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STUDY OF FERRORESONANCE FAVORABLE CASES IN ELECTRIC SUBSTATIONS

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Key words: Distribution power system, Ferroresonance, Power transformer, Grading capacitors, Alternative transient program (ATP) software.

Ferroresonance is a phenomenon of complex nature which may be studied profoundly for avoiding it and protect the power equipment with appropriate protective devices when it occurs. The accuracy of the transformer model and the power system's parameters has a direct effect on the prediction of this phenomenon. A distribution network consists of generators, transformers, capacitors, motors and protective devices may undergo a ferroresonance during some operating situations such as the de-energization of a transformer through a grading capacitor of circuit breaker, a transformer accidentally energized in only one or two phases, or transformer with ongoing phase-to-ground fault. These scenarios are simulated using the data taken from Haoud Berkaoui station in Algeria. A simulation with alternative transients program has been conducted; the obtained results are satisfactory.

1. INTRODUCTION

According to the literature, ferroresonance over-voltages were appeared in the distribution systems for the first time in 1900. Many analytical and experimental works have been carried out to explain this phenomenon. This is one of the most difficult and unpredictable problems which occur in power network containing at least the following elements: a non-linear inductance ferromagnetic, capacitor and a voltage source (generally ac) [1, 2].

Some methods have been suggested to be used in this study, which are listed as follows.

1. Practical test: there can give the most realistic observations, but it is limited to the number of tests that can be performed since it may harm the power transformer.
2. Analytical and computational method: this method provides considerable flexibility in most cases, but it can be used in single phase cases for avoiding difficulties that may be arisen in three phase cases.
3. Simulation tool: the most suitable method is to use simulation tools such as Simulink/MATLAB, and alternative transients program (ATP), which allow a grand flexibility for investigating a great number of scenarios and accommodate three phase systems.

In the last method, one of the problems may be encountered is the lack of network parameters. Houdh Berkaoui station has been chosen because it has all required parameters and represents one of ten main hydrocarbons productive zones in Algerian desert. It is installed by Schneider Electric and is powered by 60 kV from the Algerian national network (SONELGAZ). Houd Berkaoui station consists of many substations; one of them is the boosting substation that has been chosen for this case study.

This paper presents the theoretical principles, causes and effects of this phenomenon and it analyzes the simulation results generated using ATP for different situations. Energization and deenergization of the transformer are presented as a critical situation for the emergence of ferroresonance.

2. FERRORESONANCE IDENTIFICATION

Several modes of ferroresonance can be obtained by varying physical and electrical parameters [3]. Some modes may produce very high voltages while others may provide voltages close to the nominal values. This phenomenon is recognized by the following symptoms:

1) Audible noise: it occurs when the iron core is driven into saturation. In fact, the core has a high flux density due to the magneto-striction of the iron and laminations. The ferroresonance can occur when the noise is louder than the normal hum of transformer.

2) Overheating: it is due to stray flux heating in parts of the transformer where the magnetic flux crosses the tank wall and the core is saturated repeatedly which may cause the bubbling of the paint on the top of the tank. The ferroresonance may take place, when the overheating extends to internal connections. This may cause the breakdown of the insulation.

3) Arrester and surge protector failure: it is caused by overheating of the block. In the meantime, the arrester becomes very hot on the phase and thermally runs away upon restoration of full power. The failure is often produced from the arrester housing. Under-oil arresters are less vulnerable to the problems because they can dissipate quickly the heat caused by the ferroresonance current.

4) Flicker: Utility customers often face a problem of a wavering voltage magnitude due to the light bulbs flicker. In some reports, some electronic appliances are very susceptible to the voltages produced by the ferroresonance. The suspected failure mode is unknown.

5) Cable and switching action: It may be difficult to clear arcs when pulling cable elbows if the ferroresonance is developed [2, 4, 5]. Avoidance of the ferroresonance during switching action can be accomplished by dragging the elbows and energizing the unit at the primary terminals. This will produce no external cable capacitance to cause the ferroresonance. A small internal capacitance and small transformer's loss are mostly sufficient to prevent the ferroresonance.

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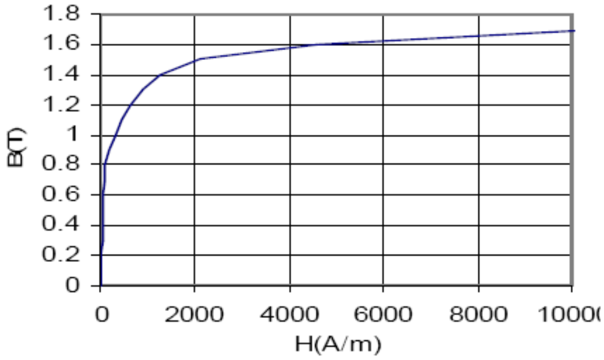


Fig.1 – Magnetization curve of a transformer [6].

3. FERRORESONANCE CHARACTERISTIC

3.1. *B-H* CHARACTERISTIC OF THE TRANSFORMER

The transformer can be represented by a non-linear saturable inductor component associated with a ferroresonant circuit due to the *B-H* characteristic of its iron core. It is characterized by low power loss and hence high efficiency due to an improved construction.

Figure 1 shows the saturation curve of the iron core of a transformer which is made from grain-oriented FeSi sheets. Consequently, the harmonics profile revealed by measurements of industrial transformers shows no sinusoidal working regime; even the supplied voltage is sinusoidal with frequency 50 Hz. The main sources of these periodic no sinusoidal behaviors are the nonlinear load and the magnetic nonlinear material of the transformer core [6]. Because of the nonlinear nature of the transformer characteristic, the behavior of the system is extremely sensitive to the system parameters change and the initial conditions. A change in the system voltage, capacitance or loss may lead to dramatic change in its behavior.

3.2. THE EFFECT OF CAPACITANCE

The system positive sequence shunt capacitance is the balanced capacitive loading of each phase. It includes both phase-to-ground capacitance and phase to phase capacitance [7, 8]. The balanced delta impedance illustrated in Fig.2a can be represented by its equivalent wye connection type. Where, the neutral point of this equivalent circuit is at the ground potential as shown in Fig.2b.

3.3. TRANSFORMER-CAPACITOR INTERACTION

There is a strong relationship between the inductor-capacitor interaction and the ferroresonance.

The system equations describing the behavior of ferroresonant circuits can be solved numerically [9].

However, in the series ferroresonant circuit, it is possible to be solved analytically, and to predict the existence of periodic, fundamental (at the power pulsation ω_0) and n-subharmonic ferroresonance (of pulsation ω_0 /n).

Periodic ferroresonance is impossible if one of the following criteria is verified [8]:

$$\frac{n}{C\omega_0} > \frac{L\omega_0}{n} \tag{1}$$

or,

$$\frac{n}{C\omega_0} < \frac{L_s\omega_0}{n}, \tag{2}$$

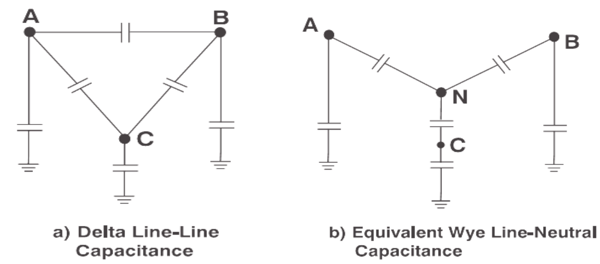
where n is the order of the sub-harmonic (n equals one in the case of fundamental ferroresonance). L is the value of the non-linear inductance in linear unsaturated state. L_s represents the saturated state. L and L_s can be determined from the magnetization curve illustrated in Fig.3.

4. MODELING AND SIMULATION OF THE NETWORK

The ATP version of electromagnetic transients program (EMTP) is an inexpensive, powerful software tool that can be used for the electric distribution grid study because it can provide accurate simulation results [10] which in turn can help the designer of power system to select the appropriate parameters for avoiding the ferroresonance. However, complex algorithms cannot be implemented in this program, MATLAB may be useful [9].

The distribution network consists of two power transformers connected to four main loads; the small city load is connected to a secondary step down transformer as represented in the one-line diagram of Fig. 4 and ATP circuit model of Fig. 5.

The three-phase 25 / 30 MVA distribution transformers with ONAN/ONAF cooling system are the most critical and expensive electric equipment involved in the power delivery process. Consequently, their operation with the electric parameters under the rated values is mandatory for power supply continuity of the electrical installation [11].



. Fig.2 – Capacitances due to the phase's interaction.

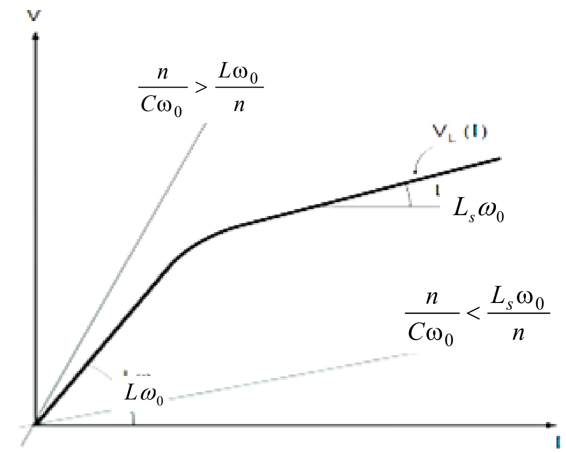


Fig. 3 – Values of *C* incompatible with periodic ferroresonance [3].

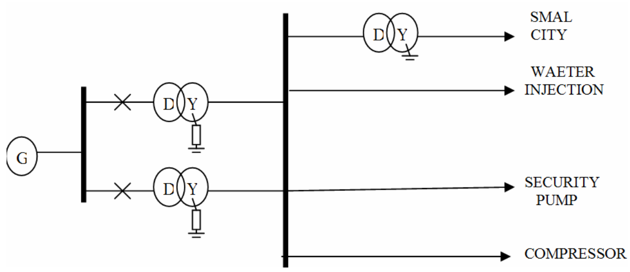


Fig. 4 – The one line diagram representation.

In this study, these transformers are delta-wye connected (30 / 5.85 kV), the main data are given in Table A1 (see Appendix). Parameters of the other components such as transformer 5.5 / 0.4 kV and transmission lines are given in Table A2 and Table A3 respectively.

4.1 EFFECT OF THE GRADING CAPACITANCE ON THE FERRORESONANCE

The circuit breaker (CB) is used for energization and de-energization after closing or opening the circuit. Discharging the CB grading capacitance and capacitive effect of the distribution lines through the transformer will lead to the iron core saturation as illustrated in Fig.6. So, the CB is the responsible device for initiation of the ferroresonance.

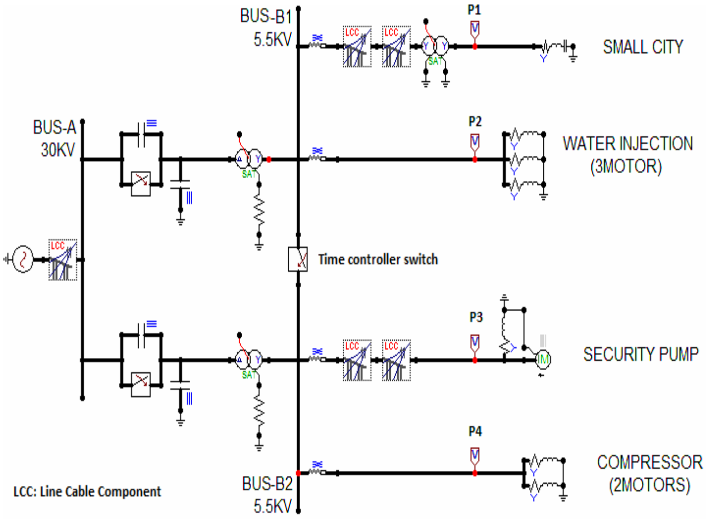


Fig. 5 – ATP circuit model (P1, P2, P3 and P4 are probe points).

For the values of the grading capacitance 2400 pF and the stray capacitance 0.5 µF, at the points P1, P2, P3 and P4 as shown in Fig.5, the simulation results are illustrated in Fig.7. In the graphs (a) and (b) of Fig.7, due to a low value of the grading capacitor (several hundred of pF) which is safe and appropriate for high switching action, the voltage goes down to the zero value directly after opening the circuit breaker. It means that the value of the grading capacitor is not enough to discharge through the stray capacitor which feeds the voltage transformer.

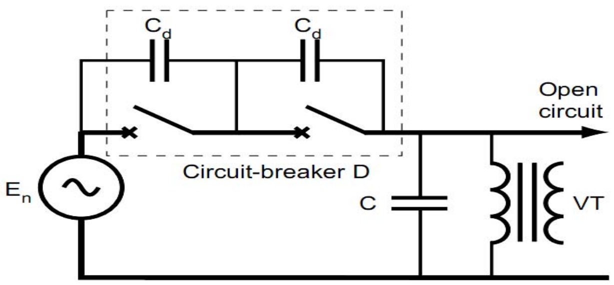


Fig. 6 – Voltage transformer connected in series with an open circuit-breaker [3].

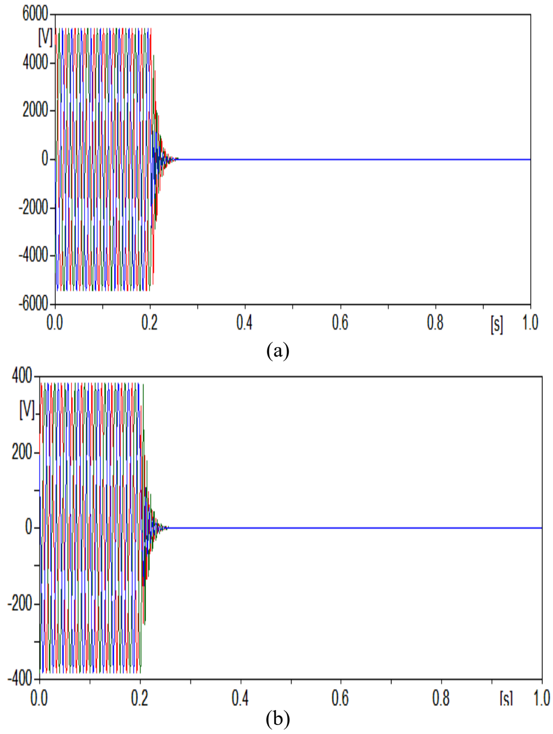


Fig.7 – De-enegization action of the loads: a) points P2, P3 and P4; b) point P1.

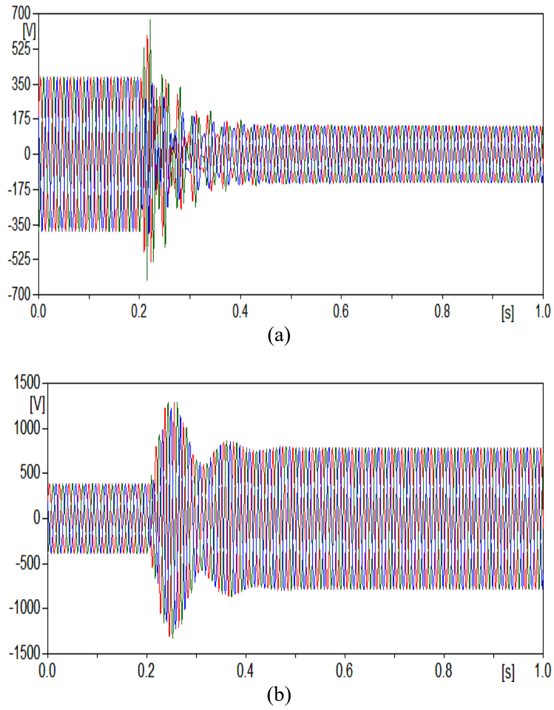
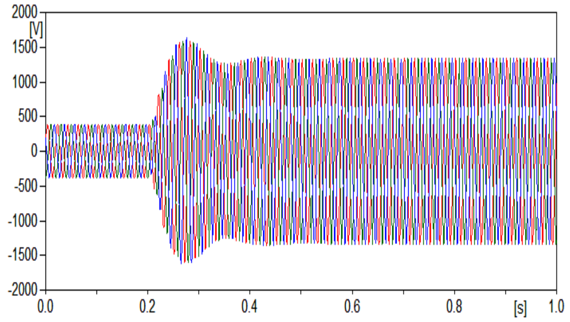


Fig.8 – De-energization of the city with grading capacitor of: a) 0.2 µF; b) 0.5 µF .

In the next simulation test, the grading capacitor will take the following values: 0.2 µF, 0.5 µF, 1.5 µF and 5 µF. The system will be lightly loaded; the point to be considered is P1. The voltage profiles at this point for different grading capacitances are illustrated in Figs. 8 and 9.



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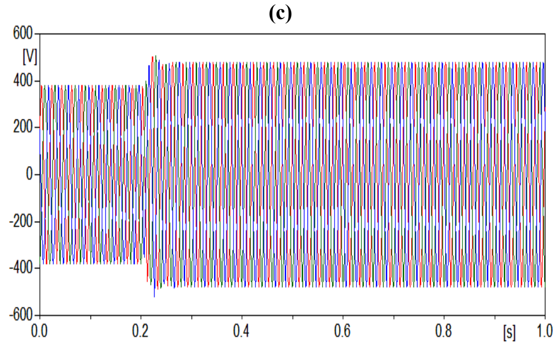


(d)

Fig. 9 – Disconnection of the city with capacitor of: a) 1.5 μF; b) 5 μF.

The variation of the peak value of the voltage at the point P1 with respect of the values of the grading capacitor are given in Table I, the ferroresonance occurs if the saturation reaches 1.5 per unit as shown in Fig. 10. Figure 10 shows that the problem begins at the value of 0.1μF because unwanted overvoltage appears after de-energization, and then it becomes even more with larger values of grading capacitances. From the graph, it can be noted that the range of the grading capacitance 0.45 μF < C < 2 μF must be avoided because it leads to ferroresonance. The best value of grading capacitor which ensures a high speed switching energization or de-energization for the (CB) is: C < 0.01 μF. The other ranges are neither compatible with ferroresonance nor good values for working.

Table I

Variation of the overvoltage with respect of the grading capacitor

Grading capacitance (μF)	<0.01	0.2	0.45	0.5	1	1.5	2	4	>5
Peak voltage (per unit)	0	0.25	1.5	2	3.5	1.95	1.55	1.35	1

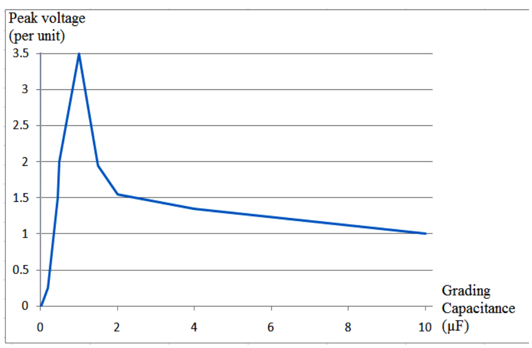


Fig.10 – Effect of the grading capacitor on the ferroresonance.

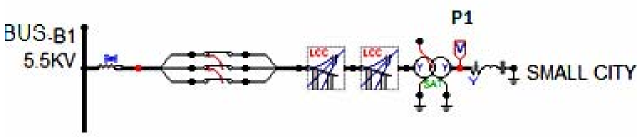


Fig.11 – Circuit energized by one phase using ATP software.

4.2. TRANSFORMER LOSING ONE PHASE

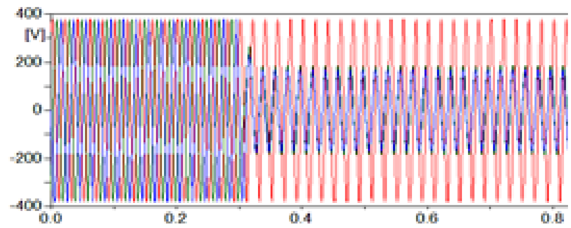
One of the most favorable cases of the ferroresonance is losing one or two phases of the sources due to fuse blow out or circuit breakers contacts failure which are familiar problems in the substation. Many power system configurations for this case may lead to abnormal steady state conditions. The circuit shown in Fig. 11 is set up using ATP software to study the different situations by adjusting the parameters which can control this phenomenon.

The 500 kVA, 5.5 kV/ 0.4 kV transformer of the station has one phase disconnected, this situation may lead to the ferroresonance. In this study, the magnetization curve of the transformer core is divided into two parts, the linear part and the saturation part, each one has a special effect on the ferroresonance.

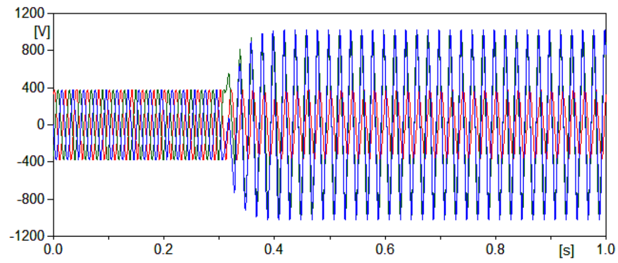
The simulation is done by varying the value of the magnetization resistance R_m, and keeping the core R_0 reluctance fixed and then, by varying the core reluctance, and keeping the magnetization resistance fixed. R_m and R_0 are parameters of the ATP transformer model. The SATTRAFO model is used in this simulation.

4.2.1. EFFECT OF THE MAGNETIZATION CURVE WITH FIXED RELUCTANCE

The circuit of Fig.11 has been simulated during 1 second with one phase switched off at t = 0.3 s; the obtained results are shown in Fig. 12.



(a)



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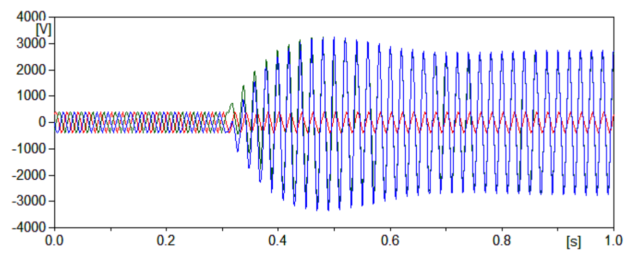


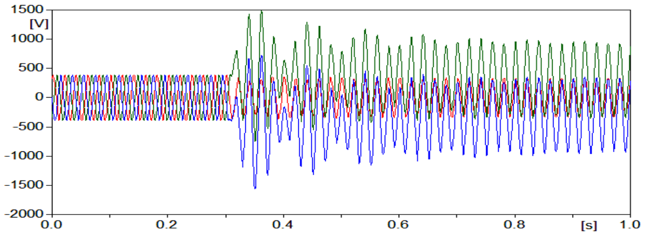
(c)

Fig.12 – The simulation results with (a) R_m = 0.25 MΩ,(b) R_m= 1.5 MΩ, (c) R_m = 7.5 MΩ.

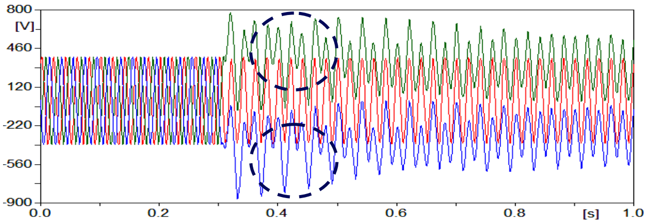
By increasing the value of the resistance, the slope of the non-saturated part of the non-linear magnetizing curve is changed, which causes more overvoltage.

4.2.2. THE EFFECT OF THE SATURATED PART OF THE MAGNETIZATION CURVE:

In order to see the effect of the losses on the system, the magnetizing resistance has been fixed at R_m = 50 MΩ and the iron reluctance takes two values R_{fe}= 4 kΩ and R_{fe} = 2 kΩ [11, 2]. The simulation results are shown in Fig.13.



(a)



(b)

Fig. 13 – Ferroresonance in case of single phasing a) R_m = 50 MΩ , R_{fe} = 4 kΩ; b) R_m = 50 MΩ , R_{fe} = 2 kΩ.

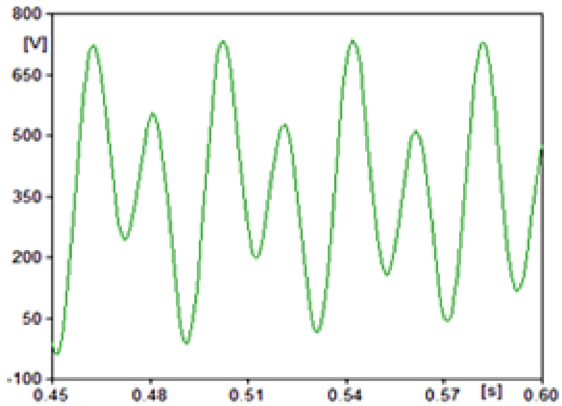


Fig.14 – Sub-harmonic waveform of the ferroresonance [3].

The zoom of Fig. 13a shows the type of the ferroresonance. Thus, Fig. 14 shows a sub-harmonic ferroresonance [12].

After the simulation, the obtained results are given in Table 2. A decrease of the value of the reluctance leads to a decrease of the slope which corresponds to each point in the saturated region of the magnetization curve, and hence a decrease of the saturation degree, due to the introduction of losses. Also in this case study, the simulation results show that the overvoltages even in the lost phases.

Table 2

Variation of the peak voltage with R_m and R_{fe}

R_m	<0.1	0.5	1	1.5	2.5	7.5	12.5	>25	25	25	25	25	25
R_{fe}	8	8	8	8	8	8	8	8	6	4	2	1	<0.5
P.V	<0.2	0.8	1.5	2.35	3.8	5.9	6.57	>7.9	4	2.35	1.5	1.2	≈1
Fr.	-	-	+	+	+	+	+	+	+	+	+	-	-

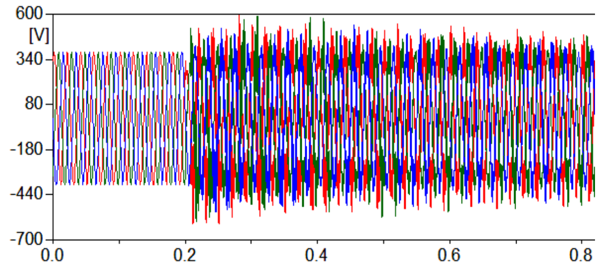
R_m:Magnetizing resistance (MΩ) , *R_{Fe} : Iron core loss* (kΩ)
P.V *: Peak voltage (per unit),* Fr: *Ferroresonance*
(+) Ferroresonance and (-) no ferroresonance

It has been noticed that both the non-linear inductance, which is modeled as reluctance of zero-sequence air-return path for flux, and the iron core losses, which are represented by the value of the magnetizing branch resistance, are parameters which can affect on the transformer function. In addition to the capacitor and the non-linear inductance; ferroresonance can occur only in low losses systems. In this case study, the modes are: fundamental, subharmonic or chaotic. Figure14 shows the sub-harmonic mode after losing one phase.

4.2.3. Y-G/Y-G TRANSFORMERS (MV/LV) WITH GROUND FAULT

The ferroresonance of fundamental mode may occur when both neutrals are isolated in Y-Y unloaded transformer [13, 14]. When a ground fault occurs on the MV side upstream from the substation transformer, it will rise to a high potential. Due to capacitive effect between the primary and secondary, overvoltages may appear on the LV side, and may produce the ferroresonance of the circuit including the capacitances and the magnetizing inductance of the power transformer.

The ATP model is used to study the phenomenon. It has been simulated during one second, and the earth fault of one phase is applied at t = 0.2 s.



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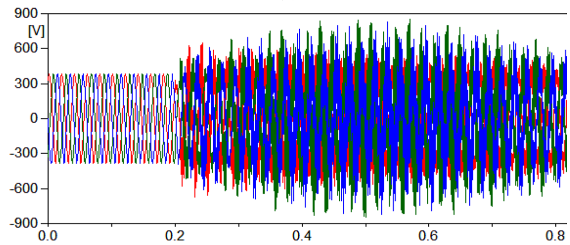

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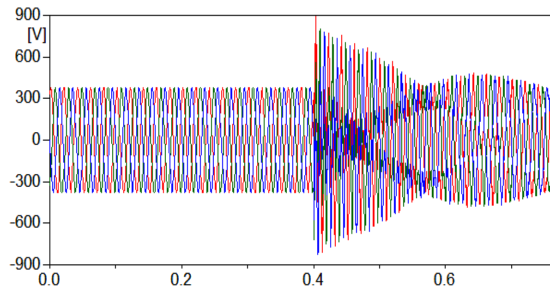

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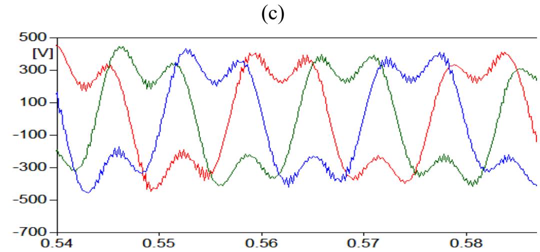

(d)

Fig. 15 – The simulation result at point P1 with zero sequence: a) capacitance = 0.05 μF; b) capacitance = 0.1 μF; c) capacitance = 0.2 μF; d) fundamental waveform mode of ferroresonance in all phases.

The values of the capacitance have been varied. The switch has been closed at t = 0.2 s, the voltage profiles for different values of the capacitance are shown in Fig. 15.

In this simulation, the effect of the zero sequence capacitance on the ferroresonance is studied. The ferroresonance mode causing harmonics in faulty system is shown in Fig.15 (d, zoomed part of the simulation result).

Figure 15a shows that the corresponding degree of saturation is 1.57 per unit which is dangerous. The selected capacitance is a low value that can store a charge, but it has a very high resistance which means no absorbing of extra power; this capacitance is a phase to ground capacitance.

In Fig.15 b, the corresponding degree of saturation is 2.05 per unit and it is so dangerous; the selected value for capacitance holds a great amount of charge and has a high resistance which means no absorbing of extra power; this capacitance is also a phase to ground capacitance.

Figure 15c shows the selected value for the capacitance is high, so it can be a shunt capacitor bank; the corresponding degree of saturation is temporarily 1.60 per unit then it became zero because the resistance of the capacitance is low, so it plays the role as damping resistor. By increasing the capacitance, the overvoltage will disappear. The ferroresonance of three phases can be noticed at the instant of fault but with a decaying fundamental voltage as illustrated in Fig.15.

4. **CONCLUSIONS**

In this case study, it can be concluded that three main situations can lead to the ferroresonance:

1– *Parameters change*: The existing parameters are changed independently and they will satisfy the condition of the ferroresonance. Thus, non linear saturable inductance, which has been estimated in the non-linear characteristic of the transformer by changing the value of the magnetizing resistance;

– A grading capacitance of circuit breaker which can cause this phenomenon,

– Low loss system, it can be seen this in two different cases; first the effect of the iron core loss and second after adding a damping resistor, introduced for eliminating the overvoltage.

2– *Interaction among parameters*: it is the most hidden part of this phenomenon, a little is known about it. Until now, the complete mathematical model that may be used to calculate the overvoltage of the ferroresonance has not yet been developed. The ferroresonance may occur due to the interaction that includes the saturation of the transformer.

3 – Actions that may cause the ferroresonance and can be simulated by ATP, are:

– Switching actions: energization and deenergization are more initiative actions for the ferroresonance because they are daily work and cannot be avoided;

– Faults: less initiative action because it's an accident action like; arcs, short circuits, losing one of the sources phases, circuit breaker failure or fuse blow out.

In the previous studies [15], the most networks undergoing the ferroresonance were 12 kV or more rated, while in this study, the phenomenon appeared even in a 5.5 kV transformer, when all conditions are satisfied. This is a new approach in the ferroresonance study leading researchers to know more in order to design reliable protection system.

APPENDIX

Table A1 – Transformer 30/5.85 kV parameters

low voltage side (No load test)	high voltageside short circuit test	Core data
Voltage = 5.85kV $P_{OC\ Losses}$ = 18 kW	*Voltage* ONAN V_{CC}=11.52 % *Voltage* ONAF V_{CC} =13.83 % P_{CC} = 138 kW	Window height: 1736.7 mm Core height: 2126.5 mm Core material: Trafoperm Core length : 1791 mm Yoke section : 2231.5 mm Leg section : 530 mm Iron section = 1940, 45 mm Saturation curve point B_s=1.75 T

Table A2 – Transformer 5.5/0.4 kV parameters

No load test (low voltage side):	short circuit test (high voltage side):
Voltage = 0.4 kV $P_{OC\ Losses}$ = 0.5 %	*Voltage* V_{CC}=11.52 % P_{CC}= 1.5 %

Table A3 – Transmission lines data parameters

Transmission lines data	Generator data	Voltage transformer
The length L = 0.7 km Cross section A = 93.3 mm^2 R = 0.303 Ω/km X = 0.359 Ω/km Grading capacitor of CB C_g = 2.4 μF Shunt capacitor bank C_s = 0.5 μF	V = 30 kV, I = 103 A, f = 50 Hz, P = 4923 W, cos φ= 0.8	The voltage ratio kV/V= 60/ 100, S = 80 VA

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