occurs as a result of nonlinear inductance and capacitance. It was not until 1940, however, that Rudenberg began researching this phenomenon [2]. In the 1950's, Hayashi analyzed the excitation characteristics and ferroresonance of transformers and this topics has received considerable attention in recent years [3]. In the event of core saturation in transformers or potential transformers (PTs), resonance can occur between the nonlinear inductance and capacitance in the electrical system. This can trigger continuous overvoltage and overcurrent, which can damage power equipment and compromise the reliability and stability of the entire system.

Frame et al. proposed a piecewise-linear approach to simulate the nonlinear inductance characteristics of saturated cores [4]. Walling et al. conducted studies on transformer cores, hysteresis loss, and eddy current loss [5]. Hopkinson investigated the influence of ferroresonance resulting from single-phase switching in three-phase distribution transformer banks [6]. Smith et al. categorized the resulting voltage and situations from ferroresonance in three-phase distribution transformers [7]. Mork et al. presented simulation and experiment techniques with a nonlinear dynamic system to understand the characteristics of ferroresonance [8].

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II. Ferroresonance, Wavelet Transform, and Intelligent Electronic Device

A. Ferroresonance

The primary cause of ferroresonance in transformers or PTs is an increase in the magnetic flux in the core following an increase in the excitation current, which increases the magnetization curve as shown in Fig. 1. Upon reaching the knee point, the flux increases only slightly even with a further increase in current, indicating that the magnetic circuit in the core has reached saturation. This state of saturation causes a plunge in the equivalent inductance of the magnetic circuit in the core, dropping from a fixed value to nearly zero, refer to (1). This sudden drop in inductance is the primary cause of ferroresonance [9].

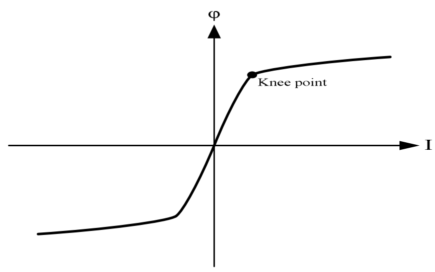


Fig. 1 Magnetization curve of transformer core

$$L = N\frac{d\phi}{di_L} \tag{1}$$

Thus, when the fault current is extremely strong, the flux in the transformer core becomes saturated leading to a decline in inductance, which reduces the inductive reactance and thereby increases the fault current even further. This vicious circle leads to overvoltage and overcurrent capable of damaging power equipment and even causing human casualties.

The parameters that influence ferroresonance include fluctuations in the supply voltage or supply frequency, the presence of harmonic components in the supply frequency, the installation of capacitor banks, modifications in the length of transmission lines (capacitance) and variations in the magnetization curve of the core. Transformers and PTs are essential, so the magnetization curves of the cores are extremely difficult to change. However, the other parameters can be altered.

The modes of overvoltage oscillation caused by ferroresonance include the fundamental mode, the subharmonic mode, the quasi-periodic mode, and the chaotic mode.

B. Wavelet Transform

Haar proposed the concept of wavelet functions in 1910 [10]; however, Morlet et al. were the first to use this term in geological probing to express the appearance of seismic waves. The wavelet transform originates from the Fourier transform; however, Fourier analysis breaks signals into a series of superposed sinusoidal waves of different frequencies, whereas wavelet analysis breaks signals into a series of superposed wavelet functions, which come from the scaling and shifting of a mother wave function. Thus, the primary feature of the wavelet transform is its ability to analyze the local features of signals in the time domain or frequency domain, which has led to its wide application in engineering. Such applications depend heavily on the selection of an appropriate wavelet function, due to the fact that analyzing a given problem with different wavelet functions can produce different results.

C. Intelligent Electronic Device

Intelligent electronic devices (IEDs) have numerous applications including programmable logic arrays, which has led to their gradual replacement of traditional relays [11-12]. IED manufacturers and users must set the primary parameters, logic, and operating programs of the protected target, operating environment, and characteristics of the operation for each IED prior to use.

The occurrence of ferroresonance in a power system can be signaled by a number of factors, such as continuous overvoltage and overcurrent. Ferroresonance detection in existing IEDs suffers from a number of shortcomings, including low sampling frequencies and a failure to resolve fault characteristic signals in a timely manner. An IED with a wavelet transform for the analysis of signal characteristics at a sampling frequency of 10 kHz would be able to detect the signal characteristic of ferroresonance in a power system. Furthermore, this would not require structural changes to the system, the addition of new equipment, or the immediate cutting of the power supply in order to prevent damage caused by overvoltage or overcurrent. An integrated supervisory control and data acquisition (SCADA) system could also be used to record overvoltage and overcurrent in the trip circuit when ferroresonance occurs, thereby enabling experts to analyze the situation in order to identify the cause of the mishap.

III. Simulation, Analysis, and the Detection of Ferroresonance

This study employed Matlab/Simulink for the development of an exemplified system with the step-down transformer of an extra high voltage substation and a wavelet transform for the detection of ferroresonance. We considered the four modes of ferroresonance in a power system: the fundamental mode, the subharmonic mode, the quasi-periodic mode, and the chaotic mode. To deal with the many transient phenomena that may occur during the normal operation of power systems, we also considered transient switching behavior such as load switching, capacitor energizing, and transformer switching to determine whether they influence the detection of ferroresonance.

This study performed simulations, analysis, and the detection of ferroresonance using the step-down transformer of a 345/161 kV substation operated by Taipower in Taiwan. At a voltage level of 345 kV, overhead lines are generally used to connect GIS switchyards to the step-down transformers of extra high voltage substations. For the most part, the capacitance of overhead lines is far below that of underground cables; therefore, the effects of the capacitance can be disregarded. However, when the length of the overhead line exceeds 80 km, the effects of capacitance must be taken into consideration. The default length of overhead lines in this study was set at 100 km. Table I presents the various parameters of the step-down transformer and the overhead line, Fig. 2 shows the core saturation characteristics of the step-down transformer in this study, and Fig. 3 displays the schematics of the exemplified system.

TABLE I
THE PARAMETERS OF STEP-DOWN TRANSFORMER AND OVERHEAD LINE

Step-Down Transformer	Overhead Line
Capacity：1000 MVA	Material：TACSR
Voltage：345/161 kV	Cross Sectional Area：908 mm^2
Impedance Z：14.5%	Resistance：0.0427 Ω/km
Primary Side Connection：Y	Inductive Reactance：0.2241 Ω/km
Secondary Side Connection：Y-G	Cap.Reactance：0.0509 MΩ•km

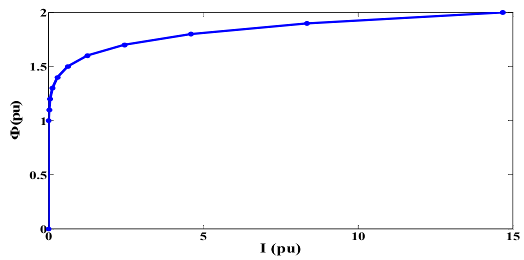


Fig.2 Core saturation characteristics of the step-down transformer

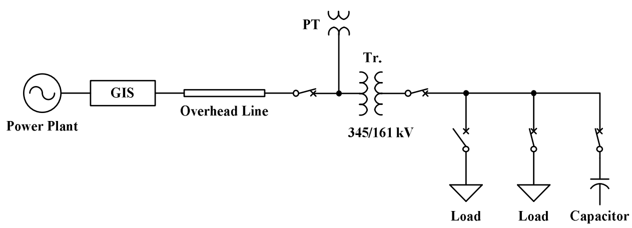


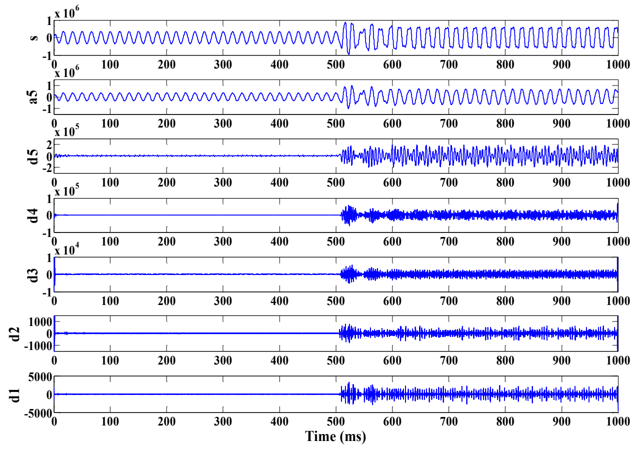
Fig. 3 Exemplified system with step-down transformer of an extra high voltage substation

Selecting an appropriate mother wavelet is crucial to the detection of ferroresonance characteristics [13]. This study considered the frequency response of the Daubechies wavelet function and the limitations of down sampling before selecting Db5 as the mother wavelet to be extracted from the voltage signal. We also adopted 10 kHz as the sampling frequency and performed five-level analysis.

In our simulations, the transformer was placed in a no-load condition. At 0.5 sec, we performed non-synchronous operations in the GIS switchyard with Phase A closed and Phases B and C tripped. This created an R-L-C series circuit with ferroresonance. We assumed the presence of abnormal components in the power supply, the sources of which are presented in Table II [14]-[17]. Fig.4 displays the results of ferroresonance analysis using the wavelet transform with fundamental, subharmonic, quasi-periodic, and chaotic modes. We also considered switching transients, such as load switching, capacitor energizing, transformer switching, which occurred in the test system at 0.5 sec. Fig. 5 presents the results of wavelet transform analysis.

TABLE II
OTHER COMMON SOURCES IN POWER SUPPLY

The type of power	Common sources
Subharmonic	Cycloconverter Arc furnace Wind generator
Quasi-periodic	DC/DC converter
Chaotic	Electric welding Arc furnace



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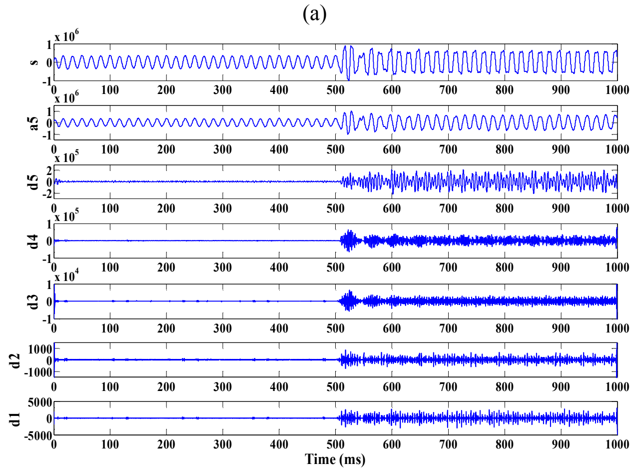

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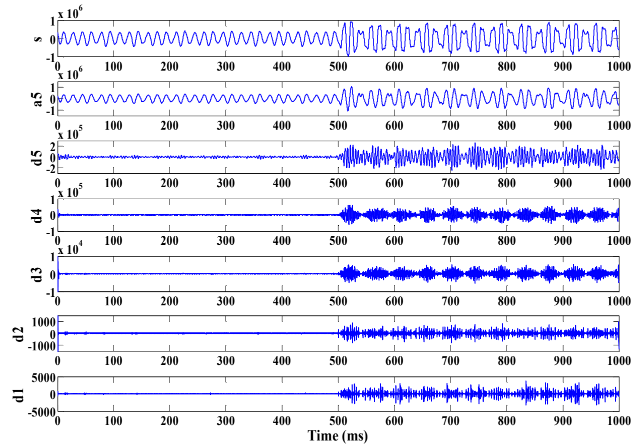

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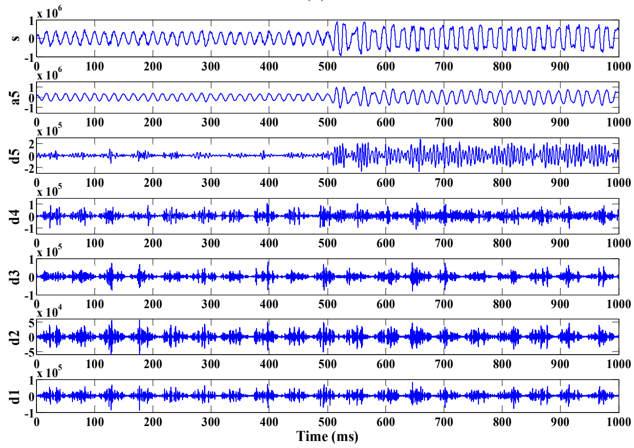
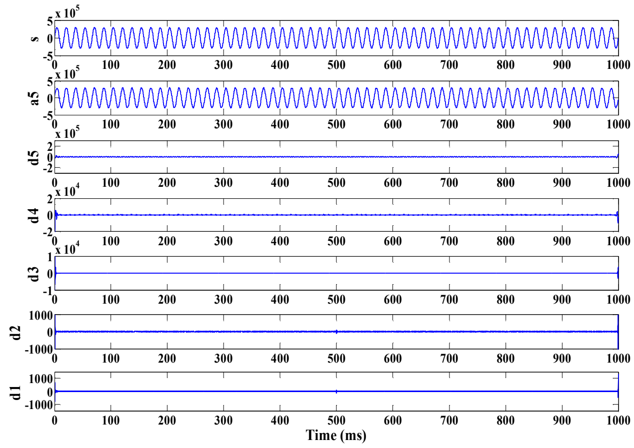


(d)

Fig. 4 Results of wavelet transform analysis of various ferroresonance modes: (a) fundamental mode, (b) subharmonic mode, (c) quasi-periodic mode, (d) chaotic mode



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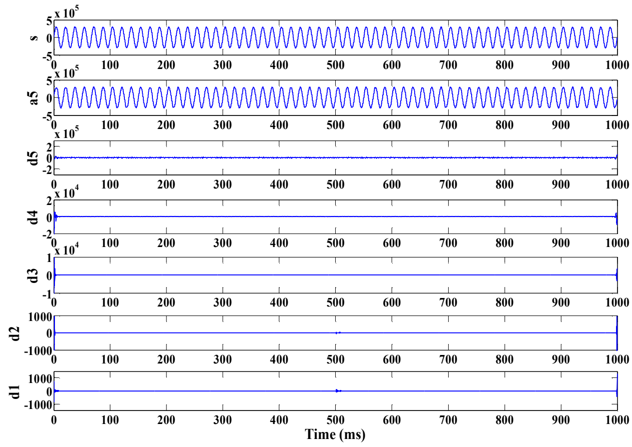

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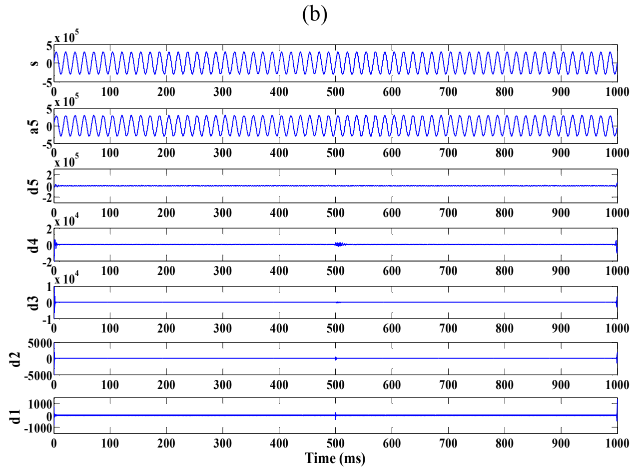

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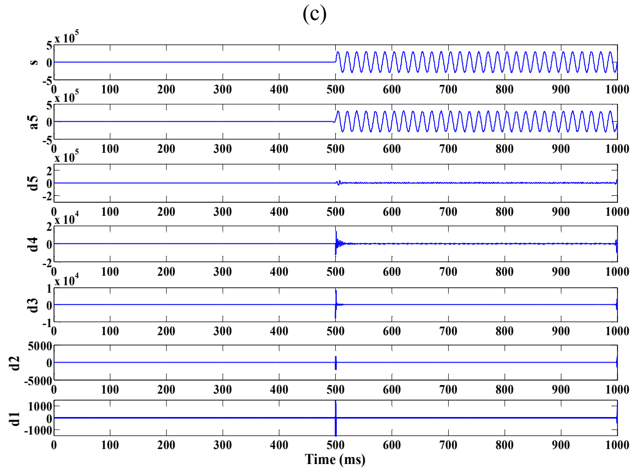

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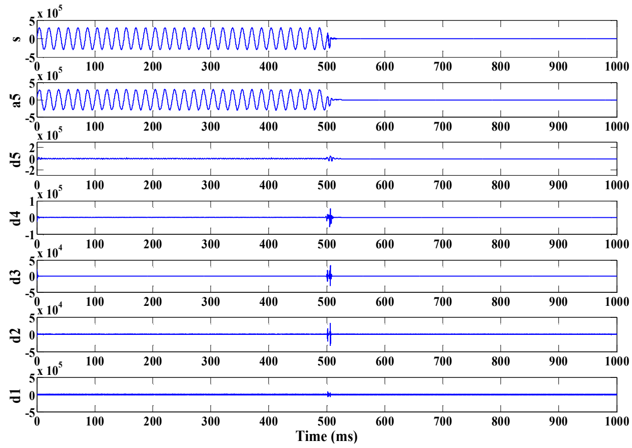


(e)

Fig. 5 Results of wavelet transform analysis with (a) load energizing, (b) load de-energizing, (c) capacitor energizing, (d) transformer energizing, (e) transformer de-energizing

Analysis of various transient phenomena associated with ferroresonance:

A. Fundamental Mode

When the power supply produced only sinusoidal waves at 60 Hz, we applied a five-level wavelet transform to the overvoltage signals created by the ferroresonance. Significant differences in the high-frequency component were observed before and after the appearance of ferroresonance, making it possible to use the high frequency components $d_1[n]$~$d_5[n]$ to verify the occurrence of ferroresonance.

B. Subharmonic Mode

When the power supply contained subharmonic components, significant differences were observed in the high-frequency components of overvoltage signals before and after the occurrence of ferroresonance, making it possible to use high frequency components $d_1[n]$~$d_5[n]$ for the detection of ferroresonance.

C. Quasi-periodic Mode

When the power supply contained quasi-periodic components, significant differences were observed in the high-frequency components of overvoltage signals before and after the occurrence of ferroresonance, making it possible to use high frequency components $d_1[n]$~$d_5[n]$ for the detection of ferroresonance.

D. Chaotic Mode

When the power supply contained chaotic components, no significant differences were observed in the high-frequency components of overvoltage signals before and after the occurrence of ferroresonance, thereby precluding the use of high frequency components $d_1[n]$~$d_5[n]$ for the detection of ferroresonance. However, distinct variations in $d_5[n]$, so $d_5[n]$ could be used for the detection of ferroresonance.

E. Load Switching

The energizing and de-energizing of loads are switching transients that do not cause ferroresonance. High-frequency component analysis with $d_1[n]$~$d_5[n]$ did not reveal significant changes before and after the occurrence of ferroresonance. In this case, any high frequency component could be used for the detection of ferroresonance.

F. Capacitor Energizing

Capacitor energizing is a switching transient that does not cause ferroresonance. In this study, the power waveforms did not present distinct changes before and after capacitor energizing. High frequency components $d_1[n]$, $d_2[n]$ and $d_4[n]$ exhibited extremely small energy bursts at the instant in which capacitor energizing occurred; however, the other high frequencies did not show significant changes. Thus, in this situation, any high frequency component could be used for the detection of ferroresonance.

G. Transformer Switching

The energizing and de-energizing of transformers are switching transients that do not cause ferroresonance. High frequency components $d_1[n]$~$d_5[n]$ displayed large energy bursts at the instant in which capacitor energizing and de-energizing occurred; however, the durations were extremely short. Thus, the high frequency components at any level could be used for the detection of ferroresonance.

In summary, this study selected the high frequency component $d_5[n]$ for the detection of ferroresonance.

We adopted a time window approach to calculate the RMS value of energy associated with the high frequency component $d_5[n]$, using (2), as follows:

$$Energy_{RMS} = \sqrt{\frac{E_1^2 t_1 + E_2^2 t_2 + \ldots + E_n^2 t_n}{T}} \tag{2}$$

where E1, E2, …, and En denote the instantaneous values of energy.

Ferroresonance can lead to continuous overvoltages that are different from the temporary overvoltages common encountered in switching transients. This study examined the differences in ferroresonance and switching transients according to this characteristic. This made it possible to use the ratio between the RMS values of cumulative energy from the $d_5[n]$ in two consecutive time windows as the basis from which to verify the occurrence of ferroresonance.

Any algorithm intended for the detection of ferroresonance must be quick; therefore, a shorter time window is preferable. However, time windows that are too short often include anomalies in quasi-periodic or chaotic modes which could be confused with ferroresonance. Thus, we set the length of the time window at one cycle in order to prevent false detections.

Table III presents the cyclic cumulative energy and ratios of cumulative energy from two consecutive cycles for the high frequency component $d_5[n]$ before and after the occurrence of ferroresonance with various power components.

TABLE III
CYCLIC CUMULATIVE ENERGY AND THE RATIOS OF CUMULATIVE ENERGY FROM TWO CONSECUTIVE CYCLES FOR HIGH FREQUENCY COMPONENT D_5[N] BEFORE AND AFTER THE OCCURRENCE OF FERRORESONANCE WITH VARIOUS POWER COMPONENTS

	Fundamental	Subharmonic	Quasi-periodic	Chaotic
A	6367.3	10819.6	13098.6	16608.3
B	31018.4	42278.3	79179.6	36779.4
C	48606.3	56930.4	107375.3	68522.9
D	70017.3	89241.3	83651.4	60702.1
E1	4.8715	3.9076	6.0449	2.2145
E2	1.5670	1.3466	1.3561	1.8631
E3	1.4405	1.5676	0.7791	0.8859

A: Cumulative energy one cycle before occurrence
B: Cumulative energy one cycle after occurrence
C: Cumulative energy two cycles after occurrence
D: Cumulative energy three cycles after occurrence
E1: Ratio of B and A
E2: Ratio of C and B
E3: Ratio of D and C

Table IV displays the cyclic cumulative energy and ratios of cyclic cumulative energy for high frequency component $d_5[n]$ before and after the occurrence of ferroresonance associated with switching transients in the power system.

TABLE IV
CYCLIC CUMULATIVE ENERGY AND THE RATIOS OF CYCLIC CUMULATIVE ENERGY FOR HIGH FREQUENCY COMPONENT D_5[N] BEFORE AND AFTER THE OCCURRENCE OF FERRORESONANCE ASSOCIATED WITH SWITCHING TRANSIENTS IN THE POWER SYSTEM

	Load Energizing	Load De-energizing	Capacitor Energizing	Transformer Energizing	Transformer de-energizing
A	4630.1	4639.2	4696.7	2.3	4591.0
B	4708.8	4662.2	4831.3	16822.1	24606.1
C	4628.8	4656.0	4272.7	4836.1	379.8
D	4608.1	4638.2	4674.2	4472.0	2.2
E1	1.0170	1.0050	1.0287	7313.9565	5.3596
E2	0.9830	0.9987	0.8844	0.2875	0.0154
E3	0.9955	0.9962	1.0940	0.9247	0.0058

Table III provides the definitions of A, B, C, D, E1, E2, and E3.

Tables III and IV reveal the threshold value of the ratio of cyclic cumulative energy immediately before and after the occurrence of ferroresonance. Setting the first ratio at 2 and the second ratio at 1 enabled the detection of ferroresonance and common switching transients.

In order to prevent the false detection of ferroresonance when the power supply contains subharmonic, quasi-periodic, or chaotic components, we calculated the total cyclic cumulative energy of the three cycles following any such occurrence as an additional threshold value for the detection of ferroresonance. This study selected 125,000 as the threshold value for cumulative energy.

This paper presents a quick algorithm capable of verifying the occurrence of ferroresonance within three cycles. Fig.6 displays the process of the algorithm, under the assumption that ferroresonance occurs during cycle n+1.

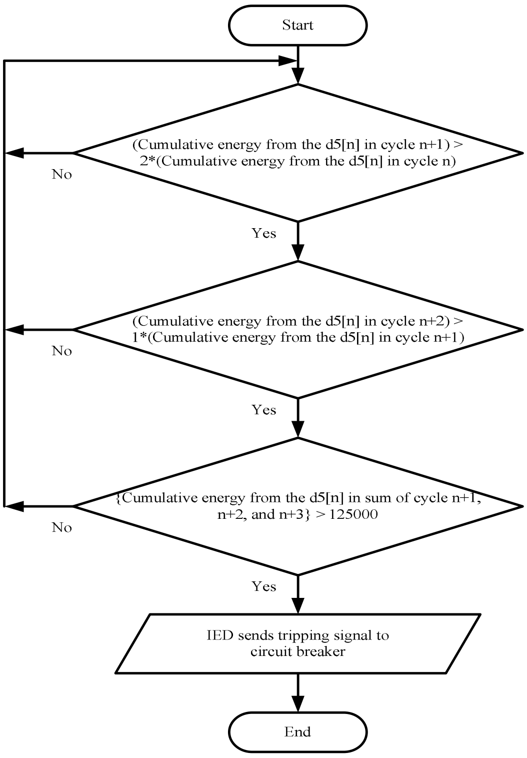
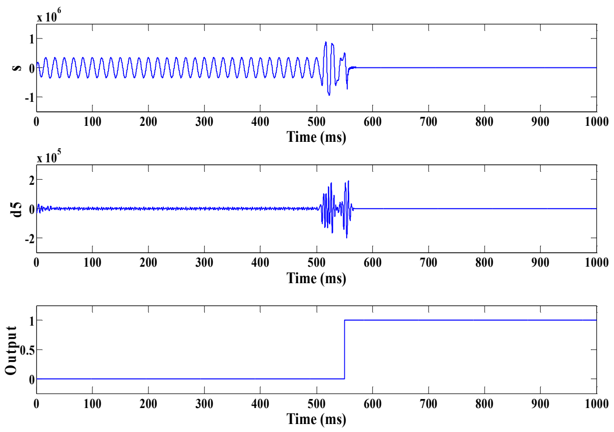


Fig. 6 Ferroresonance detection for IEDs using proposed algorithm

Fig. 7 displays the occurrence of ferroresonance when the power supply contains fundamental, subharmonic, quasi-periodic, and chaotic components. The quick algorithm enables the IED to send a tripping signal to the circuit breaker three cycles after the occurrence of ferroresonance to protect power equipment from potential damage caused by overvoltages and overcurrents associated with ferroresonance.

In the event of switching transients, such as load energizing, capacitor energizing, or transformer energizing, the quick algorithm is resistant to false detections of ferroresonance, thereby avoiding unnecessary interruptions and abnormal operations in the power supply. Fig. 8 presents the responses of the IED.



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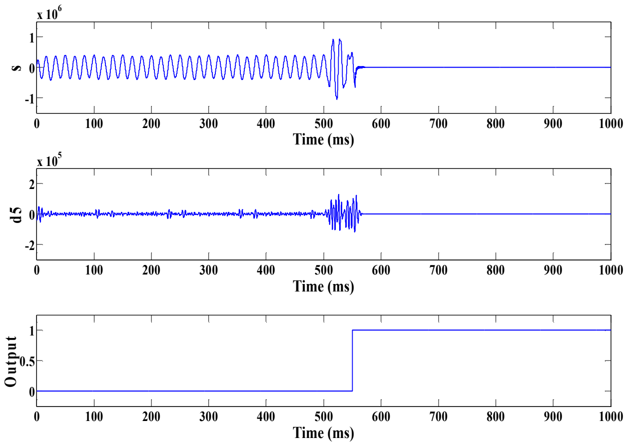

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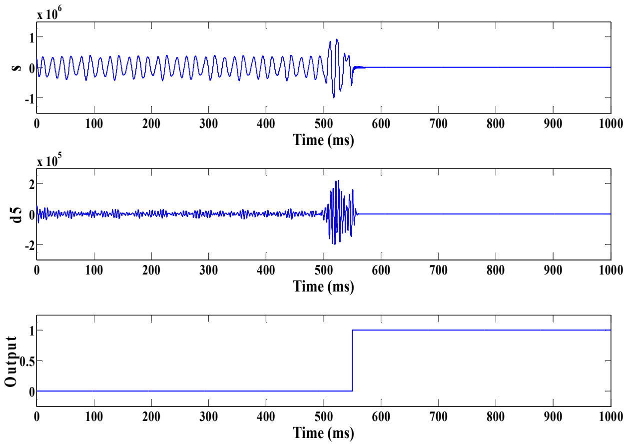

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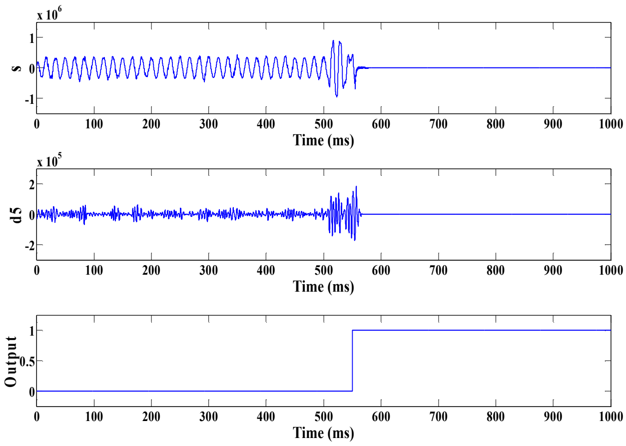

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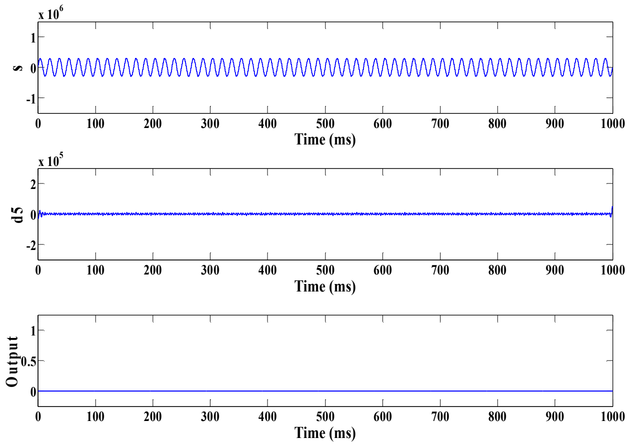
Fig. 7 Protection against ferroresonance in (a) fundamental mode, (b) subharmonic mode, (c) quasi-periodic mode, (d) chaotic mode



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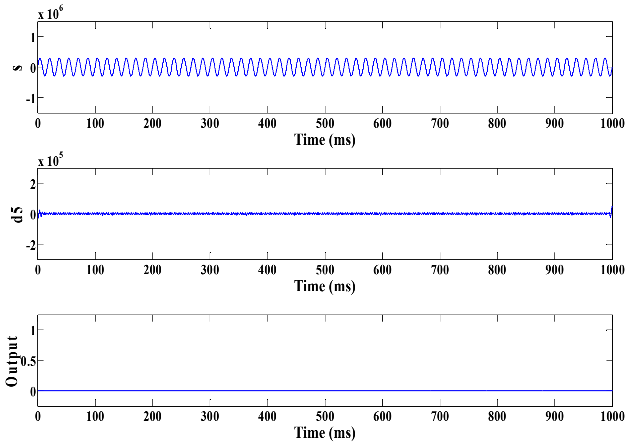

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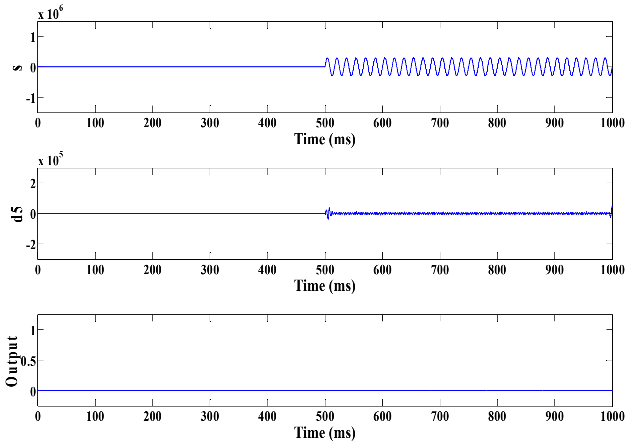

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Fig. 8 Protection against ferroresonance in (a) Load energizing, (b) capacitor energizing, (c) transformer energizing

IV. Conclusion

This study used the overvoltages and continuous distortion characteristic of ferroresonance to derive a suitable energy threshold value using the high frequency component $d_5[n]$ from the db5 wavelet transform of the voltage. Only three cycles are required to confirm the occurrence of ferroresonance, which makes it possible to trip the CB isolated power and protect power equipment from the damage associated with overvoltages and overcurrents associated with ferroresonance. This study developed a quick algorithm for ferroresonance detection by an IED based on a wavelet transform. Simulation results demonstrate the feasibility and reliability of the IED, in which specific harmonic components or switching transients in the power system prevent the occurrence of false detections. The tripping threshold set for ferroresonance in this study can be optimized according to the system in which it is applied to provide complete system protection.

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Ming-Ta Yang was born in 1968. He received the Ph. D degree from the Department of Electrical Engineering, National Taiwan University of Science and Technology (NTUST), Taiwan. He is an associate professor in the Department of Electrical Engineering, St. John's University, Taiwan. His research interests include power system protection and condition-based maintenance (CBM).