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Dynamic voltage stability constrained ATC calculation by a QSS approach

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Abstract

The evaluation of Available Transfer Capability (ATC) in deregulated power system should take into account thermal limits, transient, steady-state and dynamic angle stability as well as the voltage stability limit. The consideration of voltage stability in the determination of ATC, however, was not well researched before. On the other hand, under the power market environment, voltage instability becomes a more important consideration in many countries in recent years, especially when following a large disturbance in a heavily stressed power system over long distances. A new ATC determination scheme using Quasi-steady-state (QSS) approximation is proposed in this paper and implemented on a test system. The performance of the QSS approximation is also compared with the Full-Time-Scale (FTS) simulation. From the results, it is shown that the proposed scheme can evaluate ATC with dynamic voltage stability constraints accurately and the calculation speed is accelerated considerably to meet the real-time requirement.

Keywords: Available transfer capability (ATC); Voltage stability; Quasi-steady-state (QSS) approximation

1. Introduction

Market-based restructuring of electricity industry has been proceeding worldwide. In many countries, the original vertical integrated structure is restructured into separate entities with different functions, for example generation, transmission, distribution, etc. In general, the restructuring of generation utilities (GenCos) and power grid corporations (TransCos) is taken as the first step. Under such a deregulated environment, besides the system operator, certain real-time information of the transmission grid is also required to be known by its user especially the GenCos, so as to schedule their generation under secure operation and try to gain more profit. Real-time Available Transfer Capability (ATC) is one of the most pivotal data to be published on the Open-Access Same-Time Information System (OASIS) for market participants to arrange transmission transactions.

In 1996, Federal Energy Regulatory Commission (FERC) in USA mandated order 888 and 889, which claimed OASIS and required ATC to be posted on it. Following the FERC order, the North American Electric Reliability Council (NERC) established a framework for ATC definition and evaluation [1]. ATC is defined by the NERC as the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses with some security operation restrictions.

By definition, the evaluation of Available Transfer Capability (ATC) is determined by system security constraints, such as the thermal limits, transient, steady-state and dynamic angle stability together with the voltage stability limits. At this time, many approaches for ATC calculations with angle stability constraints are available [5–7]. Since the system operating conditions change over time, the limiting factor can be either one of the above limits. In heavy loading systems, voltage stability limit is usually dominant, and voltage instability is usually observed following a large disturbance in a heavily stressed power system over long distance [2]. This is typically the case in current market environments, as transmission systems are operating under more stressed conditions due to the increased transaction level associated with open access. In recent years, widespread abnormal voltage instability and voltage collapse have occurred in several countries, including France, Japan, USA etc. More attention is thus paid to keep the voltage profile and hold the voltage stability under control [3,4]. Sufficient attention to voltage

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stability in the determination of ATC, however, was not paid in the past as compared to what was done to angle stability.

In order to ensure system security operation, the ATC computation must be accurately and quickly updated as system conditions change. To satisfy the need of updating ATC at regular intervals, on-line voltage stability assessment with acceptable accuracy is required. However, it remains a demanding and time-consuming task, even though significant improvement has been made in the computer technology and efficient variable step size algorithms. Classified along the time-scale, the voltage stability of a system may be split into two categories: the short-term and the long-term dynamics. In practice, by fast protective devices and advanced auto-control technology, most systems respond in a stable way during the short-term following a disturbance. So when considering the determination of ATC, to simplify the calculation, the short-term dynamics may be filtered out and only the long-term dynamics is taken into account [3]. In the deregulated environment, many power grids of large size are required to transfer electric power over long distance. From the power supply side to the demand side, there are various voltage levels, and Under-Load Tap Changers (ULTC) are commonly employed to hold the voltage profile of the load area. The dynamic characteristics of ULTC and the increasing complexity of load influence the long-term dynamic security.

2. Methodology

QSS is an approximation method that has application in power system analysis either as one operation mode of dynamic simulation or as a separate time-domain simulation [10].

In this paper, Quasi-Steady-State (QSS) approximation of long-term dynamics is adopted to evaluate ATC with dynamic voltage stability constraints. ATC determination scheme using QSS approximation is proposed and implemented on a test system. The performance of the QSS approximation is also compared with the full-time-scale simulation, and the results show that QSS can simplify the analysis and accelerate the calculation speed with acceptable accuracy.

To evaluate ATC with long-term dynamic voltage stability constraints, the following assumptions are made in this paper:

1. The system has survived the short-term period following a disturbance. From then on it is driven by the long-term dynamics. During the short-term fast transients, the slow states keep unchanged.
2. The load in the test system is heavy and the transmission line is very long, so as to emerge the voltage stability limit above other limits.
3. Considering the focus of the paper, loads included in the model are designated to be with constant power characteristics as an approximation.
4. Ignore the dead-band of the ULTC.

In this research, the main concern of stability constraint type is voltage stability; regarding this consideration, to simplify the computation, constant power load is included in the load model. This simplification does not change the result much for the test system in the research. It should also be pointed out that although the load model is simplified, the generator and other components (e.g. the ULTC) are in detailed model.

In the analysis, the power flow algebraic equations are adopted to represent the network power flow as algebraic Eq. (1), and the differential equations in (2) are used to describe the short-term dynamics [8].

$$0 = \boldsymbol{t}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{Z}_c, \boldsymbol{Z}_d) \tag{1}$$

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{Z}_c, \boldsymbol{Z}_d). \tag{2}$$

In the above equations,

- $\boldsymbol{t}$ and f are smooth functions of time,
- $\boldsymbol{x}$ is the state vector during the short-term dynamics, i.e. rotor angle δ, rotor speed ω, internal transient voltage $\boldsymbol{E}'_{\mathbf{q}}$, $\boldsymbol{X}_{\mathbf{oxl}}$ of OXL (Over Excitation Limiter),
- $\boldsymbol{y}$ is the magnitudes and angles of bus voltages, i.e. $\boldsymbol{V}$, $\boldsymbol{\theta}$;
- $\mathbf{Z_c}$ and $\mathbf{Z_d}$ are respectively the continuous and discrete state vectors during the long-term dynamic, for example, $\boldsymbol{X}_{\mathbf{t}}$ of OXL is considered as $\mathbf{Z_c}$, and transformer ratio of the ULTC is treated as $\mathbf{Z_d}$. In this paper, we concentrated on the influence of ULTC on the load restoration in the long-term dynamics.

The long-term dynamics are described by both continuous and discrete equations as following:

$$\dot{\boldsymbol{Z}}_c = \boldsymbol{h}_c(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{Z}_c, \boldsymbol{Z}_d) \tag{3}$$

$$\boldsymbol{Z}_d(\mathbf{k}+1) = \boldsymbol{h}_d(\boldsymbol{x}, \boldsymbol{y}, \mathbf{Z}_c, \boldsymbol{Z}_d(\boldsymbol{k})) \tag{4}$$

In the QSS approximation, the short-term dynamics is assumed to be kept at equilibrium and the differential equation of it (Eq. (2)) may be replaced by the corresponding equilibrium equation

$$0 = \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{Z}_c, \boldsymbol{Z}_d) \tag{5}$$

Thus, in the multi-time-scale simulation, the short-term dynamics are passed over while the long-term evolution is reproduced, and the QSS approximation is yielded in the long-term dynamics.

Under the power market environment, power networks of large scale are required to deliver electric power over long distance. In many power networks, ULTC is commonly equipped between buses with different voltage levels to hold the voltage profile of the load area and restore the load power on the secondary side after a disturbance. Fig. 1 shows the trajectory of the operation point after a disturbance that shows the mechanism of the dynamic process of how the ULTC helps the network to restore at a new stable operation point. The P–V curves are of the primary side of the ULTC, and the ULTC is assumed to be an ideal transformer. In other words, it absorbs no power and there is no power loss from the primary side to the secondary side. The system originally operates at point A as the base case. After a