

Ferroresonance Experience in UK: Simulations and Measurements

Zia Emin BSc MSc PhD AMIEE
zia.emin@uk.ngrid.com

Yu Kwong Tong PhD CEng MIEE
kwong.tong@uk.ngrid.com

National Grid Company
Kelvin Avenue, Surrey KT22 7ST
UNITED KINGDOM

Abstract - Ferroresonance is a complex non-linear electrical phenomenon that can cause dielectric & thermal problems to the transmission plant and switchgear. Electrical systems exhibiting ferroresonant behaviour are nonlinear dynamical systems. The application of conventional linear mathematics is therefore not fully appropriate for the study of ferroresonance. The prediction of ferroresonance is achieved by detailed modelling using a digital computer transient analysis program such as the EMTP/ATP. This paper presents the analyses performed with ATP and compares them with system measurements to identify the crucial factor in ferroresonance.

Keywords: Ferroresonance, electromagnetic voltage transformer, traction supply transformer, ATP, nonlinear dynamics.

I. INTRODUCTION

Ferroresonance or nonlinear resonance is a complex electrical phenomenon, which may cause overvoltages and overcurrents in an electrical power system thus endanger the transmission plant, switchgear and the operational personnel. Ferroresonant overvoltages on electrical power systems were recognised and investigated as early as 1930s [1]. It occurs when a nonlinear inductor is fed from a series capacitor. The nonlinear inductor can be due to the magnetic core of a wound type voltage transformer or it may be due to the complex structure of a 3 or 5 limb three-phase power transformer. The circuit capacitance can be due to a number of elements, such as the circuit-to-circuit capacitance or parallel lines, conductor to earth capacitance, circuit breaker grading capacitance, busbar capacitance, bushing capacitance, etc.

Ferroresonance should not be confused with linear resonance that occurs when inductive and capacitive reactances of a circuit are equal. In linear resonance the current and voltage are linearly related in a manner which is frequency dependent. In the case of ferroresonance it is characterised by a sudden jump of voltage or current from one stable operating state to another one. The relationship between voltage and current is dependent not only on frequency but also on a number of other factors such as the system voltage magnitude, initial magnetic flux condition of transformer iron core, the total loss in the ferroresonant circuit and the point on wave of initial switching.

Although analytical methods, such as the principle of harmonic balance, can be employed to model and analyse ferroresonant systems, they do not provide an overall picture of the behaviour of the system. This is mainly

because of the characteristic of the analyses of forced nonlinear systems where even relatively simple nonlinear differential equations lead to algebraic equations of considerable complexity. Conventional linear mathematics is therefore inappropriate in this situation and researchers are applying nonlinear dynamics and/or chaos theory to describe the phenomenon [2, 3].

II. SYSTEM DESCRIPTION AND ATP MODELLING

Current studies related to ferroresonance in electromagnetic wound voltage transformers (VT) and single-phase traction supply transformers.

A – Voltage Transformer Ferroresonance[5,6]

During voltage transformer ferroresonance an oscillation occurs between the nonlinear inductance of the VT and the capacitance of any network remaining connected to the VT. In this case, energy is coupled to the nonlinear core of the voltage transformer via the open circuit breaker grading capacitance to sustain the resonance. The VT can be driven into saturation resulting in high currents at sub-harmonic or fundamental frequency. For the latter, very high voltage of up to 4 pu can theoretically arise in worst case conditions. Electromagnetic voltage transformers have a relatively low thermal capacity and overheating can result in insulation failure very quickly.

Fig.1 shows the single line diagram of the most commonly encountered system arrangement that can give rise to VT ferroresonance. Ferroresonance can occur upon opening of disconnector 3 with circuit breaker open and either disconnector 1 or 2 closed. Alternatively it can also occur upon closure of either disconnector 1 or 2 with circuit breaker and disconnector 3 open.

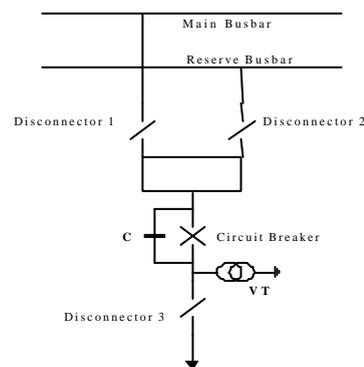


Fig. 1 System arrangement resulting to VT ferroresonance

The system arrangement shown in Fig. 1 can effectively be reduced to an equivalent circuit as shown in Fig. 2.

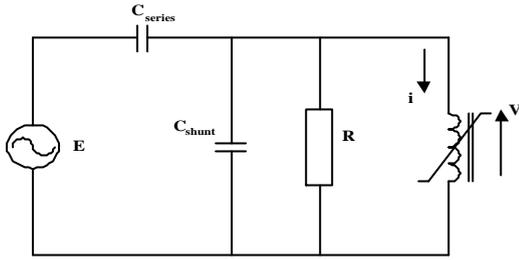


Fig. 2 Reduced equivalent ferroresonant circuit

In Fig. 2, E is the rms supply phase voltage, C_{series} is the circuit breaker grading capacitance and C_{shunt} is the total phase-to-earth capacitance of the arrangement. The resistor R represents voltage transformer core losses that has been found to be an important factor in the initiation of ferroresonance [4,8,9].

The circuit of Fig.2 is modelled in ATP [7]. Transformer magnetisation characteristic supplied by the manufacturer was used in a type-93 true nonlinear inductor to simulate the magnetic core of the VT. The VT itself is a low thermal capacity, 400kV/110V, 100VA wound voltage transformer. C_{series} and C_{shunt} were represented as lumped parameters. The resistance R was represented dynamically based on

$$R = \frac{R_{OS} - R_{MS}}{1 + \left(\frac{|B|}{B_s}\right)^a} + R_{MS} \quad (1)$$

In (1) $R_{OS}=60\Omega$, $R_{MS}=20\Omega$, $B_s=1.7T$ and $a=9.5$. At every integration time-step of ATP then the value of R is recalculated depending on the value of B.

B – Traction Supply Transformer Ferroresonance

Fig. 3 shows the single line diagram of a traction supply transformer arrangement. The single phase transformer is fed from two phases of the three-phase system. Ferroresonance occurs upon opening of circuit breakers 1 and 2 to de-energise the line and the transformer. Energy is coupled to the de-energised network from the adjacent live parallel circuit via the inter-circuit coupling capacitance, i.e. C_{series} in the equivalent ferroresonant circuit. The equivalent C_{shunt} in the ferroresonant circuit is the phase-to-earth capacitance of the line and the transformer winding and bushing capacitance.

Simulation of traction supply transformer can be carried out on a complex 3-phase network. Both the measurements and simulation results are given in figure 9. Nevertheless digital computer modelling of the traction supply transformer configuration can be simplified using the single-phase ferroresonant equivalent circuit given in Fig. 2.

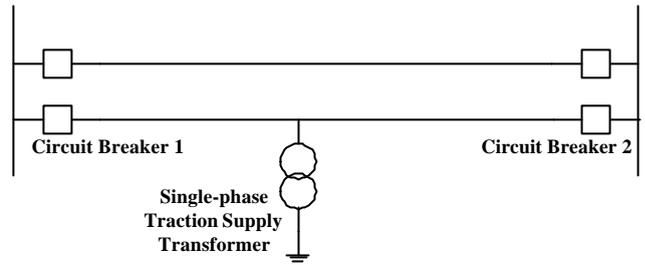


Fig. 3 Traction supply transformer ferroresonance arrangement

III. FIELD MEASUREMENTS vs SIMULATION RESULTS

A – Voltage Transformer Ferroresonance

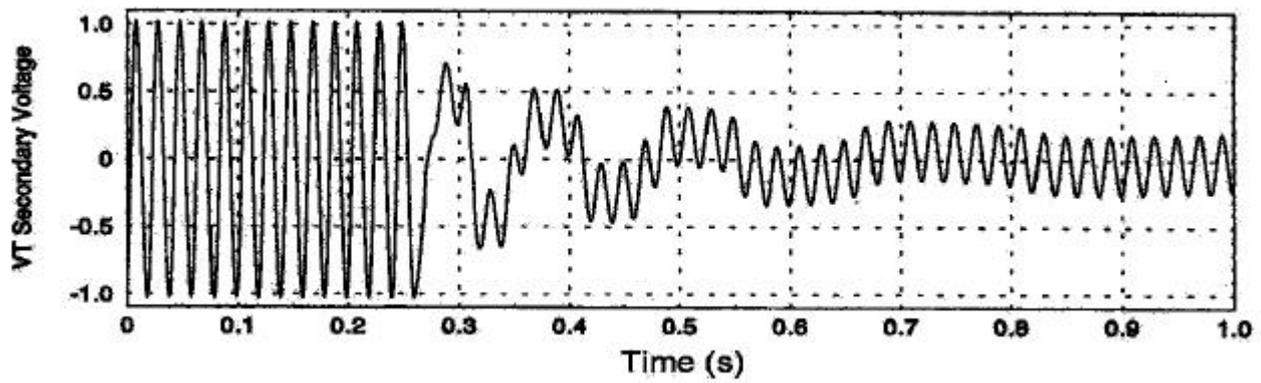
Fig. 4 (a) and (b) show the measured and simulated VT secondary voltages respectively. The measured test waveform of Fig. 4 (a) was obtained after opening disconnecter 3 in Fig. 1. As it can be seen from the graphs the VT did not go into ferroresonance. Although the simulated waveform does not match the measured test waveform exactly, its general appearance is a very close fit. It can be said that the ATP model employed in this study is capable of predicting possible ferroresonance modes as long as the parameters of the system are known or can be estimated. In the study C_{series} was set to 514pF and C_{shunt} to 1137pF to give the waveform of Fig. 4 (b). Primary current waveforms for the field measurement and the simulation study are given in Fig. 5 (a) and (b), respectively.

When the same system is tested for a second time the response is totally different to the above in that it is driven into sub-harmonic ferroresonance. Prediction of this response with digital simulation proved to be hard as the system is very sensitive to parameter changes. The measured and simulated VT secondary voltage waveforms are shown in Fig. 6 (a) and (b) and the corresponding primary current waveforms are given in Fig. 7 (a) and (b), respectively. The shape of measured and simulated waveforms in Figs. 6 & 7 (a) and (b) are of a good match. The minute difference is believed was due to the numerical and actual saturation around the “knee” point of the magnetisation curve.

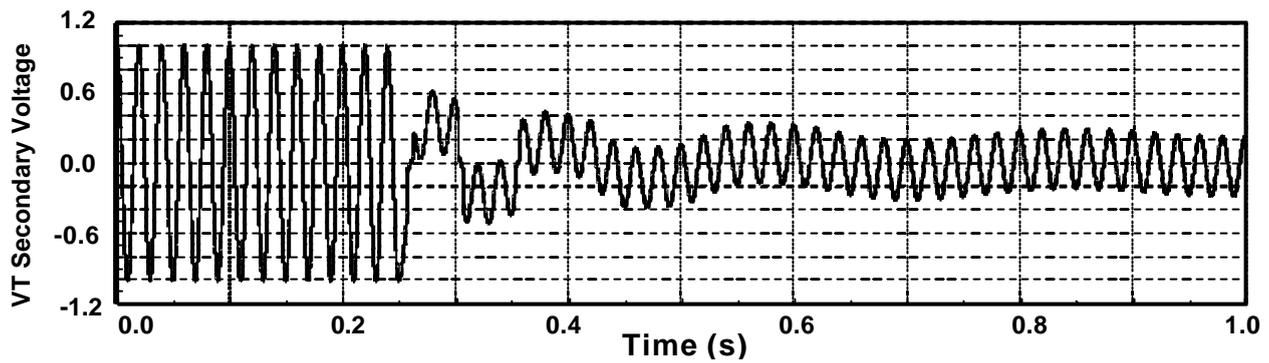
The bifurcation diagram of Fig. 10 shows the sensitivity of the model to applied voltage E. Bifurcation diagrams provide information about the dynamics of the system for range of parameter values. In the diagram of Fig. 10 all system parameters except E were constant. Values of E from 0.8pu to 1.15pu result to a normal response while at 1.15pu and onwards a fundamental ferroresonant response is present.

B – Traction Supply Transformer Ferroresonance

Figs. 8 and 9 show the results of a full scale measurement and simulation of a traction supply transformer which ferroresonated at 50Hz, the fundamental system frequency. The phase voltages and current on the de-energised transformer are presented. Clearly, the two phases feeding the transformer are in sustained fundamental frequency mode ferroresonance.

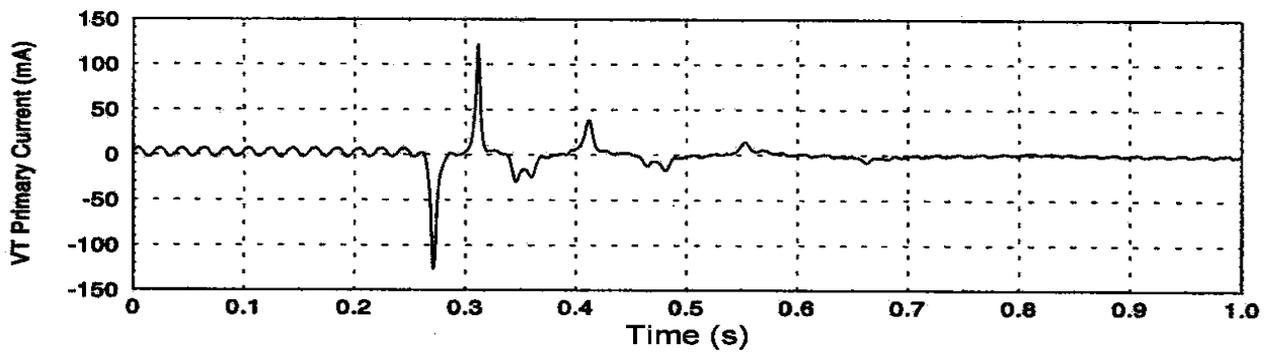


(a) field measurement

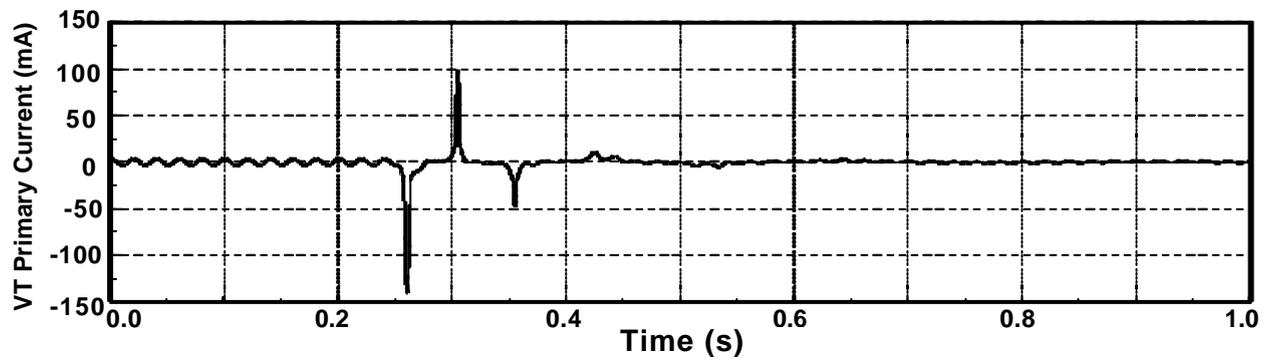


(b) digital simulation

Fig. 4 VT secondary voltages (values in p.u.) showing normal response

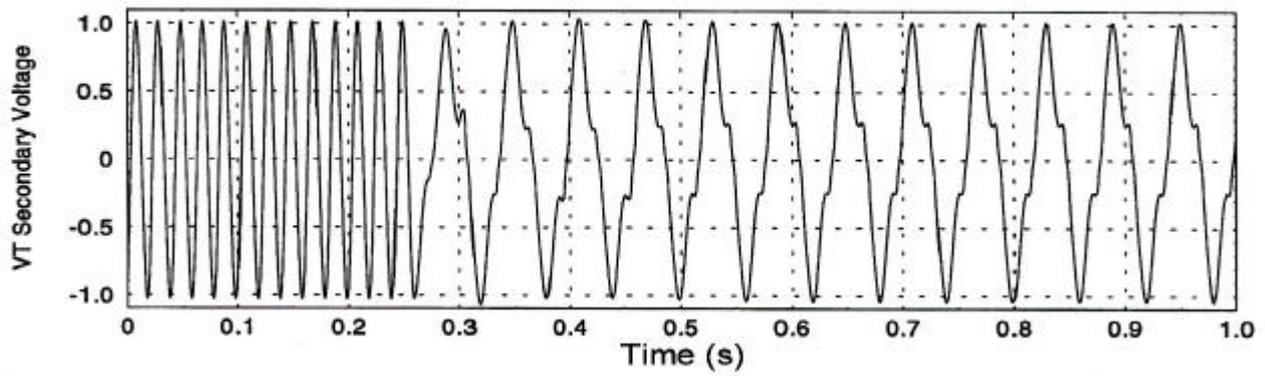


(a) field measurement

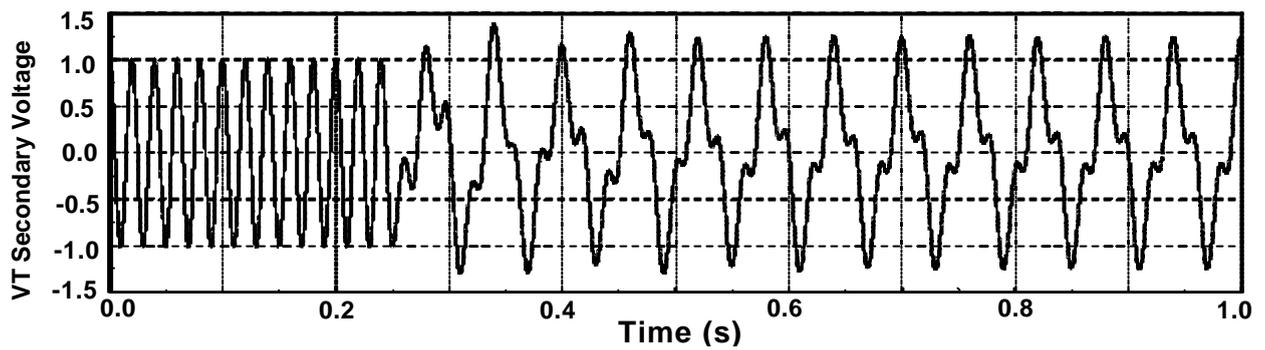


(b) digital simulation

Fig. 5 VT primary currents showing normal response

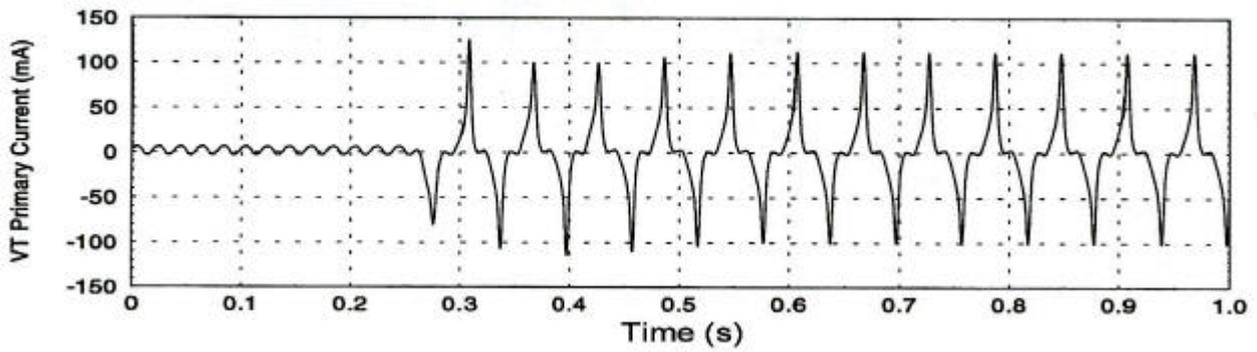


(a) field measurement

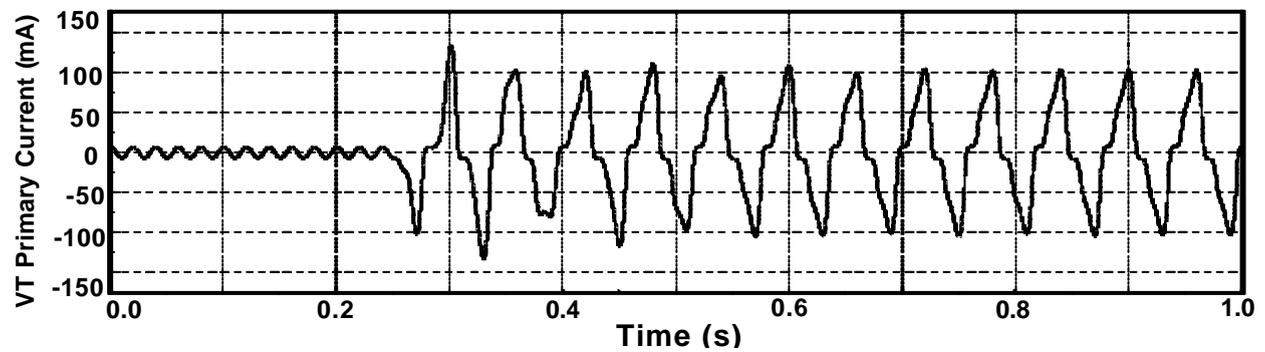


(b) digital simulation

Fig. 6 VT secondary voltages (values in p.u.) showing sub-harmonic (16.6Hz) ferroresonance



(a) field measurement



(b) digital simulation

Fig.7 VT primary currents showing sub-harmonic (16.6Hz) ferroresonance

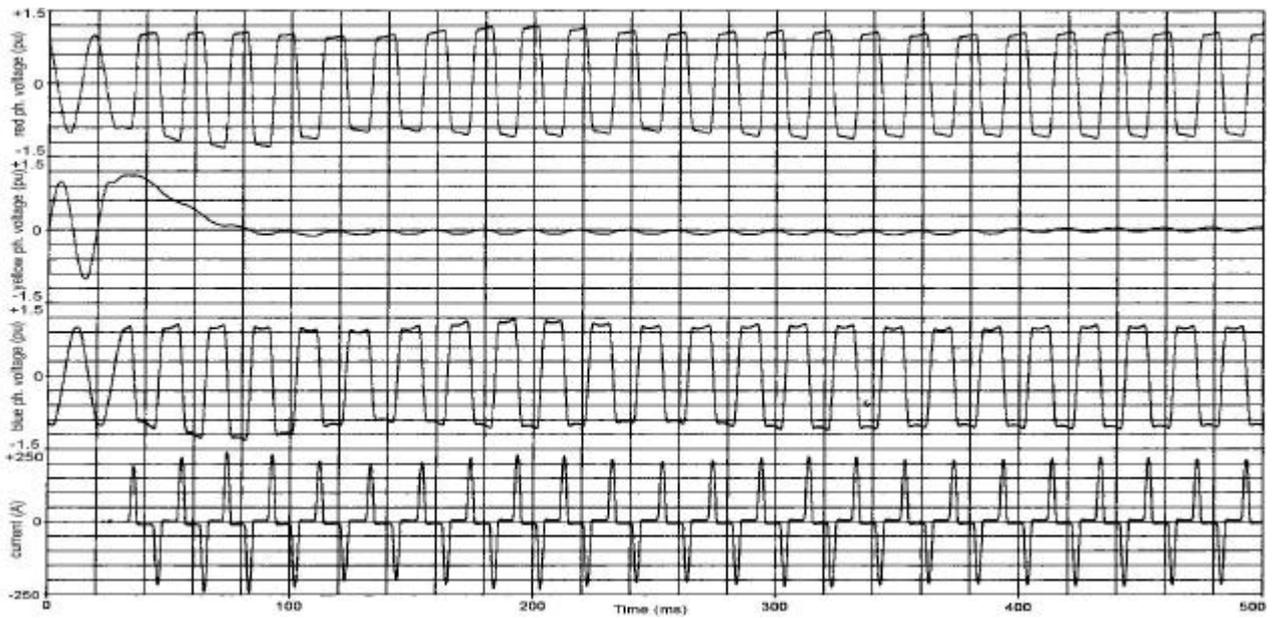


Fig. 8 Field measurements of a fundamental frequency ferroresonance in a traction supply transformer system

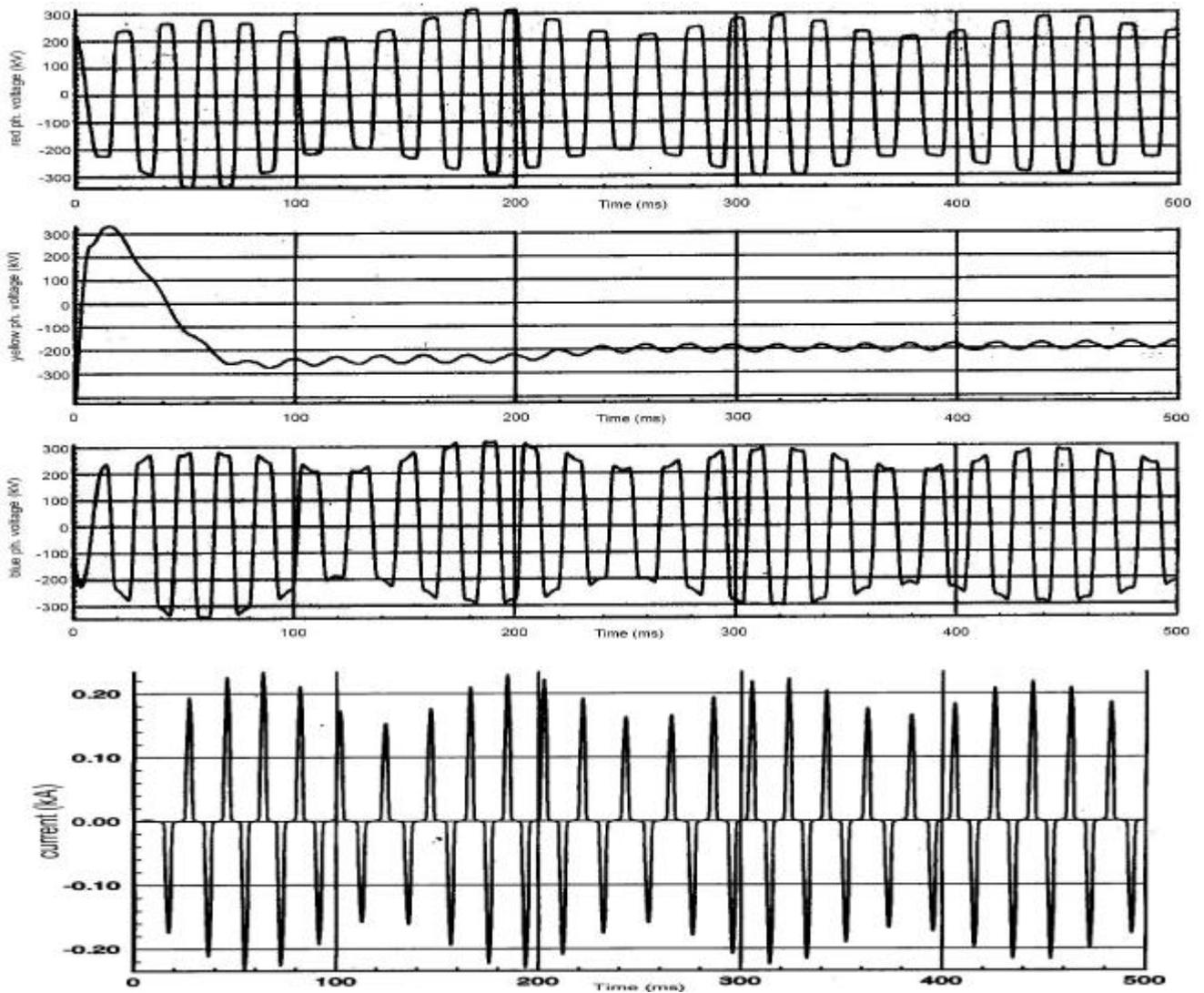


Fig. 9 Digital simulation results for the system tests shown in Fig. 8

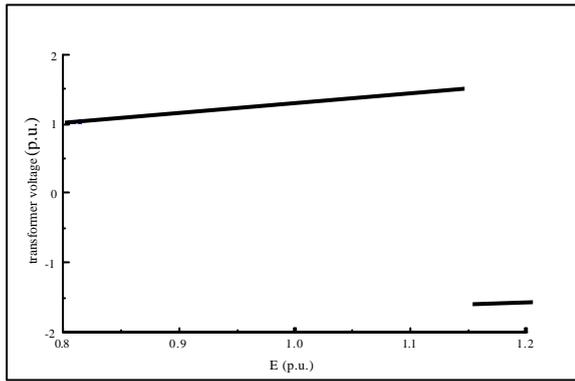


Fig. 10 Bifurcation diagram showing sensitivity of model to E (all other parameters kept constant)

IV. CONCLUSIONS

A reliable prediction of the ferroresonant voltage and current in advance can provide valuable information to planners to design the system, engineers to specify the equipment and operators to run the transmission plant within all the design and tested criteria and capabilities.

This comprehensive understanding can be achieved if all the parameters of the system and plant in question are available or can be estimated with reasonable accuracy. Although the model used in this study provided comparable result with those of field measurements, many more questions, such as the effect of magnetisation hysteresis and remnance and the Point-on-Cycle switching etc are still to be examined.

Boundary approach can be adopted to establish the interaction between the system and the plant, and subsequently bringing forward an operating window with the lowest ferroresonance risk.

V. ACKNOWLEDGEMENT

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