Ferroresonance Studies
in
Malaysian Utility's Distribution Network

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Abstract---- **In a power distribution system having long radial cable fed lightly loaded transformers provided with fuse protection at the tap off point, ferroresonance is a common phenomenon. Based on the recent studies carried out on a Malaysian utility's distribution network, the paper shows that to diagnose existence of ferroresonance, it is essential to check presence of overvoltages as well as the presence of multiplicity in periodicity through some kind of frequency spectrum analysis. Few cases with their configuration and performance as obtained through EMTDC simulation are also presented.**

Index Terms—Bifurcation, Ferroresonance, Distribution System, Computer aided analysis

I. INTRODUCTION

Ferroresonance generally refers to nonlinear oscillations in power systems involving the excitation of a nonlinear inductance of a transformer core with a capacitance in series namely capacitance of its feeding circuit. Several overvoltage incidents occurred in one of the Malaysia's largest electric utility's distribution network, resulting in damage to both utility's equipment as well as customer appliances. While investigating the causes of overvoltages with a view to identify mitigation options, it was found steady state overvoltages alone do not lead to identification of remedial measures. To verify existence of ferroresonance if any, auxiliary tests need to be carried out to recognize presence of multiplicity in periodicity, a typical feature of ferroresonance [1].

II. FERRORESONANCE SYMPTOMS

Disturbance due to ferroresonance is a common phenomenon in electric power distribution system operation. Depending on circuit conditions, its effect may be a random overvoltage that could be either a short transient for few cycle, a continuous overvoltage or even a jump resonance demonstrated by a sudden jump of voltage or current from one stable operating state to another one i.e., it is characterized by the possible existence of several stable states, besides the normal steady state, that induce dangerous over-currents and overvoltages.

It causes both phase-to-phase and phase-to-ground high sustained oscillating overvoltages and overcurrents with sustained levels of distortion to the current and voltage waveforms, leading to transformer heating together with excessively loud noise due to magnetostriction, electrical equipment damage, thermal or insulation breakdown and misoperation of the protective devices.

In this phenomenon voltage and current relationship is dependent on:

- system voltage magnitude & frequency,
- initial magnetic flux condition of the transformer iron core i.e. extent of loading,
- capacitance of the circuit, feeding the transformer primary,
- point on wave of initial switching,
- the total losses in the ferroresonant circuit.

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III. CIRCUIT CONDITIONS

A distribution system may have characteristic features such as, a low short circuit level power supply point interfacing a long overhead line or a cable feeding a delta or floating wye connected primary of a transformer serving a varying load, a three phase isolator with protective fuse on its each phase both at the tap-off point and the point immediately preceding the pad mounted transformer primary. To minimize the distribution system losses the current trend has been to provide low loss power transformers. A phase-to-earth fault is usual in a distribution system, which often leads to a blown fuse on the faulty phase only. This results in a long radial feeder connected to a delta or an ungrounded star connected transformer with blown fuse on one of the phases at the feeding point. Additionally, if the transformer happens to be lightly loaded, ferroresonance may appear.

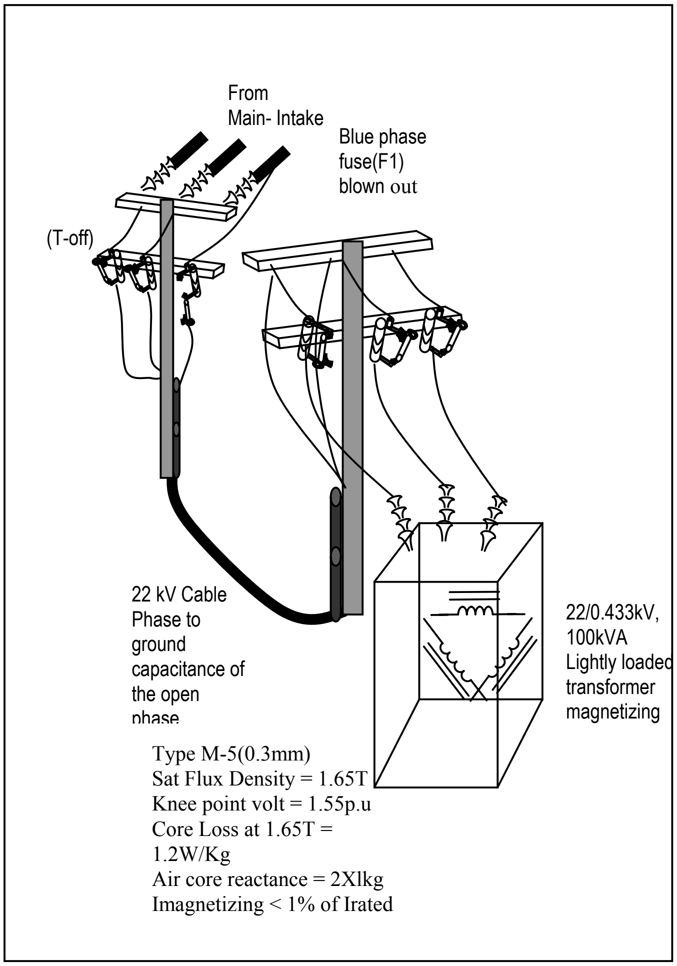

Figure 1: Distribution Circuit setup

IV. MECHANISM OF FERRORESONANCE

A distribution transformer's ferromagnetic core exhibits two important properties, saturation and hysteresis, both of which introduce nonlinearity. The saturation point is characterized by the sudden change in slope of the core's current-flux density curve, implying inductance is different in the two regions of the curve on either side of the knee point. A change in the operating point from linear region of the curve to the saturated region will see an appreciable and sudden change of inductance. The hysteresis comes in because of the loop form of the current- flux density curve, wherein the lower portion of the loop is traversed during forward increment in the core excitation current and the upper portion is traversed while the excitation is decreased. It is important to mention here that during light loading regime in a transformer, possibility of core saturation is more. Since the iron clad inductance in the transformer is saturable and the voltage across it is a function of operating frequency ω and the current, i.e. $f(I)$, the voltage across it may be expressed as $V_L = \omega f(I)$. The distribution system also has circuit capacitances in the form of phase-to-phase and phase-to-ground capacitances of the cable feeding the transformer. A blown fuse condition on one of the phases results in cable backfeed by the voltage induced in the open phase due to the magnetic coupling between phase windings in the transformer. The emerging configuration can be visualized as a resonant circuit. The inductance in this circuit is nonlinear in nature, due to the core saturation & hysteresis. The voltage across the capacitance in the circuit can be expressed as $V_C = -I/\ \omega C$. If V is the total voltage across the series circuit, the voltage across the inductance can be expressed as $V_L = V + (I/\ \omega C)$ yielding a graph as shown in figure 2, wherein point of intersection of $V_{L=}\ \omega f(I)$ and $V_C = I/\omega C$ yields the operating point. With the change in capacitance and hence in the slope given by $\tan\alpha = 1/\ \omega C$, brought about by the changes in configuration of the feeding circuit following a fuse blowing, the operating point keeps on traversing on the $V_L = \omega f(I)$ curve. On the complete characteristic given by $\omega f(I)$, the capacitance line has multiple intersections, implying multiple stable operating points. Thus, changes in inductance results in an interaction with a wide range of circuit capacitances resulting in existence of several stable steady state responses to any given change of parameter.

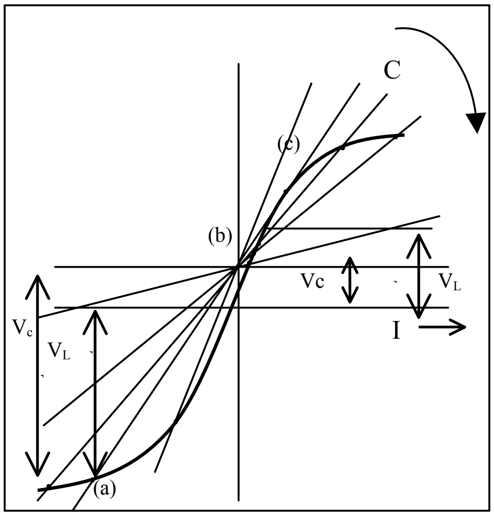

Figure 2: The effect of changing C

V. RECOGNITION OF EXISTENCE OF FERRORESONANCE

The electric utility's distribution network in all the cases, is a combination of long 22 kV distribution cables and overhead lines feeding distribution transformers with delta wound primary winding. All the incidents reported, were associated with blowing of the dropout fuse in one of the phases of the primary circuit. The root causes of these incidents of overvoltages, however, could not be described or understood. Hence, through the process of elimination the problems of overvoltage were related to ferroresonance phenomenon. However, except the reports on customer equipment damage, incidents of transformer damages in utility's distribution network and few snapshot voltage measurements on transformer secondary side, no other information were available to establish the cause of these overvoltages.

In the absence of site measurements and recordings, it was necessary to reconstruct the system operation scenario for each of the site, so that auxiliary tests could be carried out to check existence of ferroresonance using these simulated measurements. The cases are setup on PSCAD/EMTDC for scenario generation through simulation, with appropriate initial conditions as shown in figure 3. The simulation yields the temporal variation of phase and phase-to-phase voltages at the transformer primary and secondary terminals, currents in transformer windings, and flux in the transformer core after the operation of dropout fuse, and also the voltages at the points before the fuse blowing. The time plot of the values of these variables is intended to be similar to the time variations of the variables that would have occurred during actual system operation. Thus, the temporal values generated through the simulation could be used in absence of measurements.

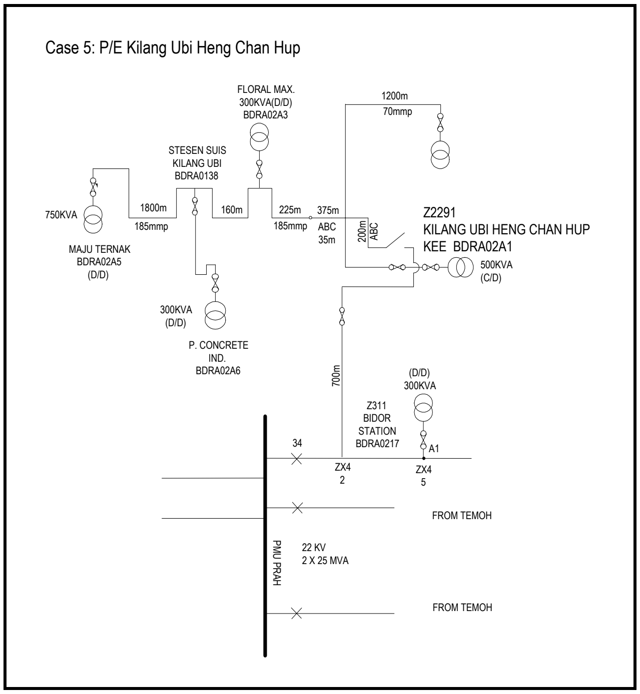

Figure 3: The network configuration of case 5

To verify existence of ferroresonance in each of the reported cases of overvoltages, auxiliary tests based on nonlinear theory are carried out on the scenarios. The auxiliary tests comprise of construction of bifurcation diagrams, s-curve and phase plane portraits to verify type of nonlinearity [2] and wavelet analysis[1] to identify dominant frequencies present in temporal values of relevant variables generated through simulation.

The jump or transition between two stable states is a typical demonstration of nonlinearity in the ferroresonance phenomenon. The extent of jump expressed through a jump index[1] further indicates the degree of nonlinearity present. The presence of multiple stable states an essential ingredient of ferroresonance, apart from the steady state overvoltages, can be gauged by the characteristic frequencies present in the signal as shown in the FFT plots of figure 4 and figure 5. The presence of more than one characteristic frequency as shown in the FFT plots demonstrates the multiplicity in periodicity. The occurrence of two dominant characteristic frequencies at subsynchronous values in the frequency spectra as shown in figure 4 demonstrates this. The relevant parameters together with the circuit status in the five cases that were studied are indicated in Table 1.

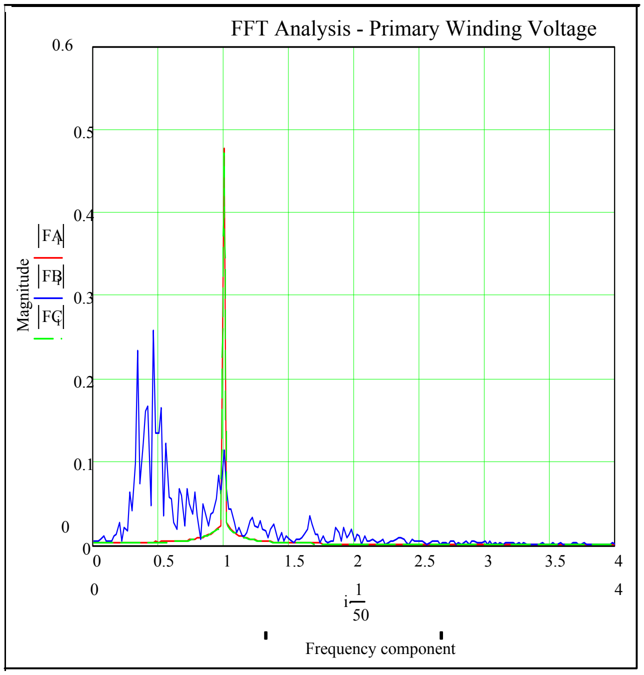

Figure 4: FFT analysis for case 1

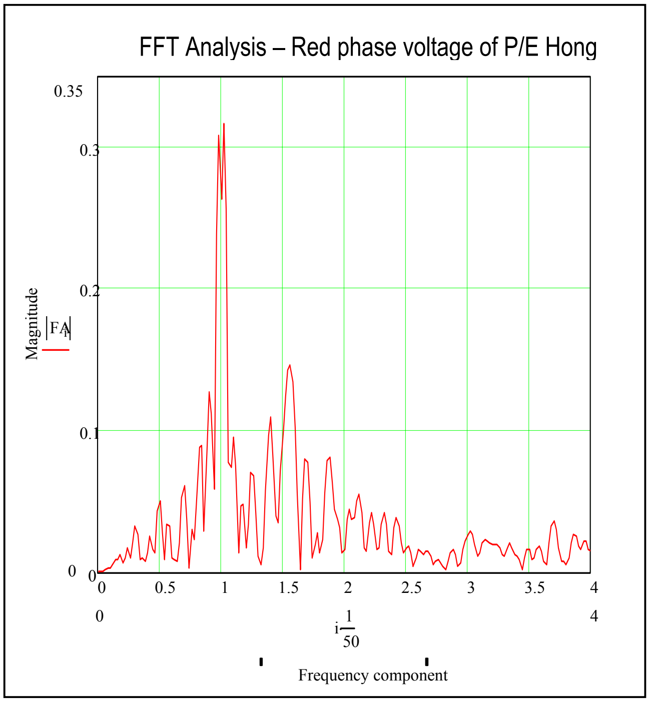

Figure 5: FFT analysis for case 5

In all the cases studied, the 22 kV grade cables are provided with inter-core shielding. Though in ferroresonance analysis, modeling of the delta primary transformer together with its feeding circuit capacitance and one of the phase fuse blown, usually requires the capacitance to be represented as C=2Cm+Cg, where Cm and Cg represent phase-to-phase and phase to ground capacitances of the feeding circuit respectively, in view of the inter-core shielding provided, only Cg was considered in the analysis. The transformer core nonlinearity is modeled through the parameter viz. knee point voltage, air core reactance and rated magnetizing current.

Case	Drop-out fuse to Trafo distance	Cable Type	Cg/m	Core	Trafo Earthing	Fuse blown	% Loading on Trans
1	2800m	70mmp PILC	355.26pF	Type M-5(0.3mm) Sat Flux Density = 1.65T Knee point volt = 1.55p.u Core Loss at 1.65T = 1.2W/Kg	DY11 Star-grounded	Y	12.94
2	1200m	70mmp PILC	355.26pF	Type M-5(0.3mm) Sat Flux Density = 1.65T Knee point volt = 1.55p.u Core Loss at 1.65T = 1.2W/Kg	DY11 Star-grounded	B	3.33
3	3000m	185mmp PILC	507.67pF	Type M-5(0.3mm) Sat Flux Density = 1.65T Knee point volt = 1.55p.u Core Loss at 1.65T = 1.2W/Kg	DY11 Star-grounded	Y	15.8
4	2105m	35mmp PILC	276.79pF	Type M-5(0.3mm) Sat Flux Density = 1.65T Knee point volt = 1.55p.u Core Loss at 1.65T = 1.2W/Kg	DY11 Star-grounded	Y	23.96
5	1235m	70mmp PILC	355.26pF	Type M-5(0.3mm) Sat Flux Density = 1.65T Knee point volt = 1.55p.u Core Loss at 1.65T = 1.2W/Kg	DY11 Star-grounded	R	9.58

Table 1: Parameters and Circuit Conditions

For each of the cases studied, the phase voltages observed are indicated in Table 2, wherein phases are designated by R, Y and B. The maximum overvoltages observed in cases 2 and 5 could be attributed to significantly low level of transformer loading shown in Table 1. In table 2 the dominant characteristic frequencies signifying multiplicity in periodicity are indicated in case 1. In other cases, the frequency magnitude spectra obtained through FFT exhibit a number of frequency components as shown in FFT plot for the representative case 5, in figure 5. The spectra in other cases also were observed to have multiplicity in periodicity. To assess the extent of jump, it is possible to obtain fastest and slowest frequency component in the primary voltage signal using wavelets[1]. It may be important to mention here that though both wavelet and FFT analysis indicate frequency components present in a time series of a variable, FFT does not preserve the time information, which wavelet does. Additionally, whereas FFT is meant for periodic functions, wavelet analysis do not have such restrictions on the nature of the time series of interest, which is phase voltage in this case. The ferroresonance phenomenon differs from harmonics with respect to the nature of its frequency. Whereas ferroresonance exhibit multiple frequencies at sub synchronous values, harmonics in general relate to multiples of fundamental frequency. In the cases studied, the frequencies are always lower than the fundamental frequency.

Case	Extent of Overvoltage						Charact Freq	Non Linarity Type
	Primary			Secondary				
	R	Y	B	R	Y	B		
1	1.04	2.05	1.01	1.70	1.73	1.01	17Hz & 23Hz	Hopf
2	1.12	1.22	4.33	1.04	2.60	2.62	Multi Period	Trans Chaos
3	1.07	1.99	1.13	1.60	1.64	1.03	Multi Period	Trans Chaos
4	1.04	2.87	2.89	2.18	2.29	2.01	Multi Period	Trans Chaos
5	4.69	1.03	1.04	2.40	1.01	2.75	Multi Period	Trans Chaos

Table 2: Network Performance

VI. CONCLUSIONS

To diagnose existence of ferroresonance, it is essential to check presence of overvoltages as well as the presence of multiplicity in periodicity through some kind of frequency spectrum analysis. The experience gained through studies carried out on Malaysian utility's distribution network demonstrates this. The mitigation options as outcome of the studies include use of Dropout fuse assembly with a capability of opening of all the three phases following one fuse blowing, downsizing 22/0.433 kV transformers wherever possible.

VII. ACKNOWLEDGEMENT

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VIII. BIOGRAPHIES

R.N Mukerjee had his doctoral studies at the Indian Institute of Technology Kharagpur during 1984 to 1987. During his employment with Metallurgical & Engineering Consultants India Ltd. from 1975 to 1991, he was involved in engineering and design of power plants and T & D networks. He was also with the Analytical Methods and Specialized Studies section of System Planning Division, Ontario Hydro Toronto where he worked on small signal stability and coherency identification problems He also taught at the Birla Institute of Technology, Ranchi and Institute of Technology, Benaras Hindu University, Varanasi, India. His fields of interest include power system dynamics, nonlinear theory, power quality, and application of AI techniques to power system problems.

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