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# Exploringthe Existence of Ferro resonance in Power Transformers Using Simulink

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***Abstract–****This research, conducted with Simulink, looked at how voltage transformers responded to the ferro resonance phenomenon. When analysing this phenomenon's behaviour, only electrical factors are taken into consideration (currents and voltages). The approach is based on documentary research, which explains the theoretical underpinnings, causes, and effects of this phenomenon while also analysing the simulation outputs produced by Simulink. With satisfactory findings, various scenarios are simulated. The transformer's energization and de-energization are described as crucial conditions for the development of ferro resonance. It has been determined through various simulations that the phenomenon is amplified when the transformer is connected in delta and the magnitude of the capacitance value and connecting the main winding of the transformer.*

***Keywords****: Ferro resonance, MATLAB / Simulink, Voltage Transformers, Simulations.*

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## I. Introduction

Having appeared for the first time in the literature in 1920, the term ferro resonancedesignatesallOscillatory phenomena that appear in an electrical circuit that comprises at least: a non-linear inductance (saturable ferromagnetic), a capacitor, a voltage source (generally sinusoidal) and weak losses.

Electrical networks contain numerous saturable inductances (power transformers, medium voltage inductive transformers, parallel reactors), as well as capacitors (cables, long lines, capacitive voltage transformers, series or parallel compensation capacitors, voltage distribution capacitors between circuit breaker cut-off chambers, armored transformation centers). Therefore, networks are susceptible to presenting configurations conducive to the existence of ferro resonance.

The main characteristic of this phenomenon is to present at least two stable permanent regimes. It appears after transients, surges of atmospheric origin, connection or disconnection of transformers or loads, appearance or elimination of defects, work under tension, among others. There is the possibility of abrupt transition from a normal stable state (sinusoidal at the same frequency as the network) to another stable ferro resonant state characterized by strong overvoltage and significant harmonic rates dangerous for equipment.

A practical example of this behavior is the disconnection of a voltage transformer when opening a circuit breaker. The transformer is powered by the capacitance of the breaker breaking chambers: the operation can lead to either a zero voltage at the transformer terminals, or a highly distorted permanent voltage and an amplitude much higher than that of the normal voltage, which it can also affect distribution systems.

To avoid the effects of ferro resonance, it is necessary to understand the phenomenon, predict it, know how to identify it, avoid it or suppress it . Due to its rarity, this phenomenon is not well known and cannot be analyzed or predicted by traditional methodologies.

A distinction between resonance and ferro resonance makes it possible to highlight the particular and sometimes puzzling characteristics of the phenomenon of ferro resonance. Practical examples of electrical power network configurations with risk of ferro resonance make it possible to identify and highlight the variety of potentially dangerous configurations. If doubts about the limit configurations persist when finalizing the design and are unavoidable, a predictive study should be carried out. Numerical analysis and simulation tools such as Simulink, allow alerting the possibility of ferro resonance in a network by simulating the energization or de-energization of three-phase transformers or transformer banks.

In the present work, the indirect analysis method is applied using the MATLAB Simulink tool, which has been chosen for its robustness in the treatment of this type of phenomena. Starting from a base system published by several cases of ferro resonance were simulated and the results were plotted through commands ofscript developed in MATLAB, whose applied methodology is efficient in terms of precision and computational time.

## II. Generalization

### A. Ferro resonance

The fundamental differences of a ferro resonant circuit with respect to a linear resonant circuit are, for a given: the ability to resonate within a large range of capacitance values; the frequency of the voltage waves and currents that may be different from those of the sinusoidal voltage source; and, the existence of several stable permanent regimes for a given configuration and parameter values. One of these regimes isthe normal regimen; the other abnormal regimes are oftendangerous. The regime achieved depends on the initial conditions (electrical charges of the capacitors, residual flux of the material that forms the magnetic circuit of the transformers, the moment of connection, among others).

Ferro resonance is therefore a special case of resonance where a non-linear inductive reactance is present that depends not only on the frequency but on the magnetic flux density in iron core transformers. Inductive reactance is represented by the saturation curve of a magnetic iron core. Theoretically, this non-linear inductance can be represented by twoInductive reactance's given by (1) and (2).

Linear zone = $X_{L\text{- linear}} = \omega L_{\text{linear}}$………(1)

Saturation Zone = $X_{L\text{- Sat}} = \omega L_{\text{Sat}}$………(2)

In Fig. 1 three possible operating points are shown, where point 1 is non-ferro resonant stable, point 2 is ferro resonant stable and point 3 is unstable operation.

It can be seen that the main characteristic of a ferro resonant circuit is that it has at least two stable points,producing a current or voltage jump from one stable operating point to another.

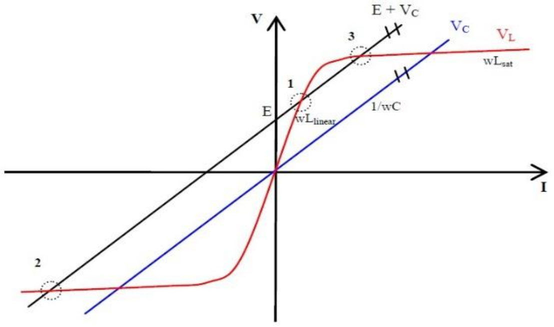


**Figure 1. Graphic solution of the series resonant circuit**

It can be seen that the main characteristic of a ferro resonant circuit is that it has at least two stable points,producing a current or voltage jump from one stable operating point to another.The final operating point will depend on the initial conditions (residual flux, value of capacitance and voltage source, connection time).

In this way, under certain initial conditions, for example, transients ofovervoltage, ferro resonance can arise manifested in oscillating over voltages and overcorrects. Once ferro resonance appears, the system remains in that state, until the source is able to maintain the power supply for the phenomenon.

Fig.2 shows the evolution of the ferro resonant operating point as the value of the voltage source changes, keeping the value of the capacitance constant.

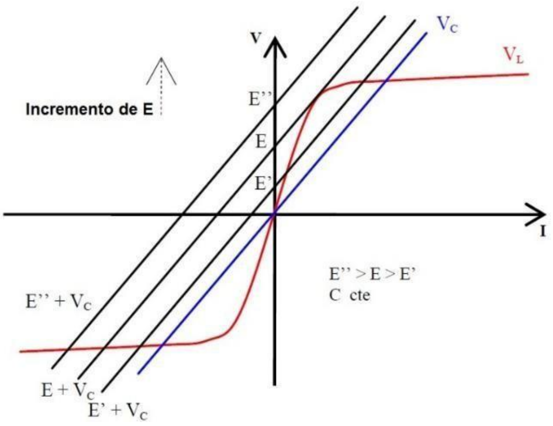


**Fig.2:Evolution of the solution increasing the tension E.**

Similarly, Fig.3 shows the evolution of the ferro resonant operating point as the value of the capacitance changes, keeping the value of the voltage source constant

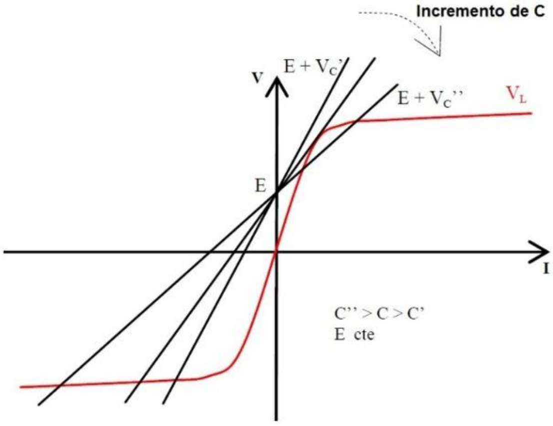


**Fig.3:Evolution of the solution increasing the capacitance C.**

The connection time is also an important factor in ferro resonant analysis and its influence is similar to the effect of the Inrush current on the energization of thetransformer.

### B. Modelofthe Three PhaseTrans-former inSimulink

In Simulink it is possible to simulate electrical machines such as transformers, motors and generators. For the transformer it is possible to simulate core saturation and connect the windings in Y, Y with accessible neutral and Delta.

The leakage inductance and the resistance of each winding can be entered in values per unit (pu) based on the nominal power of the transformer and the nominal voltage of the primary or secondary winding.Figures 4 and 5 show the model of the saturable three- phase transformer with its saturation characteristic.

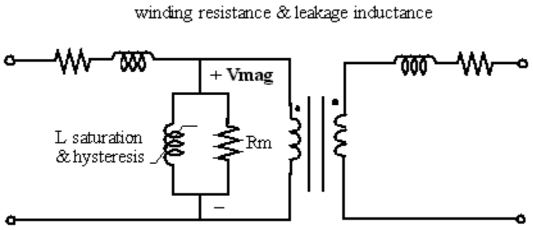
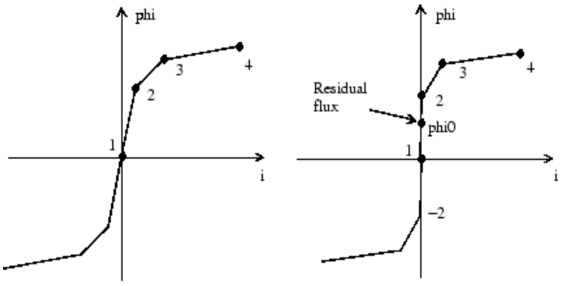


**Fig.4: Model of the Saturable three-phase transformer**



(a) No residual flux can be specified.

(b) A residual flux can be specified between points 2 and −2.

**Fig.5:Three-phase Transformer saturation characteristic**

## III. Design modes

### A. Determination of parameters

As the objective is to simulate and analyse the effect of ferro resonance in a saturable three-phase transformer, the general schematic diagram of Fig.6 is presented.

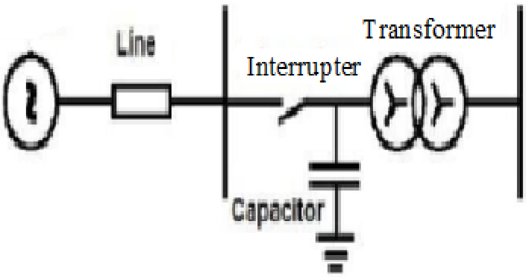


**Fig.6:General Schematic diagram of the system**

The saturation characteristic ofthe transformer is extracted from that provided which is shown in Fig. 7. The saturable three-phase transformer model in Simulink requires that the data of the saturation curve be expressed in pairs of points (magnetizing flux, magnetizing current), so from Fig. 7 a series of sample points reflected in the Table II.

Considering that the nominal voltage of the transformer is 25 kV and its nominal power is 100 MVA, applying (3) and (4) the data are obtained in the representation required by Simulink, which are shown in Table III.

Magnetization Voltage (pu) = $\frac{\frac{v(V)}{25kV}}{2\pi 50Hz}$...(3)

Magnetization Current(pu)= $\frac{i(A)}{\frac{100MVA}{\sqrt{3}*25kVA}}$...(4)

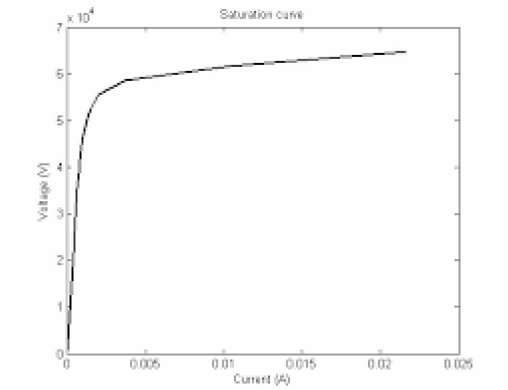


**Fig.7:V-I saturation curve of the three-phase Transformer**

**Table II**
**V-I Saturation curve Points**

| Magnetization Voltage | Magnetization Current |
|---|---|
| 0 | 0.00000 |
| 20000 | 0.00025 |
| 45000 | 0.00100 |
| 55000 | 0.00200 |
| 59000 | 0.00375 |
| 62000 | 0.01000 |
| 64000 | 0.02000 |

**Table III**
**Flux (Φ) –$I_m$Saturation Curve points**

| Magnetizing flux | Magnetization Current |
|---|---|
| 0.00000000 | 0.0000000 |
| 0.00254648 | 1.0825e-7 |
| 0.00572958 | 4.3301e-7 |
| 0.00700282 | 8.6603e-7 |
| 0.00751211 | 1.6238e-6 |
| 0.00789409 | 4.3301e-6 |
| 0.00814873 | 8.6603e-6 |

Tables IV-VII contain the rest of the transformer, generator, line and capacitor parameters, most of which are typical values found in different publications [5].

**Table IV**
**Parameters of Generator**

| Parameter | Value |
|---|---|
| Amplitude | 26000 $V_{rms}$ phase to phase Value |
| Phase | 0 degrees |
| Frequency | 50Hz |

**Table V**
**Line Parameters**

| Parameter | Value |
|---|---|
| Resistance | 0.605 ohms |
| Inductance | 0.0193 H |

**Table VI**
**Parameters of Capacitor**

| Parameter | Value |
|---|---|
| Capacitance | 10 mF |

**Table VII**
**Parameters of Transformer**

| Magnetizing flow | Magnetization Current |
|---|---|
| Primary Winding Connection | Star (y) |
| Secondary Winding Connection | Star (y) |
| Nominal Power | 100 MVA |
| Frequency | 50 Hz |
| Nominal Voltage of the Primary Winding | 25000 Vrms Phase to Phase |
| Resistance of the Primary Winding | 0.5 Ω |
| Inductance of the Primary Winding | 0.0023895 H |
| Nominal Voltage of the Secondary Winding | 25000 $V_{rms}$ phase to phase Value |

| | |
|---|---|
| Resistance of the Secondary Winding [1] | 0 ohms |
| Secondary Winding Inductance [1] | 0 H |
| Magnetization Resistance[2] | 3125.2 Ω |
| Saturation Characteristic | Table III |

**Note**1:[1]Arbitrarily taken values equal to zero (transformer without load)
**Note**2: [2]Arbitrarily large value taken (ideal transformer)

The circuit in the Simulink environment is shown in Fig.8.

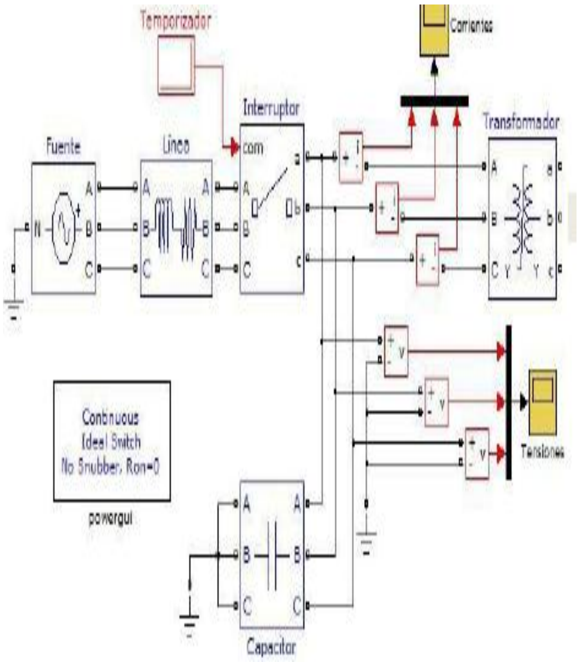


**Fig.8:Assembling components in Simulink**

## B. Component Parameterization

In the present investigation, four (4) study cases are considered to be simulated. In all cases, the assembly of Fig. 8 is used and the components are parameterized according to what is stated in Tables IV-VII, except for the exceptions that distinguish one case from another and that are shown in Table VIII. It should be noted that in all cases, the switch is actuated in two cycles with respect to the energization of the voltage source.

Taking as reference case 1, the capacitances are varied over a wide margin in order to find the optimum value that favours the appearance of the phenomenon of ferro resonance and allows corroborating the influence of the value of capacitance in the phenomenon.

**TABLE VIII**
**Cases Studies**

| Case | Initial state of Switches | Phase Switched | Connection of Transformer |
|---|---|---|---|
| 1 | Open | TO | YY |
| 2 | Open | TO | DY |
| 3 | Closed | C | YY |
| 4 | Closed | C | DY |

## IV. Results

The results of the simulation for each case study are presented below.

**A. Case 1:** Open Switches, Phase A, Connection YY Starting from the capacitance value that appears in the Table

VI, the simulation of the system was made by graphing the currents and voltages in order to take their peak values, which is reflected in Table IX, in it it can be observed that for a capacitance value of 5.3e-4 F, the ferro resonance had the highest positive and negative peak values, taking this value as a reference for the rest of the simulation cases.

**Table IX**

Capacitance and its effects on the tensions and Corrientes

| Capacit--ance F | Positive Peak voltage | Negative Peak Voltage | Positive Peak Current | Negative Peak Current |
|---|---|---|---|---|
| 1.00E-02 | 4620 | - 2970 | 56 | - 28 |
| 1.00E-03 | 40,000 | - 37000 | 118 | - 78 |
| 9.00E-04 | 47582 | - 46427 | 126 | - 86 |
| 8.00E-04 | 58228 | - 59883 | 145 | - 111 |
| 7.00E-04 | 79887 | - 81429 | 170 | - 148 |
| 6.00E-04 | 130750 | -130950 | 243 | - 274 |
| 5.40E-04 | 195640 | -195580 | 388 | - 388 |
| 5.30E-04 | 201870 | -201970 | 397 | - 400 |
| 5.20E-04 | 201450 | -201710 | 398 | - 399 |
| 5.10E-04 | 194880 | -194850 | 388 | - 387 |
| 5.00E-04 | 184390 | -184690 | 369 | - 357 |
| 4.90E-04 | 173630 | -173690 | 3. 4. 5 | - 3. 4. 5 |
| 4.00E-04 | 102360 | -103550 | 187 | - 189 |
| 3.00E-04 | 64074 | - 64660 | 135 | - 126 |
| 1.00E-04 | 32720 | - 28920 | 85 | - 80 |
| 1.00E-05 | 23056 | - 22005 | 77 | - 96 |
| 1.00E-06 | 33388 | - 40371 | 25 | - 29 |
| 1.00E-07 | 21123 | - 21122 | 2 | - 2 |

The schematic diagram representing the present case of study is shown in Fig. 9

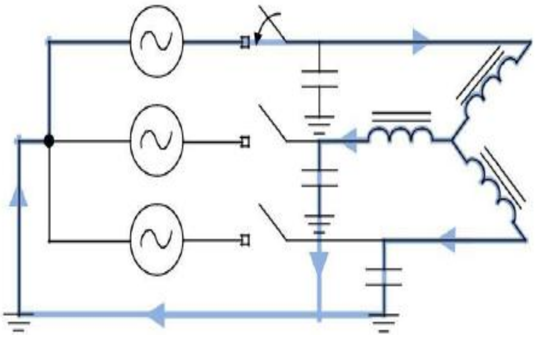


**Fig.9:Diagram: Case 1 (Open Switches, Phase A, Connection YY)**

The current and voltage signals in the present case study are shown in Figs. 10 and 11.

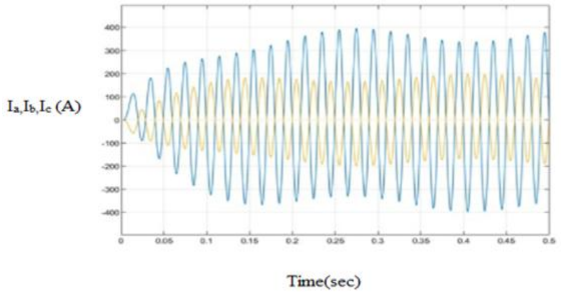


**Figure 10. Currents: Case 1 (Open Switches, Phase A, Connection YY)**

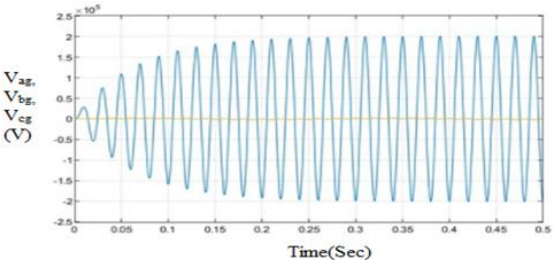


**Figure 11. Voltages: Case 1 (Open Circuit Breakers, Phase A, Connection YY)**

**B. Case 2:** Open Switches, Phase A, Connection DY
The schematic diagram representing the present case study is shown in Fig. 12 .

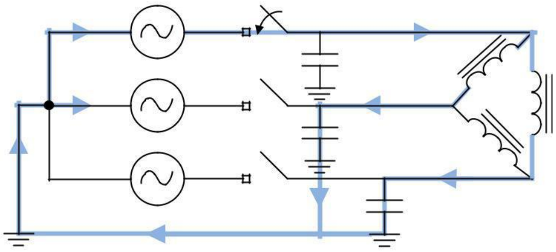


**Figure 12. Diagram: Case 2 (Open Switches, Phase A, Connection DY)**
The current and voltage signals in the present case study are shown in Figs. 13 and 14.

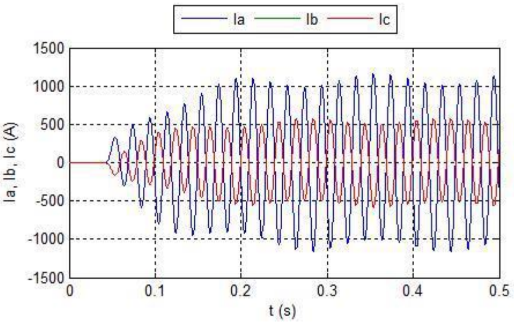


**Figure 13. Currents: Case 2 (Open Switches, Phase A, Connection DY)**

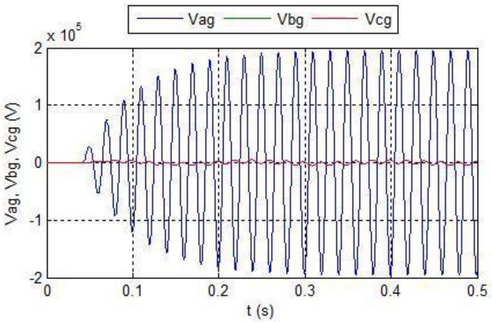


**Figure 14. Voltages: Case 2 (Open Circuit Breakers, Phase A, Connection DY)**

**C. Case 3:** Closed Switches, Phase C, Connection YY
The schematic diagram representing the present case of study is shown in Fig. 15 [9].

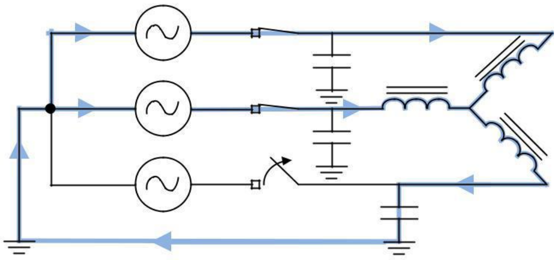


**Figure 15. Diagram: Case 3 (Closed Switches, Phase C, Connection YY)**

The current and voltage signals in the present case study are shown in Figs. 16 and 17.

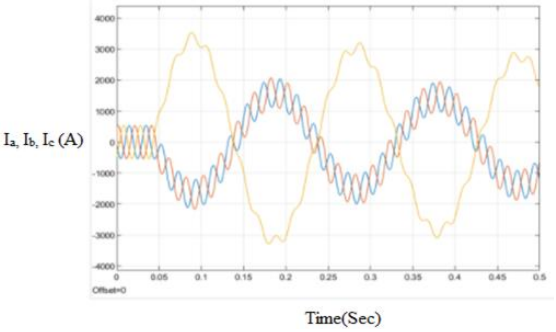


**Figure 16. Currents: Case 3 (Closed Switches, Phase C, Connection YY)**

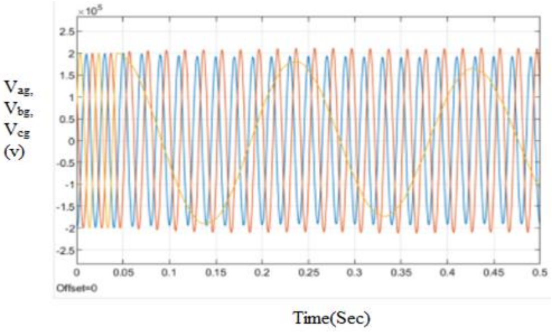


**Figure 17. Voltages: Case 3 (Closed Circuit Breakers, Phase C, Connection YY)**

**D. Case 4:** Switches Closed, Phase C, Connection DY

The schematic diagram representing the present case study is shown in Fig. 18 [9].

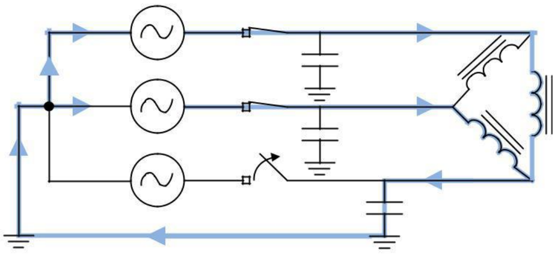


**Figure 18. Diagram: Case 4 (Switches Closed, Phase C, Connection DY)**

The current and voltage signals in the present case study are shown in Figs. 19 and 20.

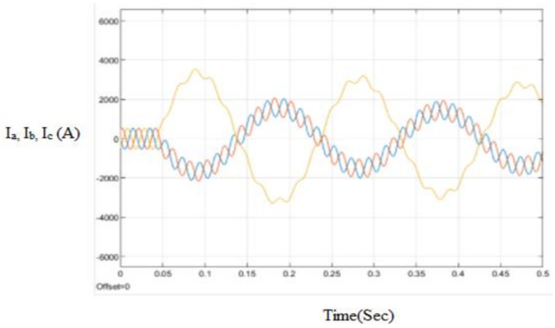


**Figure 19. Currents: Case 4 (Switches Closed, Phase C, Connection DY)**

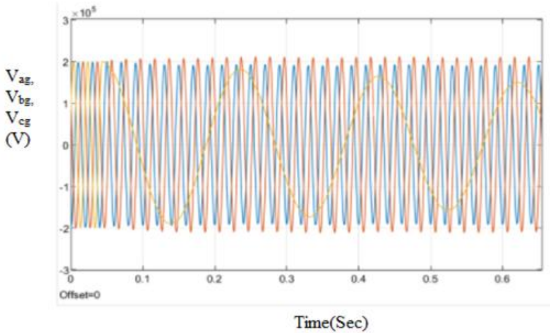


**Figure 20. Voltages: Case 4 (Closed Circuit Breakers, Phase C, Connection DY**

## V. Analysis of Results

As can be seen in Table IX, the variation in capacitance directly affects the magnitude of the overcurrent's and overvoltage's experienced by the transformer under the appearance of the phenomenon of ferro resonance. It is noteworthy that the overvoltage's reached such high levels of several times the nominal voltage of the transformer. It is also observed that at very low or very high values of capacitance the phenomenon of ferro resonance is considerably attenuated, having an optimum point close to 5.30e-4 F, where its effect is magnified. These results are consistent with the proposed ferro resonance theory, where the system solution evolves as the capacitance varies and the final operating point is the consequence of multiple factors, including the value of the capacitance.

In case 1 where the transformer connection is YY, it can be seen in Fig. 10 how the current of phase A is much higher than the currents of phases B and C, which is consistent with the diagram of the case; in Fig. 11 the three phases have voltage despite the fact that only phase A is connected, but due to the magnitude of the latter, they are considerably attenuated. In case 2 where the transformer connection is DY, it can be seen how the flow of currents is similar to case 1 with connection YY, so the graphs of currents (Fig. 13) and voltages (Fig. 14) they are similar but in greater magnitude, that is, the DY connection magnifies the effect of ferro resonance in relation to the YY connection.

In case 3 where the transformer connection is YY, it can be seen in Fig. 16 how the current of phase C is even higher than the currents of phases A and B, which is consistent with the diagram of the case; In Fig. 17 it can be seen that despite phase C being open, there is a voltage that is decreasing and tending to zero. In case 4 where the transformer connection is DY, it can be seen how the flow of the currents is similar to case 3 with the YY connection, so the graphs of the currents (Fig. 19) and voltages (Fig. 20) are similar but to a greater magnitude, that is, the DY connection this time also magnifies the effect of ferro resonance in relation to the YY connection.

In all cases it can be seen that ferro resonance is a phenomenon characterized by overvoltage's and / or sustained overcurrent's of considerable magnitude whose effect depends on a multitude of factors, some of which have been simulated in this article, such as the value of the capacitance and the type of transformer connection, others not considered in the simulation but of equal importance, constitute the instant of commutation of the switches as well as the value of the voltage source.

## VI. Conclusions

The ultimate operating point that is favourable for the emergence of the ferro resonance phenomenon is a result of this variation, and the system's solution changes as the capacitance varies. The worst-case scenario is when the transformer primary connection is in delta, which favours the necessary path for the ferro resonance to occur and causes its effect to be amplified based on the transformer connection.

The monopolar opening event also provides the required path for the ferro resonance to occur regardless of how the transformer's primary winding is connected, with the connection being in delta being the worst case.

With time, ferroresonance in the impacted phase tends to vanish. The occurrence known as ferro resonance is highlighted by oscillating overvoltage’s and over currents of considerable magnitude whose effect depends on the capacitance and the with exion of the transformer and its saturation curve.

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