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Capability constraints to mitigate voltage fluctuations from DFIG wind farms when delivering ancillary services to the network

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ABSTRACT

Majority of the wind power resources are typically sited at remote locations in power networks and generated power is transmitted through rural transmission corridors to load centres. With increased penetration level of the wind generation there is an increased requirement to provide ancillary services from distributed wind power resources, hence they are operated under different control strategies to provide ancillary services to the network. The control strategies and capability characteristics will significant impact on voltage fluctuations in distribution networks. This paper presents a comparative analysis between different wind generator control strategies (i.e. power factor control strategy, voltage control strategy and reactive power dispatch strategy) on network voltage fluctuations during variable wind conditions while considering extended reactive power capability (i.e. with both generator and power electronic converter reactive power capabilities) for the doubly-fed induction generator (DFIG). Voltage fluctuations are analysed using real wind data measured at a DFIG based wind farm, and the wind farm model was verified against real measurements. Study has shown that voltage fluctuations are exacerbated when wind generator is at mode transition (i.e. from power optimisation mode to power limitation mode). A sensitivity analysis has shown that voltage fluctuations are exacerbated due to the limitations of the reactive power capability of the DFIG, and the operating point of the DFIG power curve irrespective of the control strategy implemented at the wind generator. Furthermore, a mitigation strategy was developed as an integrated control scheme to the main control scheme in order to reduce voltage fluctuations due to wind power variations. However, effectiveness of the mitigation strategy is greatly affected by the reactive power capability of the DFIG, in particular during high wind turbulences.

Introduction

Wind power integration has given rise to power quality issues in distribution networks and flicker emission is identified as one of the power quality issues associated with wind generation [1,2]. In particular, the variable nature of wind generation results in power fluctuations hence creates voltage fluctuations in distribution feeders. A number of research studies have been conducted on flicker emission analysis [3–7], propagation [8,9] and mitigation strategies [10–14] for wind farms. Majority of these studies are focused on unity power factor operation of the wind generator, however, impact of wind generator control strategies on voltage fluctuations and reactive power capability on flicker mitigation have not been extensively analysed.

The work presented in [3] analysed the flicker emission for a fixed-speed wind generator (FSWG). Flicker study conducted in [4] advocated that it may limit the installable wind power capacity in a radial distribution feeder. In [5] the authors have analysed various factors affecting the flicker emission from wind farms such as mean wind speed, turbulence intensity, short-circuit capacity (SCC) and grid impedance angle (X/R ratio). A wind farm flicker emission study conducted in [6] has shown that wind farms at two measured locations have exceeded the flicker emission limits stipulated in the relevant grid-codes. However, these studies are limited to a single control strategy and effect of multiple renewable generators has not been considered. The studies presented in [15,16] have shown the impact of various wind farm control strategies (e.g. power factor control strategy, voltage control strategy and reactive power dispatch strategy) on flicker emission, propagation and attenuation with bidirectional power flows in a distribution network. Furthermore, it has shown that flicker severity could be exacerbated when wind farm is operating at low leading and lagging power factors [16].

In [5] the authors have proposed a control scheme for a doubly-fed induction generator (DFIG), based on the grid impedance and

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power factor angle control technique for the grid-side converter (GSC). In that scheme the voltage fluctuations during variable speed operation has been derived as a function of the grid impedance angle and the power factor angle. The study presented in [9] has also proposed flicker mitigation technique for the DFIG using power factor angle technique. However, in both studies [5,10] reactive power requirement to implement the proposed mitigation scheme has not been explicitly analysed. In [11] authors have proposed active power control method for flicker mitigation considering a permanent magnet synchronous generator (PMSG) based wind farm. In that study power oscillations have been smoothened by varying the dc-link voltage of the full-scale converter.

This paper aims to investigate various limitations associated with mitigating voltage fluctuations under different control strategies for the DFIG wind farms. In particular, limitations associated with the reactive power capability of the DFIG are analysed. Furthermore, existing mathematical models have also been extended to exemplify the flicker emission under different control strategies for the DFIG.

The DFIG model and DFIG capability characteristics

The DFIG dynamic simulation model

A DFIG dynamic simulation model was developed in DIGSILENT Power Factory considering the control philosophy of the GE 1.5 MW DFIG wind generator and parameters are obtained from [13]. The DFIG was developed as a three-mass model; hence the turbine inertia, drive-train stiffness and inertia, and generator inertia were represented separately in the DFIG simulation model. The rotor-side converter (RSC) and the grid-side converter (GSC) are developed with separate active and reactive power (PQ) controllers; hence both converters can be controlled independently of each other. The each PQ controller is consisted of two control loops (i.e. slow controller and fast current controller) [17]. In addition, the slow controller was modelled with reactive power characteristics associated with respective converter (i.e. DFIG-RSC and GSC reactive power capability characteristics). A coordinated reactive power sharing scheme was implanted as outlined in [17] to maximise the reactive power capability of the DFIG. Furthermore, the model also has the flexibility to either operate in constant power factor mode, voltage control mode and reactive power dispatch mode. A schematic of the DFIG is shown in Fig. 1.

DFIG capability characteristics

The reactive power capability of the DFIG can be attributed to both the wound rotor induction generator (WRIG)-RSC and the GSC. Theoretically, a back-to-back converter rated at 30% of the machine rating is sufficient for the full operating speed range (0.7–1.2 pu) of the DFIG. However, most commercial designs allow an additional capacity, and hence the DFIG simulation model was designed with a 50% back-to-back converter while allowing additional operating margin for the converter. The capability charts for the 1.5 MW DFIG-RSC and GSC are obtained from [17], and are illustrated in Fig. 2.

According to Fig. 2 the DFIG-RSC has the capability to operate between ±0.95 power factor without additional reactive power support from the GSC. However, +0.90 power factor operation is limited to 0.90 pu active power output, hence additional reactive power must be provided by the GSC. In addition, the reactive power capability reduces with an increase in DFIG active power output. The GSC capability chart indicates ±0.48 pu average reactive power capability for a 50% converter rating across its operating range. Therefore, a 50% converter rating indicates a combined reactive power capability of 1.28 pu during zero active power production, while during full active power production this has reduced to 0.83 pu. Therefore, the DFIG possesses a significant reactive power capability to support network requirements.

Flicker emission and wind generator control strategies

Variable wind conditions cause power fluctuations in wind farms, and ultimately cause voltage variations at the point of grid connection. This phenomenon can be understood by considering a generator feeding active and reactive power to an external grid via a distribution line (see Fig. 3).

Here P_g, Q_g, V_g, V_s, V_{g_pt}, V_{g_pr}, I_g, R, X, and θ represent active power generation, reactive power generation, generator end voltage, grid voltage, generator end voltage following power fluctuation, generator end voltage prior to power fluctuation, line current, line resistance, line reactance, and angle between active power fluctuation (ΔP) and reactive power fluctuation (ΔQ) at the generator, respectively. The relative voltage fluctuation (ΔV) at the generator due to variable active and reactive power output from a grid connected wind farm can be approximated as follows [15]:

$$\left|\frac{\Delta V_g}{V_n}\right| \approx \left|\frac{\Delta P \cdot R + \Delta Q \cdot X}{V_n^2}\right| \tag{1}$$

where V_n is the nominal system voltage. Therefore, wind power fluctuations given rise to active power fluctuations (ΔP), and hence will lead to voltage fluctuations (ΔV) at the generator terminal. Consequently, voltage fluctuations will lead to flicker emission. However, variations in reactive power output (ΔQ) are mainly determined by the control strategy of the renewable generator, hence according to (1) it will influence on flicker emission. The following reactive power control strategies are evaluated during variable wind power generation.

- Power factor control strategy
- Voltage control strategy
- Reactive power dispatch strategy.

Power factor control strategy

In power factor control strategy the average power factor is maintained at a specified value by varying the reactive power with variable active power generation. When power factor control strategy is implemented (other than unity power factor operation) when active power varies by ΔP it will maintain the average power factor at the specified value by varying the reactive power ΔQ, therefore reactive power variation can be denoted as follows:

$$\Delta Q = \Delta P \cdot \tan\phi \tag{2}$$

where ϕ denotes the power factor angle. By substituting (2) in (1), the voltage fluctuation can be denoted as follows:

$$\left|\frac{\Delta V_g}{V_n}\right| \approx \left|\frac{\Delta P \cdot (R + \tan\phi X)}{V_n^2}\right| \tag{3}$$

According to (3) any changes in wind generator active power output (ΔP) leads to voltage fluctuations, hence flicker. Furthermore, the multiplication term (i.e. $R + \tan\phi X$) depends on the operating power factor, as the X/R ratio of low voltage distribution feeders is approximately 1. Therefore, based on the operating power factor of the wind farm, the magnitude of the voltage fluctuation is also vary, hence operating power factor has a significant influence on voltage fluctuations. In particular, if the generator is operating at leading power factor that would be much detrimental than the lagging power factor operation [16].