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A novel synchronous fault identification strategy of electronic transformer based on synergy of historical data

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ABSTRACT

System disturbance caused by line fault, connection or shedding of power source and large load will frequently lead to complicated electromagnetic interference. Subsequently, the abnormal output signal of electronic transformer is likely to be generated due to the deficiency of electromagnetic compatibility, resulting in the maloperation of protection and control system. The aforementioned problems are promising to be solved with the development of substation area protection. In this paper, the existence of the similar region within which the dynamic characteristics of the transmission line fault are of high similarity is proved. Furthermore, the discreteness hypotheses of topology and state of power system are proposed, and the concept of transmission line same-type fault is acquired subsequently. In addition, based on the similarity between a certain dynamic case and the historical case, the principle, criterion as well as implementation to identify the synchronous fault of electronic transformer are proposed, and the evaluation index for describing the fault degree is also given. The feasibility and applied value of the proposed identification strategy are proved based on the simulation model in PSCAD.

1. Introduction

With the continuous application and promotion of information network technology, more and more advanced applications appear in the new generation of power grid and make it more intelligent in terms of dispatch, protection and control [1,2], so that the power grid can adapt to the developmental trend of increasing scale, complexity, and diversification, the foundation of which lies in acquisition of data and innovation of sharing mechanism [3,4]. Therefore, how to ensure the reliability of information flow within electric network becomes crucial to the normal operation of new generation of power grid.Electronic transformer, with the advantages of great transient performance, wide measurement frequency band as well as digital output [5–12], has become a new type of intelligent device oriented to the smart grid with distinguished characteristics of informatization, automation and interaction. It has been an inevitable developmental trend of modern power grid that the electronic transformer substitutes the traditional electromagnetic transformer and becomes the core device of key data acquisition of power grid operation. However, as a new and developing device, electronic transformer can be vulnerable to environmental impact, especially the electromagnetic interference [13–15] due to the design defects and insufficient operating experience. When a fault occurs, the output signal of electronic transformer will be distorted if lacking in electromagnetic compatibility. Without effective identification, it will lead to serious consequences like protection maloperation. In fact, there have been a great many project cases in China where the synchronous faults of electronic transformers lead to the maloperation of relay protection in the building process of smart substations during the past decade, which have aroused concerns for the application of smart substation in the industry field.

At present, tremendous work is going on from various researchers for the influence factor of measurement performance and error analysis of electronic transformer. For example [16–18], has analyzed the influence of ambient temperature on the measurement accuracy of electronic transformer. The problem of electromagnetic compatibility has been pointed out in [19–21] when electronic transformer encounters

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the electromagnetic interference during operation. In [22–24], the fault error characteristics of electronic transformer has been analyzed and the mathematical description has been given. The electromagnetic transient model of Rogowski coil has been built and then a novel system for dynamic response testing has been carried out in [25].

However, few researches focus on the synchronous fault identification method of electronic transformer at present. In fact, the electronic transformer is an emerging type of electrical equipment, thus the research on fault diagnosis and identification strategy is still in the initial stage, and few relevant research results are achieved. Nevertheless, considerable fault identification methods of traditional electromagnetic transformers and sensors have been studied. Composed of electronic component and photovoltaic conversion element, the electronic transformer is applied to the information acquisition as well. Therefore, some existing fault identification methods may be considered to be referenced adequately for electronic transformers. For example, in [26,27], fault diagnosis system using the model-based expert system has been proposed, in which the fault diagnosis is simulated by comparing the simulation results with the actual monitoring information. However, owing to the incomplete research and expertise, mathematical models for the electronic transformers are hard to be set up. Other methods based on the signal process such as wavelet algorithm have been proposed in [28–30], which could detect the variation points of the signal by utilizing wavelet algorithm to implement the fault identification when a prior model is unavailable. In this paper, the electronic transformer fault which occurs simultaneously with the system large disturbance process is called the synchronous fault, otherwise it is called the asynchronous fault. The above method based on signal process can only identify the asynchronous fault, while the synchronous fault has not been taken into consideration. Specifically, when the synchronous fault occurs, the abrupt changes induced by the system disturbance will appear in the output signals of all the transformers and be detected by wavelet algorithm, thus this kind of method fails to identify the real fault transformer. In fact, the transformer with hardware defect is easily vulnerable to the system large disturbance and becomes out of order, that is to say, the main fault in the actual operation is the synchronous fault.

All the methods based on analyzing the single transformer output independently are unable to distinguish the transformer faults from system disturbance, which means they are not capable of covering all the scenarios for the synchronous fault effectively. However, the comparison of multiple transformers sampling signals is an effective solution. By comparing the sampling signals of multiple electronic transformers acquired simultaneously, the identification of synchronous fault becomes feasible. The development of substation area protection provides the basis of hardware and platform for the aforementioned assumptions. In this paper, the existence of the similar region within which the dynamic characteristics of the transmission line fault are of high similarity is proved, and the concept of transmission line same-type fault is obtained. Then the discreteness hypotheses of topology and state of power system are proposed. According to the similarity between system dynamic cases and historical cases, the identification principle, criterion and implementation of electronic transformer synchronous fault are proposed combined with the data acquisition system of substation area protection, and the evaluation index of electronic transformer fault degree is given. Finally, the simulation results of a typical power system model based on PSCAD verify that the proposed strategy can identify not only the fault transformer accurately, but also the electronic transformer with fault trend, and is capable of providing the quantitative assessment of fault degree correspondingly. Furthermore, this strategy can detect the sampling data of fault transformer before the operation of main protection, and replace the fault data with grid redundant data, or modify the fault data by utilizing highly shared data based on substation area protection, which ensures the correct operation of protection and control system.

2. Research on transient similarity of same-type fault on transmission line

Dynamic power system can be described by a set of Differential Algebraic Equations (DAE) [31]. In order to consider the dynamic behavior of algebraic state value, and avoid some singularities of DAE, the Singular Perturbation Differential Equation (SPDE) [32] can be acquired by replacing algebraic equation with differential equation, as follows:

$$\begin{cases} \dot{x}_1 = f(X_1, X_2) \\ \varepsilon \dot{x}_2 = g(X_1, X_2) \end{cases} \tag{1}$$

where f is defined to describe the characteristics of the dynamic components in the system, g represents the network power flow model, $X_1 = [x_1, \cdots, x_m]$ is the state variable of m-dimensional system, the dimension of X_2 depends on distribution of PQ node and PV node in system power flow equation, and ε is a positive number tending to 0. Expand the Formula (1) at the equilibrium point before the fault using Taylor Expansion, and keep it to the 2nd order, as follows:

$$\dot{x}_i = A_i x + x^T H^i x/2 \tag{2}$$

where A is the system Jacobian matrix, and H represents Hessian matrix. Solve the Formula (2) as follows:

$$x_i(t) = \sum_{j=1}^{m+n} u_{ij} z_{j0} e^{\lambda_j t} + \sum_{j=1}^{m+n} u_{ij} \sum_{k=1}^{m+n} \sum_{l=1}^{m+n} h_{kl}^{j} z_{k0} z_{l0} e^{(\lambda_k+\lambda_l)t} \tag{3}$$

where λ is the eigenvalue of A, which determines the frequency and attenuation characteristics of the dynamic component, z_{j0} corresponds to the initial value of the j-th state value, u_{ij} is the element in eigenvector matrix U of A, h_{kl}^{j} depends mainly on λ, H and U, z_{j0}, u_{ij} and h_{kl}^{j} .

Based on the aforementioned analysis, it will be proved that there exists Δl called similar region of line fault, which is big enough, and when the same-type fault occurs within the range of Δl, the system transient process will be of high similarity, as follows:

In Fig. 1, when a fault occurs at P_1, the normal network will experience a disturbance, which will bring g from 0 to a fixed value. For this dynamic process, suppose that there are m dynamic characteristic equations in the system, and the i-th equation is as follows:

$$\dot{x}_i = f_i(X_1, X_2) \tag{4}$$

Suppose that there are $(n+1)$ nodes in the network, the first p nodes are PQ nodes, the $(n+1)$-th node is equilibrium node, and the others are PV nodes. Use the vector $Y = [\theta_1, \cdots, \theta_n, V_1, \cdots V_p]$ to substitute the vector X_2, where $\theta_1, \cdots, \theta_n, V_1, \cdots V_p$ are node phase angles and voltage variables, $V_{p+1}, \cdots V_n$ are known node voltage constants.

The equation of active power unbalance in system power flow model is shown in (5), where $i = 1, \cdots, n$.

$$g_i = \Delta P_i = P_i - V_i \sum_{j=1}^{n} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \tag{5}$$

The equation of reactive power unbalance in system power flow model is shown in (6), where $i = 1, \cdots, p$.

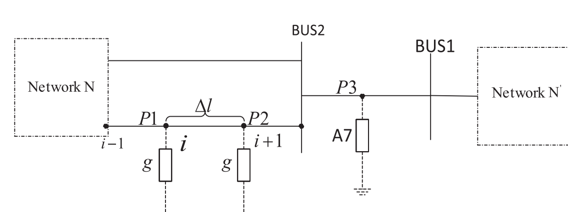

Fig. 1. Typical transmission network.