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PMU-based voltage stability prediction using least square support vector machine with online learning

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ABSTRACT

Composite load model comprising an impedance-current-power (ZIP) load and an induction motor (IM) is widely used for dynamic voltage stability analysis. With the load model, this paper proposes a new PMU-based method to predict short-term voltage instability (STVIS). Using synchronous measurements, the method firstly performs online contingency analysis to obtain a set of three-element look-up tables comprising the presumed contingency, the corresponding post-fault stable and unstable equilibrium point (SEP and UEP) for each IM load individually. Next, when a fault really occurs, the time-series of IM slip is computed by an Euler algorithm based on local PMU measurements, and then a new time-series prediction method is proposed for rolling prediction of IM slip trajectory by introducing least square support vector machine (LSSVM) with online learning. Finally, from the view of IM stability mechanism, the STVIS status can be detected in advance by monitoring that the predicted slip trajectory reaches the IM's UEP in the look-up table. The effectiveness of the proposed method is verified on the New England 39-bus system.

1. Introduction

Short-term voltage stability (STVS) refers to the ability of power system to keep steady voltages at all buses after a large disturbance in a transient time frame [1]. Unlike the rotor angle stability focusing on generators' synchronism, STVS closely relates to the stability of dynamic loads. The short-term voltage instability (STVIS) is mainly caused by the IM dynamics tending to restore the power consumption beyond the capability provided by the post-fault system, resulting in IM stalling. During the stalling process, much reactive power is absorbed, deteriorating the voltage levels. Further, this in turn can make more IMs installing, and consequently, STVIS occurs. In modern power system, as the penetration of IMs (e.g. air conditioners and industrial motors) increases, it is crucial to predict the STVIS status and timely activate emergency control measures.

For the steady-state voltage stability analysis, there are some mature methods, such as continuation method [2], singular value decomposition [3], and Thevenin equivalent based method [4]. However, these approaches are derived from power flow equations based on the static models of system, and hence cannot be applied for STVS analysis. Many studies on STVS analysis focus on analyzing the IM dynamics after a large disturbance [5–8]. In Ref. [9], by using the transient P–V curves, the load characteristics of IM in the P–V plane is introduced and then an analytical method for STVS is put forward in a single-load infinite-bus system. In Ref. [10], to prevent IM from losing stability, the critical clearance time (CCT) of voltage sag is analytically derived, also in a single-load infinite-bus system. Due to the same time frame of STVS and rotor angle stability, the impacts of generator out-of-step on IM stability are studied in Ref. [11]. Inspired by the energy function method on rotor angle stability analysis, Refs. [12,13] used it to analyze voltage stability. However, the method may have difficulties for STVS analysis when applied to real systems with many IM loads. So far, time domain simulation (TDS) is still an effective way for large-bulk systems. Although the above methods play important roles in addressing STVS problems, they are still difficult for fast real-time detection of STVIS. In practice, the STVIS is detected by industrial experiential criteria in which only the duration of voltage sag of any bus under a predefined threshold exceeds a time-period, the STVIS status is detected [14]. But, the experiential criteria may lack reliability and explanation for different systems.

Given the increasing placement of phasor measurement units (PMUs) in system, some machine-learning techniques have been adopted for real-time stability assessment, such as neural network

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(NN), support vector machine (SVM), decision tree (DT), time series shapelet, and intelligent system [15–21]. Based on these techniques, the stability assessment is treated as a binary classification problem, and it mainly includes two stages: offline training and online application. The classifier is obtained after offline training stage where a large stability/instability database are needed. At the online stage, with post-fault dynamic features (e.g. voltage trajectories) inputting into the classifier, the stability status can be detected early. These methods rely on massive TDSs requiring detailed system models and their accurate parameters. However, for complex system, the components' parameters and models may be uncertain, and the generated stability/instability database based on TDS may be insufficient for training stage. Both may result in an unreliable classifier, and give unreliable conclusions. Further, these methods focus on the data themselves rather than the intrinsic mechanism of STVS, which may also lead to an unreliable result. Except the above machine-learning methods, Lyapunov exponent method is an effective tool to diagnose the system chaotic behavior [22]. In Ref. [22], by measuring the post-fault time series of voltage with PMUs, the maximum Lyapunov exponent is computed and then the STVIS status can be detected by the Lyapunov exponent.

Currently, for STVS assessment, the key problem is that the appropriate dynamic load model should be adopted. For engineering and research experience, the composite load model is increasingly recommended and widely adopted in network operators for dynamic stability analysis, especially STVS analysis [23,24]. And, thanks to the wide use of PMUs, the accuracy of parameter identification of composite load is improved greatly by using measurement-based methods [25–28].

In this paper, with the composite load, we propose a PMU-based method to predict STVIS for multi-bus power systems. The method is divided into two stages. The first stage use synchronous measurements in operation center to perform online presumed contingency analysis to create a look-up table. In second stage, with local measurement, the post-fault STVIS status is detected in advance based on time-series prediction and the look-up table. The main contributions are as follows. 1) The method is a semi-parameter-free approach where only the power flow data and the parameters of composite load are required, which greatly reduces the dependence on the dynamic modeling and parameters. 2) By introducing LSSVM with online sequential learning, a new time-series prediction method is proposed to predict the IM slip trajectory in a rolling way. 3) With the predicted slip trajectory, the STVIS status can be detected in advance based on the instability mechanism of IM, rather than the experience criteria. 4) The method has applicability under symmetrical/asymmetrical fault conditions.

The rest of this paper is organized as follows. In Section 2, the composite load model is briefly reviewed, and then the method to calculate the post-fault SEP and UEP of IM is presented. The STVS assessment based on the SEP and UEP is also introduced here. Section 3 provides a new time-series prediction method based on online learning LSSVM, and the scheme of PMU-based STVIS prediction method is presented. Simulation results are illustrated in Section 4, followed by conclusions in Section 5.

2. Short-term voltage stability assessment

2.1. Composite load model

The structure and circuit diagram of the composite load are shown in Fig. 1 where r_s is the stator resistance, x_s is the stator reactance, r_r is the rotor resistance, x_r is the rotor reactance, x_m is magnetizing reactance and s is the IM slip.

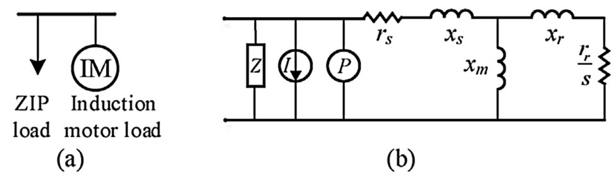

Fig. 1. (a) Composite load structure. (b) Circuit model of composite load.

The static ZIP load is formulated as follows:

$$P_{zip} = P_0\left[p_z\left(V/V_0\right)^2 + p_i\left(V/V_0\right) + p_p\right] \tag{1}$$

$$Q_{zip} = Q_0\left[q_z\left(V/V_0\right)^2 + q_i\left(V/V_0\right) + q_p\right] \tag{2}$$

where V_0 and V are the rated voltage magnitude and operating voltage magnitude, respectively; P_0 and Q_0 are real and reactive power respectively, before disturbance; both parts of (p_z, p_i, and p_p) and (q_z, q_i, and q_p) are the coefficients for the real and reactive power, respectively, which the sum of each part is 1.

For IM, its equations are described as:

$$\frac{d\dot{E}'}{dt} = -js\dot{E}' - \frac{1}{T'}[\dot{E}' - j(X - X')\dot{I}] \tag{3}$$

$$\frac{ds}{dt} = \frac{1}{2T_j}(T_m - T_e) \tag{4}$$

$$\dot{V} = \dot{E}' + (r_s + jX')\dot{I} \tag{5}$$

where $T_e = Re\left(\dot{E}'\dot{I}^*\right)$, $T_m = T_0\left[A(1-s)^2 + B(1-s) + C\right]$, $T' = (x_r + x_m)/r_r$, $X = x_s + x_m$, $X' = x_s + x_r x_m/(x_r + x_m)$. In the above equations, $\dot{E}'$ refers to the transient EMF of IM; $\dot{I}$ is the stator current phasor; T_j is the inertia constant; $\dot{V}$ is the voltage phasor. T_m and T_e are the mechanical and electrical torque, respectively; T_0 is the initial mechanical torque and A, B and C are the torque coefficients that has $A+B+C=1$. Usually, the values of B and C are zeros. **Re** denotes the function to obtain the real part of phasor.

Based on Eqs. (1)–(5), the model of composite load can be formulated by a set of differential-algebraic equations (DAEs), where the STVS can be evaluated by analyzing the dynamics of the composite load. For more details about the composite load, please refer to Refs. [25,26]. The measurement-based methods for estimating the parameters of composite load can be seen in Refs. [25–28]. In this study, we mainly focus on the application of the composite load for STVS analysis.

2.2. Look-up table of SEP and UEP of composite load

The SEPs and UEPs of post-fault system play important roles in analyzing the stability based on the stability theory of dynamic system. For the STVS analysis, to obtain the post-fault IM's SEP and UEP is of great concern. Here, the method for solving the post-fault SEP and UEP is as follows.

In Eqs. (3) and (4), by setting the differential term to 0, we get:

$$0 = js\dot{E}' + \frac{1}{T'}[\dot{E}' - j(X - X')\dot{I}] \tag{6}$$

$$0 = T_0\left[A(1-s)^2 + B(1-s) + C\right] - Re\left(\dot{E}'\dot{I}^*\right). \tag{7}$$

To solve SEP and UEP of IM slip in Eq. (7), the expressions of $\dot{E}'$ and $\dot{I}$ are first obtained by combining Eqs. (5) and (6):

$$\dot{E}' = \dot{V}\frac{j(X - X')}{(r_s - sT'X') + j(sT'r_s + X)} \tag{8}$$

$$\dot{I} = \dot{V}\left\{\frac{1}{r_s + jX'}\left[1 - \frac{j(X - X')}{(r_s - sT'X') + j(sT'r_s + X)}\right]\right\}. \tag{9}$$