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Distributed generation support for voltage regulation: An adaptive approach

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ABSTRACT

Distributed generation is expected to introduce additional issues in the operation of distribution networks. Among these, voltage variation is of particular concern and needs to be addressed concisely. Conventionally, voltage regulators are placed in transmission level, where they use reactive power control to alter voltage levels. This approach has been particularly effective due to the inductive nature of transmission networks. However, seen from that point of view, distribution networks are different. Hence, this paper introduces a new methodology to address the problem of DG units dispatch while maintaining voltage levels within desired levels. This approach, termed identification-based adaptive voltage regulation (I-BAVR), uses real-time identification of the Thevenin equivalent circuit of the system, giving the X/R ratio to identify the active and reactive power dispatch of the DG unit. The I-BAVR approach has been validated though several steady-state and dynamic simulation scenarios on a typical medium voltage network. These simulations show that by using an appropriate control strategy, DG can regulate the voltage to the specified levels by adapting the amounts of it active and reactive power to the systems operational changes.

1. Introduction

Today, the distribution network is experiencing a structural change so significant that there is an urgent need to consider new ways of operation to improve flexibility, efficiency, sustainability and intelligence [1]. The main cause of this structural change is the introduction of small generating units into the distribution network, known as Distributed Generation or DG [2]. Several research activities and case studies have shown that current distribution network design does not allow DG to be integrated at higher levels [1]. This limitation is the consequence of DG causing a reversal in power flow in the system, a situation which was previously seen only in transmission networks. Hence, one of the major barriers against major deployment of DG into the distribution network is their impact on voltage levels [3].

Voltage control is traditionally done via reactive power control, using synchronous generators, capacitors and recently FACTS devices [4]. This approach was and still is an effective way of dealing with voltage regulation problems in transmission grids due to their inherent inductive nature. This inductive nature makes decoupling possible between active power, used to regulate frequency, on the one hand, and reactive power, used to regulate voltage, on the other hand. Transmission networks were and are and regarded as the backbone of today's power systems, incorporating all control actions necessary for proper operation [5].

Nevertheless, as mentioned earlier, this paradigm is changing and voltage regulation is becoming one of the main issues in distribution networks. The way this issue needs to be dealt with however, cannot be the same as the one used in the transmission level [4,6]. Indeed, distribution (medium and low voltage) systems are known to have X/R ratios close to or even below unity. This fact translates into reactive power being ineffective as the sole mean of improving voltage levels. Bollen et al. [7] proposed a droop control strategy for sharing the voltage control task among several DG units. The voltage regulation is achieved by injecting both active and reactive power into the grid. De Brabandere et al. [8] proposed a different droop using the so-called finite output impedance emulation. Several other works have introduced the use of real power from DGs for voltage regulation [9–11]. These strategies are all based on prior knowledge of the network impedance, which is either not always readily available or is not constant due to a change in the networks operating conditions. In this work it will be shown that the X/R ratio is an adequate parameter for achieving effective voltage regulation in any given system. Consequently, this work exploits this idea and introduces a new distributed generation dispatch scheme while maintaining voltage levels at the desired levels. This approach consists of first obtaining the grid's equivalent Thevenin circuit parameters in real time and consequently the grid's X/R ratio via an online identification

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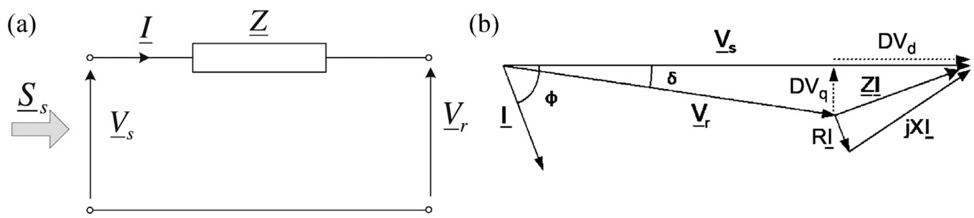

Fig. 1. (a) Equivalent circuit of power line, (b) phasor diagram.

scheme, and then using this information for deriving the exact amounts of active and reactive power for voltage regulation.

This paper is organized as follows: in Section 2, conventional voltage regulation strategy is revisited including a discussion of the basic theory behind such a strategy. After showing the limitations of this conventional approach, a new concept – the Pseudo-reactive power concept – is introduced as a universal quantity that can regulate voltage efficiently regardless of the system's characteristics. Section 3 introduces the identification-based adaptive voltage regulation (I-BAVR) scheme, giving a general description briefly describing the steps involved. Section 4 elaborates on the different steps used to indentify, in real time, the Thevenin equivalent circuit parameters: first voltage and current phasors are identified through Kalman filtering, and then these phasors are used by a Constrained Recursive Least Squares (CRLS) algorithm to identify the Thevenin parameters. Finally in Section 5, the I-BAVR approach is validated through a case study, where several tests are carried out both in dynamic and steady-state conditions in order to prove the performance of the proposed method.

2. Voltage and reactive power control

2.1. Conventional reactive power control

Referring to Fig. 1, the apparent power following from point A to point B is given by:

$$\underline{S}_s = \underline{U}_s \underline{I}^* = \frac{U_s^2}{Z} e^{j\theta} - \frac{U_s U_r}{Z} e^{j(\theta+\delta)} \quad (1)$$

where $\underline{S}_s$, $\underline{U}_s$, $\underline{U}_r$, $\underline{I}$ are apparent power phasor, sending-end phasor, receiving-end phasor and current phasor respectively. δ is the angle between sending and receiving end voltages, θ is the impedance ($\underline{Z}$) angle, and ϕ in Fig. 1 is the load angle.

According to (1), and by letting $R = Z\cos\theta$ and $X = Z\sin\theta$, the active and reactive power flow in the line is given by:

$$P_s = \frac{U_s}{R^2 + X^2}(R(U_s - U_r\cos\delta) + XU_r\sin\delta) \quad (2)$$

$$Q_s = \frac{U_s}{R^2 + X^2}(X(U_s - U_r\cos\delta) - RU_r\sin\delta) \quad (3)$$

Hence, the direct and quadrature voltage drops, ΔV_d and ΔV_q respectively, are given by:

$$\Delta V_d = U_s - U_r\cos\delta = \frac{RP_s + XQ_s}{U_s} \quad (4)$$

$$\Delta V_q = U_r\sin\delta = \frac{XP_s - RQ_s}{U_s} \quad (5)$$

In transmission lines, the line impedance is predominantly inductive ($R \ll X$). Assuming a small power angle ($\sin\delta = \delta$), (4) and (5) simplify to:

$$\Delta V_d = U_s - U_r = \frac{XQ_s}{U_s} \quad (6)$$

$$\Delta V_q = U_r\delta = \frac{XP_s}{U_s} \quad (7)$$

In such conditions, the voltage drop is directly caused by the reactive power flow, and load angle (and consequently frequency) is caused by active power flow across the line. Thus the frequency and amplitude of the grid voltage are controlled by adjusting P and Q independently.

2.2. Pseudo-reactive power concept

The X/R ratio of the short circuit impedance of the grid plays a crucial role in the voltage control performance. Indeed, (4) and (5) show that when there is no assumption to be made on the X/R ratio i.e. no predominance of the inductive part of the line impedance over the resistive part and vice versa, the voltage drop across the power line does not only consist of a reactive part, but has an active component as well. So in order to address the voltage regulation problem in the general case, the *Pseudo-reactive* power or *Pseudo-Q* concept is introduced. The aim is to find a mapping that relates the voltage magnitude to the active and reactive power without making any assumption on the X/R ratio of the line. A graphical illustration of this concept is given in Fig. 2. In case of high X/R and assuming a small load angle δ, compensation for the voltage drop is provided mainly by reactive power supplement Q_c. However, in the general case with regards to the X/R, it is the Pseudo-Q entity which needs to be compensated for. This entity has an active part and a reactive part which are defined as follows:

$$\begin{aligned} P &= \text{Pseudo-Q}\cos\theta = \frac{R}{Z}.\text{Pseudo-Q} \\ Q &= \text{Pseudo-Q}\sin\theta = \frac{X}{Z}.\text{Pseudo-Q} \end{aligned} \quad (8)$$

where P and Q are the required active and reactive power respectively, so that the magnitudes of the sending and receiving end voltages are equal.

Similarly, in the same way the *Pseudo-reactive current* or *Pseudo-I_q* is defined. In which case, the active and reactive currents used to regulate voltage are given by:

$$\begin{aligned} I_d &= \text{Pseudo-}I_q\cos\theta = \frac{R}{Z}.\text{Pseudo-}I_q. \\ I_q &= \text{Pseudo-}I_q\sin\theta = \frac{X}{Z}.\text{Pseudo-}I_q. \end{aligned} \quad (9)$$

where I_d and I_q are the active and reactive current respectively. This concept therefore uses the X/R information of the grid to determine the amounts of active and reactive power (or active and reactive current), and can be used on any type of system.

2.3. System identification-based adaptive voltage regulation

Based on the Pseudo-reactive power concept, an active and reactive power dispatch scheme is proposed to deal with voltage changes encountered in a distribution line. The basis of this strategy is to perform an online identification on the Thevenin equivalent circuit, which would provide the X/R information of the grid. Using