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Preventive reactive power management for improving voltage stability margin

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A B S T R A C T

Voltage stability imposes important limitations on the power systems operation. Adequate voltage stability margin needs to be obtained through the appropriate scheduling of the reactive power resources. The main countermeasures against voltage instability could be distinctly classified into preventive and corrective control actions. This paper proposes a preventive countermeasure to improve the voltage stability margin through the management of the reactive power and its reserve. The voltage and reactive power management is studied from the generator's point of view to maximize effective generator reactive power reserve (*EGRPR*). Detailed model of the generators including the armature and field current limits, as well as the switch mode between the voltage control and the reactive power limitations are considered to maximize the reactive power capability of the generators in emergency states. One-stage and two-stage optimization approaches are utilized to find the optimum solution. The proposed optimization procedure is applied on a 6-bus system and the New England 39-bus system to illustrate the effectiveness of the method.

1. Introduction

The voltage and reactive power management has been a concern for power system operators, especially after the restructuring of the power industry. In the restructured environment, the operation of the system is constrained by strict economic constraints. As a result, the network is frequently operated under stress and closer to its operating limits. The evidence of these circumstances is widespread blackouts in the recent two decades. Insufficient voltage and reactive power support was an origin or a factor in the major power outages worldwide [1].

In the context of the electricity market, the voltage and reactive power control service is classified as one of the ancillary services. Until now the system operator is the sole responsible for the management of this critical ancillary service to ensure secure and reliable operation of the system.

Sufficient voltage stability margin (VSM) should be provided to preserve the security of the bulk power system against the short- and long-term instabilities and subsequent voltage degradation and collapse. For this purpose, appropriate control actions should be continuously acquired, deployed and maintained from the control resources. These control actions comprise reactive power reserve (RPR) and emergency countermeasures that can be considered, respectively, as preventive and corrective control actions. The corrective actions include load tap changer blocking, capacitor switching, voltage and reactive power rescheduling, then active power rescheduling, and as the last resort load shedding [2]. The main preventive actions against voltage instability are (1) management of reactive power resources through load tap changing, capacitor switching, and (2) implementation of hierarchical or centralized voltage and reactive power control schemes, which both of them affect the RPR. Also, the active power rescheduling can be included in the preventive actions which is not taken into consideration in this paper [3]. Here, the focus is only on the management of the reactive power resources as the most important preventive action.

In order to provide RPR appropriately, both reactive power generation and its reserve should be considered simultaneously in the procurement and the scheduling of the reactive power resources. The RPR can be taken into account from the load or the generator point of view which is called *LRPR* and *GRPR*, respectively. The literature paid more attention to *LRPR* than *GRPR* and so more investigation is needed for the latter. Moreover, the system operator usually has to manage its reactive power resources for a specified active power dispatch obtained from the active power market. For this purpose, it is assumed that the management of the active and reactive power is decoupled. Furthermore, the increasing interest for the setup of a reactive power market, raise the interest for RPR analysis from the generators' side, since they are the main providers of this service. As a result, this paper focuses particularly on the *GRPR*.

In this paper, an optimization procedure is proposed for reactive power management considering an operating point correlated to a voltage collapse point to improve the VSM. The aim of the proposed

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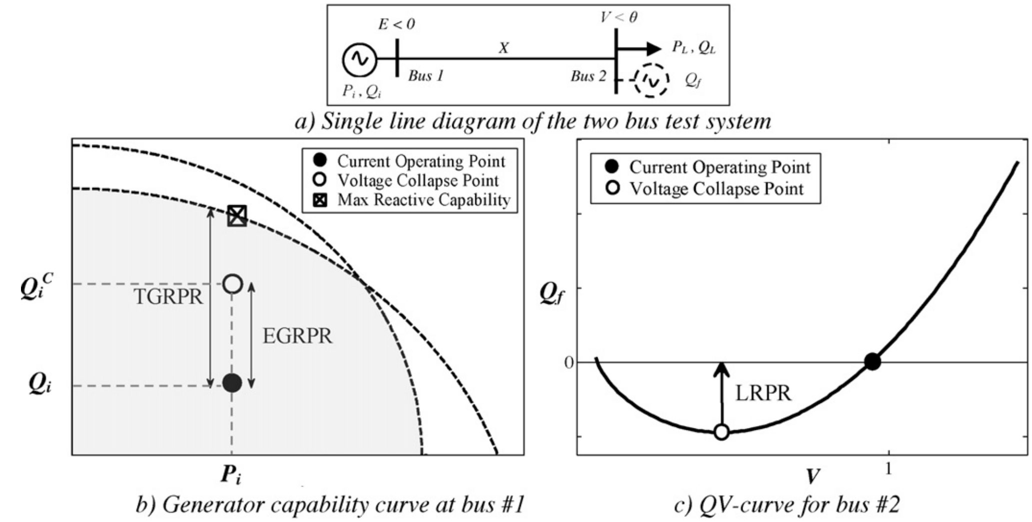

Fig. 1. *LRPR*, *TGRPR*, and *EGRPR* for the two bus test system.

scheme is to distinguish and to improve the effective RPR of the generators. To deal with it, in Section 2, fundamentals of *GRPR* and *LRPR*, are discussed more in depth. The proposed reactive power management method regarding VSM is presented based on one-stage and two-stage optimization approaches in Section 3. Finally, the proposed method is applied and tested on a 6-bus test system and on the 39-bus New England system. The simulation results and analysis are given in Section 4.

2. Fundamentals on reactive power reserve

The RPR is a spare reactive power capability available in the system to assist the voltage control. This capability should be considered to respond to unforeseen events that lead to a sudden change of reactive power requirement. The system operator needs to assign sufficient RPR on the best response resources. Thus, the generators are commonly the main resource of RPR which they are also referred as spinning RPR.

The RPR can be viewed from the load's and the generator's perspective. The two bus test system, shown in Fig. 1a, is used to illustrate the various viewpoints of the RPR. A generator and a load are connected to bus 1 and bus 2, respectively. The *QV*-curve method, for which more details are given in [4], is used to obtain the reactive power margin to a voltage collapse point. For this purpose fictitious reactive power supports Q_f's are connected to certain load buses referred as pilot nodes. Here, the term "pilot node" is explicitly used for this purpose. The *QV*-curve, shown in Fig. 1c, expresses the relationship between the reactive power support (Q_f) at the given bus and the voltage (V) at that bus [2]. The minimum point of the *QV*-curve shows the reactive power margin until the voltage instability. This point is called voltage collapse point and it is indicated by the white circle. The current operating point without compensation ($Q_f = 0$) is indicated by the black circle. The generator reactive power output of the current operating point and the voltage collapse point are shown on the generator capability curve in Fig. 1b. In this paper, the optimal power flow is used to calculate the reactive power margin to the voltage collapse point [5].

The load RPR (*LRPR*), shown in Fig. 1c, is defined as the minimum amount of the reactive load increase for which the system loses its operability. According to the literature, it is also referred as reactive power margin. The generator RPR (*GRPR*) focuses on the effectiveness of the provided RPR by each generator. Technical generator RPR (*TGRPR*), is defined as the difference between the maximum reactive power capability of the generator and its reactive power generation at the current operating point. This quantity may not represent the useful quantity of the *GRPR* since at the collapse point all the amount of the *TGRPR* cannot be utilized. Effective generator RPR (*EGRPR*), as achievable representative of the *GRPR*, is defined as the difference between the generator's reactive power output at the voltage collapse point and the generator's reactive power output at the current operating point. The *TGRPR* is an upper bound for the *EGRPR*. The *LRPR*, the *TGRPR*, and the *EGRPR* for the two bus test system are shown in Fig. 1c and b.

The system operator defines the set-points of the voltage and reactive power controllers by using different criteria such as minimization of reactive power injection (or maximization of *TGRPR*), minimization of voltage profile deviation, and minimization of transmission losses. These different objectives would result into different amount of RPR and consequently different security margins. Nevertheless, the RPRs should be appropriately managed from the available resources to enhance the VSM.

Improving the VSM has been considered in the literature in different ways. The proposed VAR scheduling methods in [6–8] add a penalty factor to the OPF to maximize the VSM. The penalty factor is derived from the eigenvectors and/or the generators' participation factors related to the Jacobian matrix.

RPR provision is widely proposed in literature based on: (a) security constrained OPF (SCOPF) to assess the RPR with different constraints [3,9] and (b) voltage stability constrained OPF (VSCOPF) to determine preventive [10,11] and corrective [10] controls considering voltage stability.

Regarding the literatures on *LRPR* [12], defines a reactive reserve as the sum of the exhausted reactive reserves at the minimum point of the *QV*-curve. The RPR-based contingency constrained OPF (RCCOPF) presented in [3] utilizes a decomposition method to solve the preventive voltage control in normal state while considering the active power margin of post-contingency states. The proposed RPR management in [5] utilizes a two level Benders decomposition, including a base case and stressed cases, to ensure the feasibility of the stressed cases.

Most of the studies on *GRPR* like in [13] and [14] are performed on *TGRPR* since it can be calculated easily regardless stability analysis. On the other hand, *EGRPR* depends on the generators capability curve and the network characteristics [15]. That means the maximization of *TGRPR* does not imply necessarily the maximization of *EGRPR* all the times. The *GRPR* is studied from the *EGRPR* point of view more in depth in [15] and [16]. The *EGRPR* for a bus or an area is determined in [17] as the weighted sum of the individual