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Ferroresonance Suppression in Voltage Transformers

***Abstract**. Ferroresonance is a special case of disturbance that involves high levels of overvoltage and overcurrents distortion. This phenomenon can severely affect voltage transformers and its consequences can be catastrophic. This paper analyses different practical solutions against ferroresonance phenomenon in voltage transformers, highlighting the current development of ferroresonance detection techniques. In this regard, this paper introduces a novel ferroresonance detection technique based on Artificial Neural Networks (ANNs).*

***Streszczenie.** Ferrorezonans w transformatorze jest zakłóceniem wprowadzającym przepięcia i przeciążenia prądowe. Może on popwodować nawet zniszczenie transformatora. W artykule zaproponowano szereg metod umożliwiających stłumienie ferrorezonansu. Ferrorezonans jest wykrywany dzięki technice bazującej na sztucznych sieciach neuronowych. (**Tłumienie ferrorezonansu w transformatorach napięciowych**).*

Keywords: Ferroresonance, Voltage Transformer, Artificial Neural Network, Multi-Layer Perceptron.
Słowa kluczowe: ferrorezonans, transformator, sztuczne sieci neuronowe.

1. Introduction

The word “ferroresonance” includes all the oscillatory phenomena that take place in an electric circuit comprising a nonlinear inductance, a capacitance, a voltage source and low losses. That is why it is a frequent phenomenon in voltage transformers, due to their nonlinear magnetic characteristic and their operation conditions, similar to no-load ones.

This phenomenon appears after transient disturbances (transient overvoltage, lightning overvoltage or temporary fault) or switching operations (transformer energizing or fault clearing). Its effects are characterized by high sustained overvoltages and overcurrents with maintained levels of current and voltage waveform distortion, producing extremely dangerous consequences.

In the last 25 years, the interest in this phenomenon has undergone an important increase in the field of research in electrical engineering. The constant evolution of electrical power systems has given rise to a significant increase in the amount of failures caused by ferroresonance. These failures have their origin in different causes, amongst which should be included the increased use of underground cables in primary circuits, single-phase operations, low-loss transformers, replacement of gapped SiC arresters by gapless metal-oxide arresters, etc. [1].

The first step against ferroresonance is always to prevent it from appearing, either by modifying the initial design of the installation or by deciding about the appropriate actions to take. If the establishment of the ferroresonant circuit cannot be avoided, it is necessary to take some preventive measures that make it possible for this phenomenon to be damped.

These measures basically consist of introducing some losses in the system, in order to make the energy supplied by the power source insufficient to maintain this phenomenon. These losses can either be temporary or permanent. On the one hand, the latter may affect the efficiency of the installation in a considerable way, even provoking thermal failures under unbalanced situations. On the other hand, if the introduction of these losses were temporary, some sort of ferroresonance detection device would be necessary.

Nowadays, the current development level of this kind of detection systems is quite limited, although during the last years, the production of detection techniques and devices has started to be increased.

This paper analyses the ferroresonance suppression techniques in voltage transformers, highlighting those that promote the detection of the phenomenon. In the last part of the paper a novel ferroresonance detection technique based on the identification of the ferroresonant voltage waveform is introduced. The identification process is developed using Artificial Neural Networks (ANNs).

2. Theoretical principles of ferroresonance

The ferroresonance phenomenon is associated with the coexistence, in the same electric circuit, of a non-linear inductance and a capacitor or capacitive load. This phenomenon is characterised by showing at least two stable steady-state responses for a particular range of circuit parameters: a ferroresonant one and a normal operation one (non-ferroresonant). Furthermore, considering the dynamic characteristics of this nonlinear disturbance, the abovementioned ferroresonant response can manifest itself in different ways, as periodic oscillations at the fundamental frequency of the power system (fundamental mode) or at sub-multiple values of the fundamental frequency (subharmonic mode). In some cases, the oscillations can even be non-periodic with a discontinuous (quasi-periodic mode) or continuous (chaotic mode) frequency spectrum [2].

The jump from one stable steady-state response to another one is highly dependent on the initial conditions of the system (residual flux, capacitance value, voltage source, switching instant, etc). Thus, a little variation in the transient state or in some of the parameters of the network may be the trigger that causes a sudden jump, leading to the appearance of the ferroresonance response. This way, the events associated to ferroresonance are usually transient disturbances (lightning, electrical faults, insulation failures) or switching operations.

Once the ferroresonance has appeared, the system keeps working under ferroresonance situation until the source fails to provide the necessary energy to maintain the phenomenon or a new jump to a non-ferroresonat situation is provoked.

Due to the difficulty in controlling and quantifying each and every one of the factors that influences ferroresonance, it is frequently regarded as an unpredictable or random phenomenon. Despite being a phenomenon with high prediction difficulties, some phenomena related to ferroresonance have been observed through the years. These phenomena can help to identify a ferroresonant situation. Some of them are overvoltages and overcurrents, sustained levels of distortion, loud noise (magnetostriction), misoperation of protective devices, overheating, electrical equipment damage, insulation breakdown or flicker [3-5].

3. Measures against ferroresonance in voltage transformers

Voltage transformers are devices particularly prone to ferroresonance on account of its nonlinear character and operating characteristics, because they are designed to work under conditions similar to no-load ones.

On the one hand, inductive voltage transformers are even more susceptible to ferroresonance, since they have a higher inductive character and, consequently, they need a lower capacitance to form the ferroresonant circuit [6]. This tendency of inductive transformers to be prone to ferroresonance becomes more important when operating in isolated grounded systems or when feeded by circuits that include circuit breakers with grading capacitances.

On the other hand, the design of capacitive voltage transformers includes a capacitive divider that increases their tendency to ferroresonance occurrence.

3.1. Inductive Voltage Transformers

It has been almost a century since, for the first time, L.N. Robinson dealt with ferroresonant problems in voltage transformers [7]. Since then, several authors have studied the possibilities of preventing the ferroresonant oscillations in this kind of transformer [8-9]. Most of these analyses have concluded that one of the best options to control these oscillations is to insert a damping circuit in the transformer's open-delta secondary (tertiary) winding (Figure 1).

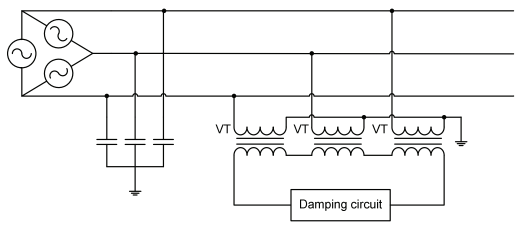

Fig. 1. Damping circuit in the transformer's open-delta secondary (tertiary) winding

The most typical damping circuit consists of the permanent inclusion of a simple resistor. However, its application may imply several problems, especially in isolated systems. These systems can operate under ground fault conditions for a long time, causing severe overvoltages in the open delta. Therefore, the thermal dissipation in the resistor may be too high, leading to serious safety problems. This effect becomes worse in modern low-loss voltage transformers, where the damping resistor needs to have a very low value [5,8,10].

A more advanced solution than the previous one consists of designing a damping circuit formed by a resistor connected in series with an LC filter or a saturable inductor. The performance of LC filters is used to damp the ferroresonant oscillation at frequencies different from the fundamental one. On the contrary, the use of a saturable inductor connected in series with a resistor makes the damping circuit adequate for every ferroresonant oscillation, since its performance with regard to saturation does not depend on the frequency content. This way, the inductor works as a magnetic switch: when the ferroresonant phenomenon appears, the inductor gets saturated, giving way to the reduction of its impedance and inserting the series-connected resistor that allows damping the ferroresonance [11].

In recent years, some researchers [12] have proposed the selectively connection of the damping resistor. This way, the damping circuit is only connected under ferroresonance situation and the possible thermal damage under unbalanced situation is avoided. This selective connection implies the necessity of a ferroresonance detection system. In this field, there are currently four main lines of research, depending on the criteria used to detect the phenomenon: saturation analysis [9,11,13], overvoltage analysis [14], zero-sequence voltage analysis [12] and identification of waveforms [15-16].

3.2. Capacitive Voltage Transformers

These kinds of transformers usually include a ferroresonance suppression system (Figure 2). Although the aim of this system is to damp effectively the ferroresonance phenomenon, its inclusion may affect considerably the transient response of the transformer, causing misoperation of protective relays and associated systems [17-20].

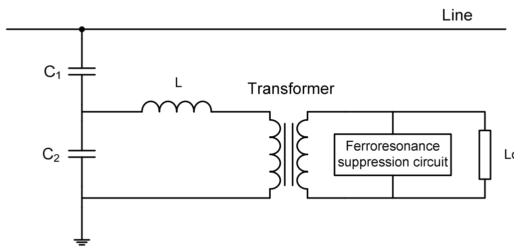

Fig. 2. Graphical solution of a series ferroresonant circuit

Nowadays, there are mainly two types of ferroresonance suppression circuits in capacitive voltage transformers: Active Ferroresonance Suppression Circuits (AFSC), based on a series-parallel RLC filter, and Passive Ferroresonance Suppression Circuits (PFSC), based on a saturable inductor in series with a damping resistance.

AFSC are more effective in damping the ferroresonant oscillations than PFSC, although its influence on the transient response of the transformer is higher. Both systems usually incorporate surge protection devices. Figure 3 shows the typical elements included in the design of a ferroresonance suppression circuit. In recent years, the use of electronic systems based on power electronic devices is on the increase due to its effectiveness and low cost.

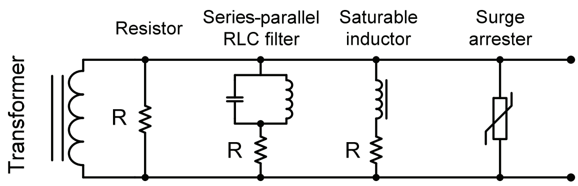

Fig. 3. Basic circuits for ferroresonance suppression [18]

4. A novel method for ferroresonance suppression

In this section the authors present a novel technique for ferroresonance detection using Artificial Neural Networks (ANNs). The developed technique is based on the line of research that analyses the identification of the ferroresonant waveforms.

Ferroresonant oscillations adopt characteristic waveforms that may be used to identify the phenomenon. As the detection technique is focused in voltage transformers, the voltage waveform (secondary measured voltage) has been selected to identify the phenomenon. This voltage waveform is different, depending on the ferroresonant mode. The most common one is the fundamental mode [21-22]. That is why the developed detection technique focuses its attention in the fundamental ferroresonance.

4.1. Artificial neural networks

Artificial neural networks are models based on the neural structure of the brain. They are composed of a large number of processing components highly interconnected among them. These basic components are known as neurons or nodes, and they try to replicate the most basic functions of the brain via their multiple connections, working in parallel at the same time for the solution of specific problems. Consequently, they have the capacity to learn from representative examples of the problem.

Artificial neurons are grouped by layers, with a typical structure of an input layer, an output layer, and one or more hidden layers. Each neuron in a hidden layer receives the outputs from all the neurons in the previous layer, and passes its output to all the neurons in the following layer. The internal operation of an artificial neuron is shown in Figure 4. The mathematical symbol, x_n, represents the inputs to the neuron. Each of these inputs is multiplied by a connection weight, represented by w_{in}. These products are treated, fed through a propagation rule *H(t)*. Each neuron has a threshold value or bías term θ_i. and a transfer function f_i, to generate the neuron output, represented by y_i. The most common activation functions are linear functions, step functions or sigmoid functions.

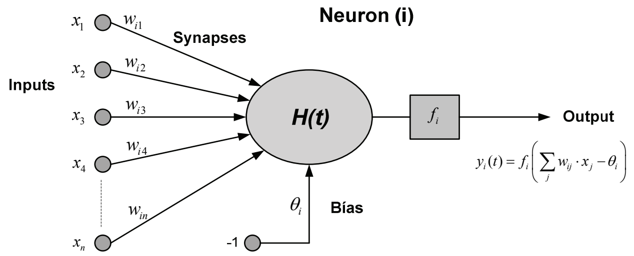

Fig. 4. Artificial neuron model

Once the network structure has been defined, it has to be trained according to a particular application. During the learning process, the connection weights are modified until the network is able to generalize from the training data. Once the network has been trained, it is prepared to accept input values, providing output values.

There are different types of ANNs depending on the neural model, the topology of the connections and the learning process. One of the most important and widely used network is the Multi-Layer Perceptron (MLP). MLP network is a unidirectional network of supervised learning. The topology of a MLP network consists of an input layer, an output layer and an undefined number of hidden layers, fully connected between them, but without intra-layers connections. The typical learning algorithm of an MLP network is the back propagation (BP) training, which is a gradient descent based method that adjusts the network weights in order to minimize the errors between network outputs and expected outputs.

4.2. Ferroresonance Detection Based on ANNs

This detection technique analyses the direct sampling of a full-cycle data window of the voltage signal at the fundamental frequency. The neural network used to identify the full-cycle data window is a MLP network. The only data conditioning that has to be made is to scale down the samples in a range between 0 and 1.

The quantity of input data to the neural network coincides with the number of samples per cycle gathered from the signal. The choice of the sampling frequency has been decided by considering the following three criteria:

- The sampling frequency should be commonly used by typical power relays.
- The number of samples should be high enough to obtain a reliable representation of the voltage waveform.
- The number of samples should be low enough not to overload the final design of the neural network.

Taking into consideration the abovementioned three criteria, the sampling frequency that has been finally chosen is 32 samples/cycle. In this case, if the neural network classifies the signal as "ferroresonant" according to the 32 samples used as input data, the network provides "1" as output. On the other hand, if it is classified as "non ferroresonant", the output changes to "0". The basic scheme of the proposed detection technique is shown in Figure 5.

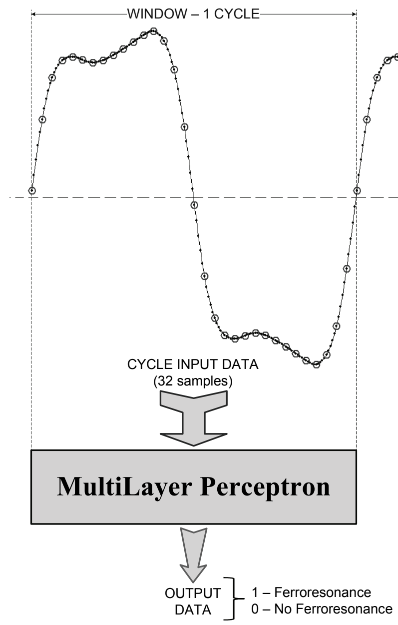

Fig. 5. Ferroresonance detection scheme

The representative examples of the problem have been obtained by software simulation, with the development of a voltage transformer in MATLAB/Simulink environment. Not only have ferroresonant conditions been simulated, but the results from non-ferroresonant oscillations have also been obtained, so as to get enough operating conditions for the ANN in the training stage. These situations include normal operating conditions, ground-faulted system and different switching operations.

The ANN training process has been undertaken with the help of the SARENEUR software application [23], developed with the Neural Network Toolbox of MATLAB.

Different MLP network architectures have been trained, considering one or two hidden layers. The sigmoid activation function has been implemented in the neurons of the hidden layers, and the identity function has been applied to the neurons of the output layer. Furthermore, the Levenberg-Marquardt learning algorithm has been used during the training process.

The network architectures with better responses correspond to networks with a number of neurons over 20 in the first hidden layer and some few neurons in the second hidden layer.

The network responses are being highly satisfactory. Figure 6 shows the response of a trained ANN under a ferroresonant situation obtained by simulation. The ANN is composed by 24 neurons in the first hidden layer and 15 neurons in the second hidden layer. As can clearly be seen, once the ferroresonance appears, the ANN identifies the phenomenon providing a continuous output of 1. Once the ferroresonance has been successfully detected, a damping resistance is inserted so as to make ferroresonant oscillations disappear.

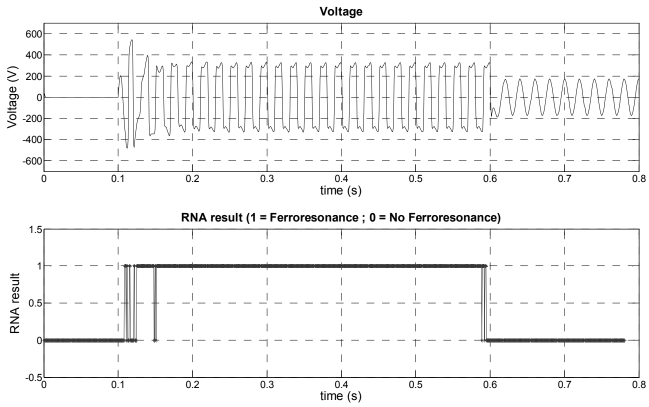

Fig. 6. ANN response under a fundamental ferroresonance situation.

Several laboratory tests are currently being conducted with real voltage transformers, providing equally satisfactory results.

5. Conclusions

Ferroresonance is a widely studied phenomenon but it is still not well understood because of its complex behaviour. Its effects on electrical equipments are still considerable nowadays.

With regard to voltage transformers, there are different solutions against ferroresonance phenomenon. The most typical one is the permanent connection of a damping circuit (normally a resistance) in the secondary terminals of the transformer. This permanent damping circuit may provoke failures under unbalanced situations or affect the transient response of the transformer. Thus, in recent years, several authors propose the selective connection of the damping circuit, developing new ferroresonant detection techniques.

In this regard, this paper introduces a novel ferroresonant detection technique based on ANNs. This technique has the capability to detect fundamental ferroresonance situations with high degree of accuracy. The technique has been developed by simulation and it is currently being verified by laboratory tests.

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