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Reactive power management of distribution networks with wind generation for improving voltage stability

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ABSTRACT

This paper proposes static and dynamic VAR planning based on the reactive power margin for enhancing dynamic voltage stability of distribution networks with distributed wind generation. Firstly, the impact of high wind penetration on the static voltage stability of the system is analysed and then the effect of composite loads on system dynamics is presented through an accurate time-domain analysis. A new index, reactive power loadability (Q-loadability), is used to measure the vulnerability of the network to voltage collapse. Compensating devices are located using Q-loadability to increase the system voltage stability limit. Finally, a cost-effective combination of shunt capacitor bank and distribution static compensator (D-STATCOM) is determined through static and dynamic analyses to ensure voltage stability of the system after a sudden disturbance for different wind penetration levels. This study takes into account the induction motor dynamic characteristics which influence the transient voltage recovery phenomenon. The results show that the proposed approach can reduce the required sizes of compensating devices which, in turn, reduces costs. It also reduces power losses and improves the voltage regulation of the system.

1. Introduction

In recent years, distributed generation (DG) has attracted strong interest because of economic and environmental factors. Its potential benefits include improved system reliability, reductions in greenhouse gas emissions and energy losses, and increased flexibility in investments [1]. However, the increased penetration of DG presents a significant challenge to distribution network operators as traditional distribution networks were generally not designed to connect power generation facilities. DG integration in these passive networks will add a new dynamic element due to the variability and uncertainty inherent in the operation of renewable energy sources. In this context, it is very important to understand the behaviour of DG-integrated systems to facilitate the overall planning of power distribution systems [2,3].

The load of a distribution network is always changing due to variations in consumer demands. In certain industrial areas, it has been observed that under certain critical loading conditions, the distribution system experiences voltage collapse [4]. The connection of a generator to the distribution system affects the flow of power and voltage profile of the system and the profiles are different for different types of loads [5]. The importance of load characteristics in power system simulation studies is highlighted by the IEEE Task Force in Ref. [6].

The main classification of loads is into static and dynamic types. Static loads can be classified as constant impedance, constant current and constant power loads. The modelling of loads is complicated because a typical load bus represented in a stability analysis is composed of a large number of devices, such as fluorescent and incandescent lamps, refrigerators, heaters, compressors, motors, furnaces, etc. The exact composition of a load is difficult to estimate as the load magnitude and composition vary greatly with location, temperature, time of day, season, etc. In power flow studies, the common practice is to represent the load characteristics as seen from power delivery points [7]. Most conventional load flows use a constant power load model in which it is considered that active and reactive powers are independent of voltage magnitudes. In distribution systems, nodal voltages vary widely as most of the buses are not voltage controlled [8]. Therefore, the load characteristics are important for distribution systems analysis.

Due to the integration of DG, distribution networks are becoming active systems where generation and load nodes are

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mixed. The interaction between generators and load characteristics affects the operation of distribution systems and proper reactive power planning is required as it is directly related to the voltage level control of distribution networks. This important issue has attracted much less attention in the available literature. Most of the papers in distribution systems have analysed the impact of DG penetration in the system considering static load models [9–11]. Static load models are not accurate enough for capturing all the dynamics of a network. In reality, distribution networks have composite loads which are composed of both static and dynamic elements. As loads are closer to the DG, the interaction between them is direct. This situation may require high dynamic compensation to ensure fast voltage recovery under post-fault condition.

Of the different dynamic compensating devices available, the static synchronous compensator (STATCOM) is increasingly being used to enhance dynamic voltage stability of the system [12]. However, the performance of a STATCOM depends upon its controller parameters and suitable location in the power network. Power quality and voltage stability of the system can be ensured using distribution static compensator (D-STATCOM) in low voltage (LV) grids with distributed energy resources (DERs) [9,13]; but in Refs. [9,13], a strategy for placing compensating devices with the new generation in distribution networks is not provided. A STATCOM with a suitable control has the potential to significantly increase the transient stability margin as well as voltage stability of a system [14]. However, it is an expensive device and should not be used without proper planning. Fuzzy logic based reactive power compensation planning for radial distribution feeders is proposed in Ref. [15]. But the analysis is carried out for only a shunt capacitor bank which cannot ensure dynamic voltage recovery. The reactive power delivered by the shunt capacitor is proportional to the square of the terminal voltage, which means that during low voltage conditions VAR support drops, thereby compounding the problem [16]. This situation may become worse when static load models are replaced by composite ones. A multi-objective approach for reactive power planning with wind generators is proposed in Ref. [17]. The methodology proposed in Ref. [17] determines the optimal location of, and reactive power injection from, static VAR compensator (SVC) sources in order to improve system's static voltage profile and power loss. However, the dynamic voltage stability issue is not considered in Ref. [17]. In our previous work [18], due to the lack of adequate placement planning, a large D-STATCOM was required to improve the dynamic voltage profile of distribution networks with constant PQ loads.

The main aim of this paper is to enhance the dynamic voltage stability of distributed generation systems in a cost-effective way which complies with industry standards. The effect of load models in distributed generation planning is demonstrated through nonlinear simulations. A new index, reactive power loadability (Q-loadability), is used to determine the best location for the D-STATCOM to enhance voltage stability. Both static and dynamic analyses are carried out to determine its required size. The parameters of the controller are also tuned to reduce the D-STATCOM's rating.

The remainder of this paper is organised as follows. In Section 2, the background of the proposed methodology is given. Section 3 presents the system description. Simulation results showing the impact of high wind penetration and different load characteristics on the system voltage stability are given in Section 4. The proposed planning approach is demonstrated in Section 5. The effectiveness of the proposed methodology is investigated through several case studies in Section 6 and the paper concludes with brief remarks in Section 7.

2. Background

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses under both normal and abnormal (such as following a disturbance) operating conditions [16]. The main factor causing voltage instability is the inability of power systems to meet the demand of reactive power. In power systems, P–V (MW margins) and Q–V curves (MVAr margins) are used to determine the ability of a system to maintain voltage stability under normal and abnormal conditions. The P–V and Q–V curves are obtained through a series of AC power flow solutions [19]. The P–V curve is a representation of voltage changes as a result of an increased power transfer between two systems and the Q–V curve is a representation of reactive power demand by a bus or buses as voltage level changes.

The power flow relationship between the source and load can be illustrated by considering the simple radial network shown in Fig. 1 which consists of a constant voltage source (V_s) supplying a load (Z_{load}) through a series impedance (Z_{line}) [16].

The expression for current in Fig. 1 is

$$\tilde{I} = \frac{\tilde{V}_s}{\tilde{Z}_{line} + \tilde{Z}_{load}}, \tag{1}$$

where $\tilde{I}$ and $\tilde{V}_s$ are phasors, $\tilde{Z}_{line} = Z_{line}\angle\theta$, $\tilde{Z}_{load} = Z_{load}\angle\phi$. The magnitude of the current is

$$I = \frac{V_s}{\sqrt{(Z_{line}\cos\theta + Z_{load}\cos\phi)^2 + (Z_{line}\sin\theta + Z_{load}\sin\phi)^2}}, \tag{2}$$

which may be expressed as

$$I = \frac{V_s}{\sqrt{F}Z_{line}}, \tag{3}$$

where

$$F = 1 + \left(\frac{Z_{load}}{Z_{line}}\right)^2 + 2\left(\frac{Z_{load}}{Z_{line}}\right)\cos(\theta - \phi). \tag{4}$$

The magnitude of the receiving end voltage is given by

$$V_r = Z_{load}I = \frac{V_s Z_{load}}{\sqrt{F}Z_{line}}, \tag{5}$$

and the power supplied to the load is

$$P_r = V_r I\cos\phi = \left(\frac{Z_{load}}{F}\right)\left(\frac{V_s}{Z_{line}}\right)^2\cos\phi. \tag{6}$$

The loading of the network can be increased by decreasing the value of Z_{load}. For P–V analysis, the loading of the network is

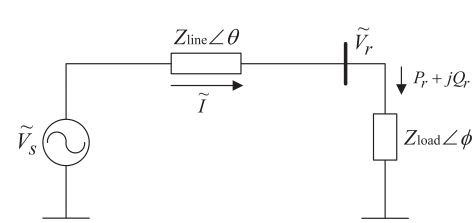

Fig. 1. A simple radial distribution system.