Electrical Power and Energy Systems 73 (2015) 734–742

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Voltage stability index-based reactive power compensation scheme [☆]

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ARTICLE INFO

Article history:
Received 11 May 2014
Accepted 25 April 2015
Available online 18 June 2015

Keywords:
Power system planning
Power system operation and control
Knowledge base system
Newton–Raphson method
Power system monitoring and reactive power

ABSTRACT

Reports of various committees set up to review the 2003 North American major power outages pointed out that a major exacerbating factor has been lack of situational awareness by power system operators. To improve reactive power compensation and contribute to the mitigation of power outages associated with the present near-limit operated commercialized grid, a bus voltage stability (BVS) index based reactive power compensation scheme has been developed. BVS index is a hybrid voltage stability computation model involving the two machine modeled L-index and a complex power Π-transmission line structure modeled Ls-index developed by the authors. The current regional wheeling of power across transmission distance far beyond the two machine model has necessitated the development of a novel Ls-index model suitable for long lines. The composite scheme was then incorporated into Newton–Raphson's (N–R) power flow which encompasses multiple shunt devices (multi-shunt). This arrangement provided a knowledge based system for power system monitoring. Results obtained from applying the developed models and schemes in the IEEE 300 bus system with zoning and under varying operating conditions showed the system's capability to provide improved system monitoring and optimal compensation based on availability.

Introduction

With growing concern for voltage instability and the need to improve power system performance to meet load demand occasioned by deregulation, the industry has focused attention on providing greater reactive support to the distressed grid [1–3]. Consequently, Flexible AC Transmission Systems (FACTS) and distributed energy resources (DERS) in the form of micrograds have also been utilized [4–15]. The basic categories of precipitating events or causes of the August 14th 2003 North American blackout were: (i) "inadequate situational awareness" on the part of FirstEnergy; (ii) FirstEnergy's failure to "manage adequately tree growth in its transmission right-of-way"; and (iii) "failure of the interconnected grid's reliability organizations to provide *effective diagnostic support*" [16]. In view of this report and those of other large scale power system outages [17–22], which started occurring since this period of deregulation and inception of modern reactive compensation schemes there is the utmost need to develop an improved power system status indicator. The status indicators could be in the form of thermal stability or voltage stability. However, since this research is focused primarily on reactive power compensation which is directly related to the power system voltage, this work dwells on the voltage stability based index. Existing voltage stability index models have been presented in [23,24].

Considering the medium and long distance bulk wheeling of power between various independent system operators (ISOs), regional transmitting organizations (RTOs) and over international boundaries, a novel bus VSI (Ls-index) suitable for medium and long transmission line application using the Π-complex transmission line model was developed [25–27]. The results obtained from applying Ls-index had been compared with L-index developed using two-machine transmission line model [24,26]. The results showed the effect of interconnecting transmission line distances on power system stability status [24]. In this paper, a hybrid voltage stability index scheme will be presented after combining the applications of L-index and Ls-index since most power system networks are composed of a mix of short, medium and long transmission lines.

This hybrid scheme will be applied with the Newton Raphson's (N–R) power flow model to determine the weak buses that require compensation. Thereafter, shunt FACTS device will be included in

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[☆] This work was supported by the Office of Research and Graduate Studies, Tennessee Technological University Cookeville, TN 38501, U.S.A.

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http://dx.doi.org/10.1016/j.ijepes.2015.04.016
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the N–R power flow model. With this new model, a new load flow result will be obtained and used to compute the hybrid voltage stability index. This will give an independent indication of power system status which can be read to determine the impact of the reactive compensation on the entire network. The compensation device can be set appropriately and if it is not given the desired support, it may be replaced.

The same philosophy may be applied to the transmission line voltage stability index models [26] and used to determine the lines which need compensation, the level of compensation required, and the effects on a selected portion, or the entire interconnected network. Some of the formulations and selection criteria as discussed by the authors earlier [26,27] with IEEE 14 and 30 bus system was modified and incorporated in the IEEE 300 bus system. The algorithm developed here also includes a feature to sub-divide large networks into groups to enhance faster operation and closer monitoring. It is hoped that the outcome of this work will provide efficient tools for the determination of power system status, ensure optimal utilization of the dynamic reactive power compensation devices, and reduce system outages through improved system monitoring.

The paper is arranged in the following manner. Section 'Justification for the use of voltage stability index in facts schemes' presents justifications for the introduction of an independent monitoring index in the power system compensation scheme. In Section 'Modeling of long transmission system bus voltage stability index', modeling of both the bus voltage stability index and the selected transmission line stability indexes are depicted. Section 'Scheme implementation algorithm' contains the development of implementation algorithm. Section 'Results and discussions' exhibits simulated results for the test system and accompanying discussions. Finally, the conclusions are given in Section 'Conclusion'.

Justification for the use of voltage stability index in facts schemes

To be able to address the two critical issues stated as the major causes of the 2003 blackout – "inadequate situational awareness" and "failure of the interconnected grid's reliability organizations to provide effective diagnostic support" [16], it is important to examine further the operational limitations of reactive power compensation devices as applied to the present power system.

Cost of FACTS devices

The cost of procurement, installation and maintenance of most of the FACTS devices are exorbitant and therefore, economically non-viable. Though SSSC, UPFC, IPFC and GUPFC have been tested in pilot projects [28,29], cases of practical installation are very insignificant. This has left system operators to continue making use of the simple and relatively cheap compensation devices like the SVC and the STATCOM as well as their offshoots [30–36]. Therefore, there is a need to incorporate status monitoring devices which will also guide in the appropriate utilization of these preferred devices.

Compensation devices not suitable for faulty operating conditions

Most compensation devices like the TCR, SVC STATCOM, TCSC and SSSC are designed to operate under specified limits. These limits correspond to their normal operating conditions. However, during faulty conditions in the network which are outside the operational limits, these devices give unreliable results. Due to the fast varying load types and near limit operating conditions of current power systems, there is a need to incorporate an additional status monitoring scheme. Doing this will help in the early determination of some of these abnormal situations.

Effect of reactive power compensation not localized

Generally, the present day power systems are composed of interconnected complex transmission lines, transformers, network compensators and varied types of load and generator buses spanning regional and international barriers. To ensure that the realization of the two basic objectives of power system compensation, namely, increasing the power transfer capability of transmission systems and keeping power flow over designated routes [29], thyristor switches are utilized to control the combined reactive impedance of both the capacitor and reactor banks.

Modeling of long transmission system bus voltage stability index

In an earlier effort to estimate the voltage stability of a power system, a two machine transmission line structure was used to develop a short line voltage stability indicator (L-index) [23]:

$$L_j = \max_{j \in \alpha_L} \left| 1 - \frac{\sum_{i \in \alpha_G} F_{jk} V_k}{V_j} \right| \tag{1}$$

$$\text{where } F_{jk} = -[Y] \left| Y_{jj} \right|^{-1} \tag{2}$$

The L-index was validated when it was compared with the voltage ratio index to determine the strength of each of the buses in IEEE 14 bus network [24]. However, the authors went further in [26] to develop an algorithm which made it possible to consider the effect on longer transmission line distances in the voltage stability of a given network.

In view of the long distance bulk wheeling of power between different ISOs and RTOs due to seasonal and hourly difference in power generation and peak load demand as well as reduced cost in remote generations, it became necessary to further consider the effect of transmission line distances on the voltage stability index models [25]. Therefore, a complex long transmission line structure as presented in Fig. 1 was used to develop a new Ls-index.

The line parameters are defined hereunder. Modified total line series impedance,

$$Z' = Z_c \sinh \gamma l = Z \frac{\sinh \gamma l}{\gamma l}$$

Modified total line-neutral admittance $\frac{Y'}{2} = yl = \frac{Y}{2} \frac{\tanh(\gamma l/2)}{\gamma l/2}$

The characteristic impedance and propagation constant are:

$$Z_c = \sqrt{\frac{z}{y}}$$

$$\gamma = \sqrt{yz}$$

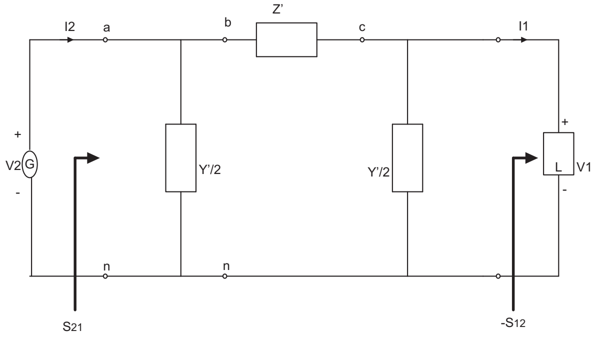

Fig. 1. Transmission line complex pi-model [25].