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Application of Bayesian method for electrical power system transient stability assessment

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ABSTRACT

In this article we present a short-term (short-transient) dynamic stability assessment methodology for generators of a power system at characteristic/relevant operation modes. The suggested methodology combines a classical simulation methodology and Bayesian approach, the latter being widely applied in a variety of areas nowadays. The proposed methodology reduced the number of calculations and the respective cut in computational time, enabled obtaining quite precise results in case of the lack of real measurements. The idea was to replace the major portion of calculations with a mathematical model of the power system by estimation procedure. As for the specification of its features, the methodology takes into account characteristic operation modes of the system in annual cycle and uses dependency functions of the generators relating dynamic stability reference characteristics with the estimated characteristics.

The estimated dynamic stability characteristics of the same generators were found with the Bayesian-approach-based estimation model which was trained by data sequence of true points from the reference characteristics. The performance of the methodology was examined by testing the dynamic stability of the generators of the power system and statistically analysing the test results. In summary, it can be reasonably argued that the best estimates were produced when the estimation model was trained with one dynamic stability reference characteristic and three true points of the characteristic for the considered generator. The verification of the suggested methodology for the aforementioned test system revealed that it reduces the computational time by several times, in comparison to "classical" methodology (based only on mathematical modelling of the power system).

1. Introduction

In the recent decade the growth of customer loads in power systems has been going in parallel with the permanent extension of electricity markets and, as a consequence, the increased power transfers and transits across several control areas [1]. Fast concurrent integration of renewable energy sources (the first and foremost, wind and solar) into electricity generation significantly contributes to these transfers and transits [2,3]. Nevertheless, the bigger the transfers and loadings of power systems become, the greater risk of operational failures emerges. It implies that the extended power transfers in the transmission grid are achieved at the expense of power system reliability and security. In addition, the intermittent generation mode of renewable energy based power plants aggravates the management of system reliability and security issues. As a whole, this brings up new tasks for power system operators as how to control power systems in a more reliable and secure mode, holding them in dynamic stability against various disturbances and emergencies.

Given the aforementioned trends in the development of power systems, the scientific concerns about the increased reliability as how to maintain power systems within operational safety limits, including dynamic stability conditions, were reported [4,5]. Numerous authors suggest various modified or novel approaches, methodologies and techniques to improve power system reliability analysis and evaluation, with dynamic stability considerations taken into account [6,7].

One of the dynamic stability criteria is critical post-fault dynamic stability time (further "critical post-fault time") of kth generator $T_{crit}(k)$. It refers to the maximum permissible duration of non-isolated fault for the kth generator. The extension of post-fault time beyond the $T_{crit}(k)$ brings kth generator beyond the dynamic stability limits, and first of all, to the rotor angle instability (oscillations) accompanied by the probable instabilities of some other

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generators. This is the reason why the tripping (fault clearance) time T_{trip} (k) with respect to kth generator (for, instance, 0.14 s in the 330 kV Lithuanian transmission grid) is always less than T_{crit} (k), where the T_{trip} (k) includes setting time of the major relay and opening time of the respective circuit breaker.

T_{crit} (k) strongly depends on electrical power system (EPS) load L_{PES}, rising with the increase of L_{PES}. Fig. 1 presents a typical characteristic of such dependence. It is explained by the simple relationship between the load L_{PES} and generation of the system: a greater load is balanced with additional generation units and/or outputs. As a result, it enhances the torque of the power system, i.e. its inertia and the robustness of EPS to triggering events.

The characteristic discloses the increased stability area of the kth generator located above the imaginable horizontal line at the level of the point (k,1) in Fig. 1. The zone provides for additional time for reserving relays to clear a fault if the major relay fails.

The critical post-fault characteristics rests upon several key points (for instance, four points as in Fig. 1. corresponding to four system load levels). To find the values of these key points, an extensive simulation of the EPS is necessary. In this case, a typical (we also refer to it as "classical") assessment methodology includes the following: the choice of adequate mathematical model of a power system with extended description of generating units; the choice of dynamic stability analysis and assessment procedure with respective scenarios (situations) to be examined and algorithms to be applied; the input of power system data; numerous simulations using specialised software packages, e.g.: PSS®E, Matlab Power System Toolbox, PSMS™, which enable the run of the model, scenarios and algorithms [8–11]. As for models, a number of them is aimed at better accuracy of critical post-fault times, mostly named as critical clearing times. The paper [12] considers two techniques to estimate critical values of the parameters of interest in a power system, such as clearing time of circuit breakers and mechanical input power. The former functions via the sensitivity of the transient energy function (TEF) and the latter through the computation of the norm of the trajectory sensitivities. Both these methods require some a priori information about the range of critical parameters. The authors of [13–15] suggest an accurate analysis of the transient stability problems involving a step-by step calculation of the motion of each machine in the system. A common shortcoming of such methodologies is the exhaustiveness of the study. To ensure that the study provides fairly accurate dynamic stability results, a lot of scenarios (failure mode, failure location, generator concerned) should be developed, simulated and assessed. It means that significant efforts in searching and computational time are needed. To be more specific, such problem arises

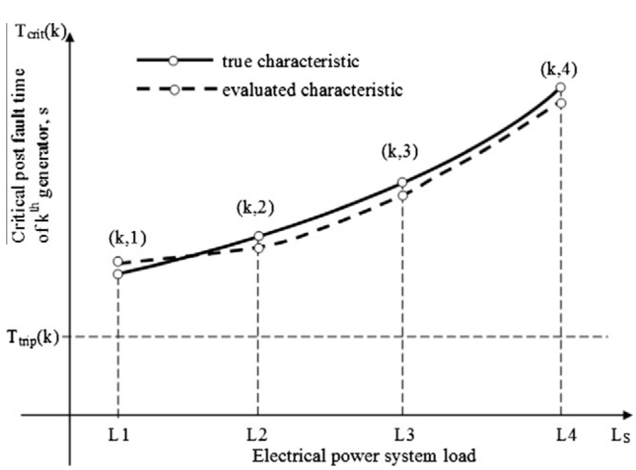

Fig. 1. Characteristics of critical post-fault time of kth generator.

practically for all power systems and particularly for those (1) with a large number of generation sources or (2) modelled for the purposes of short-term dynamic stability planning.

Hereinafter, the characteristic constructed using typical methodology is assumed to be true (Fig. 1 continuous line). The second one (in dash line) represents the desirable estimated characteristic, which would be constructed in an easier way using a smaller number of true points.

In this paper we present a novel short-term (short-transient) dynamic stability assessment methodology as critical post-fault time assessment methodology for system generators. Its idea is to replace the major portion of calculations with a mathematical model of the power system by estimation procedure. As for the specification of its features, the methodology: (1) takes into account characteristic operation modes of the system (system load levels) in annual cycle; (2) uses dependency functions of the generators relating dynamic stability reference characteristics with the estimated characteristics (the functions are based on Bayesian approach).

We regard the suggested methodology as classical dynamic stability analysis methodology [16] complemented by Bayesian approach (BA). The latter is widely applied nowadays, particularly in areas dealing with the classification and optimisation problems [17–21]. For the purposes of this paper, the performance of the methodology was examined by testing the dynamic stability of generators and statistically analysing test results.

This methodology will serve as a component of energy security assessment methodology based on calculation of integrated security index. The latter is currently under development in the Lithuanian Energy Institute and Vytautas Magnus University [25,26].

2. Mathematical modelling of electrical power system

To ascertain the adequacy of the suggested methodology and to prepare the "initial input data", it is necessary to conduct a detailed mathematical modelling focused on load flow calculations and dynamic behaviour of generators. In its essence, a power system is a complicated physical system consisting of a variety of elements: generators, turbines and boilers with regulation systems, transmission lines, transformers, reactive power compensation devices, consumer loads, etc. All these elements are mathematically described by their intrinsic parameters.

The following items are the basic input data for the power flow calculations [8–11]: transmission line impedances and charging admittances (capacitances); transformer impedances and tap ratios; admittances of shunt-connected devices, such as static capacitors and reactors; load (power demand) at each bus (node) of the system; real-power output of each generator or generating plant; either voltage magnitude at a generator bus or reactive power output of a generating plant; maximum and minimum reactive power output limits for a generating plant.

Physical elements in dynamic behaviour simulations are mainly characterised by two categories of input data [16]: time constants; gain coefficients which specify the relative strength of the voltage and current inputs to the excitation power source.

The power flow calculation is a network solution problem. The network of transmission lines and transformers is described by the linear algebraic equation:

$$I_n = Y_{nn} \cdot V_n, \qquad (1)$$

where I_n is the vector of positive-sequence currents flowing into the network from its nodes (buses), V_n is the vector of positive-sequence voltages at the network nodes (buses) and Y_{nn} is the network admittance matrix [8].

Dynamic simulation of a physical process consists of three basic steps [8]: