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Suppressing ferroresonance in potential transformers using a model-free active-resistance controller

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ABSTRACT

Ferroresonance, excited by saturated electromagnetic voltage transformers, can severely damage power systems because it produces long duration large overvoltages. In this paper, a method is developed to eliminate potential transformer (PT) ferroresonance through a model-free method. First, a structural diagram of the ferroresonance eliminating device is established based on a practical ferroresonant circuit. The effect of the adjustable parameters of the device is investigated, including resistance, pulse frequency, and pulse duty cycle. Then, Iterative control strategies are developed to adjust the gate signal duty cycle of the controller for limiting the ferroresonance to a normal status and then switching off the elimination device. Finally, simulations are conducted demonstrating that the method proposed was effective.

1. Introduction

Ferroresonance is a complex nonlinear phenomenon that threatens transmission and distribution equipment in power systems. Improved methods and devices to eliminate ferroresonance are urgently required to avoid unexpected damage [1]. Considering the complexity of ferroresonance, control theory of nonlinear dynamics and chaos have been introduced to study the characteristics of ferroresonance and its suppression [2–8]. Despite serving an important function in ferroresonance studies, these methods require further investigation before they can be applied in practical power systems.

Given the particularity of ferroresonance in neutral-grounded systems, the most effective ferroresonance suppression methods are: install a metal oxide arrester (MOA) [9,10] in parallel with the potential transformer (PT) and add damping resistance to the delta or wye secondary side of PT [11–13]. Ref. [9] showed that MOA can limit ferroresonant overvoltage; however, MOA cannot eliminate it completely. Determining the damping resistance value required to control various ferroresonant modes is difficult [12,13]. Once ferroresonance is curbed, the suppression devices should be switched off. However, [13,14] showed that this action might excite ferroresonance again.

Ref. [13] proposed a method to suppress ferroresonance, in which several parallel resistors are simultaneously connected to the wye secondary circuit of the PT. The thyristors are closed at the end of the transient state by the signals emitted by digital I/O cards in sequence to avoid exciting ferroresonance again. This method can be applied to practical power systems. However, two issues may cause failure. The first issue is that ferroresonance is very complex in a practical power system [15] due to its various modes (normally classified as fundamental, sub-harmonic, harmonic, quasi-periodic, and chaotic ferroresonance [16,17]), various saturation levels (one ferroresonant mode may have different saturation levels [6]), and the effect of multiple factors (such as circuit parameters and residual flux [18,19]) on its performance. However, the value of the equivalent resistance connected to the wye secondary circuit is discontinuous. As a result, ferroresonance with different modes and saturation levels may not be suppressed successfully. The second issue is that the alternating status of the bidirectional thyristor results in discontinuous changes in the equivalent resistance, and these changes may excite ferroresonance again.

In this paper, the limitations of ferroresonance suppression methods are considered. A secondary active damping resistance and an iterative learning control method [20] are developed based

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on model-free control theory. A typical 110 kV ferroresonant circuit is studied, and all analysis is based on this circuit. Parameters of the ferroresonant circuit are determined to excite different ferroresonant modes, including chaotic ferroresonance, which is the most complicated mode because of its complex frequency components [21]. A new elimination method was proposed, and the sensitivity of its adjustable factors was studied. Results show that the ferroresonance can be eliminated by the proposed method and strategy by adjust the parameters of the controller.

2. Neutral-grounded ferroresonant model and its analysis

Fig. 1(a) shows a typical ferroresonant circuit on a 110 kV neutral-grounded substation. An electromagnetic PT is energized by an alternating current (AC) source through a circuit breaker (CB). Fig. 1(b) shows the single-phase equivalent circuit of Fig. 1 (a) with a secondary damping resistance added. Fig. 1(c) shows the reduced equivalent circuit based on Thevenin's theorem. The secondary damping resistance R_{y2} is referred to the primary side as the damping resistance R_{y1} (resistance can be considered infinite when no resistance is connected to the secondary side of the PT). The system AC source is $\sqrt{2}E\sin\omega t$, where ω is the angular frequency. C_{cb} represents the grading capacitance of the CB. C_{pg} is the parameter representing different capacitances: the stray capacitance in the transformer primary winding, the transmission line capacitance and stray capacitance in the transformer secondary winding, referring to the primary winding, and stray capacitance of the busbar. L represents the nonlinear inductance of the PT core and R_{pt} represents the core loss of the PT. The nonlinear characteristics of the PT may cause large overvoltages on the PT during the operation of the circuit breaker. Ferroresonance may be excited when CB is switched off.

Transformer current is represented by a single-value function. The measured transformer magnetization curve can be modeled by a seventh-order polynomial Eq. [3]:

$$i_L = f_L(\phi) = a\phi + b\phi^n \quad (n = 7) \tag{1}$$

where i_L is the magnetizing current of the PT, and ϕ is the transformer flux linkage (both in pu).

According to Fig. 1(c), the behavior of the basic ferroresonant circuit is described by two differential equations

$$\begin{cases} \frac{d\phi}{dt} = u \\ \frac{du}{dt} = \frac{C_{cb}}{C_{cb}+C_{pg}}\sqrt{2}E\omega\cos\omega t - \frac{f_L(\phi)}{C_{cb}+C_{pg}} - \frac{u}{R(C_{cb}+C_{pg})} \end{cases} \tag{2}$$

where $R = R_{pt}//R_{y1} = R_{pt}//(n_{12}^2 \cdot R_{y2})$, and n_{12} is the turns ratio of the PT.

The typical model parameters can be summarized as follows:

$$\text{Base power } S_b = 300 \text{ VA}; \text{Base voltage } U_b = 63.51 \text{ kV} \tag{3}$$

$$E = 63.51 \text{ kV}; \omega = 2\pi \times 50 \text{ rad/s} \tag{4}$$

$$C_{pg} = 100 \text{ pF}; C_{cb} = 2500 \text{ pF} \tag{5}$$

$$R_{pt} = 1000 \text{ M}\Omega \tag{6}$$

$$i_L = 3.42\phi + 0.41\phi^7 \text{ pu} \tag{7}$$

The parameters in (3)-(5) are acquired from a real 110 kV power substation (Xianfeng substation, Chongqing, China). The parameters in (6) and (7) are acquired from [22,23] and can reflect the main nonlinear characteristics of the PT, which does not affect the study on the ferroresonance control strategy in this paper. With respect to (3), all parameters can be converted to pu. Eq. (2) was solved numerically using the Runge–Kutta integration

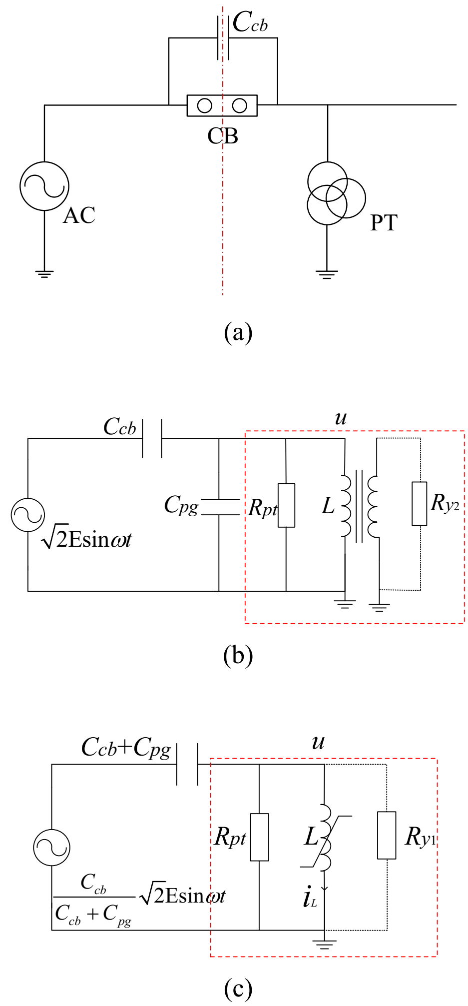

Fig. 1. Single-phase ferroresonant circuit. (a) A 110 kV neutral-grounded system, (b) equivalent circuit, and (c) reduced equivalent circuit.

method. All of the simulations and testing of the proposed method were carried out by solving the differential equations presented in (2) using MATLAB. Because the resistance R in (2) changes during the control process, a function is programmed based on the Runge-Kutta algorithm, in which the adjustable resistance R can be the input quantity of the function. The flowchart of the proposed method is presented in Fig. 2, which contains three parts as follows:

(1) Ferroresonance behavior. The capacitances and the core loss resistance are changed in Fig. 1(a) by removing the control part. Through the programmed function, one can obtain the ferroresonance overvoltage waveform, the phase plane, and Poincaré map of Section 3, and the bifurcation diagrams without damping resistance presented in Section 4.1.
(2) The sensitivity of the adjustable factors in control device. The damping resistance, the frequency, and the duty cycle are changed step by step to study the influence of the adjustable factors on the control results. The bifurcation diagrams in Sections 4.1 and 4.3 can then be acquired.
(3) The application of the proposed control strategies. The control strategies presented in Section 5.1 were used to determine the duty cycle of the GTOs gate signals. The transient of the control processes presented in Sections 5.2 and 5.3 can then be obtained.