Electrical Power and Energy Systems 83 (2016) 134–139

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Analyzing the stochastic behavior of ferroresonance initiation regarding initial conditions and system parameters

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ARTICLE INFO

Article history:
Received 11 February 2015
Received in revised form 31 March 2016
Accepted 4 April 2016
Available online 16 April 2016

Keywords:
Ferroresonance
Stochastic behavior
Nonlinear resonance
Nonlinear circuits

ABSTRACT

Power quality and power disturbances are the most important increasing factors throughout electrical networks. Ferroresonance as one of these disturbances can cause quality and security problems. This paper analyzes the stochastic behavior of ferroresonance as a nonlinear resonance phenomenon of the erratic nature and difficult prediction. Furthermore, the impact of different parameters on the initiation of ferroresonance is investigated. It is illustrated that a small change in the initial conditions leads to a large difference in the long-term behavior of the system, and this makes the future of the system unpredictable. Based on the stochastic behavior of ferroresonance some papers took different parameters into account and attempted to identify the basins of attraction for different ferroresonance regions. Here, according to real condition it is illustrated that these basins are highly depending on the initial conditions and there are no transparent boundaries for them. Also, by changing different parameters and initial conditions, the probability degree of ferroresonance initiation is calculated and depicted. Moreover, the impact of source angle on the ferroresonance initiation is investigated.

Introduction

Power quality and power disturbances have become important increasing factors throughout electrical networks. Ferroresonance is one of these disturbances that can lead to the quality and security problems. Ferroresonance can occur when an unloaded 3-phase system consisting mainly of the inductive and capacitive components is interrupted by some single phase loads [1,2]. In the electrical distribution field, this typically occurs on a MV electrical distribution network of transformers (inductive component) and power cables (capacitive component). If such a network has little or no connected resistive load and one phase of the applied voltage is interrupted, ferroresonance can occur. If the remaining phases are not quickly interrupted and the phenomenon continues, overvoltage can lead to the breakdown of insulation in the connected components resulting in their failure. The phenomenon can be avoided by connecting a minimal resistive load on the transformer secondaries or by interrupting the applied voltage by a 3-phase interrupting device such as a ganged (3 pole) circuit breaker [1].

Despite the great amount of researches and works in identifying the behavior of ferroresonance, the problem is still unpredictable in practical terms due to its stochastic nature. The stochastic nature emanates from the sensitivity to changes in the system parameters and initial conditions [2]. Some of the system parameters cannot be exactly measured and may be changed, but they can be estimated and limited to a range of the realistic values [3].

Based on the literature findings, the main feature of the ferroresonance is that more than one stable steady state response is possible for the same set of the network parameters that are highly depended on the initial conditions of circuit or loads. Transients, lightning overvoltage's, energizing or de-energizing of transformers, occurrence or removal of faults, live works, etc. can initiate ferroresonance. The response can suddenly jump from one normal steady state response (sinusoidal at the same frequency as the source) to another ferroresonant steady state response characterized by high overvoltages and harmonic levels, which can lead to serious damage to the equipment [4,5].

Six basic steady-state types of ferroresonance have been identified: mono harmonic (sinusoidal) steady-state, poly harmonic steady-state with odd harmonics only, poly harmonic steady-state with even and odd harmonics, quasi-periodic steady-state, poly harmonic steady-state with sub harmonics, and chaotic steady-state [6–12]. All steady-states apart from the mono harmonic one are considered to be ferroresonance. In other words,

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http://dx.doi.org/10.1016/j.ijepes.2016.04.016
0142-0615/

ferroresonance is defined as the change from mono harmonic to a non-mono harmonic steady-state.

This paper analyzes the stochastic behavior of ferroresonance as a nonlinear resonance phenomenon of erratic nature and difficult prediction. In this regard, the impact of different parameters on the initiation of ferroresonance is investigated. It is illustrated that a small change in the initial conditions leads to a large difference in the long-term behavior of a system threatened by ferroresonance.

Some papers took different parameters into account and attempted to identify the basins of attraction for different ferroresonance regions [1–4,13]. In these papers, methods such as bifurcation theory are used to analyze the ferroresonance behavior. Here, and based on using a real world condition, it is illustrated that these basins are highly depending on the initial conditions and there are no transparent boundaries for them. Besides that, by changing different parameters and initial conditions, the probability degree of ferroresonance initiation is calculated and depicted. Added to this, the impact of source angle on the ferroresonance initiation is investigated. It should be noted that, the drawn conclusions from this case study is based on the theories taken from pertinent available papers and are extensible for any system threaten by ferroresonance.

The rest of the paper is organized as follows. Section 'Equivalent circuit model and mathematical formulation' includes the equivalent circuit model and parameters' values of the system as well as the related mathematical formulations. Some theoretical concepts along with simulation results are provided in Section 'Simulations results'. Finally, the deduced remarks are presented in Section 'Conclusion'.

Equivalent circuit model and mathematical formulation

Heretofore, various configurations of a network including ferroresonance problem have been investigated in detail [14–19]. Here, the simplified equivalent circuit of ferroresonance shown in Fig. 1 has been chosen, because it is the simplest model that describes parts of electrical power network in which ferroresonance may occur [1,20].

The parameters' values of this equivalent circuit are taken from [1,13] and listed in Table 1 again. The values are for a wound potential transformer (PT) at the 230 kV Dorsey station of Manitoba Hydro system. The PT is modeled by the nonlinear magnetizing characteristic (1) in parallel with resistor R_m representing the core losses, and the system is represented by its Thevenin equivalent parameters seen from the PT ends. All parameters' values are referred to the primary side of the PT. The leakage inductances and ohmic resistances of the PT windings are assumed to be negligible. C_b is the total stray capacitance of PT, bus and equipment, and C_g denotes the parallel grading capacitance of an open circuit breaker. Note that, the network connected to the open circuit breaker is modeled as the voltage source V_S wherein, the phase angle φ depends on the switching instant i.e. the time of breaker opening.

Magnetizing current i_L is defined by the nonlinear magnetization characteristic and is represented as a function of the transformer flux linkage λ, in the following single valued polynomial form

$$i_L(\lambda) = a_1\lambda + a_n\lambda^n \quad (1)$$

However, from the Kirchhoff current law:

$$i_L(\lambda) + \frac{1}{R_m}\frac{d\lambda}{dt} + C\frac{d^2\lambda}{dt^2} = CV_m\omega\cos(\omega t + \varphi) \quad (2)$$

where V_L is replaced by $d\lambda/dt$. Units of $i_L(\lambda)$ and λ in (2) are in ampere and volt-second, respectively. To work with per unit values, let us substitute $i_L(\lambda)$ by $I_b i_L(\text{pu})$ and λ by $\lambda_b\lambda(\text{pu})$ i.e. $(V_b/\omega_b)\lambda(\text{pu})$

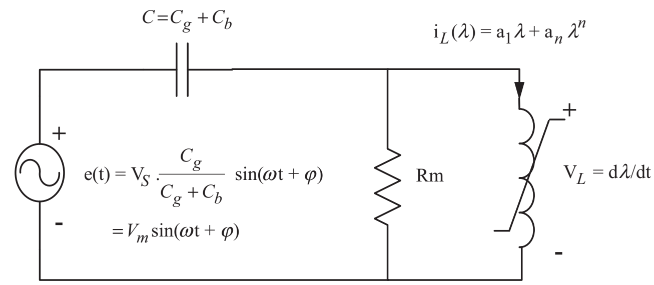

Fig. 1. The equivalent circuit model of ferroresonance.

Table 1
The parameters' values.

PT rating capacity		4 kVA
PT transforming ratio		138 kV grounded wye-115 V/69 V
PT core loss at nominal voltage		200 W
PT core loss resistance, reflected to the primary side	R_m	95.2 MΩ
Source, base voltage	V_S, V_b	187794.2 V
Base current	i_b	1.0 A
Source, base frequency	ω, ω_b	376.991 rad/s
Base flux linkage	λ_b	498.14 Wb
Saturation curve parameter	a_1	0.1
Saturation curve parameter	a_3	1.0
Saturation curve parameter	n	3

that ω_b denotes the base frequency in rad/s. So, (2) can be rewritten as follow:

$$I_b i_L(\text{pu}) + \frac{V_b}{R_m\omega_b}\frac{d\lambda(\text{pu})}{dt} + \frac{CV_b}{\omega_b}\frac{d^2\lambda(\text{pu})}{dt^2} = CV_m\omega\cos(\omega t + \varphi) \quad (3)$$

Now let the magnetizing current $i_L(\text{pu}) = a_1\lambda(\text{pu}) + a_n\lambda^n(\text{pu})$ and substitute into (3). Finally, (3) can be rewritten and simplified by $\lambda(\text{pu}) = \lambda$.

$$\frac{d^2\lambda}{dt^2} + k\frac{d\lambda}{dt} + C_1\lambda + C_3\lambda^n = G\cos(\omega t + \varphi) \quad (4)$$

where $k = 1/R_mC$, $C_1 = \omega_b I_b a_1/CV_b$, $C_3 = \omega_b I_b a_n/CV_b$, $G = \omega_b\omega V_m/V_b$.

Eq. (4) is a nonlinear differential equation for the PT flux linkage with the initial values of λ (calculated from the PT magnetizing current i_L) and $d\lambda/dt$ (equal to the PT primary voltage V_L). This equation can be solved by numerical integration methods such as Euler and Runge–Kutta methods. In this research work, the numerical integration based solver of ode15s in MATLAB toolbox is used to solve the equation.

Simulations results

In this section, different simulations are implemented to analyze impact of various parameters on the ferroresonance initiation in the above mentioned PT. At first, taking damping load, the capacitor C and the voltage magnitude V_m variations into account, the stochastic behavior of ferroresonance initiation is studied. Note that damping load is the sum of PT core losses and power consumed by permanently connected damping resistor [13]. In Fig. 2, for five levels of damping load and different values of V_m and C, the probability of the ferroresonance initiation is depicted. Note that, to set the damping load value the parallel resistance R_m is changed. In this figure, the darker points denote increase in