Electrical Power and Energy Systems 61 (2014) 346–354

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Experimental investigation of impact of remnant flux on the ferroresonance initiation

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ARTICLE INFO

Article history:
Received 17 April 2013
Received in revised form 14 March 2014
Accepted 21 March 2014

Keywords:
Bifurcation
Remnant flux
Ferroresonance
Ferroresonance circuits
Modelling
Nonlinear circuits

ABSTRACT

Objective: The paper presents an experimental and numerical investigation carried out on a ferroresonant circuit in order to determine to what extent the initiation of ferroresonance depends on remnant flux.
Methods: In order to gain the full insight of impact of initial conditions on the initiation of ferroresonance in general, the investigation was carried out varying the initial capacitance voltage and the phase shift as well. Ferroresonant circuit under study comprises a linear capacitor, sinusoidal voltage source and a coil designed for 30 V nominal primary voltage with the core made of oriented transformer sheets (M5-type). Additionally, the response of the circuit was obtained using a coil with the same core type (M5-type), but designed for higher nominal primary voltage (36 V) and a coil designed for 30 V nominal primary voltage, but with the core made of Ni–Fe alloy (Trafoperm N3).
Results/Conclusions: Based on measurements and simulation results, it is shown that the remnant flux and initial conditions in general, as well as phase shift have significant impact on initiation of ferroresonance for all used coil types. Thereby, the odd-symmetry of responses was observed as a consequence of odd-symmetric characteristics of passive circuit elements. The impact of initial conditions is explained theoretically as well, using a bifurcation diagram and calculation of Floquet multipliers.

Introduction

Ferroresonant circuit comprises a linear capacitor in series with a nonlinear inductor supplied with a sinusoidal voltage source, Fig. 1. Although various configurations of the studied network have been investigated in detail in previous works [1–6], the ferroresonant circuit shown in Fig. 1 has been chosen because it is the simplest model that describes parts of electrical power network in which ferroresonance can occur [7], and as such it is comprehended as a starting point to show clear and definite impact of chosen parameters and remnant flux in particular.

Six basic steady-state types have been identified in ferroresonant circuit: monoharmonic (sinusoidal) steady-state, polyharmonic steady-state with odd harmonics only, polyharmonic steady-state with even and odd harmonics, quasi-periodic steady-state, polyharmonic steady-state with subharmonics, and chaotic steady-state [8–14].

All steady-states apart from the monoharmonic one are considered to be ferroresonant. Ferroresonance is defined as the change from monoharmonic to a non-monoharmonic steady state where significantly higher state variable magnitudes are present. A small perturbation introduced to a system parameter results with a large change in state variable magnitude.

With possible catastrophic damage to electrical equipment due to overvoltages that can be sustained under ferroresonance conditions, the ferroresonance phenomenon is of special importance to power network utilities since it is affecting the reliability of power networks [15–18].

Despite the great amount of research and work in identifying the behaviour, the problem is still very unpredictable in practical terms. The seemingly stochastic nature derives from the sensitivity to system parameters and initial conditions which cannot be measured sufficiently accurate to predict a steady-state unambiguously.

In the context of this paper, ferroresonance is defined as any bifurcation, i.e. a sudden change in the behaviour of a state variable, from a normal response to a harmonic (integer or non-integer) response mainly due to a small perturbation introduced to a system parameter.

Ferroresonance phenomenon consists of different types of bifurcations such as period doubling bifurcation, saddle node bifurcation, Hopf bifurcation and chaos that occurs in the system from a sequence of period doubling bifurcations. The types of bifurcations

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http://dx.doi.org/10.1016/j.ijepes.2014.03.036
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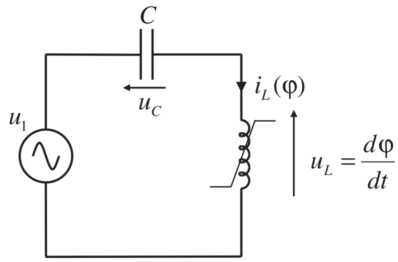

Fig. 1. Ferroresonant circuit.

and the impact of circuit parameters have been investigated in detail in previous works [1,3–7,9–14,18–22].

In a normal response the frequency spectrum of state variables results in a fundamental frequency sinusoidal waveform, as opposed to a frequency spectrum where some form of harmonic frequencies are present for which the response is termed of ferroresonant type. Besides from the frequency content, the two types (normal and ferroresonant type) also differ in the amplitude; the ferroresonant type is of considerably higher value compared to the normal response [1].

This paper focuses on an experimental investigation of ferroresonant circuit formed by a linear capacitor of 20 μF and a nonlinear coil based on the primary winding of a toroidal iron-cored two-winding transformer. The transformer is rated for 200 VA with a nominal primary voltage of 30 V. The core is made of oriented transformer sheets (M5-type) and is strip wounded.

A 10 kV A autotransformer with a source frequency of 50 Hz was used as the variable voltage source. The output voltage amplitude of this source could be varied up to an RMS value of U = 260 V in steps of 0.4 V approximately.

For any number of system parameters, keeping all but one constant, several ferroresonant responses can be obtained [1,13]. However, this paper concentrates only on the initiation of ferroresonance, i.e. change from a normal response into a ferroresonant response and vice versa. With such approach, obtained results are of more practical importance. Thereby, the emphasis is placed on the impact of remnant flux in particular, because the research up to date did not include detailed experimental investigation of impact of remnant flux.

During the experiments and the numerical calculations a substantially long delay was introduced for the capture of waveforms such that the system had enough time to settle down to a steady-state response, be it normal or ferroresonant type, eliminating any transitory effects. Identified steady-state types were collected and put onto a so called response map to provide a visual state for a particular case. Thereby, the steady-state types were colour-coded as white and black squares in the case of ferroresonant and normal response, respectively.

Measurements

The preliminary measurements were carried out increasing the source voltage RMS value continuously from 0.4 V with a step of 0.4 V approximately. In this way the source voltage RMS value at which the ferroresonance is initiated is determined, i.e. the normal response changes into a ferroresonant response, Fig. 2. Following this increase, the source voltage RMS value was reversed to its initial value of U_1 = 0.4 V using the same step size in order to determine the source voltage RMS value at which the normal response is re-established.

Table 1 shows the steady-state responses obtained from the experimental setup. The steady-state response for the range of source voltage RMS value 10 V $\leqslant U_1 \leqslant$ 21.6 V is ambiguous. For source voltage RMS values within the range the response is normal when the source voltage RMS value is in an increasing direction, compared to a ferroresonant response when the source voltage RMS value is in a decreasing direction.

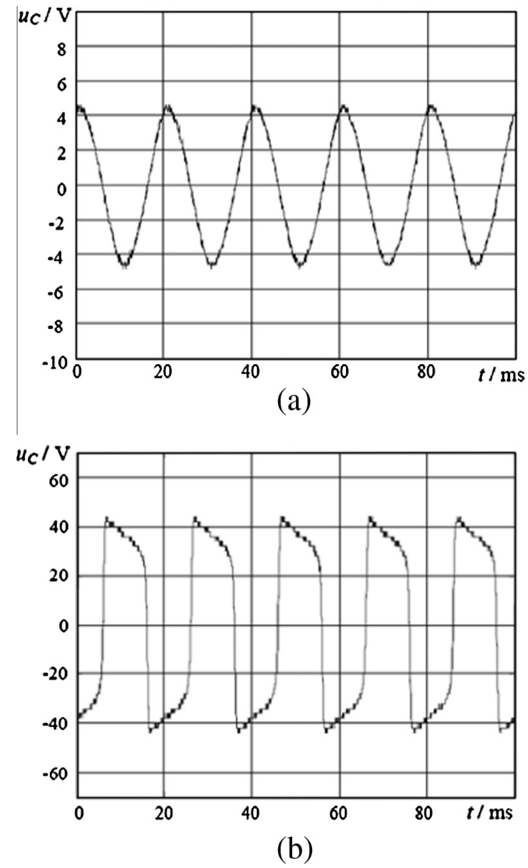

Fig. 2. Steady-state types: (a) normal response at U_1 = 12 V obtained for increasing U_1. (b) Ferroresonant response at U_1 = 12 V obtained for decreasing U_1.

Table 1
Steady-state types obtained experimentally.

Steady-state type	Source voltage RMS value	
	Increasing U_1	Decreasing U_1
Normal response	0–21.6 V	Initiated at 9.6 V
Ferroresonant response	Initiated at 22 V	10–22 V

As the source voltage RMS value is adjusted manually via the potentiometer of the autotransformer, it was not possible to set and keep other parameters (phase shift of the source voltage, the initial values of capacitor voltage and coil flux) constant at the moment of variation. This parameter uncertainty is identified already as the reason for ambiguous response in prior research [7,23–26]. However, preceding research did not include the varying of remnant flux as experimental method [23,26], i.e. the remnant flux was set to an absolute zero value [24] or to an unknown non-zero value [25], respectively.

In order to determine the influence of the initial conditions, and remnant flux in particular, on the ferroresonance initiation, the experiments shown in this paper are carried out varying the circuit parameters in a controlled manner by using the measurement circuit with electronically controlled switches, Fig. 3:

- The moment of closing of switch $S1$ determines the phase shift α of the source voltage u_1.