FERRORESONANCE PERFORMANCE STRATEGY VIA NONLINEAR THEORY

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Abstract-- **Ferroresonance is a common phenomenon in a power distribution system having long radial cable fed transformers provided with fuse protection at the tap off point. During expansion and operational planning of a distribution system, to shortlist critical operating conditions exhibiting ferroresonance for detailed temporal simulation, the paper proposes a system parameter based index named characteristic ratio CR and determines its relationship with the geometrical ratio GR a descriptor of the phase plane trajectory. A table showing CR and corresponding GR values based on initial detailed studies can be used during subsequent planning process, for identifying only the critical cases for detailed studies and determining the limiting parameters, to avoid ferroresonance.**

Index Terms—Bifurcation, Ferroresonance, Distribution System, Computer aided analysis, Contingency Analysis.

1. INTRODUCTION

In electric power distribution system operation, disturbance due to ferroresonance is a common phenomenon. Depending on circuit conditions, it may be in the form of random over voltage that could be either a short transient for few cycles, a continuous over voltage or a jump resonance. It causes both phase-to-phase and phase-to-ground high sustained over voltages and over currents with sustained levels of distortion to the current and voltage waveforms, leading to transformer heating together with excessively loud noise, electrical equipment damage, thermal or insulation breakdown and mal-operation of the protective devices [1],[2],[3].

A distribution system may have characteristic features such as long overhead line or cable feeding a delta or floating wye connected primary of a transformer serving a consumer load varying during peak load to lean load transitions, a low short circuit level power supply point interfacing the transformer feeder, a three phase isolator with protective fuse on its each phase provided at the tap-off point feeding 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 result in a long length feeder with one open phase feeding a transformer, which could also be lightly loaded.

The distribution system also has circuit capacitances in form of phase-to-phase and phase-to-ground capacitances of the cable feeding the transformer. A distribution transformer's ferromagnetic core saturates and exhibits hysteresis. The saturation point is characterized by a dramatic change in the slope of the core's current-flux density curve. The slope of the curve is proportional to the inductance of the winding. As the current in a ferromagnetic coil increases beyond the saturation point, its inductance changes rather suddenly, achieving minimum inductance value in the saturated region of the core. The hysteresis in a ferromagnetic material is due to two current-flux density characteristics. The magnitude of excitation current causing the transformer core to go into saturation and the magnitude of excitation current at which the core comes out of saturation are different. As the iron core goes into saturation due to increased excitation current in a lightly loaded transformer with its feeding circuit's one of the phases open, the sudden change in transformers inductance triggers a sudden change in the frequency at which it may resonate with circuit capacitance. Sudden and unpredictable changes means an interaction with a wide range of circuit capacitances and existence of several stable steady state responses to any given change of parameters. Once the ferromagnetic inductance crosses into saturation, it remains saturated until the current magnitude decreases. If the saturated inductance matches the capacitive reactance of the feeding circuit resulting in resonance, the current magnitude increases dramatically, driving the core into saturation and making the resonant point stable. If the current in the circuit is able to drop below the saturation point, the inductance comes out of saturation, and again the inductance value changes. These dramatic changes in inductance account for the dynamical and multiple stable response characteristic of ferroresonant circuit, a nonlinear behaviour.

To predict existence of multiple stable states for the same operating voltage in a distribution system, many variants and combinations of parameters, initial conditions and switching instants for a given circuit configuration need to be simulated to determine generalised values of parameters that will ensure good operating safety margin. During system expansion and operational planning exercises, detection of possibility of ferroresonance is of preliminary interest.

2. HYSTERESIS, AN ANALYTICAL LOOK

The hysteresis in a transformer and the resulting multiple stable resonant states due to different inductance values, interacting with wide range of circuit capacitances can be explained in a bifurcation theory framework. A three phase cable feeding a transformer with delta connected primary and a fuse blown on one of the phases can be represented by a Thevenin's equivalent circuit having a sinusoidal source feeding a capacitance in series with a nonlinear inductance f(I). The series capacitance C is given by C=2Cm+Cg, where Cm is phase-to-phase and Cg is phase-to-ground capacitance of the feeder cable [4]. The loop equation

$$V=\omega f(I) - I/\omega C \qquad (1)$$

has two right hand terms viz. $V_L = \omega f(I)$ giving a smooth curve and $V_C = -I/\omega C$ giving a straight line plot having a slope $\tan_a = 1/\omega C$, which reduces as C or the cable length is increased. Each straight line corresponds to a specific cable length and the applicable inductance; L on the smooth curve depends on the initial circuit operation together with state of saturation of the transformer core. Depending on the operating condition and circuit configuration i.e. L & C parameters, operating point voltages for a current will be given by the intersection of the smooth curve and the relevant straight line. The intersections on the linear region of the curve yield stable equilibrium or operating points while intersections on the saturated region result in unstable operation or jumps. The simultaneous intersections of the straight line with the inductance curve at two or more than two points yields multiple stable operation. The series circuit yields a second order differential equation given by

$$Ae^{-I/B}\, dI/dt + (1/C) \int I\, dt = V \sin(\omega t+\phi) \qquad (2)$$

and the associated phase portrait shown in figure 1 gives the stable orbit structure [5] of the differential equation corresponding to stable equilibrium points, sufficiently small variations of the parameters around which do not cause alteration in qualitative structure of the flow. The parameter values in the saturated region of the curve $V_L=\omega f(I)$ are bifurcation values.

At the point of intersections V_L equals V_C implying

$$I\omega L = I / \omega C \qquad (3)$$

since at this point $\omega f(I) = \omega L$. This yields a resonant frequency $1/(2\pi\sqrt{LC})$. The resonance is described by

$$Ld^2I/dt^2 = (I/C) \qquad (4)$$

indicating multiple solutions. Resonance implies complete to and fro energy transaction between circuit capacitance and the transformer coil, the inductance and circuit capacitance being both energy storage elements. A loaded transformer will result in bleeding of some of the stored energy in the coil during each transfer cycle and will introduce damping. Considering no damping, at resonance

$$\frac{1}{2} LI^2 = \frac{1}{2} CV^2 \qquad (5)$$

yields a characteristic ratio

$$\sqrt{\frac{l}{I(2Cm+Cg)}} \qquad (6)$$

implying severity of ferroresonance with reduction in the ratio, which could be either due to inductance approaching its saturated value or due to increase in feeder length. At minimum value of the ratio jump or branching may be witnessed. The proposed characteristic ratio a system parameter based index, is linked to geometrical descriptors of a phase plane portrait, to facilitate short listing of only critical cases for detailed study during operational planning of a power distribution system.

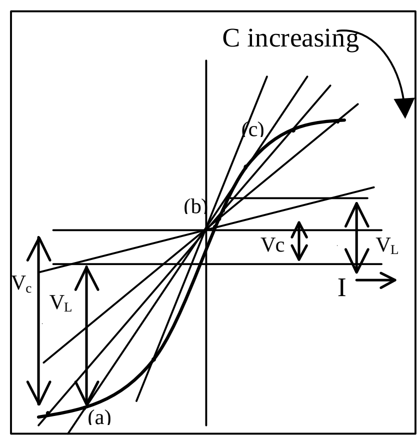

Figure1: The effect of increasing C

3. SYSTEM STUDY

Effectiveness of the proposed characteristic ratio is verified using the 22kV system shown in figure 2. The EMTDC simulation for generating time samples of source voltage, transformer primary voltage, transformer primary delta winding flux and it derivative and the phase current, is carried out for 0.56 seconds with phase-A fuse opening at 0.2 secs. Simulation is repeated for source voltage variation from to 1.5 p.u. The delta-star transformer is kept on close to no load.

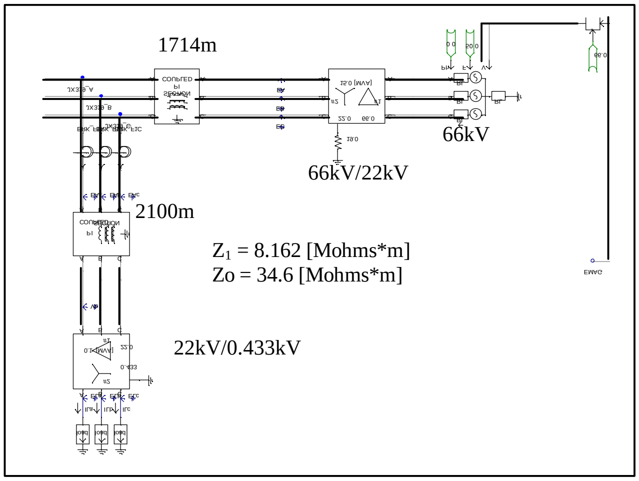

Figure 2: Case study network

4. NONLINEAR PERFORMANCE

Branching or bifurcation diagrams together with Phase plane trajectories, serve as unique form of identifiers for detecting existence of ferroresonance. For the network studied, bifurcation diagram in Figure 3 is plotted for source voltage varying from 0.1 to 1.5p.u. Here circuit capacitance is not changed. However, due to change in source voltage and hence the change in state of core saturation, transition without jump takes place implying soft loss of stability or periodic behaviour up to 0.85 p.u. excitation. As the source voltage is increased beyond 0.9 p.u., aperiodic period doubling scenario is witnessed. Phase plane portraits of phases AB and CA with flux in the winding plotted on X-axis and its derivative plotted on Y-axis, while source voltage clamped at 1.0 p.u. in Figure 4 & Figure 5, clearly show the period doubling phenomenon. Periodic solution during initial period shown by closed phase plane trajectories or periodic attractors can also be seen.

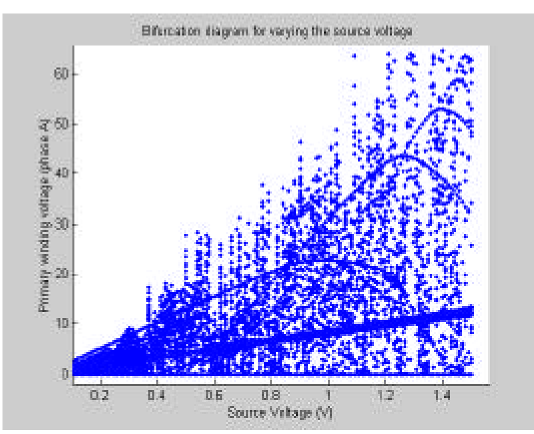

Figure 3: Bifurcation diagram with varying E

The trajectories during the later part do not close back on themselves and exhibit period doubling [6]. These are strange attractors indicating a nonperiodic or chaotic waveform since they are attracted to a constrained region and seem to wander randomly within this region. These attractors exhibit sensitive dependence of the nonperiodic ferroresonance on initial conditions. Initial condition here implies circuit condition before fuse blowing.

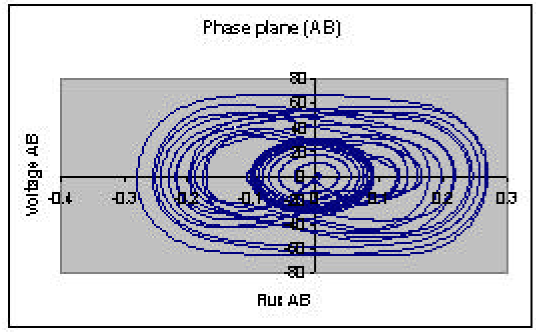

Figure 4: Phase plane portrait of phase AB

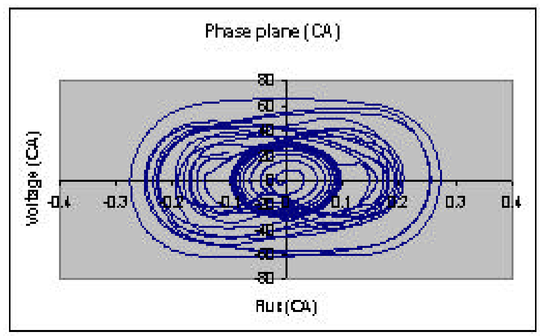

Figure 5: Phase plane portrait of phase CA

To shortlist only the critical cases out of the large number of possible operating configurations for detailed temporal simulation and to identify the limiting parameters so as to avoid occurrence of ferroresonance, a characteristic ratio is proposed and the same is linked to geometrical descriptors of the likely phase plane trajectory. Figure 6 depicts the characteristic ratio as seen by phase AB as the inductance changes over time corresponding to a source voltage of 1.0 p.u.

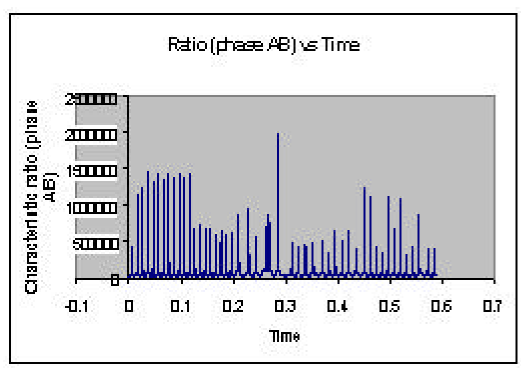

Figure 6: Characteristic ratio of phase AB

The regimes of high and low characteristic ratios are identified and the corresponding phase plane trajectories drawn are shown in figure 7 & 8 for phase AB.

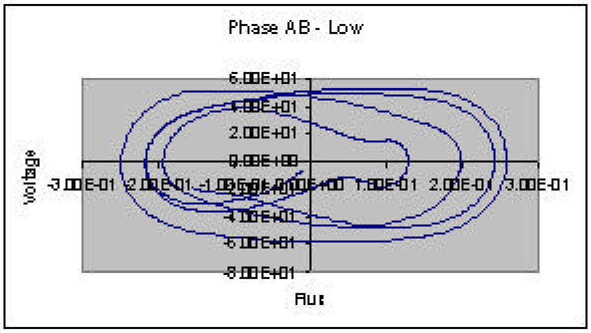

Figure 7: Phase plane corresponding to Low CR

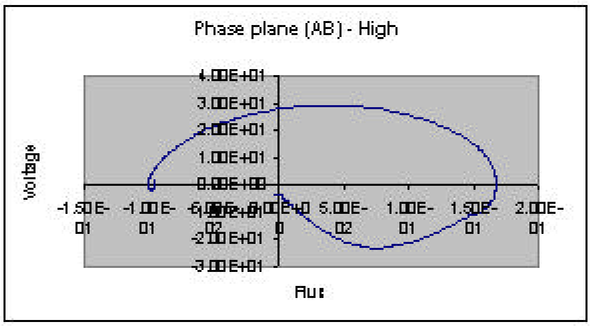

Figure 8: Phase plane corresponding to High CR

Phase		Characteristic Ratio (CR)	Geometrical Ratio (GR)
AB	Low	500,000	2.197
	High	2,000,000	2.02
CA	Low	500,000	2.43
	High	6,000,000	2.27

Table 1: Characteristic ratio and Geometrical ratio

Lower the characteristic ratio, more critical is the operating condition. The geometrical ratio of the maximum spreads of a elliptical trajectory along X and Y-axes is also higher for the phase plane trajectory corresponding to the regime of low characteristic ratio. The elliptical phase plane trajectories depict the existence of ferroresonance with increase in severity being indicated by increasing degeneration in elliptical shapes. The proposed system parameter based characteristic ratio (CR) correlates well with the geometrical descriptors (GR) of the phase plane trajectories. A table indicating values of these parameter based indices CR with their likely phase plane trajectory patterns encrypted in terms of their geometrical descriptors GR can be framed for a system, on the basis of detailed simulations carried out initially. The table 1 clearly brings out that lower the value of CR, higher the value of GR implying a more degenerated elliptical phase plane trajectory. During subsequent planning studies, only cases requiring detailed investigation can be short-listed using the table 1.

5. CONCLUSIONS

During expansion and operational planning of a distribution system, to shortlist only the critical cases out of the large number of possible operating configurations for detailed temporal simulation, the paper proposes a system parameter based index termed characteristic ratio CR and determines its relationship with the geometrical descriptor (GR) of the phase plane trajectory. A table showing CR and corresponding GR values based on initial detailed studies can be used during subsequent planning process, to select only the critical cases for detailed studies to determine the limiting parameters, and avoid ferroresonance.

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