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Electromagnetic transient study on flexible control processes of ferroresonance

Ming Yang [a,b,*], Wenxia Sima [a], Pan Duan [c], Mi Zou [a], Daixiao Peng [a], Qing Yang [a], Qichang Duan [b]

[a] *State Key Laboratory of Power Transmission Equipment & System Security and New Technology, and College of Automation, Chongqing University, Chongqing 400044, China*
[b] *College of Automation, Chongqing University, Chongqing 400044, China*
[c] *State Grid Chongqing Electric Power Company Nan'an Power Supply Filiale, Chongqing 400060, China*

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ABSTRACT

Ferroresonance, which is a common phenomenon in power systems, have threatened the security of power systems for a long time. Although several ferroresonance suppression measures have been applied in power systems, ferroresonance still occurs occasionally. In this study, a flexible control strategy to control different ferroresonant modes is proposed. The behavior of a typical ferroresonant circuit acquired from a ferroresonance testing system to obtain the electromagnetic transient and control details of the control method is also investigated. The key parameters in the control module are determined, including the switching frequency and the coefficients of the proportional–integral (PI) controller. Then, six typical ferroresonant overvoltages are selected as control systems using the proposed method. Given the effect of a damping resistor and fully controllable power electronic switches with a gate signal controlled by a proportional–integral (PI) control system, these six typical ferroresonant overvoltages can all be suppressed in 0.12 s to the non-ferroresonant state after the controller is activated. The electromagnetic transients, including the essential system state quantity transients in the control process, are also investigated. At last, a laboratory prototype is implemented, and the experimental results show that the proposed method is useful for ferroresonant overvoltage control.

1. Introduction

Ferroresonance is a common nonlinear electrical phenomenon in power systems that is usually characterized by overvoltage and irregular wave shapes and associated with the excitation of one or more saturable inductors like a potential transformer and capacitance like stray capacitance [1,2]. Ferroresonance causes overvoltage and overcurrent that last for a long time and sometimes may even exist stably, threatening the security of power system equipment and operational personnel [3,4]. Ferroresonance is a complicated phenomenon. Various situations can lead to ferroresonance [5–7] and its various modes [8–11]. The four modes of ferroresonance based on frequency components are as follows: fundamental ferroresonance (FF), subharmonic ferroresonance (SHF), quasi-periodic ferroresonance (QF), and chaotic ferroresonance (CF) [12,13].

Many studies have been conducted by scholars around the world to clarify the mechanism of ferroresonance and the factors influence it [1,14,15]. Several methods have been proposed to restrict and eliminate ferroresonant oscillations by revising switching procedures, interlocking, relocating potential transformer (PT), arc suppression coil, circuit breaker (CB) accurate modeling, changing circuit breaker shunt resistance [16], accurate magnetic core modeling of transformers [17,18], connecting metal oxide varistor [19], using memristor-based system [20], adding fault current limiter [21,22] and adding circuit losses, such as damping resistors [23,24], damping reactors [25], and active damping devices [26–29]. Refs. [27,23] proposed a novel method to suppress ferroresonance, which require several resistors and electronic switches located at the secondary side of the bus PT. The method is flexible because damping resistance can be changed to satisfy different ferroresonant situations. However, several resistors should be deployed to suppress all potential possibilities because ferroresonance is complicated. Although ferroresonance can be classified into these four ferroresonant modes, the amplitude of ferroresonance varies for varying core saturate levels under different conditions. Thus, the suppression effect of discontinuous damping resistors is limited. As such, how do we use a few resistors to cover all ferroresonant overvoltage?

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* Corresponding author at: State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, China.

E-mail addresses: cqucee@cqu.edu.cn (M. Yang), cqsmwx@cqu.edu.cn (W. Sima), duanpankamino@163.com (P. Duan), zoumi@cqu.edu.cn (M. Zou), 20151102019t@cqu.edu.cn (D. Peng), yangqing@cqu.edu.cn (Q. Yang), qichangduan@cqu.edu.cn (Q. Duan).

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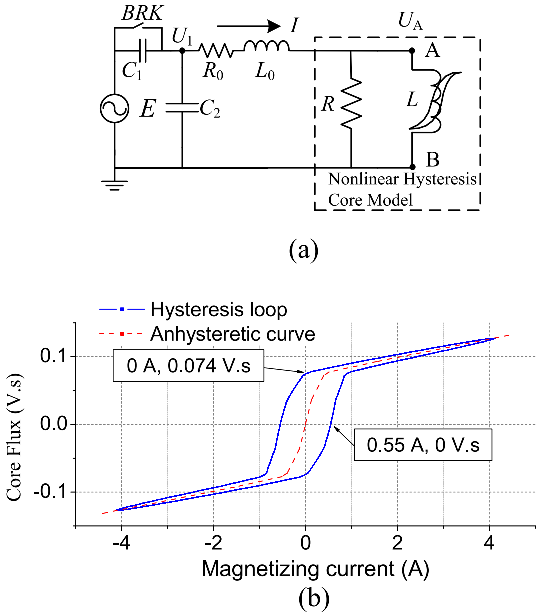
We can use high-frequency fully controllable electronic switches for these resistors to generate a continuously adjustable resistance for the power system frequency. Damping resistors and fully controllable power electronic switches are used to generate a flexible control module to control different types of ferroresonant overvoltage, and core saturation levels [30]. In this paper, we focus on determining the parameters of the control module, the voltage transient, and the control signal transient based on the electromagnetic transient study to verify the mechanism of the flexible control strategy.

The paper is organized as follows. Section 2 describes the basic ferroresonant model, wherein core hysteresis is considered to investigate the behavior of a typical ferroresonant circuit. Section 3 presents the details of the flexible control strategy for ferroresonance. Section 4 describes the determination of the control parameters and the simulation conducted. Section 5 gives a brief experimental validation, and Section 6 concludes the paper. The main contributions of this paper are a comprehensive investigation on the performance of the ferroresonance circuit with a broad range of parameters, a modified method based on our previous work [30] to improve the robust of the method avoiding convergence, introduction of our method to determine the complicated control parameters including gate signal frequency and PI parameters, detailed information about the electromagnetic transient of the whole control process, designing and producing circuit board as well as it experimental study.

2. Basic ferroresonant circuit and its behavior

A primary ferroresonant circuit was established and tested in the laboratory to investigate the behavior of ferroresonance. A ferroresonance simulation model is developed based on the test circuit, as shown in Fig. 1(a), where E is the system power supply; R_0, L_0, R, and L represent the winding resistance, leakage inductance, core loss, and nonlinear saturable iron core inductance of the scaled-down PT, respectively. C_1 represents the grading capacitance of the circuit breaker. C_2 represents the transmission line capacitance and stray capacitance in the transformer windings. *BRK* represents a breaker to excite ferroresonance. The laboratory ferroresonant circuit can be visualized as a scaled-down electrical power network with ferroresonant characteristics, but with higher losses [31,32]. Different steady-state responses of the ferroresonant circuit should be first investigated by simulation to verify the electromagnetic transient of the control process. In Fig. 1(a), the voltage source E is a sinusoidal alternating current (AC) source with a peak value of 21 V (slightly larger than the rated voltage to generate different ferroresonance modes) and a frequency of 50 Hz. R_0 and L_0 are 2.21 mΩ and 3.45 μH, respectively. The magnetization characteristics are shown in Fig. 1(b), and Type-96 element in ATPDraw [33] is utilized to simulate the magnetizing characteristics. Table 1 presents it positive side magnetizing characteristics. Series capacitance C_1 varies from 45 μF to 2000 μF, and the stray capacitance C_2 ranges from 1 μF to 2000 μF. The capacitance value is larger than that in [1,5,8,15,32], because our ferroresonant circuit is established on a tailor-made transformer in our library and the voltage level of the transformer is less than 21 V (peak value). The prerequisite of ferroresonance is that the voltage–current characteristic curves of the nonlinear inductance and equivalent series capacitance have at least one intersection point. A PT with high rated voltage may have a more steep voltage–current characteristic curve than the low one. Study [5] also shows that large capacitance is required to exciting ferroresonance in low voltage level systems. Ferroresonance can be excited by opening the breaker *BRK* at 0.2 s. The PT voltage (ferroresonant overvoltage) then settles to a steady state after a sufficiently long duration. The harmonic content of the PT voltage can be determined and used for ferroresonant mode identification employing fast Fourier transformation.



(a)

(b)

Fig. 1. Schematic diagram of the simulation model for ferroresonance: (a) ferroresonant circuit and (b) magnetization characteristics of the PT core.

The PT voltage (peak value) of each steady state with different values of C_1 and C_2 is recorded. The results are shown in Fig. 2 as a contour diagram, which represents the details of the

Table 1
Numerical values of the magnetizing curve used in the simulation.

Point	Magnetizing current (A)	Flux (V s)
1	0	0
2	0.0141	0.0048
3	0.1324	0.0365
4	0.3953	0.0719
5	0.5134	0.0772
6	1.5514	0.0927
7	4.4148	0.1315
8	8.4653	0.1424
9	17.8755	0.1448

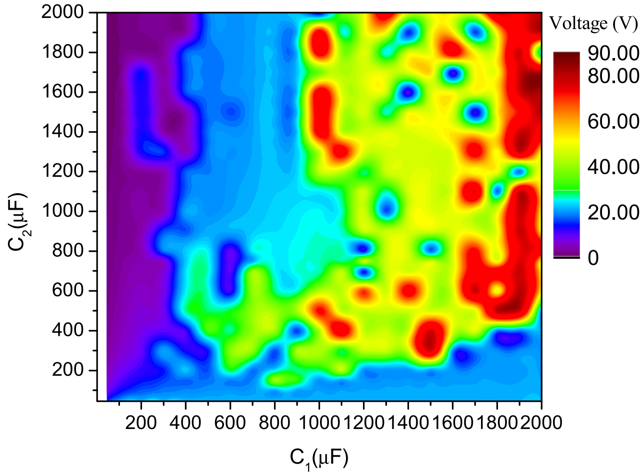


Fig. 2. The peak value of the PT voltage contour diagram.