

## FERRORESONANCE IN THREE-PHASE POWER DISTRIBUTION TRANSFORMERS: SOURCES, CONSEQUENCES AND PREVENTION

Garikoitz BUIGUES, Inmaculada ZAMORA, Victor VALVERDE, Angel Javier MAZÓN, José Ignacio SAN MARTÍN  
University of Basque Country (Spain)  
garikoitz.buigues@ehu.es, inmaculada.zamora@ehu.es

### ABSTRACT

*Ferroresonance is a phenomenon that involves high distorted levels of overvoltage and overcurrents. During the last decades, the three-phase ferroresonance research has suffered several changes due to the continuously changing equipment and network. This paper analyses every main factor that is somehow related with the origin, consequences and the preventive decisions that may lead us to avoid the three-phase ferroresonance to appear. Besides this, it gives the opportunity to get a quick identification of such a complex phenomenon.*

### INTRODUCTION

Although the word ferroresonance first appeared in 1920 to describe a complex electrical phenomenon, today it remains hard to analyze, maintaining the erratic nature of its performance and its difficulty to be predictable.

Ferroresonance is a resonance situation with nonlinear inductance, in which the inductive reactance not only depends on frequency but also on the magnetic flux density of an iron core coil (e.g. transformer iron core). Theoretically, this nonlinear inductance could be represented by two inductive reactances (linear zone and saturation zone), according to the situation on the saturation curve.

Nowadays, the connection of three-phase transformers through underground cables is growing fast in residential, commercial, industrial and rural applications. Due to this increasing situation, the possibilities of having a series connected capacitance and a non-linear inductance, prone to ferroresonance, become more probable. Not only is the cable capacitance (and consequently its length) an important factor to take into account in the transformers ferroresonance, but also other elements are completely necessary for ferroresonance to appear.

All those factors affect the ferroresonance appearance in several ways, producing the phenomenon just as well as making some damaging consequences appear. Consequently, it is necessary to have a general idea about what would be the best preventive decisions to take in order to avoid unexpected surprises.

### SOURCES OF THREE-PHASE FERRORESONANCE

#### Influential factors

The possibility of a ferroresonance phenomenon appearance is mainly based on an existing series connected capacitance and a non-linear inductance. But, factors that may influence on it are not only limited to the cable capacitance consideration, but also to several constructive, design, operation and protective parameters, such as:

- One or two phase fuse operation and switching with phase opening/closing delays.
- Transformer primary winding connections.
- Transformer core design and the use of low-loss transformers.
- Transformers with low load levels or in an unloaded situation.
- The capacitance provided by many elements: underground cables, overhead conductors, shunt capacitors, transformer stray capacitance and grading capacitance of circuit breakers.
- Network characteristics (voltage rating, short circuit power, transformer power)
- Initial conditions: remanent flux, switching instant, circuit losses and charge in the capacitances

Although up to three decades ago the problem of ferroresonance was limited to certain situations, the significant evolution of the electrical networks has led the phenomenon to a more complex analysis. Therefore, the main elements involved in this complexity increase are the following ones:

- The increasing use of insulated underground cables with higher capacitance
- Single phase connection and disconnection
- The extended use of MOV type surge arresters
- Improved low-loss core transformers with different magnetic response

### Conditions of ferroresonance

During many decades, the three phase ferroresonance was assumed to be only a problem of transformers with non-grounding primary connections, such as delta, ungrounded wye or open delta. In these cases, when three-phase primary switching, protective or sectionalizing devices are not used, a ferroresonant circuit may appear by the establishment of a current from the energized phase through primary winding to the non-connected phases shunt capacitance (figure 1).

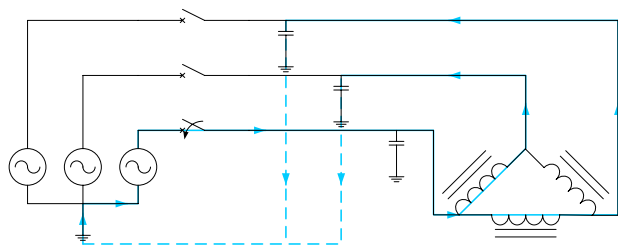


Fig. 1. Ungrounded transformer single-phase operation

As the underground distribution systems increased, the ferroresonance phenomenon has turned out more frequent. So the majority of American utilities decided to change to grounded-wye primary windings (79% of underground rural distribution systems in USA use the grounded-wye to grounded-wye configuration) [1].

However, with grounded primary windings the choice of the transformer core type results to be essential. The winding grounding solution would be acceptable in those transformers with no magnetically and capacitively coupled phases (i.e. transformer banks composed of single phase units or those with triplex construction). This way, single phase operations will not induce voltages on the other phases. The only possibility for ferroresonance to appear would be the existence of capacitor banks or important phase to phase capacitive coupling (figure 2).

Nowadays, other core designs are usually used in order to reduce cost and weight (i.e. three, four or five legged cores). The magnetic phase-phase coupling through the core make this kind of transformers prone to ferroresonance regardless of what is the transformer connection. A good example of this situation would be pad-mounted transformers, which are mainly manufactured in a five-legged wound core construction. Although they have been traditionally used for decades in America, these transformers have started recently to be installed in the European distribution systems.

Another important factor to take into account is the amount of losses introduced in the ferroresonant circuit. This factor is mainly affected by two elements: the quality of the magnetic core and the load connected on the transformer secondary.

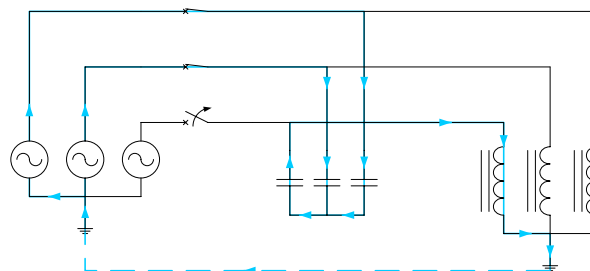


Fig. 2. Grounded-Wye transformer single-phase operation

As it has been mentioned, the less loaded the transformer is, the less the system damping and the more probable the ferroresonance becomes (during night time, weekends, holidays, etc.). For an open phase system, a very few percentage of the transformer rating can be enough to damp out the ferroresonance. But in two-phase open system it is sometimes more difficult to avoid the ferroresonance appearance by the use of a secondary load. Generally, the amount of load necessary will depend on the capacitance connected to the open phases (mainly cable length) and on the parameters and connection of the transformer.

On the other hand, the evolution of transformer manufacturing through the core material improvement has resulted in low loss transformers. This would imply lower cost transformers but the development and installation of these transformers coincided with an increasing frequency of ferroresonant situations. Consequently, the core loss is the best indicator of how long the cable length should be to guarantee the absence of ferroresonance in a transformer single-phase switching [3].

Furthermore, the voltage rating of the transformer connected network is almost equally important. If we compare a 35-kV-class transformer with a 15-kV-class one, the magnetizing curve of transformers installed at higher voltage level is steeper than those of lower voltage class (higher magnetizing reactance). In other words, the possibility of damaging ferroresonance to appear is considerably more common at the higher voltages. Generally, the ferroresonance susceptibility increases with the square of voltage and it is inverse with the transformer apparent power [4].

But even more important than the previous characteristics, it is necessary to mention the different elements that may contribute to get the necessary series-connected capacity. Obviously, the most important element is the underground primary cable and its length, because the capacitance provided by the overhead lines is usually insufficient to cause the ferroresonant state. Besides, the stray capacitance of transformer windings and bushings has also to be considered, especially when using high voltage transformers or low apparent power transformers.

Finally, another important element is the grading capacitance of one or more open circuit breakers. The circuit breaker technology has substantially evolved during the last century. From the bulk oil breakers to the modern SF6 breakers, as the interrupting medium has improved, the number of interrupting chambers has decreased while the grading capacitance has been increased.

Apart from the elements mentioned above, other capacitive elements are the capacitor banks, series connected capacitances, etc.

### **FERRORESONANCE SYMPTOMS AND CONSEQUENCES**

As it may be seen hereinafter, due to the different factors involved in the ferroresonance phenomenon, when it occurs the situation can be rather disconcerting. That is why it is so important to get to identify the most common symptoms of a ferroresonance situation, such as audible noise, overheating, arrester and surge protector failure and flicker [5].

Because of the wide variety of electrical distribution networks, this phenomenon is not limited to public networks but it can also be found in power plant auxiliaries and in industrial distribution networks. The result of ignoring some basic rules to prevent ferroresonance situations, may lead the power system to suffer one or several of the consequences stated below.

#### **High sustained overvoltages**

One of the most dangerous consequences of the ferroresonant phenomenon is the damaging level of overvoltage that may lead the electrical system components (cables, switchgear, transformers and surge arresters) to a sudden failure with disastrous consequences.

The most important factor to get to know the possible overvoltage level is the transformer winding connection. The magnitude of the overvoltages reported for grounded transformers rise up to 2.5 p.u. In contrast, the situation in ungrounded transformers may become more worrying, with 5 p.u. and higher magnitudes [6].

#### **Power quality problems, due to the distortion of current and voltage waveforms**

The high harmonic distortion of ferroresonant voltage and current waveforms usually lead the electric system to have several power quality problems. A good example of this would be flicker, as a consequence of the wild voltage fluctuation (figure 3).

The customer circuit appliances that may be affected by this distorted voltage waveforms may vary, from the light bulbs flicker to some electronic appliances, even shortening their

expected life.

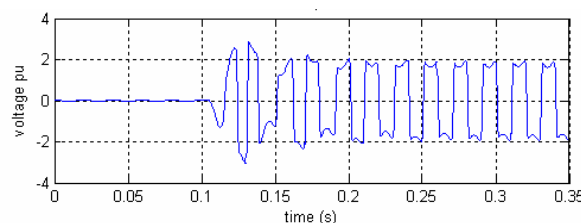


Fig. 3. Typical ferroresonant overvoltage

### **Transformer heating and loud noise**

One of the most significant situations is the anomalous temperature reached by the transformer as a result of overcurrents in primary windings, which are caused by the saturation of the magnetic core. Another symptom of the ferroresonance come from the transformer heating caused by the stray flux in parts where it is supposed not to be (tank wall and other metallic parts). This can be sometimes detected just by the appearance of paint charring or bubbling on the top of the transformer enclosure [8].

Consequently, in the absence of a quick detection, the transformer may suffer severe damages, leading to dangerous situations such as insulation failure, short-circuit, explosion or even fire.

On the other hand, the typical ferroresonant noise should be indicative that something is wrong. When the magnetic core is deeply driven into saturation, the movement of core laminations and the magnetostriction produce a distinctive banging from within the transformer tank. Once it has been firstly heard by the maintenance personnel, they would be able to recognize it immediately.

### **Electrical equipment damage**

In addition to the possible transformer failure, the other main element that has to cope with the ferroresonant threat is the surge arrester. The overvoltage levels and the energy involved under ferroresonant conditions may be too high to be absorbed reliably. Therefore, both sides of the transformer can be affected somehow: those arresters involving customer appliances and those located in the distribution network.

The use of gapless MOV type surge arresters applied to underground distribution networks make the ferroresonance something to look for, in order to avoid being at risk. The gapped SiC arresters, which were more frequently used some decades ago, failed less frequently under ferroresonant overvoltages [9]. On the contrary, although the gapless ZnO arresters might be able to withstand several overvoltage events, the long duration overvoltage may rise over its definite energy absorption capability.

Under-oil arresters are less prone to this catastrophic failure due to its better thermal behaviour with higher heat dissipation.

Moreover, the surge protectors widely used on many appliances on the customer side may be more susceptible to these sustained overvoltages. Accordingly, many end-user facilities can also be affected and even be seriously damaged, such as computer and other consumer appliances, office equipment, factory machines, etc.

### Apparent failure of protective devices

Another consequence of a ferroresonant state can be an apparent mis-operation or tripping of some protection devices [10]. For instance, the usual operation of protective relays is mainly based on fundamental frequency sensing. However, the ferroresonant circuits present high magnitude peaks with low fundamental components (obviously, it depends on the oscillation mode). That is why the relay may take disconcerting trippings when sensing the ferroresonant magnitudes.

### PREVENTION OF FERRORESONANCE

Considering the situations analyzed above, the preventive decisions that can be taken to avoid the appearance of the ferroresonance are based in three main points:

- Avoid the configurations prone to ferroresonance, not only during the design process but also during the system normal operation (i.e. selecting the correct combination between the transformer connections and the core construction type, three-phase switching, etc.).
- The system parameters have to keep out of the dangerous ferroresonance zone (i.e. minimizing the capacitance by switching very close to the transformer terminal, using larger transformers and shorter cables, etc.)
- Make sure the energy provided by the source is not enough to maintain the phenomenon, introducing losses to reduce its effects (i.e. switching transformers with some load, grounding the primary windings through a resistance, etc.)

In order to study and assess this phenomenon three are the main methods to use:

- Laboratory and field tests. Although results can be more realistic, they are usually limited by the amount of tests that can be done
- The use of mathematical models and analytic techniques. In spite of the great variety of scenarios that may be studied, this method is usually limited to single-phase transformers due to its complexity.
- The use of digital tools to simulate the three-phase transformer and its surrounding electrical system.

Although these programs have the possibility of using different methods of numerical integration, the validity of the obtained results depends heavily on the models used and on its nonlinear parameters. Unfortunately, the progress in three-phase transformer modelling is not as good as the single-phase one

### CONCLUSION

In this paper, all the main factors involved in the ferroresonance appearance are thoroughly described, analyzing every situation implied in the three-phase transformer ferroresonance. This way, it is possible to obtain a wide overview of this phenomenon, helping the people in charge of electrical operation and maintenance departments to get a quick identification and possible solutions to the problem.

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