Characterization of Ferroresonant Modes in HV Substation with CB Grading Capacitors

M. Val Escudero, I. Dudurych and M. A. Redfern

Abstract--This paper reports a ferroresonant experience involving inductive Voltage Transformers (VT's) in a 400kV substation equipped with circuit breaker grading capacitors. Field measurements are presented and compared with ATP/EMTP simulation results, showing very good agreement. A parametric analysis has been performed to investigate the effect of the substation capacitance on the occurrence of ferroresonance. Fundamental frequency and sub-harmonic ferroresonant modes have been identified and compiled in a bifurcation diagram. The methodology presented can be used to create risk maps of avoidable switching operations or substation configurations.

Keywords: Ferroresonance, Non-Linear Dynamics, Inductive Voltage Transformers, Circuit Breaker Grading Capacitors, Power System Modelling, ATP/EMTP.

I. INTRODUCTION

FERRORESONANCE in Power Systems has been studied for over 80 years [2]. It refers to an oscillating phenomenon between a non-linear inductance and a capacitor that can result in highly distorted overvoltages and overcurrents. Analytical work, digital simulation studies, field measurements and lab tests have been widely reported [1] [13]. Despite the extensive literature available, ferroresonance still remains widely unknown and it is generally feared by Power Systems Operators as it seems to occur at random, normally resulting in the catastrophic destruction of plant equipment. This general lack of awareness means that ferroresonance is, by and large, overlooked at the planning and design stages or, at the other extreme, held responsible for inexplicable equipment failures. By rising awareness of the network conditions that can result in ferroresonance and the various ferroresonant modes that can be expected, adequate mitigation options can be put in place to avoid equipment damage.

Depending on their frequency content, steady-state ferroresonant oscillations are normally classified as [1]:

1. Harmonic ferroresonance: periodic waveforms with a frequency multiple of the power system frequency.
2. Fundamental ferroresonance: periodic waveforms with the same period as the power system.
3. Sub-harmonic ferroresonance: periodic waveforms with a period multiple of the power system period.
4. Quasi-periodic ferroresonance: non-periodic waveforms with a discontinuous frequency spectrum.
5. Chaotic ferroresonance: non-periodic waveforms with a continuous frequency spectrum.

This paper's scope is to report a fundamental frequency ferroresonant experience and to identify other possible ferroresonant modes in a HV substation when inductive VTs are isolated using circuit breakers equipped with grading capacitors. The ferroresonant circuit consists of a series combination of:

- Voltage source: The energised busbar.
- Capacitance: a combination of circuit breaker grading capacitors and the busbar or line bay stray capacitance.
- Non-linear inductance: VT's magnetic core.

A detailed physical explanation of the phenomena can be found in [1] and [12]. Similar filed experiences of VT ferroresonance in HV substations have been reported in [7]-[12].

II. FERRORESONANCE EXPERIENCE IN 400KV SUBSTATION

Switching operations performed during the commissioning of a new 400kV substation in Ireland inadvertently drove two single-phase Voltage Transformers (VT's) into a sustained ferroresonant state. Fig. 1 shows the single-line diagram of the line bay involved in the incident. Of especial importance is the VT's location, on the bay side of the line disconnector (DL).

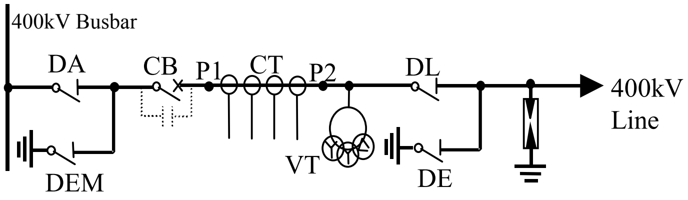

Fig. 1. 400kV Line Bay

Following a "live test" consisting on the energization of the VT's from busbars with the line disconnector (DL) open, the line VT's were de-energized by opening the circuit breaker (CB). A ferroresonant circuit was immediately created upon opening the circuit breaker with the busbar disconnector (DA) closed and the line disconnector (DL) open. Sustained overvoltages of 2p.u. were recorded in two phases. Additionally, a very loud humming noise was reported by local operators.

After this first ferroresonant experience, and in accordance to VT's manufacturer recommendations, a damping resistor of 0.5Ω was connected across the open delta tertiary windings of

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M. Val Escudero is with ESB International, 19/21 Stephen Court, Stephen's Green, Dublin, Ireland (e-mail: marta.valescudero@esbi.ie).

I. M. Dudurych is with TSO EirGrid, Ireland. Power System Operations, 27 Lower Fitzwilliam Street, Dublin 2, Ireland (e-mail: idudur@ieee.org).

M. Redfern is with the Department of Electrical Engineering, Bath University, Claverton Down, Bath, UK (e-mail: m.a.redfern@bath.ac.uk).

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the VTs and further switching operations were performed to assess its effectiveness.

The first two tests performed with the damping resistors resulted in some initial quasi-periodic oscillations that died out in about six cycles. These evolved into a “normal” steady state response with power frequency voltages of 0.5pu, as shown in Fig. 2.

The third switching test, however, produced a completely different response with apparently the same initial conditions. Recorded waveforms are included in Fig. 3 showing the severity of the continuous overvoltages. It can be seen that the resonant condition also initiated as a quasi-periodic oscillation but, after nearly 300ms, it jumped into a sustained ferroresonant state with voltages reaching 2p.u. in two phases. The frequency spectrum of the recorded ferroresonant waveforms is shown in Fig. 4 and reveals a predominant fundamental frequency component with a number of decaying odd harmonics including the 3rd, 5th, 7th and 9th. This frequency spectrum is typical of a fundamental frequency ferroresonant mode [1].

A very unusual loud noise combined with high voltage readings prompted the local operator to isolate the 400kV busbar within seconds, which terminated the ferroresonant oscillation and prevented the catastrophic failure of the VTs. It is evident that the 0.5Ω damping resistor connected across the open delta tertiary windings failed to suppress the ferroresonant oscillations. Yunge Li et al [9] reported a similar experience in which open delta damping resistors as low as 0.1Ω did not suppress ferroresonance either.

III. System Analysis

Following the ferroresonant experience described above, a study was undertaken to investigate the phenomena and to evaluate mitigation options.

A. ATP/EMTP Model

The circuit shown in Fig. 1 was represented in detail using ATP/EMTP. The model included VTs, CB, disconnectors and relevant busbars and bay sections. The circuit breaker grading capacitance and line bay stray capacitance were 600pF and 460pF, respectively. A graphical representation of the model is shown in Fig. 5.

Preliminary simulations indicated that an accurate modelling of the Voltage Transformers was essential to reproduce the measured waveforms. These were represented as three single-phase, three-winding transformers using BCTRAN. The secondary windings were “Wye” connected and the tertiary windings were in an open-delta configuration. The tertiary delta connection was closed using a 0.5Ω resistor. The magnetic behaviour of the core was externally represented by means of its saturation curve, derived with SATURA from the no-load V-I curve supplied by the manufacturer. VT’s saturation curve is shown in Fig. 6.

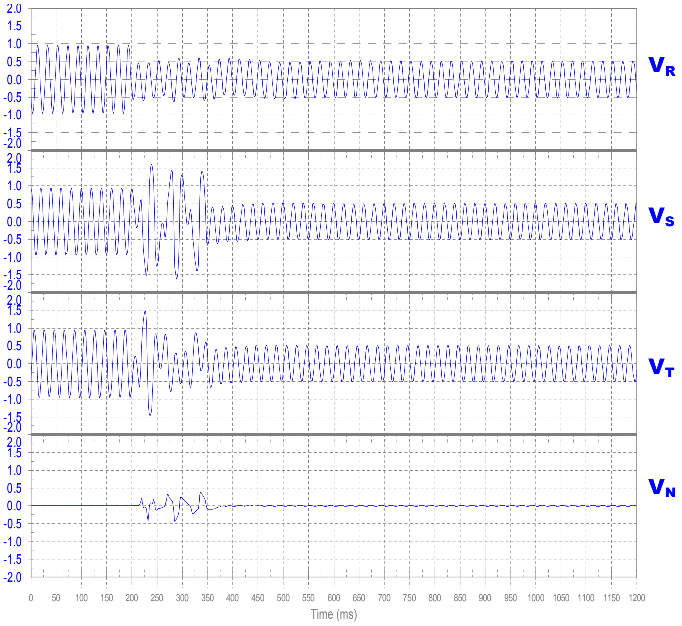

Fig. 2. Recorded p.u. voltages during the first switching operation showing normal steady state response.

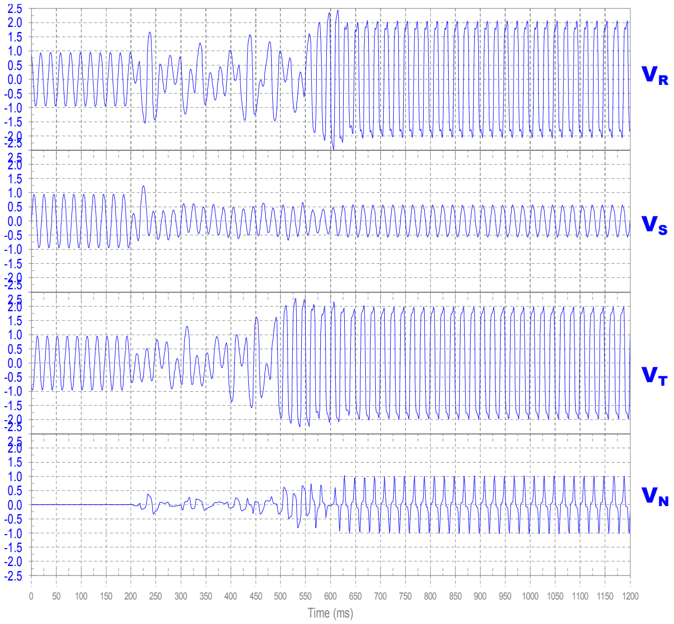

Fig. 3. Recorded p.u. voltages during the third switching operation showing sustained period-1 ferroresonance

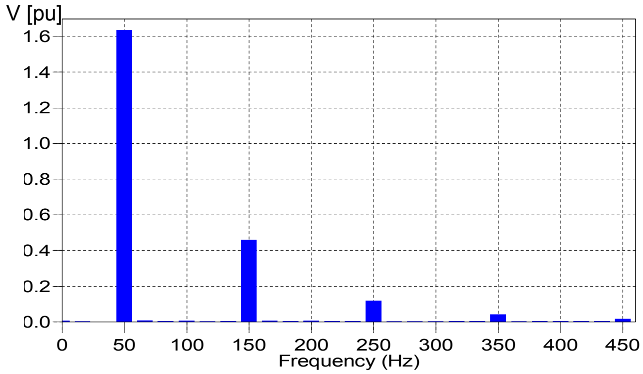

Fig. 4. Frequency spectrum of recorded period-1 ferroresonant voltage

The hysteretic behaviour of the steel core is important since it imposes additional losses that are crucial for the stability of a ferroresonant state. It has been reported in [8] that the equivalent iron-core losses of a 245kV gas-insulated VT can increase to four times its nominal value when working in a high saturated region. Some attempts have been made to represent deep saturated iron core losses using dynamic resistors that take flux levels into account [11] or as a function of the amplitude and shape of the oscillation [13]. The main difficulty when trying to implement any of those dynamic models is the lack of measurements for validation. As hysteresis measurements were not available for the VT's under study, the iron core losses were simply represented by a lumped linear resistor of 182MΩ (293W at 400kV).

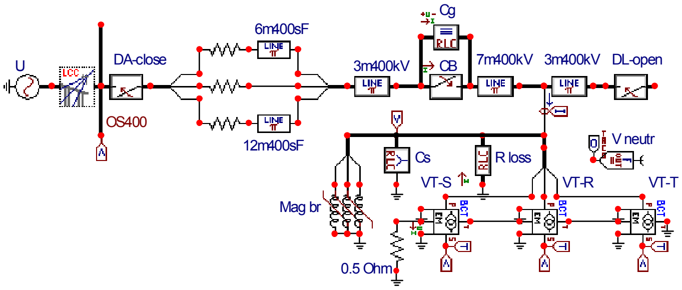

Fig. 5. ATPDRAW representation of 400kV Substation.

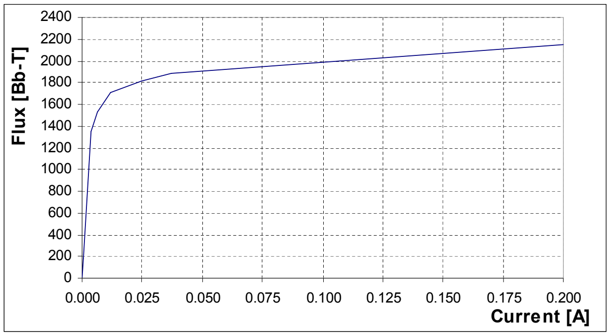

Fig. 6. Saturation curve of 400kV VT.

B. Model Validation

Simulation results of the switching operation leading to a sustained fundamental frequency ferroresonance are shown in Fig. 7. These compare well with recorded waveforms shown in Fig. 3. The shape and amplitude of the sustained ferroresonant overvoltages were reproduced with very good accuracy. The quasi-periodic oscillations prior to the steady-state ferroresonant condition, from 200 ms to 500 ms in Fig. 3, were almost impossible to replicate, although simulated waveforms also displayed a quasi-periodic behaviour. It is suggested that this is due to a random combination of parameters such as switching time, pre-switching voltage, remnant magnetization and power losses, the latter being variable during high saturation in the magnetic cores.

Even though the exact wave shapes were slightly different, the simulation results presented sufficient replication of the field measurements to validate the ATP/EMTP model and to use it as a basis for exploring further scenarios.

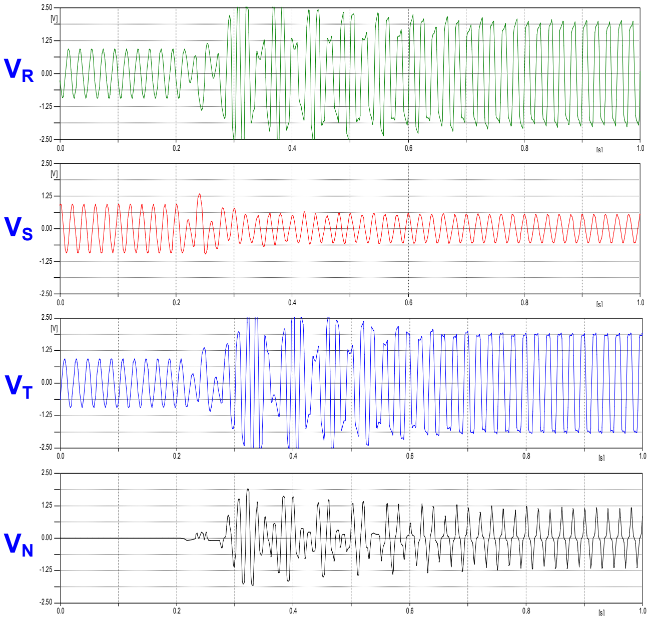

Fig. 7. Simulation results of switching operation in 400kV Substation showing sustained fundamental frequency ferroresonance

C. Parametric Analysis

Further simulations were aimed to analyse the effect of the substation configuration on the occurrence of various ferroresonant modes. For this purpose, the stray capacitance was selected as the variable in a parametric study. This scenario represents the isolation of a set of busbars/bay VTs through the grading capacitance of one circuit breaker while the busbar/bay length is varied. Bifurcation diagrams were then created showing the amplitude of the voltage at the VT's terminals and the type of ferroresonant oscillation observed in the simulation.

Bifurcation diagrams have traditionally been generated using the slow parameter varying approach [6], which facilitates the production of a large amount of simulation results with relatively low computational effort. Despite the higher computation and data post-processing burden, the authors' preferred approach was to run a different simulation for each varied parameter. The advantage of this approach is that breaker operations can be simulated and, therefore, the various ferroresonant modes triggered by switching transients could be detected.

Phase-plane diagrams and Poincaré sections [6] of voltage vs. flux were produced to assist identification of the observed ferroresonant modes. Phase-plane diagrams give an indication of periodicity since periodic signals follow a closed-loop trajectory. The signal's period can be determined by following trajectories in the phase-plane diagram. As an example, one closed loop reveals a fundamental frequency periodic signal; two closed loops reveal a signal period twice the forcing signal's period, and so on. With large number of closed trajectories period identification becomes quite difficult. Poincaré sections can be used to easily identify the signal's period in these cases. In order to create a Poincaré section from a phase-plane diagram the voltage and flux outputs are sampled once per power frequency cycle. This way the number of different states appearing in the Poincaré section becomes a multiple of the forcing signal's period.

A total of 1050 simulations were performed starting from 0pF and increasing the shunt capacitance in steps of 10pF up to 10,500pF. The simulation period was 8s, with the circuit breaker initially closed and opened at t = 0.3s. The output variables were sampled once per power frequency cycle. In order to eliminate switching transients from the sampled output, VT's voltage and flux were brought into TACS and their sampling was initiated at t = 5s. The 0.5Ω damping resistor was not included in any of the parametric simulations. Detailed results are included in the next section.

IV. FERRORESONANT MODES IN HV SUBSTATION

A. *Normal Response*

No ferroresonance was observed for substation capacitance values in the range 10pF-100pF and 950pF-2320pF. Simulation results displayed normal system response with low voltages and currents, similar to the recorded waveforms shown in Fig. 2.

B. *Fundamental Frequency Ferroresonance*

Shunt capacitance values from 110pF to 950pF resulted in a sustained fundamental frequency ferroresonance with waveforms similar to those shown in Fig. 3, which corresponds to a line bay capacitance of 460pF.

Fundamental frequency ferroresonant voltages were above 2pu in all cases, as shown in Fig. 17.

The phase-plane diagram of voltage versus flux, Fig. 8, displays a single loop trajectory. Furthermore, the Poincaré section shown in Fig. 9 consist on one operating point indicating that the response is periodic with the same frequency as the sampling frequency, 50Hz.

C. *Sub-Harmonic Ferroresonant Response*

The first sub-harmonic ferroresonance was found for a substation shunt capacitance of 2320pF. As depicted in the Poincaré section of Fig. 10, the system response was periodic at $1/7^{th}$ of the sampling frequency. This represents a period-7 ferroresonant mode. The distorted ferroresonant voltage waveform is shown in Fig. 11.

No other ferroresonant case was encountered up to a capacitance value of 2590pF, in which the system response exhibited a chaotic behaviour for nearly 4 seconds until it jumped into a normal 50Hz steady state, with low voltages and currents. The Poincaré section and voltage waveform are shown in Fig. 12 and Fig. 13 respectively.

As the substation capacitance was increased further many other spontaneous jumps were detected.

The first sustained sub-harmonic ferroresonance was finally observed again for a shunt capacitance value of 3090pF. The phase-plane diagram in Fig. 14 shows a periodic response, although characterization of the ferroresonant mode is more obvious with the assistance of a Poincaré diagram, Fig. 15, which reveals three clusters of five points each, indicating a period-15 ferroresonance.

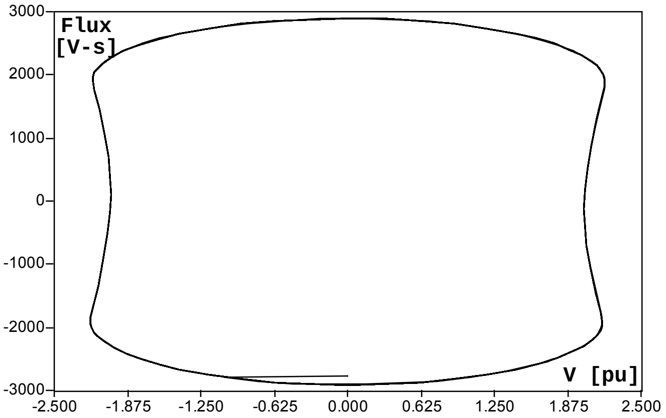

Fig. 8. Phase-plane diagram of voltage vs flux for C_{Shunt}=460pF showing period-1 ferroresonance. Circuit Breaker grading capacitance = 600pF.

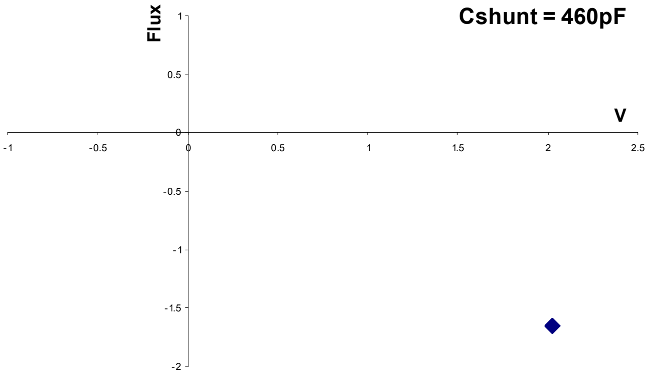

Fig. 9. Poincaré section of voltage for C_{Shunt} = 460pF showing period-1 ferroresonance. Circuit Breaker grading capacitance = 600pF.

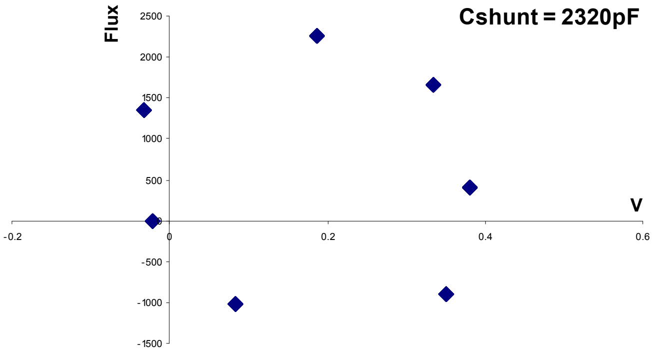

Fig. 10. Poincaré section of voltage for C_{Shunt} =2320pF showing period 7 ferroresonance. Circuit Breaker grading capacitance = 600pF.

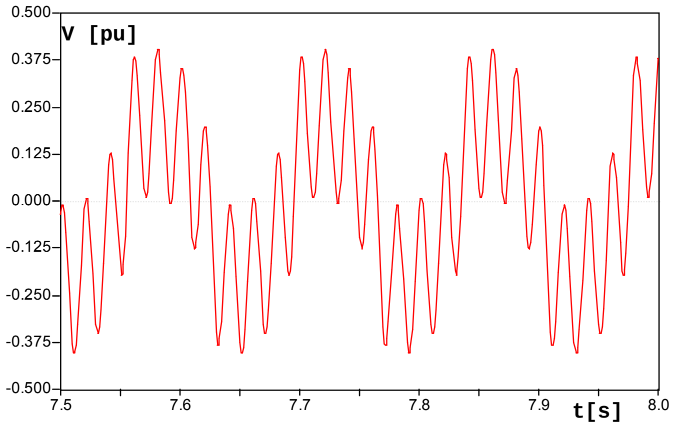

Fig. 11. Phase-R voltage waveform for C_{Shunt} =2320pF showing period-7 ferroresonance. Circuit Breaker grading capacitance = 600pF.

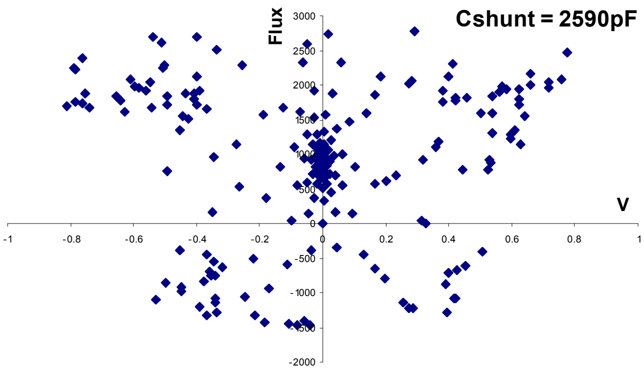

Fig. 12. Poincare section of voltage for C_{Shunt} =2590pF showing chaotic response. Circuit Breaker grading capacitance = 600pF.

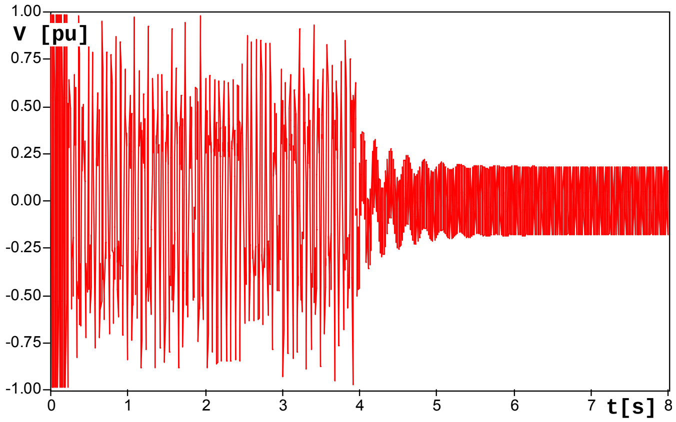

Fig. 13. Phase-R voltage waveform for C_{Shunt} =2590pF showing a jump from chaotic ferroresonance to normal steady state. Circuit Breaker grading capacitance = 600pF.

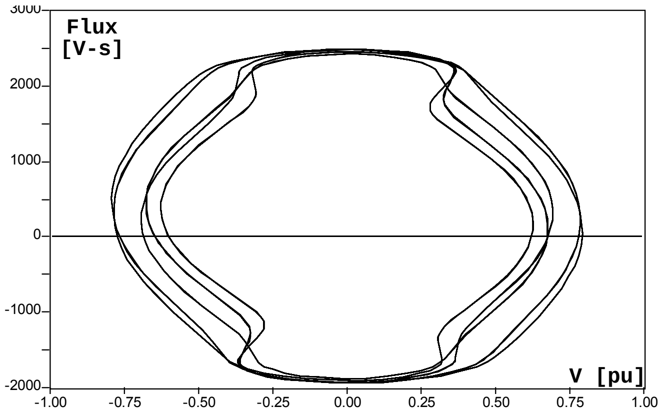

Fig. 14. Phase-plane diagram of voltage vs flux for C_{Shunt}=3090pF showing periodic response. Circuit Breaker grading capacitance = 600pF.

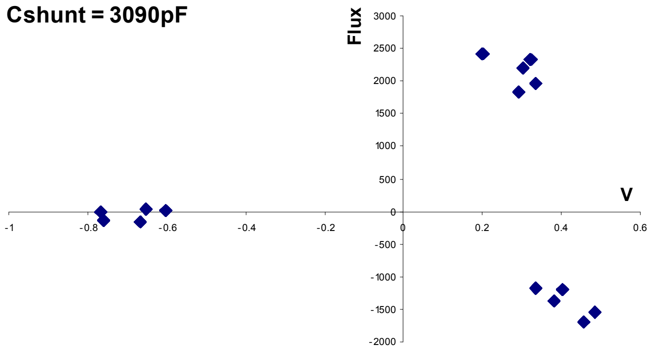

Fig. 15. Poincaré section of voltage for C_{Shunt}=3090pF showing period-15 Ferroresonance

Sustained Period-3 ferroesonance was first encountered for a substation capacitance of 4040pF. Fig. 16 shows the voltage waveforms comparing the normal response in two phases with the ferroresonant response of the remaining phase.

As the substation capacitance was continuously increased the system response was predominantly sub-harmonic with periods of 3, 6, 9 or 15 times the power frequency period.

Simulation results are summarised in Fig. 17.

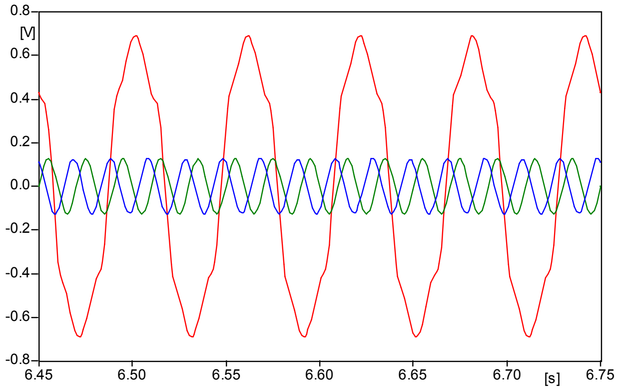

Fig. 16. Line to ground voltages for C_{Shunt}=4040pF showing period-3 ferroresonance in one phase.

V. Discussion of Results

ATP/EMTP simulations as well as field tests have demonstrated the chaotic nature of ferroresonance. Small variations in the model parameters or initial conditions lead to different final steady states, as shown in Fig. 2, Fig. 3 and Fig. 17. This behaviour requires a huge amount of simulations in order to identify each possible ferroresonant mode and to assess the effectiveness of a particular mitigation scheme.

For the particular model parameters under study, which include the VT saturation curve shown in Fig. 6 and a circuit breaker grading capacitance of 600pF, the following was observed:

1 Low values of substation capacitance corresponding to busbar or line bay lengths in the range of 10.5m to 80m resulted in fundamental frequency ferroresonance with line voltages exceeding 2pu. This level of overvoltage can result in damage to other equipment connected to the same circuit such as CTs, surge arresters and open CBs.

2 A safe area corresponding to busbar lengths between 90m and 220m was identified. No ferroresonance was detected in that range.

3 Spontaneous jumps between chaotic oscillations and normal sinusoidal response were observed for shunt capacitance values corresponding to busbar lengths in the range of 250m to 290m. No sustained chaotic ferroresonance was observed in any case.

4 For shunt capacitance values corresponding to busbar lengths between 295m and 1km, the predominant response was sub-harmonic ferroresonance. Amplitude of line voltages were below 1pu, which do not represent a threat to the insulation of other plant equipment. However, VT's magnetic cores were driven into deep saturation with large flux and current, which may result in overheating and damage in the VT core and windings.

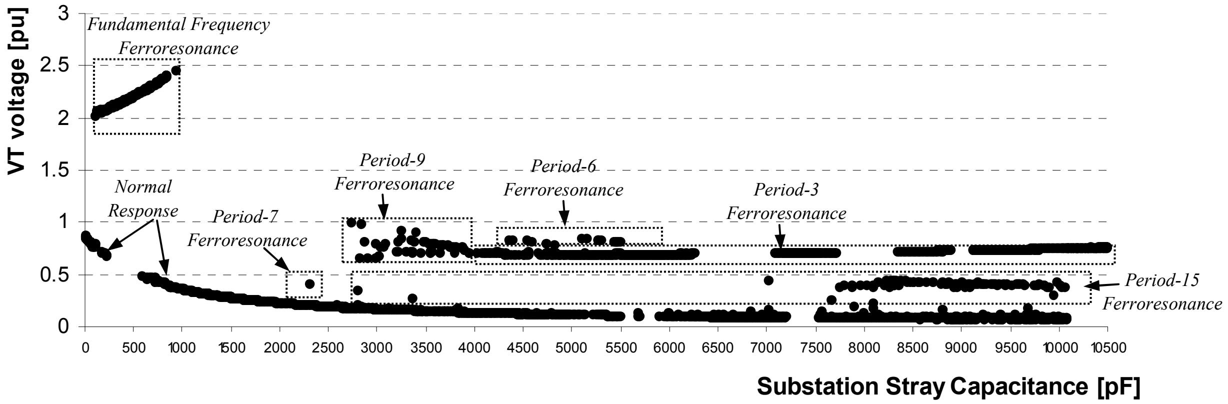

Fig. 17. Bifurcation Diagram: Steady-State Line-to-Ground Voltage as a function of the Substation Stray Capacitance

VI. CONCLUSIONS

A fundamental ferroresonant experience involving inductive VTs in a 400kV substation has been reported. Field measurements have been presented and compared against ATP/EMTP simulation results, showing good agreement.

A parametric analysis has been performed using the substation capacitance as the study variable. Simulation results have shown a variety of system responses and ferroresonant modes as the capacitance was varied. The same methodology can be applied by selecting the circuit breaker grading capacitance as the study variable with the purpose of obtaining a family of bifurcation curves representing each possible substation and switching configuration.

Phase-plane diagrams and Poincaré sections have proved to be very useful tools in the characterisation of ferroresonant modes.

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VIII. BIOGRAPHIES

Marta Val Escudero received her degree of Industrial Electrical Engineer from the University of Zaragoza, Spain, in 1994. From 1994 to 1997 she was with CIRCE (Centre of Research for Energy Resources and Consumption) in Zaragoza. In 1997 she joined ESB International in Dublin, Ireland, where her main working areas include electromagnetic transients, HV insulation co-ordination, short-circuit and load flow analysis, power transfer capability, voltage and frequency control and system stability analysis. She is currently pursuing Mphil studies at the University of Bath (UK) by research of resonant conditions in Power Systems.

Ivan M. Dudurych (M'96, SM'02) received his degree of electrical engineer from the Lviv Polytechnic Institute in 1980 and his Ph D degree from Kyiv Polytechnic Institute in 1990 for his work on analysis of switching transients of 1150 kV OHL. Associate Professor of the National University "Lviv Polytechnic", Ukraine, he was a ESB Newman Scholar at University College Dublin, Ireland from 2001 to 2003. At present he is with Ireland's Transmission System Operator EirGrid, Plc as a senior engineer at Power System Control. His interests include modeling and simulation of electric power systems, their lightning performance and protection, methods and algorithms of power system analysis, problems of deregulation and privatization of electric power industry, incorporation of wind generation into power systems.

Miles Redfern (M' 79) received his BSc degree from Nottingham University and PhD degree from Cambridge University in 1970 and 1976 respectively. In 1970, he joined British Railways Research, and in 1975, moved to GEC Measurements where he held various posts including Head of Research and Long Term Development and Overseas Sales Manager. In 1986, he joined Bath University with research and teaching interests in Power Systems Protection, Control and Industrial Management.