

Studying Voltage Transformer Ferroresonance

¹Hamid Radmanesh and ²Hamid Fathi

¹Electrical Engineering Department, Islamic Azad University, Takestan Branch, Takestan, Ghazvin, Iran

^{1,2}Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

Abstract: This study studies the effect of Circuit Breaker Shunt Resistance (CBSR), Metal Oxide Varistor (MOV) and Neutral earth Resistance (NR) on the control of ferroresonance in the voltage transformer. It is expected that NR can controlled ferroresonance better than MOV and CBSR. Study has been done on a one phase voltage transformer rated 100 VA, 275 kV. The simulation results reveal that considering the CBSR and MOV exhibits a great mitigating effect on ferroresonance overvoltages, but these resistances cannot control these phenomena for all range of parameters. By applying NR to the system structure, ferroresonance has been controlled and its amplitude has been damped for all parameters values.

Keywords: Bifurcation diagram, chaos, Circuit Breakers Shunt Resistance (CBSR), ferroresonance, MOV, Neutral earth Resistance (NR), voltage transformers

INTRODUCTION

Ferroresonance overvoltage on electrical power systems were recognized and studied as early as 1930s. Kieny first suggested applying chaos to the study of ferroresonance in electric power circuits (Kieny, 1991). He studied the possibility of ferroresonance in power system, particularly in the presence of long capacitive lines as highlighted by occurrences in France in 1982 and produced a bifurcation diagram indicating stable and unstable areas of operation. Special ferroresonance phenomena on 3-phase 66 kV VT-generation of 20 Hz zero sequence continuous voltage is given in Nishiwaki *et al.* (2007). Voltage transformer ferroresonance from an energy transfer standpoint is given in Andrei *et al.* (1989). In this paper, a new approach to determine whether ferroresonance can occur is developed based on the energy transferred from the system to the voltage transformer during the switching transient. Discussion of modeling and analysis guidelines for slow transients has been studied in Xusheng (2003). Transformer models for transient studies based on field measurements are investigated in DICK and WATSON (1981). Digital simulation of transient in power system has been done in (Dommel *et al.*, 1983). Application of nonlinear dynamics and chaos to ferroresonance in the distribution systems can be found in Mork and Stuehm (1994). Fast ferroresonance suppression of Coupling Capacitor Voltage Transformers (CCVT) was done in Graovac *et al.* (2003). This paper describes a procedure for fast suppression of the phenomenon of ferroresonance in CCVT without major change in the CCVT design. It will

be shown that it is possible to adjust parameters of the secondary overvoltage protection and the filter circuit so that the ferroresonance can be cleared in very short time interval. Modeling iron core nonlinearities has been illustrated in Neves and Dommel (1993). Mozaffari has been investigated the ferroresonance in power transformer and effect of initial condition on these phenomena, he analyzed condition of occurring chaos in the transformer and suggested the reduced equivalent circuit for power system including power switch and trans (Mozaffari *et al.*, 1997; Mozaffari *et al.*, 1995). The mitigating effect of transformer connected in parallel to a MOV has been illustrated in Al-Anbarri *et al.* (2001). Analysis of ferroresonance in voltage transformer has been investigated in Al Zahawi *et al.* (1998) and Emin *et al.* (1997). Ferroresonance conditions associated with a 13 kV voltage regulator during back-feed conditions are given in Shoup *et al.* (2007). Performance of various magnetic core models in comparison with the laboratory test results of a ferroresonance test on a 33 kV voltage transformer investigated in Rezaei-Zare *et al.* (2007). Mitigating ferroresonance in voltage transformers in ungrounded MV networks has been reported in Piasecki *et al.* (2007). An approach for determining the subsystem experiencing and producing a bifurcation in a power system dynamic model has been reported in Ben-Kilani and Schlueter (2000). Current paper compares the effect of MOV and CBSR on the global behavior of a VT ferroresonance and finally controlling ferroresonance for all possible ranges of parameters by considering NR resistance.

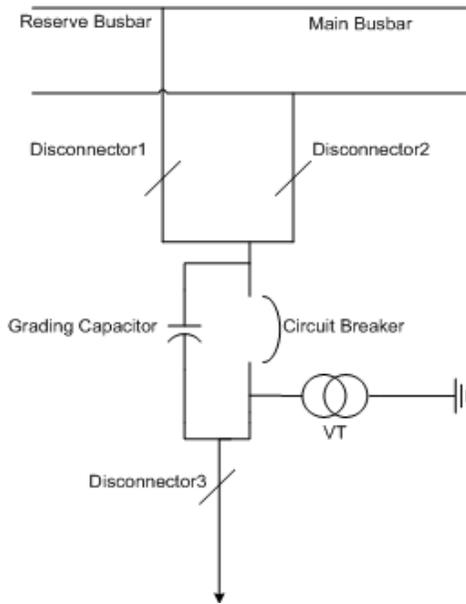


Fig. 1: System one line diagram arrangement resulting to VT ferroresonance (Radmanesh and Rostami, 2010)

Power system description without connecting CBSR and MOV: During VT ferroresonance some oscillations occur between the nonlinear iron core inductance of the VT and capacitances of the power system. So, energy is coupled to the nonlinear core via the open Circuit Breaker Grading (CBG) capacitance or system capacitance (Radmanesh and Rostami, 2010). The result may be saturation in the VT core and very high ferroresonance overvoltage up to 4 p.u can gain in worst case conditions. Figure 1 shows the single line diagram of the system arrangement that can give rise to VT ferroresonance (Radmanesh and Rostami, 2010). Ferroresonance can occur upon opening of disconnector 3 with CB open and

either disconnector 1 or 2 closed. Alternatively it can also occur upon closure of both disconnector 1 or 2 with circuit breaker and disconnector 3 open.

The system arrangement shown in Fig. 1 can effectively be reduced to an equivalent circuit as shown in Fig. 2, while MOV and CBSR are added to the initial ferroresonance circuit.

In Fig. 2, E is the rms supply phase voltage, C_{series} is the CBG capacitance and C_{shunt} is the total phase-to-earth capacitance of the power system. The resistor R represents VT core losses. The MOV and CBSR have been added to the initial equivalent circuit. In the peak current range for steady-state operation, the flux-current linkage can be approximated by a linear characteristic such as $i_L = a\lambda$ where the coefficient of the linear term (a) corresponds closely to the reciprocal of the inductance ($a \approx 1/L$) (Radmanesh and Rostami, 2010). However, for very high currents the iron core might be driven into saturation and the flux-current characteristic becomes highly nonlinear, here $\lambda-i$ the characteristic of the voltage transformer is modeled as in Radmanesh and Rostami (2010) by the polynomial:

$$i = a\lambda + b\lambda^7 \quad (1)$$

where, $a = 3.14$, $b = 0.41$

Because of the nonlinear nature of the transformer magnetizing characteristics, the behavior of the system is extremely sensitive to change in the system parameter and initial conditions. A small change in the value of system voltage, capacitance or losses may lead to dramatic change in the behavior of it.

System dynamic and equation: Equations of the system can be presented as below:

$$e = \sqrt{2}E \sin(\omega t) \quad (2)$$

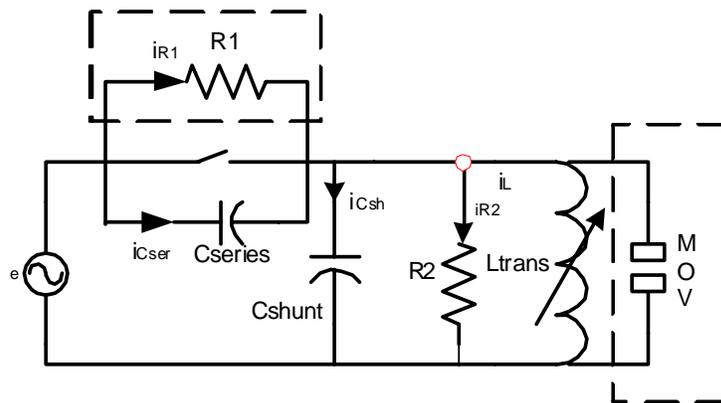


Fig. 2: Equivalent ferroresonance circuit with MOV and CBSR

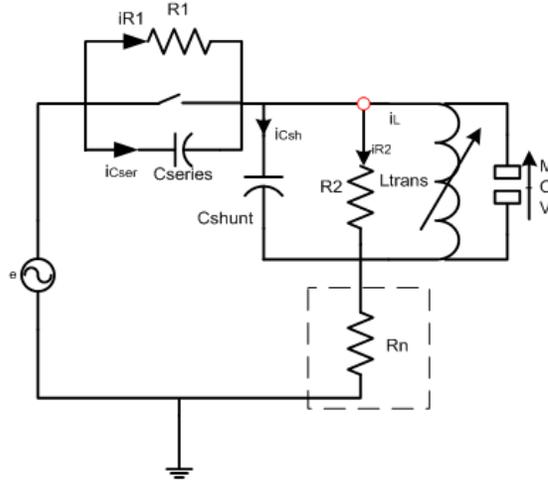


Fig. 3: Basic reduced equivalent ferroresonance including NR

$$i_L = a\lambda + b\lambda^7 \tag{3}$$

$$v_L = \frac{d\lambda}{dt} \tag{4}$$

$$i_{Mov} = \left(\frac{v_L}{K}\right)^\alpha \tag{5}$$

$$\left(\frac{C_{ser}}{C_{ser} + C_{sh}}\right) \sqrt{2} \omega E \cos(\omega t) + \left(\frac{1}{R_{C.B}(C_{ser} + C_{sh})}\right) \sqrt{2} E \sin(\omega t) = \frac{d\lambda}{dt} \left(\frac{R + R_{C.B}}{R R_{C.B}(C_{ser} + C_{sh})}\right) + \frac{d^2 \lambda}{dt^2} + \frac{1}{C_{ser} + C_{sh}} (a\lambda + b\lambda^7) + \left(\frac{1}{k}\right)^\alpha \left(\frac{d\lambda}{dt}\right)^\alpha \tag{6}$$

where, ω is supply frequency.

Power system configuration considering neutral earth

resistance: The primary purpose of inserting impedance between the star point of a VT and earth is to limit ferroresonance current. The value of impedance required is easily calculated to a reasonable approximation by dividing the rated phase voltage by the rated phase current of the VT. NR is conventionally achieved using resistors rather than inductors, so as to limit the tendency for the fault arc to persist due to inductive energy storage. These resistors will dissipate considerable heat when ferroresonance current flows and are usually only short term rated, so as to achieve an economic design. Due to the explanation above, In Fig. 3, R_n is the NR. Typical values for various system parameters has been considered for simulation were kept the same by the case 1, while NR has been added to the system and its value is given below:

$$R_{neutral} = 50 \text{ k}\Omega$$

Nonlinear equation of this circuit is given in (7).

$$C_{Series} C_{Shunt} R_n \frac{d^2 v_L}{dt^2} = C_{Series} \sqrt{2} E \omega \cos(\omega t) + \frac{1}{R_1} \sqrt{2} E \sin(\omega t) - C_{Series} \frac{dv_L}{dt} - C_{Series} R_n a \frac{d\lambda}{dt} - C_{Series} R_n b q \lambda^6 \frac{d\lambda}{dt} - C_{Series} \frac{R_n}{R_2} \frac{dv_L}{dt} - C_{Series} R_n \left(\frac{1}{k}\right)^\alpha \omega v_L^{\alpha-1} \frac{dv_L}{dt} + \frac{v_L}{R_1} + \frac{R_n}{R_1} \left(C_{Shunt} \frac{dv_L}{dt} + a\lambda + b\lambda^7 + \left(\frac{v_L}{k}\right)^\alpha + \frac{v_L}{R_2} \right) - C_{Shunt} \frac{dv_L}{dt} - \frac{v_L}{R_2} - (a\lambda + b\lambda^7) - \left(\frac{v_L}{k}\right)^\alpha \tag{7}$$

For the initial conditions, we have:

$$\lambda(0) = 0.0; \quad v_1 = \frac{d\lambda}{dt}(0) = \sqrt{2} \tag{8}$$

SIMULATION RESULTS

Equation (6) and (7) contain a nonlinear term and do not have simple analytical solution. So the equations were solved numerically using an embedded Runge-Kutta-Fehlberg algorithm with adaptive step size control. In this analysis values of C_{series} and C_{shunt} were given in Table 2. Also, base value of the power system is Table 1.

VT simulation without MOV and CBSR effect: An example of chaotic ferroresonance conditions is presented in Fig. 4 and 5 showing waveform and phase space for ferroresonance case.

Table 1: Base values of the system used for simulation

Base value of input voltage	275/sqrt(3) kV
Base value of volt-amperes	100 VA
Base angular frequency	2π50 rad/sec

Table 2: Parameters used for various states simulation

Parameters	C_{series} (nf)	C_{shunt} (nf)	R_{core} (M)	R_n (k)	ω (rad/sec)	E (kV)
Value	3	0.1	1900	50	314	275

In Fig. 4 System behavior is completely chaotic and ferroresonance overvoltages reach to 5 p.u. In the equal condition, by applying CBSR, this overvoltage has been damped and behavior of system goes to the linear region. According to the Fig. 5 system behavior is chaotic and voltage on the VT is reached to 5 p.u.

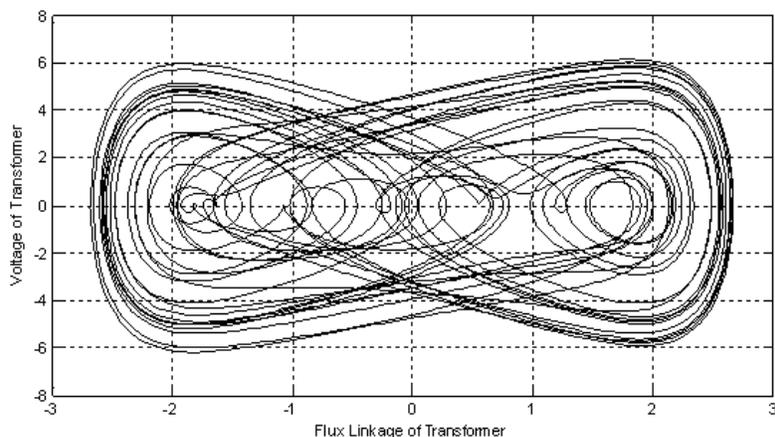


Fig. 4: Phase plan diagram for chaotic ferroresonance motion without MOV and CBSR

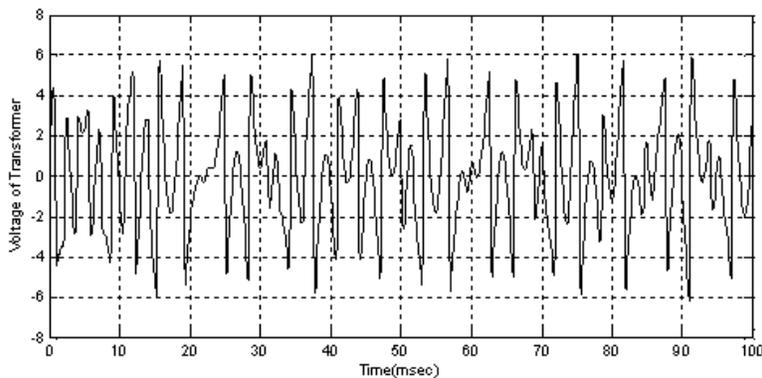


Fig. 5: Time domain simulation for chaotic ferroresonance motion without MOV and CBSR

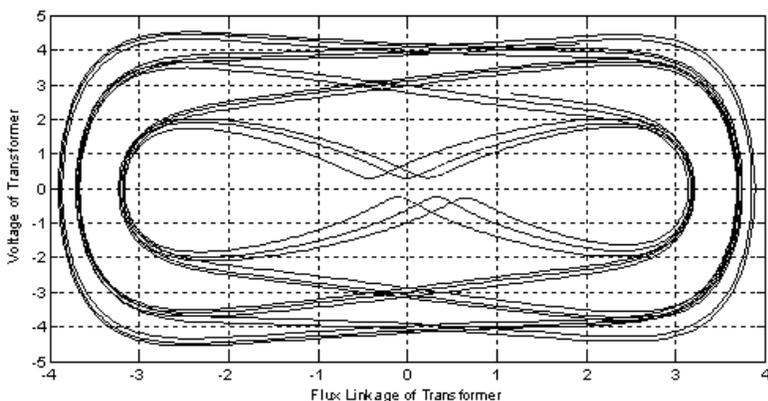


Fig. 6: Phase plan diagram for period 9 motion considering CBSR effect

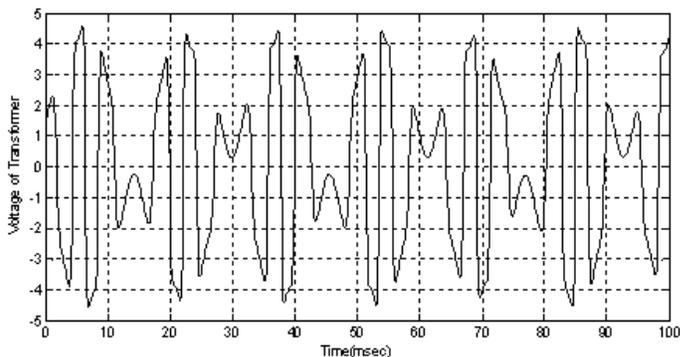


Fig. 7: Time domain simulation for period 9 motion considering CBSR effect

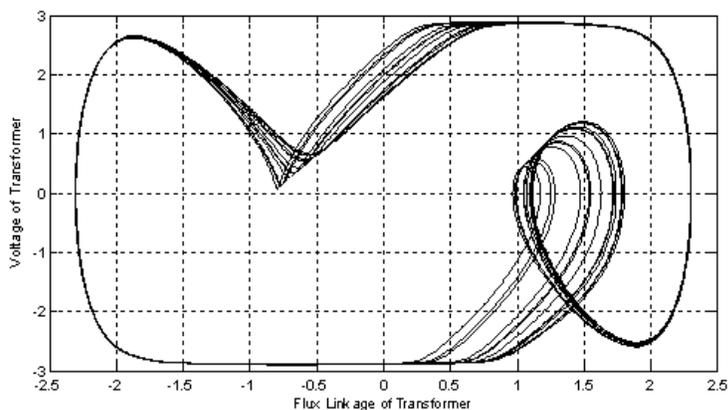


Fig. 8: Phase plan diagram for fundamental oscillation

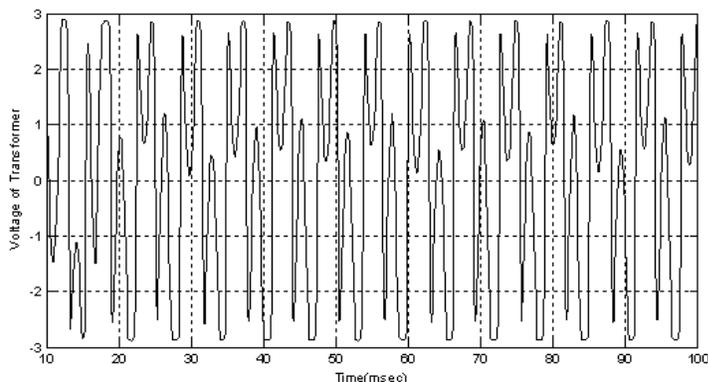


Fig. 9: Time domain simulation for fundamental oscillation

VT simulation applying CBSR: An example of period 9 oscillations is presented in Fig. 6 and 7. Amplitude of this resonance is reached to 5 p.u with period 9 oscillation.

Figure 7 shows time domain simulation which represent the fundamental and subharmonic wave for $E = 1$ p.u. By comparing the simulation result with the previous simulation, the effect of CBSR on system

behavior and clamps chaotic ferroresonance is clearly obvious.

VT simulation applying MOV: An example of fundamental oscillation is presented in Fig. 8 and 9. Corresponding phase plan diagrams has been shown the apparent the MOV effect for $E = 1$ p.u. It is obviously shows that MOV clamps the ferroresonance overvoltage

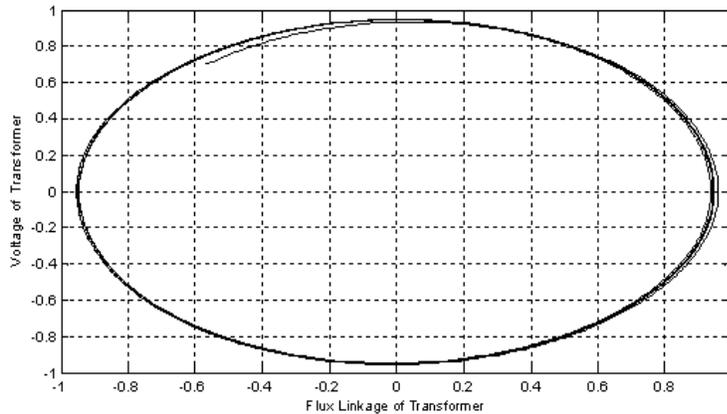


Fig. 10: Phase plan diagram for periodic motion considering MOV, CBSR and NR effects

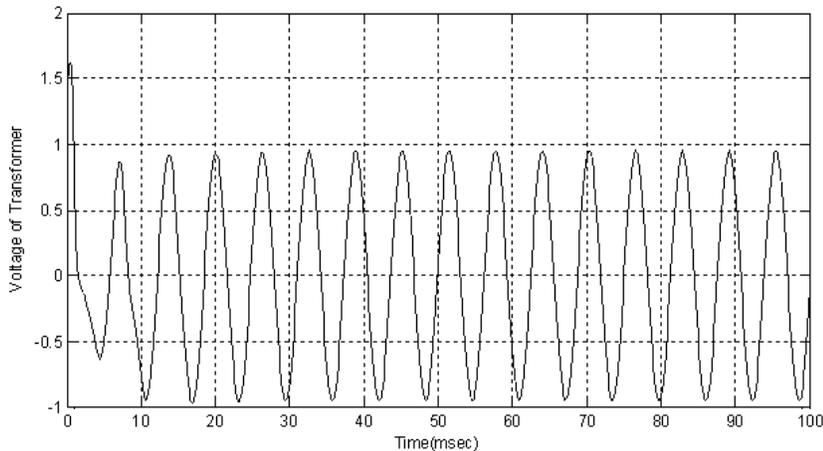


Fig. 11: Time domain simulation for periodic motion considering MOV, CBSR and NR effects

and keeps it in $E = 2.5$ p.u. Controlling effect of MOV is better than CBSR effect. In this case, amplitude of the overvoltages is 2.5 p.u which shows clearer response than CBSR effect.

VT simulation considering CBSR, MOV and NR effects: Normal periodic oscillations conditions is presented in Fig. 10 and 11.

Figure 10 and 11 clearly show the effect of NR on the control of ferroresonance in VT. By comparing this case with the previous case of simulation, it is shows that subharmonic resonance has been changed to the periodic oscillation. By considering MOV and CBSR, system shows better oscillations and overvoltage decreases.

CONCLUSION

Low capacity VTs fed through CBG capacitance have been shown to exhibit fundamental frequency and chaotic ferroresonance conditions similar to high capacity power transformers fed via capacitive coupling from neighboring sources. It has been shown that CBSR can

cause ferroresonance drop out and can control it. Also, MOV can cause ferroresonance drop out for some ranges of parameters value, but these two resistances cannot control ferroresonance for wide range of parameters. By considering both of them, ferroresonance can be better controlled. By connecting NR to the system configuration, ferroresonance has been controlled for all values of system parameters and chaotic ferroresonance doesn't appear. A comprehensive understanding of the possibilities that exist for ferroresonance is very desirable for engineers so that they can operate their systems outside dangerous regions and can plan the expansion of systems without enhancing the possibility of ferroresonance.

REFERENCES

- Al-Anbarri, K., R. Ramanujam, T. Keerthiga and K. Kuppusamy, 2001. Analysis of nonlinear phenomena in MOV connected transformers. IEE Proc. Gener. Transm. Distr., 48: 562-566.

- Al Zahawi, B.A.T., Z. Emin and Y.K. Tong, 1998. Chaos in ferroresonant wound voltage transformers: Effect of core losses and universal circuit behavioral. *IEE Proc. Sci. Measurement Technol.*, 145: 39-43.
- Andrei, R.G. and B.R. Halley, 1989. Voltage transformer ferroresonance from an energy transfer standpoint. *IEEE T. Power Deliver.*, 4(3): 1773-1778.
- Ben-Kilani, K. and R.A. Schlueter, 2000. An Approach for determining the subsystem experiencing and producing a bifurcation in a power system dynamic model. *IEEE T. Power. Syst.*, 15(3): 1053-1061.
- Dick, E.P. and W. Watson, 1981. Transformer models for transient studies based on field measurements. *IEEE T. Power. Deliver.*, PAS, 100(1): 409-419.
- Dommel, H.W., A. Yan, R.J.O. De Marcano, A.B. Miliiani, 1983. Tutorial Course on Digital Simulation of Transients in Power Systems. IISc, Bangalore, (Chapter 14), pp: 17-38.
- Emin, Z., B.A., T. Al Zahawi, D.W. Auckland and Y.K. Tong, 1997. Ferroresonance in electromagnetic voltage transformers: A study based on nonlinear dynamics. *IEE Proc. Gener. Transm., Distr.*, 144(4): 383-387.
- Graovac, M., R. Iravani, Xiaolin Wang and R.D. McTaggart, 2003. Fast ferroresonance suppression of coupling capacitor voltage transformers. *IEEE T. Power Deliver.*, 18(1): 158-163.
- Kieny, C., 1991. Application of the bifurcation theory in studying and understanding the global behavior of a ferroresonant electric power circuit. *IEEE T. Power Deliver.*, 6: 866-872.
- Mork, B.A. and D.L. Stuehm, 1994. Application of nonlinear dynamics and chaos to ferroresonance in distribution systems. *IEEE T. Power Deliver.*, 9: 1009-1017.
- Mozaffari, S., S. Henschel and A.C. Soudack, 1995. Chaotic ferroresonance in power transformers. *Proc. IEE Gener. Transm. Distr.*, 142: 247-250.
- Mozaffari, M., Sameti and A.C. Soudack, 1997. Effect of initial conditions on chaotic ferroresonance in power transformers. *IEE Proc. Gener. Transm. Distr.*, 144: 456-460.
- Neves, W.L.A. and H. Dommel, 1993. On modeling iron core nonlinearities. *IEEE T. Power. Syst.*, 8: 417-425.
- Nishiwaki, S., T. Nakamura and Y. Miyazaki, 2007. A Special Ferro-resonance Phenomena on 3-phase 66kV VT-generation of 20Hz zero sequence continuous voltage. Presented at the International Conference on Power Systems Transients (IPST'07), in Lyon, France.
- Piasecki, W., M. Florkowski, M. Fulczyk, P. Mahonen and W. Nowak, 2007. Mitigating ferroresonance in voltage transformers in ungrounded MV Networks. *IEEE T. Power Delivery*, 22(4): 41-49.
- Radmanesh, H. and M. Rostami, 2010. Effect of circuit breaker shunt resistance on chaotic ferroresonance in voltage transformer. *Adv. Electr. Comput. Eng.*, 10(3): 71-77.
- Rezaei-Zare A., H. Mohseni, M. Sanaye-Pasand, S. Farhangi and R. Iravani, 2007. Performance of various magnetic core models in comparison with the laboratory test results of a ferroresonance test on a 33 kV voltage transformer". Presented at the International Conference on Power Systems Transients (IPST'07), in Lyon, France.
- Shoup, D., J. Paserba and A. Mannarino, 2007. Ferroresonance conditions associated with a 13 kv voltage regulator during back-feed conditions. Presented at the International Conference on Power Systems Transients (IPST'07), 2: 1212-1215.
- Xusheng, C., 2003. Discussion of "Modeling and analysis guidelines for slow transients-Part 3: The study of ferroresonance. *IEEE T. Power Delivery*, 18(3): 1098-1105.