Energisation of an Unloaded Transmission Grid as Part of Restoration Process

H. Kuisti[1]

(1) Department of System Engineering, Fingrid Oyj, P.O.Box 530, FIN-00101, Helsinki, Finland (e-mail: harri.kuisti@fingrid.fi)

Abstract –**In the top-down restoration strategy as applied in the Finnish transmission system after a black-out condition the 400 kV grid is energised first. The duration of the restoration process depends on how large parts of the grid can be energised at a time. To analyse this the energisation of the Finnish transmission grid as a whole and in smaller parts was simulated using PSCAD/EMTDC software. The whole grid consists of 4000 km of power lines and of 40 power transformers. An oscillation occurs at the energisation giving rise to overvoltages. A non-harmonic oscillation occurs when energising the whole grid. The attenuation of the oscillation depends on the size of the grid and on the degree of saturation of transformers and consequently on the voltage level in the grid. The attenuation of the oscillation can therefore be ensured by sufficient overcompensation. Due to the non-linearity of the system including many saturable power transformers short time-steps have to be used to get stable results when the oscillation is a sustained one.**

Keywords – restoration, black-out, energisation, oscillation, resonance, transformer saturation, electromagnetic transient analysis, overvoltages, compensation.

I. INTRODUCTION

After a major black-out condition in a transmission system there is an urgent need to restore voltage in the grid to minimize the economic losses. The faster the voltage supply is restored to power stations the better are the chances of avoiding their complete shut-down [1,2]. This has also an impact on the duration of power supply interruption experienced by the end-user of electricity.

The so called top-down restoration strategy is applied in the Finnish transmission grid. It involves the energisation of large parts of the 400 kV grid in an unloaded state, before any generators and loads are connected to it. The process is simplified and speeded up, if large sections of grid can be energised at the same time. This has been mentioned e.g. in the reference [3], but so far no theoretical or practical limits for the allowable size of the grid section energised at a time have been presented in the literature.

The purpose of the study reported in this paper was to investigate the phenomena encountered when large parts of an unloaded grid are energised. A model of the whole Finnish 400 kV grid was therefore built using the PSCAD/EMTDC software.

It was observed, that a potentially sustained non-harmonic oscillation may appear when energising the whole grid at a time. The oscillation resembles that related to a ferroresonance in smaller systems.

When simulating unlinear systems like a transmission grid with saturable transformers the numerical integration algorithms based on the stepwise linearisation of the system are bound to introduce error. The consequences of this are discussed briefly in the chapter dealing with the simulation results.

A concept for a safe and fast restoration strategy is outlined as part of the conclusions.

II. THE MODEL

The power lines and the power transformers the most important components in the simulation model of an unloaded transmission grid.

A. Power Lines

A frequency dependent power line model based on the formulas presented in the references [4,5] is used in the PSCAD/EMTDC software. The performance of the model was compared to the measurement data available. The match between the simulations and test results was satisfactory in terms of the the skin-effect and the attenuation of the modal components.

It turned out, that not even considerable changes in line constants had any significant impact on the results obtained when simulating the energisation of an unloaded grid. The unlinear behaviour of the saturable power transformers had a much higher influence.

B. *Transformers*

The saturation behaviour of power transformer models is crucial to the trustworthiness of results when simulating the energisation of lines ended with transformers. The best match between the results of transformer energisation tests and the simulation results was obtained by building the three-phase model out of single-phase umec models of PSCAD/EMTDC. The deviation in terms of inrush current peaks was 10-20 % at the maximum.

In Finland the shunt reactors of the 400 kV transmission grid are located in the delta-connected medium voltage tertiary windings of power transformers. These were modelled by ideal inductances, since they are non-saturable air-core reactors.

A typical rating of the YNynd11-connected five-leg transformers is 400/400/125 MVA and a typical shunt reactor size is 60 MVAr in the Finnish 400 kV grid.

III. THE SIMULATION RESULTS

When simulating the energisation of the grid, the following observations were made.

A. Non-Harmonic Oscillation

When energising a grid consisting of appr. 4000 km of 400 kV lines and of 40 power transformers, a non-harmonic oscillation (see figure 1) involving transformer saturation throughout the grid appears according to simulations. The oscillation gives rise to overvoltages which do not exceed the insulation levels but which can cause overheating of transformers and metal-oxide varistors (MOV). One interesting feature of the oscillation is, that it appears to be potentially sustained even when the steady-state fundamental frequency voltage at the transformers is lower than their saturation voltage.

There appears to be a critical length rather than size of grid above which a sustained non-harmonic oscillation becomes possible. If the line length of the grid as measured from the source to the farthest end of the grid is more than or equal to 1000-1100 km, a non-harmonic sustained oscillation may occur. If the length is less than that, no sustained oscillations appear according to simulations provided that the steady-state voltages do not exceed the saturation limits of transformers.

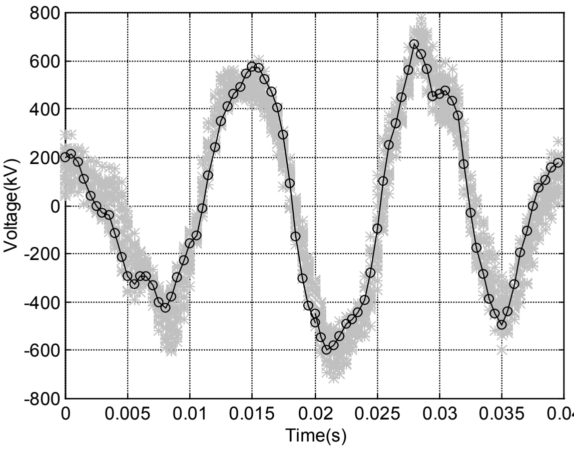

Fig. 1 A sustained non-harmonic oscillation. The phase voltage values simulated over one second and marked with '*' form a gray area, inside which the instantaneus values over the last 40 ms cycle are seen as a solid line marked with 'o'.

Another feature of the non-harmonic oscillation is that its sustainability has a certain probability, when the oscillation is in the border-zone between an attenuating and a sustained oscillation. One set of circuit breaker closing instants may lead to an attenuating oscillation whereas another one gives a sustained oscillation. Likewise a small increase of voltage level of the feeding source may turn a relatively fast attenuating oscillation to a sustained one.

The time required for the simulation of one energisation of a large grid is too long for a high number of random runs to be feasible when using a common desk-top computer. The statistical nature of the sustainability of the non-harmonic resonance can however be demonstrated by varying the closing instants of circuit breakers systematically by an increment of e.g. 0.5 ms.

A simple indicator for the attenuation or sustainability of the oscillation is needed, since visual inspection is not practical. In the following example the integral of the absolute value of the zero sequence current of one transformer is used as the indicator.

If the oscillation attenuates fast, so does the zero sequence current resulting from the saturation of the transformer, which leads to low values of the integral. In the case of a sustained oscillation even the zero sequence current is sustained and high values of the integral are obtained. The integrals have a probability distribution of the type shown in the figure 2, when the risk of a sustained oscillation is high (in the case of figure 2 appr. 80 %).

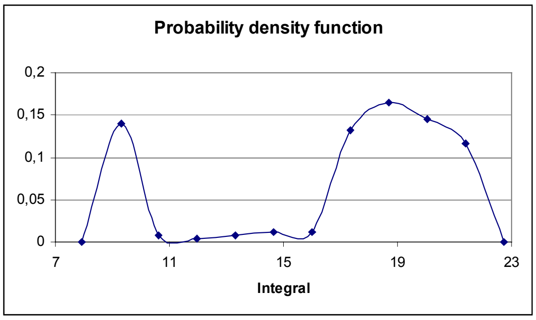

Fig. 2 An example probability distribution of the integral used to indicate, whether the oscillation attenuates or not. The higher values of integral mean a sustained oscillation.

When the grid is sufficiently overcompensated and the voltage level in the energised grid low, the non-harmonic oscillation decays fast, as seen in the figure 3. The grid is the same as in the case of figure 1. Only the number of shunt reactors in use is higher giving the degree of compensation of 120 %.

A relatively strong feeding source has been used in the simulation model (positive sequence: $\underline{Z}_1 = 12\Omega\angle 87°$ and zero sequence: $\underline{Z}_0 = 11\Omega\angle 85°$), which results in the worst case in terms of transformer saturation. When higher equivalent source impedances are used, the non-harmonic oscillation decays faster.

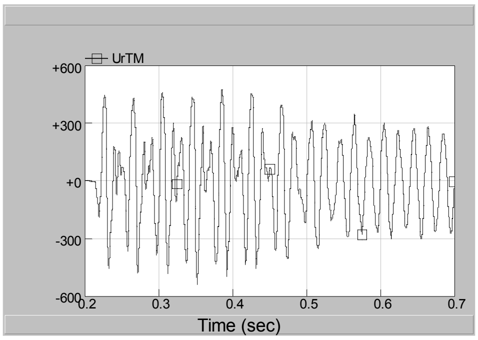

Fig. 3 One phase voltage during an attenuating non-harmonic oscillation.

B. Numerical Issues

Numerical problems are encountered when simulating a large grid with a high degree of unlinearity in the form of saturable power transformers. The simulation time-step has to be the shorter the more severe the saturation of transformers is to get sufficiently stable results. When the non-harmonic oscillation is attenuating fast due to slight saturation of transformers the simulation time-step is allowed to be 1-2 decades longer than when simulating a sustained oscillation involving more severe saturation.

The impact of the simulation time-step is illustrated by the following figure representing one phase voltage at one node of the grid during a sustained oscillation. The actual waveforms differ from each other the more the longer time has elapsed after the energisation. The overall pattern of the waveform characterised by the fluctuating amplitude is however the same regardless of the choice of time-step.

The small differences in the waveforms result from the highly unlinear behaviour of saturable power transformers. When the oscillation is at the brink of being a sustained one, the choice of time-step may therefore determine, whether the simulated oscillation attenuates or not.

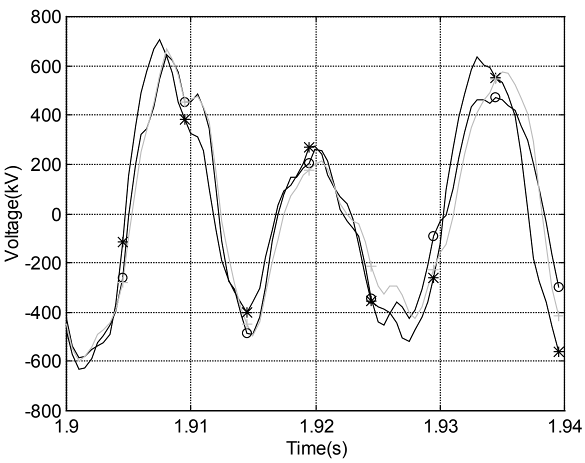

Fig. 4 The dependence of voltage waveforms on the simulation time-step. Time-steps: '*': 20 µs, 'o': 0.5 µs and '+': 0.1 µs. The energisation took place at t = 0.2 s.

IV. ENERGISATION OF AN UNLOADED GRID

Theoretical and practical issues related to the energisation of an unloaded grid are discussed in more detail in the following sections.

A. The Non-Harmonic Oscillation as a Phenomenon

The appearance of a non-harmonic voltage component in a long grid is analogous to that of a harmonic one in a shorter grid or line. In the case of a harmonic resonance the current injection from saturated transformers produce harmonic components of voltage, since the driving point impedance of the grid as seen from the transformer is high at one of the harmonic frequencies [6,7]. In a long unloaded grid one of the local maximums of the driving point impedance may occur at a non-harmonic frequency between 50 and 100 Hz (see figure 5), which can lead to a non-harmonic voltage component.

In the example grid the driving-point impedance is high at appr. 70 Hz throughout the grid (see figure 5). It is shown in the figure 6, how the general pattern of the simulated voltage shown in the figure 1 can be produced by the superposition of voltage components of frequencies of 50 and 70 Hz. Since the energising voltage has a cycle of 20 ms, the transformer current injection and the resulting non-harmonic voltage component are roughly synchronised to that cycle resulting in a basic cycle of 40 ms (see figure 1).

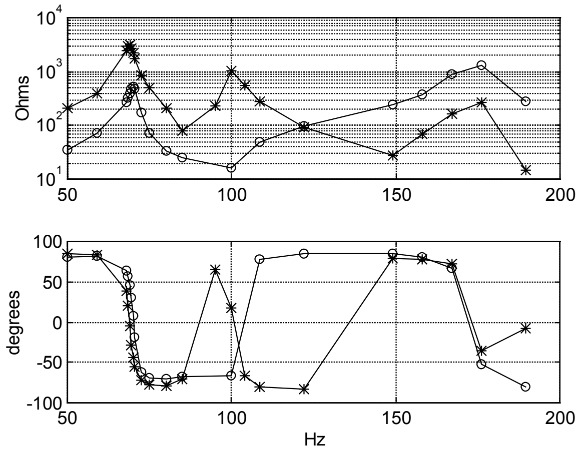

Fig. 5 The driving point impedance as the function of frequency at two nodes of the large example grid. 'o' : Near the feeding point, '*' : At the farthest end of the grid.

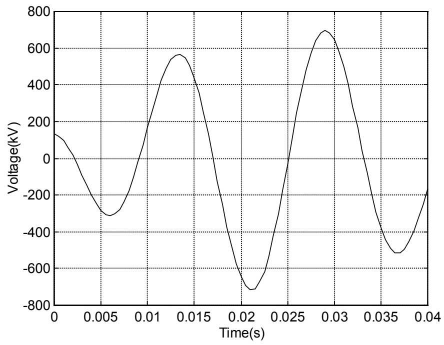

Fig. 6 The voltage calculated for comparison by $u(t) = [300\sin(100\pi t - 1.67) + 420\cos(140\pi t)]kV$.

B. Comparing the Non-Harmonic Oscillation to Ferro-resonance

The observed non-harmonic oscillation resembles the subharmonic mode of ferroresonance [11]. A ferroresonance can occur in small systems consisting of saturable lightly loaded transformers like voltage transformers and capacitances formed for instance by sections of cable. Ferroresonance has been observed also in a system consisting of an EHV line together with a power transformer [12].

The basic cycle of the subharmonic mode is nT, in which T is the fundamental cycle and n is usually an odd integer [11]. In the non-harmonic oscillation reported in this paper the integer n is however an even one, 2.

A ferroresonance is a complicated phenomenon, in which the same system may have several different steady-state modes and even chaotic modes of oscillation depending on the initial conditions. The non-harmonic oscillation related to the energisation of a large grid does not have this feature. The initial conditions determined by the closing instants of the circuit breaker poles and by the voltage level may however determine, whether the oscillation attenuates or not.

C. Can a Non-Harmonic Oscillation be a Sustained One ?

A harmonic oscillation can decay very slowly according to literature [7,8,9,10]. An absolutely sustained oscillation however does not appear as long as the steady-state voltage levels at the transformers do not exceed their saturation voltages. The harmonic oscillation appears only as long as the transformer is saturated and able to inject harmonic currents to the grid. Due to resistances between the energised transformers and the feeding source the inrush currents will eventually die away and the harmonic components of voltage as well.

The non-harmonic oscillation appears to differ from the harmonic one in this respect. According to the simulations reported in this paper a non-harmonic oscillation can be a sustained one even though the steady-state voltage level is clearly below the saturation voltages of transformers and there is some resistance in the power lines and in the transformers of the grid. A possible explanation is as follows.

Let us examine an equivalent circuit of a long grid (see figure 7). The series resistances and inductances of lines have been combined with those of the source to form R and L_1. C and L_2 represent the equivalent shunt capacitances and inductances of the whole grid by assuming that they are all connected in parallel. Since the series impedances between a line capacitance and the nearby shunt inductances are usually small, it is a reasonable simplification not to have series impedances between C and L_2.

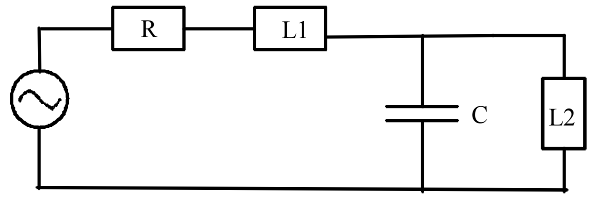

Fig. 7. An equivalent circuit of the grid.

The longer the grid is the bigger become R and L_1 as seen from the farthest nodes of the grid. The oscillation therefore takes place increasingly in the circuit formed by C and L_2. The oscillation frequency therefore gets closer to the fundamental frequency as the length of the grid is increased, if the degree of shunt reactor compensation is 100 %. Another consequence is that the losses related to the oscillation get smaller.

The energy related to the oscillation is proportional to the capacitive energy of the lines of the grid, because the oscillation is basically a process in which the capacitive energy is successively turned to an inductive form and back to the capacitive one. The longer the grid is the higher is then the oscillation energy. It follows, that the ratio oscillation energy/losses increase as the length of the grid is increased.

This effect was examined by simulating a simple radial line along which there were only seven transformers. The transformer models were non-saturable to study the oscillation only.

The results are shown in the figure 8. The simulated voltages had the same steady-state values, since the three cases were obtained by modifying all line lengths by the same factor and by increasing the shunt reactor capacity accordingly. It is seen, that the longer the grid is, the higher the maximum voltage peak-values related to the energisation are and the more slowly does the oscillation involving overvoltages attenuate.

New oscillation energy is injected to the grid during the period of high amplitude of voltage involving transformer saturation. The injection of new energy depends on the voltage level of the grid in relation to the saturation limits of transformers, but also on the equivalent impedance of the feeding source. The smaller it is the higher can the injected energy be.

As the length of the grid exceeds a certain limit the losses may decrease so much that they become equal to the injected new energy, which leads to a sustained oscillation.

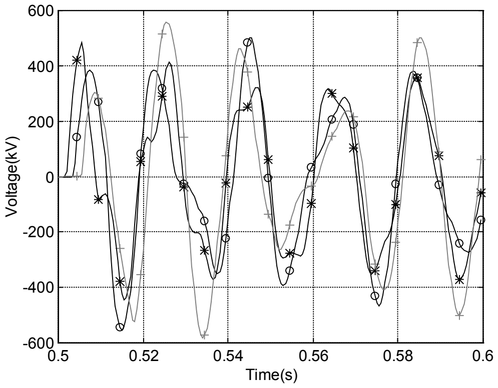

Fig. 8. One phase voltage at the end of the grid, when the grid is energised at a time. The length of the grid is '*': 500 km, 'o': 1000 km and '+': 1500 km. The transformers are non-saturable to study the impact of the grid length only.

A sustained oscillation of this kind obviously would not violate the laws of physics, since the continuous injection of new energy is involved. Oscillations related to a ferro-resonance of a smaller system can be sustained if losses are sufficiently low [11,12]. It is however hard to prove analytically the existence of a sustained non-harmonic oscillation in a complex grid.

Since an analytical proof for the existence of a sustained or very slowly attenuating non-harmonic oscillation has not been presented, it cannot be ruled out that the apparent sustainability of the simulated oscillation could have its origin in numerical problems related to the simulation of unlinear systems. This is however unlikely, because the same pattern of voltage is obtained by different simulation time-steps. Numerical instability usually manifests itself by producing highly different results with different time-steps [13].

Regardless of the answer to the academic question of absolute sustainability of a non-harmonic oscillation it can be concluded that the oscillation can be a sustained one from practical point of view according to simulations. Such an oscillation involves so high overvoltages that it cannot be allowed to start and decay at its own pace.

D. Overcompensation

According to the simulation results, the non-harmonic oscillation attenuates fast if the voltage level and consequently the saturation of transformers is reduced by sufficient overcompensation in the energised grid.

In the Finnish transmission grid there is a sufficient shunt reactor capacity to compensate for the reactive power produced by all power lines. Since there is a number of redundant lines not needed to energise all 400 kV stations, it is possible to arrange a considerable degree of overcompensation by leaving some of the lines out of the energised section of grid. In this way it is possible to keep the voltage level and the degree of saturation of power transformers sufficiently low to guarantee the attenuation of the non-harmonic oscillation.

The low voltage level in the overcompensated grid will lead to the switching off of some shunt reactors which may raise the voltage level so much, that some shunt reactors are subsequently switched on. This may lead to the so called hunting phenomenon in which shunt reactors are switched in turn on and off [14]. This has to be prevented by disabling temporarily the control devices of shunt reactors.

The voltage level has to be raised after the energisation by disconnecting some shunt reactors or by taking more power lines into use, before generators or loads can be connected to the grid.

E. Equivalent Source Impedance

According to the simulation results the non-harmonic oscillation attenuates faster with higher equivalent source impedances. This is understandable, since a higher equivalent source impedance limits transformer inrush currents.

If the equivalent impedance can be increased without weakening the feeding grid in terms of dynamic and voltage stability, it is beneficial to do so. One way of doing this could be to use only one line between the feeding grid and the energised one. It is also beneficial to by-pass all series capacitors on the interconnecting lines and on the lines of the energised grid, because even this increases the equivalent source impedance as seen from the transformers.

V. CONCLUSIONS

The following conclusions can be made based on the simulation results and on the analysis presented in the chapter IV.

A.How Large an Unloaded Grid can be energised at a Time ?

A sustained or slowly attenuating non-harmonic oscillation involving overvoltages may appear, when a large unloaded transmission grid is energised at a time. The oscillation is kept up by current injection from saturable transformers. The oscillation therefore attenuates, if the saturation of transformers is reduced by decreasing the voltage level in the energised grid.

The voltage level depends on the degree of shunt reactor compensation. If overcompensation is possible either by disconnecting redundant lines or by a surplus of shunt reactor capacity, then fast attenuation of the non-harmonic oscillation can be ensured even for a 1000-1100 km long grid with a total line length of 3000 km and with 30 power transformers.

If sufficient overcompensation cannot be applied, then the end-to-end length of the unloaded grid should be less than 1000 km to avoid the potentially sustained non-harmonic oscillation.

B. The Proposed Concept of Energisation

It is assumed here that the feeding source is able to feed the reactive power demand of the overcompensated unloaded grid, that there are enough shunt reactors in the grid to facilitate the required degree of overcompensation and that the end-to-end line length of the grid does not exceed 1000-1100 km. The following steps can then be taken to energise a grid in a safe and fast manner.

1) All shunt reactors are taken into use.
2) Transformers without shunt reactors are disconnected from the grid to be energised.
3) Lines not necessary for the energisation of all stations are disconnected. The configuration giving smallest possible total line length is chosen. Redundant lines are disconnected also in the feeding grid to increase the equivalent source impedance.
4) Series capacitors are by-passed to increase the impedance between transformers and the source and to decrease the currents of saturated transformers.
5) Control devices of shunt reactors are disabled temporarily to prevent the hunting phenomenon.
6) The grid is energised in 1-3 parts. No generators or loads are connected to the grid between the successive energisations.
7) When the whole grid has been energised, the voltage is increased to the nominal level by disconnecting shunt reactors or by taking lines into use.

REFERENCES

[1] E. Mariani, F. Mastroianni, V. Romano, “Field experiences in reenergisation of electrical networks from thermal and hydro units,” IEEE Trans. Power App. and Syst., Vol. PAS-103, No 7, pp. 1707-1713, 1984.
[2] E. Agneholm, “The Restoration Process following a Major Breakdown in a Power System,” Technical Report, Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 1996, Licentiate thesis, no. 230 L.
[3] M.M. Adibi, R.W. Alexander, D.P. Milanicz, “Energizing high and extra-high voltage lines during restoration,” IEEE Transactions on Power Systems., Vol. 14, No 3, pp. 1121-1126, 1999.
[4] L.M. Wedepohl, D.J. Wilcox, “Transient analysis of underground power-transmission systems, System-model and wave-propagation characteristics,” Proc. IEE, Vol. 120, No 2, pp. 253-260, 1973.
[5] A. Deri, G. Tevan, A. Semlyen, A. Castanheira, “The complex ground return plane, A simplified model for homogenous and multi-layer earth return,” IEEE Transactions on Power Apparatus and Systems., Vol. PAS-100, No 8, pp. 3686-3693, 1981.
[6] G. Sybille, M.M. Gavrilovic, J. Belanger, V.Q. Do, “Transformer saturation effects on EHV system overvoltages,” IEEE Transactions on Power Apparatus and Systems., Vol. PAS-104, No 3, pp. 671-680, 1985.
[7] D. Lindenmeyer, H.W. Dommel, A. Moshref, P. Kundur, “Analysis and Control of Harmonic Overvoltages during System Restoration,” IPST '99, International Conference on Power Systems Transients, June 20-24, 1999, Budapest, Hungary. pp. 635-640.
[8] J. Kattelus, “A resonance phenomenon observed in the 400 kV system,” Offprint from SAHKÖ-Electricity in Finland 38 (1965), No. 4, pp. 137-140.
[9] M.M. Adibi, R.W. Alexander, B. Avramovic, “Overvoltage Control During Restoration,” IEEE Transactions on Power Systems., Vol. 7, No 4, pp. 1464-1470, 1992.
[10] D. Lindenmeyer, T. Niimura, H.W. Dommel, A. Moshref, P. Kundur, “Prony analysis of electromagnetic transients for automated system restoration planning,” IPEC '99, International Power Engineering Conference, May 24-26, 1999, Singapore, pp. 804-809.
[11] P. Ferracci, "Ferroresonance", Cahier Technique Schneider n° 190, http://www.schneiderelectric.com, 1998, 30 p.
[12] E.J. Dolan, D.A. Gillies, E.W. Kimbark, "Ferroresonance in a transformer switched with an EHV line", IEEE Power Apparatus and Systems, 1972, pp. 1273-1280.
[13] X. Chen, “Negative Inductance and Numerical Instability of the Saturable Transformer Component in EMTP,” IEEE Transactions on Power Delivery., Vol. 15, No 4, Oct. 2000, pp. 1199-1204.
[14] E. Agneholm, J.E. Daalder, “Shunt reactor behaviour during power system restoration,” International Symposium on Modern Electric Power Systems, Wroclaw, Poland, 1996, pp. 154-161.