Modeling Ferroresonance in Asymmetric Three-Phase Power Transformers

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***Abstract*—Ferroresonance is a highly dynamic and nonlinear power quality phenomenon notorious for causing severe damage to power systems. The nonlinear inductances in ferromagnetic materials (e.g., transformer core structures) and power system capacitances can sometimes lead to oscillatory ferroresonance modes with large over-voltages and distortions. Largely neglected in system studies is the interaction of ferroresonance with multi-legged three-phase transformer cores, especially with respect to the asymmetric magnetic cross-coupling effects. This paper investigates such nonlinearities by employing a suitable duality-based time-domain model of an asymmetric three-phase nonlinear transformer. The impact of system capacitances and open-phase behavior (e.g., single-phase circuit breaker operation) are analyzed. The seemingly innocuous action of unbalanced switching is shown to cause a wide variety of ferroresonance modes. For a better understanding of the dynamics and stability domain of ferroresonance in asymmetric transformers, bifurcation and phase-plane analysis techniques are applied in this work.**

***Index Terms*—Asymmetric, bifurcation, ferroresonance, harmonics, nonlinear dynamics, power quality, transformer.**

I. Introduction

FERRORESONANCE is one of the longest recognized power quality disturbances in the history of AC power systems. The symptoms of ferroresonance are regarded as most serious and typically result in large currents and over-voltages that can reach in excess of 4 p.u. accompanied with severe waveform distortion. Several blackouts and significant equipment damage have been attributed to ferroresonance in various incidents [1]–[5].

Ferroresonance is known to be caused by the interaction of system capacitances with nonlinear inductances associated with wound magnetic cores in power transformers and instrument voltage transformers. Many stable and unstable operating points (ferroresonance modes) are possible due to the constantly changing transformer inductances during its magnetizing and demagnetizing cycles.

Sources of capacitances can include circuit breakers equipped with grading capacitors, shunt and series transmission line capacitances (overhead and underground) and stray capacitances in transformer windings, bushings, bus bars and feeders. Furthermore, initial conditions and system perturbations play an important role in ferroresonance behavior whereby many operating modes for the same set of system parameters can be observed. Hence, different instances of ac voltage amplitude at breaker operation, load transients and residual core fluxes can initiate widely different ferroresonance behavior [6].

The possible ferroresonance modes which can occur are typically classified into four types: (1) fundamental, (2) subharmonic, (3) quasi-periodic and (4) chaotic modes. Fundamental ferroresonance is characterized by waveforms having a period corresponding to the power system frequency. Subharmonic ferroresonance waveforms have periods that are integer multiples of the system period (nT). Quasi-periodic waveforms are aperiodic with constantly shifting waveform periods. Chaotic waveforms represent unpredictable harmonic rich components resembling broadband noise.

Despite extensive literature and experience in this area, prediction and modeling of ferroresonance remains a challenging task. For a deeper understanding of these complex nonlinear dynamical systems, researchers must resort to more sophisticated mathematical techniques beyond simple time and frequency-domain analysis (e.g., bifurcation, phase-plane and Poincaré analysis [7]–[10]). Furthermore, accurate nonlinear transformer models are essential tools for studying power quality disturbances. To that effect, there has been significant work over the last two decades toward developing improved transformer models for the study of ferroresonance and other power quality phenomena.

One important aspect largely neglected in ferroresonance investigations is the asymmetric core structure and magnetic cross-coupling effects in three-phase multi-leg transformers. Modeling of this behavior is important for a true representation of three-phase transformers and therefore could influence ferroresonance predictions. This paper investigates such nonlinearities by applying a modified asymmetric nonlinear three-phase three-leg transformer model for ferroresonance analysis.

II. Modeling and Analytical Approaches to Ferroresonance Studies

A. Nonlinear Dynamical Systems

A thorough analytical study of ferroresonance is not possible without applying theory founded in nonlinear dynamical and chaotic systems. Mork proposed the connection between ferroresonance and nonlinear dynamical systems and chaos theory in his PhD dissertation and subsequent publications [9], [11]. These mathematical notions best illustrate the many complex ferroresonance modes that can exist in a power system. Such complexities are not obvious in ordinary time and frequency-domain analysis.

One of the key aspects of any nonlinear dynamic system is that many oscillatory modes of operation are possible for the same set of system parameters. This is because of the sensitivity to initial conditions and transients which can excite a system into many different steady-state and chaotic modes.

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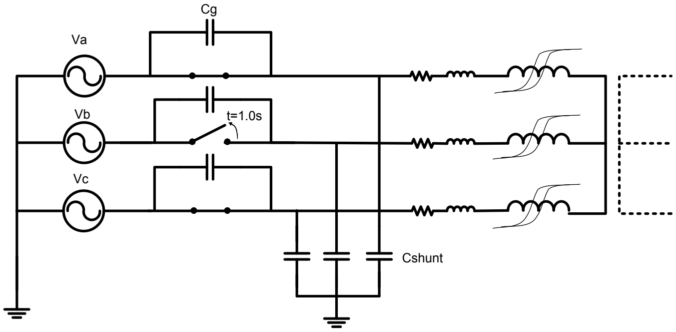


Fig. 1. Ferroresonance circuit with unloaded asymmetric core model

This fact is particularly relevant in modern power systems because variations in circuit breaker operating times, random switching events, phase angle of voltages and residual fluxes are all variable initial conditions which affect how and which ferroresonance mode(s) occur.

Phase-plane diagrams are most useful for characterizing the time evolution of ferroresonance modes. For a given system state variable x (e.g., transformer voltage), the time derivate of this variable $\dot{x}(t)$ is plotted against the variable magnitude $x(t)$ and traced out in time. The shape of resulting trajectories can be interpreted for useful insight into the time evolutionary behavior of a nonlinear dynamical system. A simplified phase-plane representation can be obtained by sampling the state variable at the power system frequency and plotting the points 'stroboscopically' on the phase-plane diagram. This is called a Poincaré map. Drawing accurate conclusions from these diagrams requires good interpretative experience with phase-plane techniques. Reference [10] provides a good introduction to these diagrams and how to analyze them.

Bifurcation diagrams are a useful design tool in identifying system parameter values conducive to ferroresonance. Bifurcation plots demonstrate the effect of varying a system variable (e.g., shunt capacitance) and its impact on observable system outputs (e.g., transformer voltages) which aid in ferroresonance identification. A bifurcation diagram is constructed from a family of Poincaré diagrams computed for a range of system variable values. For this paper, the analytical methods described here are used in conjunction with a suitable nonlinear transformer model.

B. Existing Modeling Approaches

There has been significant work performed on developing transformer models for ferroresonance investigations [7], [12]–[34]. Most of the effort is directed towards instrument voltage transformers (VTs) or single-phase power transformers with very few attempts at modeling three-phase transformers. The most appropriate approach is by time-domain analysis using software packages such as Electromagnetic Transient Package (EMTP), MATLAB simulink and PSPICE/PSIM. These software packages typically employ numerical integration time stepping algorithms to solve the nonlinear differential equations describing circuit behavior. The nonlinear $\lambda - i$ characteristics of ferromagnetic materials is typically represented by piece-wise functions or mathematical functions.

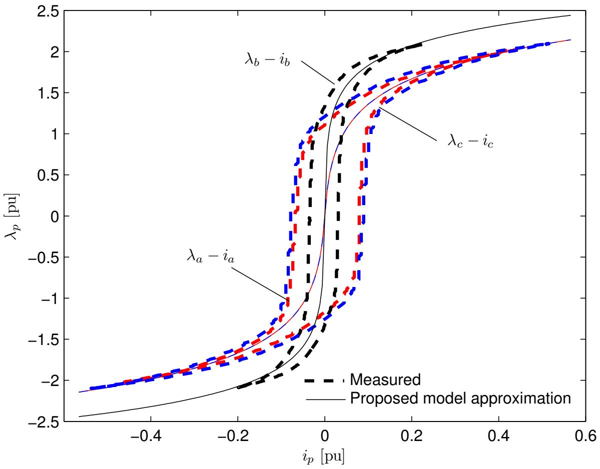


Fig. 2. Measured asymmetric $\lambda_p - i_p$ characteristics for transformer model

C. Proposed Modeling Approach

Multi-leg transformers such as the commonly used three-leg and five-leg designs have multiple flux paths with unique path lengths giving rise to asymmetry in the core structure. Therefore, it is necessary to account for this nonlinearity in the transformer model because there is an interaction due to magnetic cross-coupling across the phases. Such interaction could affect the formation of ferroresonance in asymmetric transformers. There have been few attempts at modeling asymmetric nonlinearities [35]–[40] but none as yet have been applied to ferroresonance analysis. Previous ferroresonance research with multi-leg transformers were based on symmetric leg magnetizing behavior.

For this paper, an asymmetric transformer model for three-phase three-leg cores is implemented with coupled electric and magnetic circuit equivalents (duality principle). A time-domain solution of nodal equations is computed by the Newton-Raphson numerical technique. In the magnetic circuit, the asymmetric nonlinear behavior of each core leg is approximated by the newly defined $\phi(f)$ logarithmic function

$$\phi(f) = \mathrm{sgn}(f) \cdot \alpha \log(\beta |f| + 1) \tag{1}$$

This function has the advantage of only having two fitting parameters α and β, which were determined by trial-and-error based on measured $\lambda - i$ characteristics for this paper. The function is fitted to individual legs true $\phi(f)$ magnetizing characteristics of a real power transformer (Figs. 1-2). The asymmetric $\lambda - i$ measurements from a laboratory transformer were obtained using the technique proposed by [41].

The electrical equivalent circuit includes the lossy elements of the transformer (core-losses R_c and ohmic winding losses R_Ω) and the leakage flux inductances (L_p, L_s). The induced voltages (e_p, e_s) are modeled from Faraday's Law using voltage sources controlled by the time derivate of fluxes linking directly to the magnetic circuit (Figs. 1-2, [38]). The parameters of the electrical equivalent circuit can be obtained from three-phase open and short circuit tests.

III. SIMULATION RESULTS AND ANALYSIS

Simulation results computed from the implemented nonlinear asymmetric transformer model are presented here. Simulations are performed for a three-phase transformer (1.6 kVA, 440/55 V, 50 Hz, Y-Y connection) with measured $\lambda - i$ characteristics (Fig. 2). The scenarios explored in the following sections are for an open-phase condition at $t = 1.0s$ for phase B during steady-state no-load operating conditions. This is typical of a single-phase fault being cleared by circuit breaker or fuse operation. The system capacitances (Fig. 1) consist of series circuit breaker grading capacitors and shunt capacitances (e.g., transmission line reactances).

A. Bifurcation Analysis for $C_{shunt} = 0.2 - 50\mu F$

A useful and effective approach for identifying system parameters conducive to ferroresonance is carried out through bifurcation analysis. The shunt capacitance is chosen as the system variable and the primary phase voltage is studied. The simulation is repeated for C_{shunt} ranging from 0.2 μF to 50 μF in 0.2 μF steps under the same single-phase fault clearing condition. For each simulation set, the primary voltages for the open phase (B) are sampled at the power system frequency and plotted on the bifurcation diagram (Fig. 3). The other phases produce similar bifurcation diagrams to Fig. 3 and are therefore omitted. In addition to voltage waveforms, the flux and magnetizing current waveforms are also computed.

Figs. 4-8 show the system behavior for selected C_{shunt} values conducive to ferroresonance as identified from Fig. 3. The phase-plane plots are derived from the time-domain simulations of the nonlinear transformer and cover the period just before circuit breaker operation to several seconds after. On the other hand, to clearly illustrate how the system evolves some time after circuit breaker operation, the bifurcation plot and Poincaré sections do *not* cover the transient period at breaker operation time.

B. Fundamental Ferroresonance: $C_{shunt} = 0.6\mu F$

Fig. 4 demonstrates the occurrence of fundamental ferroresonance for $C_{\text{shunt}} = 0.6\mu$F. The phase-plane diagram shows the system settling to what is known as a stable cyclic attractor. Steady-state oscillations corresponding to the fundamental forcing frequency is the most common behavior expected in all nonlinear dynamical systems as demonstrated here. In this case, the voltage waveforms exhibit fundamental ferroresonance evident from the single cluster of Poincaŕe points. The periodic non-circular nature of the phase-plane trajectories indicate the presence of voltage harmonics. The open-phase condition causes a flux imbalance in the transformer core. As a matter of fact, the leg fluxes in the open-phase rise and saturate the core which influence ferroresonance distortions (Fig. 4a).

C. Nominal Operation: $C_{shunt} = 5\mu F$

Fig. 3 indicates sporadic regions where no ferroresonance occurs. For example, if $C_{\text{shunt}} = 5\mu$F the voltage waveforms quickly settle to stable sinusoidal behavior (Fig. 5). Therefore, it is said that the system returns to a single stable attracting limit cycle.

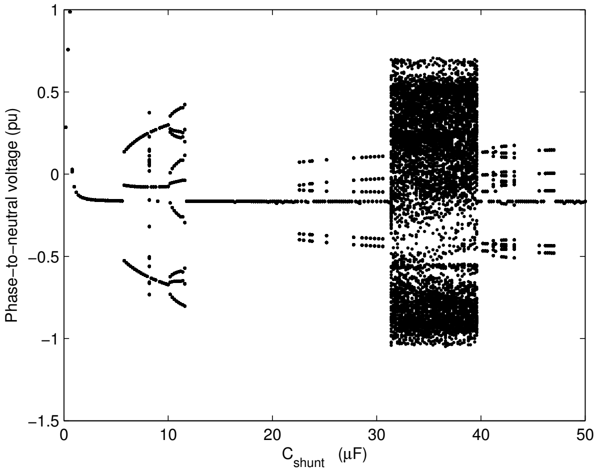
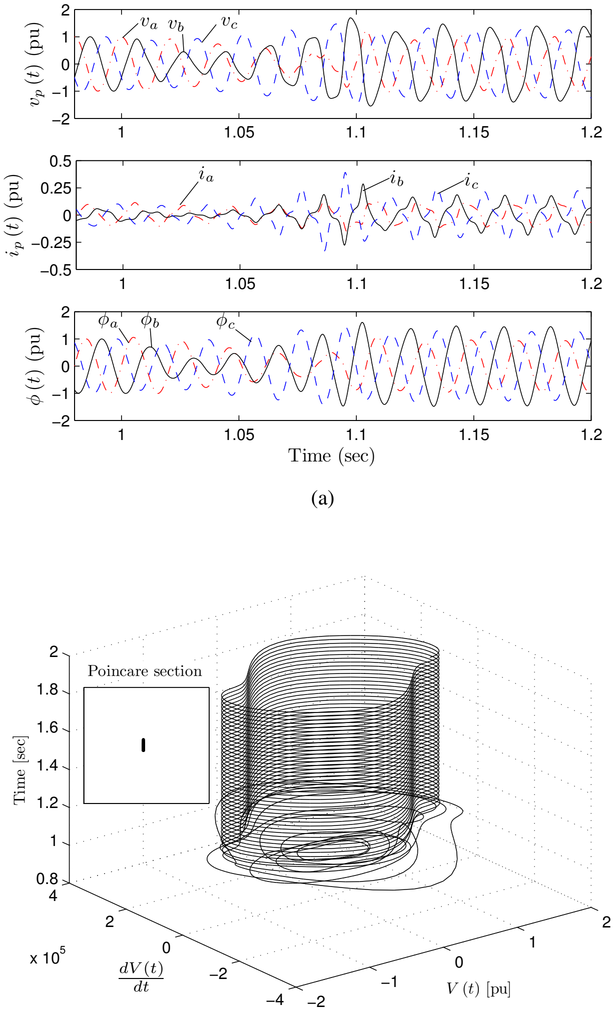


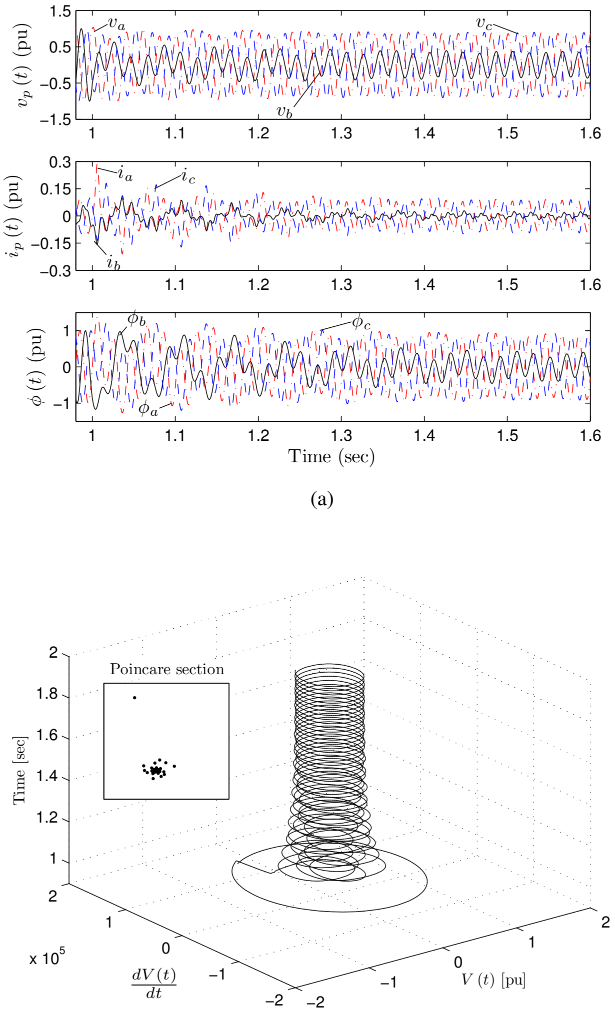
Fig. 3. Bifurcation diagram of primary phase voltage response (V_{pb})



(a)

(b)

Fig. 4. Fundamental ferroresonance occurring at $C_{\text{shunt}} = 0.6\mu$F; (a) time-domain waveforms indicating a flux imbalance in the transformer core, (b) phase-plane diagram showing the system settling to a stable cyclic attractor.



(a)

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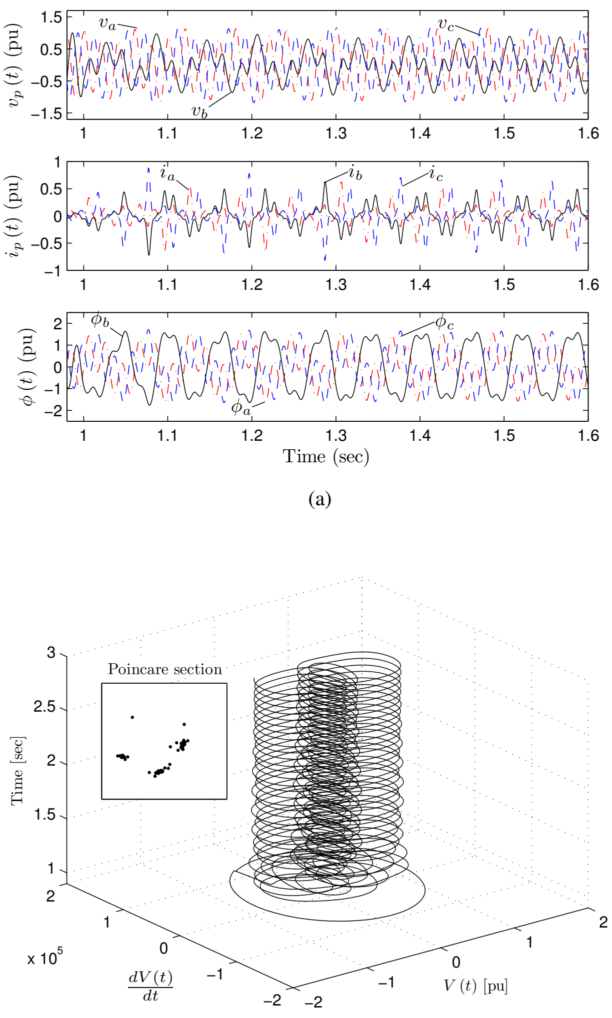
Fig. 5. Nominal case (after circuit breaker opening) with no ferroresonance occurring at $C_{\text{shunt}} = 5\mu$F; (a) time-domain waveforms indicating the system quickly settling to stable sinusoidal behavior, (b) phase-plane diagram showing the system returning to a single stable attracting limit cycle.



(a)

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Fig. 6. Period-3 subharmonic ferroresonance occurring at $C_{\text{shunt}} = 10\mu$F; (a) time-domain waveforms showing the flux and magnetizing current waveforms exhibit asymmetric nonsinusoidal behavior, (b) phase-plane diagram indicating the initial transitory period after circuit breaker operation and the subsequent oscillations due to at least two competing cyclic attractors.

D. *Subharmonic Ferroresonance: $C_{shunt} = 10\mu F$ and $30\mu F$*

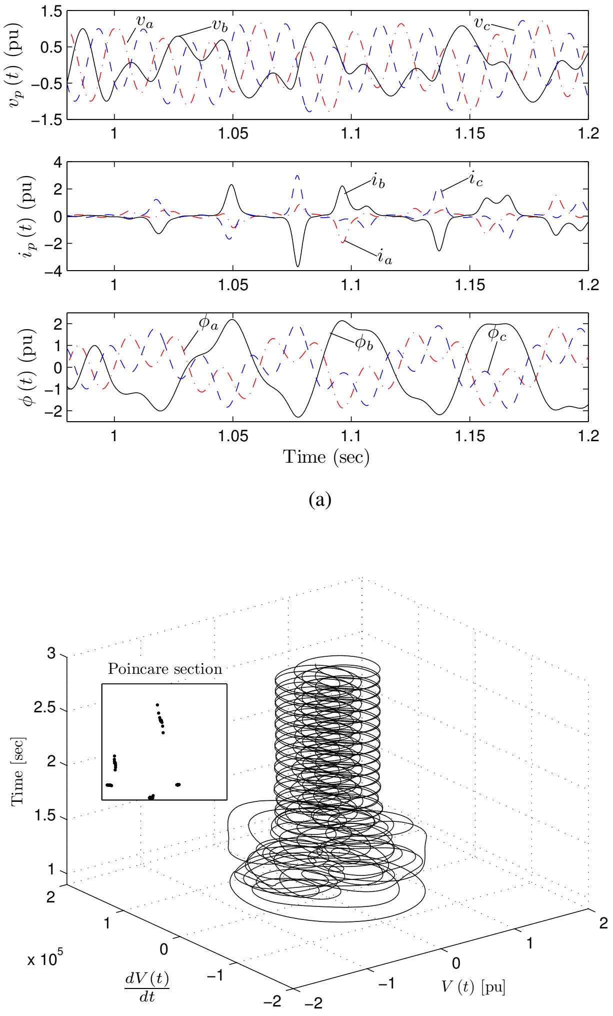
Period-3 subharmonic ferroresonance is shown in Fig. 6 for $C_{\text{shunt}} = 10\mu$F. This is indicated by the formation of three groups of Poincaré points. The phase-plane projections show the initial transitory period after the simulated circuit breaker operation and the subsequent oscillations due to at least two competing cyclic attractors. Similarly, period-5 subharmonic ferroresonance is simulated in Fig. 7 for $C_{\text{shunt}} = 30\mu$F. The transient period is sustained for a longer duration than the previous case before settling between competing cyclical attracting states. In both cases, the flux and magnetizing current waveforms exhibit asymmetric nonsinusoidal behavior.

E. *Quasi-periodic Ferroresonance: $C_{shunt} = 38\mu F$*

The bifurcation diagram (Fig. 3) highlights a region of highly dynamic ferroresonance modes for C_{shunt} values between 32μF to 40μF. The phase-plane trajectories and Poincaré sections have a non-repeating structure which suggests aperiodicity. The question remains whether this system is chaotic or quasi-periodic. By closer inspection of the phase-plane portrait for this system (Fig. 8), nearby trajectories do not appear to diverge exponentially which suggests the system is not chaotic, but quasi-periodic. This quasi-periodicity is due to weakly coupled incommensurate modes of oscillations which result in aperiodic behavior.

IV. CONCLUSION

A new analysis of the stability domain of ferroresonance in three-phase three-leg transformers has been performed using a time-domain nonlinear asymmetric transformer model. The developed model is capable of computing a number of useful outputs such as phase-plane trajectories, Poincaré maps and bifurcations. Furthermore, time-domain waveforms of fluxes, voltages and magnetizing currents can be computed under



(a)

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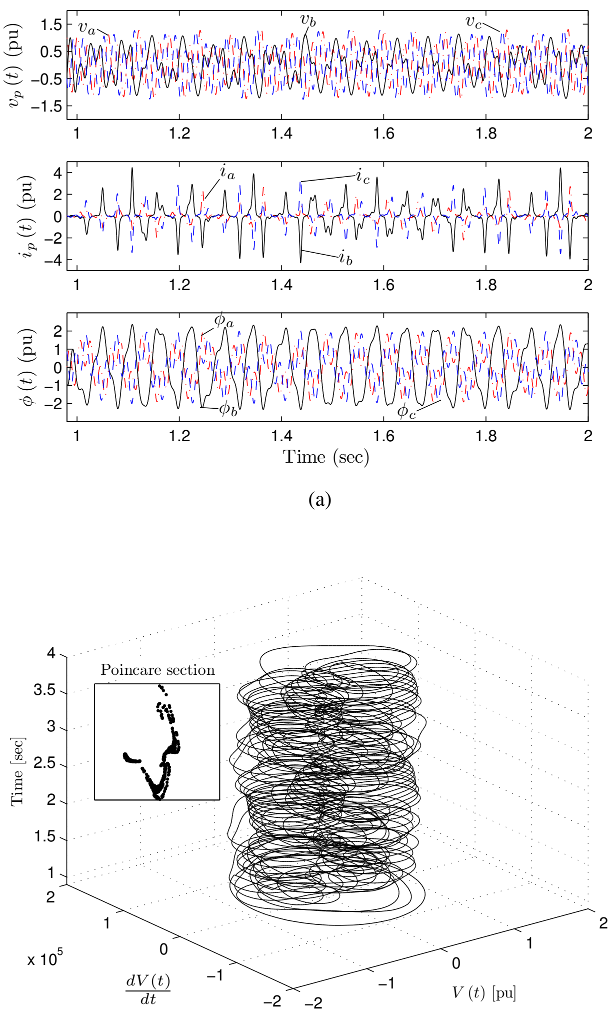
Fig. 7. Period-5 subharmonic ferroresonance occurring at $C_{\text{shunt}} = 30\mu\text{F}$; (a) time-domain waveforms, (b) phase-plane diagram.



(a)

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Fig. 8. Quasi-periodic ferroresonance occurring at $C_{\text{shunt}} = 38\mu\text{F}$; (a) time-domain waveforms, (b) phase-plane diagram.

ferroresonance conditions. Several interesting case studies are presented demonstrating different ferroresonance modes for an open-phase condition. The main observations of this paper are:

- Ferroresonance under unbalanced open-phase conditions can cause asymmetric core saturation compounding ferroresonance distortions.
- Magnetic coupling in multi-leg transformer cores may influence ferroresonance modes and therefore should not be ignored in transformer models.
- The approach adopted in this paper can be used for design purposes to identify system parameters (e.g., capacitance) conducive to ferroresonance.

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