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Grid voltage control with distributed generation using online grid impedance estimation

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ABSTRACT

Distributed generation (DG) units usually do not participate in the grid voltage control and inject power regardless of the grid voltage. Only when the grid voltage level surpasses a certain threshold, these units shut down to avoid any damage. In this paper, a method is presented to control the grid voltage with both active and reactive power with a DG unit. The effect of active and reactive power exchange on the grid voltage depends on the grid impedance ratio R/X of the whole electrical power network the converter is connected to. Therefore, the presented grid voltage control method uses a grid impedance estimation method. In an online manner, a current harmonic is injected into the network and the harmonic response is analysed. This way, the DG unit provides improved grid voltage control, automatically adjusting to changes in the grid voltage and impedance. The end result is that the DG unit can still generate power under sub-optimal grid voltage conditions and more renewable energy is harvested. The presented method is generally applicable to DG units of any rated power. The effectiveness of the method is demonstrated by means of both simulations and experiments, showing the positive effect on the grid voltage.

1. Introduction

As distributed generation (DG) gains popularity, measures should be taken to make sure these units do not burden the electric power network [1–3]. If there is a lot of power production and little consumption, the grid voltage might rise. On the contrary, too much power consumption may result in decreased grid voltage levels. Elevated grid voltage levels can be harmful for the loads connected to the network. Fortunately, most of these loads – or the power lines connecting them to the network – are fitted with overvoltage protections which disconnect them when the grid voltage becomes too high. Either way, overvoltages or disconnection from the network are both situations to be avoided.

DG units have an overvoltage protection too: they shut down when the grid voltage transcends a certain limit. In the European EN 50160 power quality standard [4], it is noted that if the DG unit measures a grid voltage deviating 10% from the nominal value, it has to shut down to protect itself from any damage caused by the voltage deviation. In brief, when there is a lot of renewable energy and little power consumption, either the DG unit injects all of its available energy and raises the grid voltage unacceptably or all renewable energy is wasted due to the disconnection of the DG unit. This may also lead to on–off oscillations resulting in bad voltage quality and loss of a significant amount of renewable energy [5].

Currently, DG units do not participate in grid voltage control to overcome this problem and inject active power regardless of the grid voltage. Larger units may employ a reactive power control, but this only has significant influence in inductive networks. For DG units which are connected to the distribution grid, exclusively using reactive power control does not only have little effect on the grid voltage, it also lowers the maximum injectable active power due to the limitation on the apparent power of the converter. It has become clear that in order to diminish voltage stability issues in the network, DG units call for a grid voltage control where both active and reactive power have to be controlled, with a dependency on the impedance of the network.

A solution is to control both the active and reactive power output of the DG unit dependent on the grid voltage level [6–13]. When the grid voltage deviates from the nominal grid voltage, active and reactive power injection is adapted to control the grid voltage accordingly. It is known that in resistive networks,

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the grid voltage is mainly influenced by the active power. In inductive networks, the grid voltage is influenced by the reactive power [14,15]. In practice however, both active and reactive power have an influence on the grid voltage. This paper proposes a droop grid voltage control where the active and reactive power output is adapted depending on the grid impedance ratio, which is estimated. This ratio is defined as R/X of the grid impedance $R+jX$ of the whole electrical network, as seen from the point of common coupling of the grid-connected converter. By using this method, active and reactive power are used more effectively to control the grid voltage.

A static estimation of the grid impedance ratio can be hard-coded into the voltage control. However, the grid impedance ratio can change over time due to various reasons. The ratio changes with the network load, for example during the afternoon peak every day. Fast-paced urbanisation causes the network topology – and thus the impedance ratio – to change. In microgrids, the grid impedance can change significantly when loads are switched. The grid impedance ratio is also different after a network fault, when the network has to be reconnected. Especially in low-voltage distribution networks, the range of the grid impedance ratio is large [16].

When the droop voltage controller uses a grid impedance ratio which does not match with the actual ratio, the active power output could be decreased more than necessary – sacrificing renewable energy – or too much reactive power could be injected into the network—limiting the active power output due to the limitation on apparent power. The grid voltage control would gain significant responsiveness and efficacy with real-time knowledge of the grid's impedance. This paper introduces this synergy between grid voltage control and grid impedance estimation, so that the grid voltage control is improved over traditional ways of voltage control, which is typically absent in DG units.

This method allows the surpassing of grid voltage limits to be deferred such that the DG unit does not have to shut down and can continue generating renewable energy. Moreover, power quality is improved since the grid voltage is closer to its nominal value. The method is confirmed to have desirable results by using both a simulation model and a test set-up.

This paper is organised as follows. The control of grid voltage achieved by active and reactive power is derived in Section 2. The method for controlling active and reactive power by a DG unit is explained in Section 3. The grid impedance estimation used to improve the grid voltage control is explained in Section 4. Simulations of the control are performed using Matlab and the results are presented in Section 5. Finally, the control is tested on an experimental set-up in Section 6 to demonstrate its behaviour in practice.

2. Grid voltage and frequency control

The grid voltage is controlled by active power in resistive networks and by reactive power in inductive networks. The following droop control equations for the grid voltage and frequency are well-known in literature [17]:

$$X \ll R : \begin{cases} f - f_0 = +k_q(Q - Q_0) \\ V - V_0 = -k_p(P - P_0) \end{cases} \tag{1}$$

$$R \ll X : \begin{cases} f - f_0 = -k_p(P - P_0) \\ V - V_0 = -k_q(Q - Q_0). \end{cases} \tag{2}$$

In resistive networks, an active power output difference of a DG unit results in a proportional change in the voltage difference. In inductive networks, the effect of active and reactive power output is the opposite of those in resistive networks.

The parameters V and f are the instantaneous grid voltage and grid frequency, P and Q are the instantaneous injected active and reactive power of the DG unit and R and X are the resistance and inductivity of the grid impedance of the whole network the DG unit is connected to. For voltage and frequency, V_0 and f_0 are equal to the nominal grid voltage and frequency respectively. For active and reactive power, P_0 is equal to the maximum power point (MPP) of, e.g., the wind turbine or PV panel, and Q_0 is equal to zero. It can be noted that the transmission system operator may also impose a non-zero setpoint for reactive power.

The droop control of (1) and (2) can be combined to embed a general grid impedance [17]:

$$f - f_0 = -k_p \frac{X}{Z}(P - P_0) + k_q \frac{R}{Z}(Q - Q_0) \tag{3}$$

$$V - V_0 = -k_p \frac{R}{Z}(P - P_0) - k_q \frac{X}{Z}(Q - Q_0). \tag{4}$$

In this paper, (3) and (4) are inverted since the grid voltage and frequency are measured and the active and reactive powers are controlled by the inverter:

$$P - P_0 = -\frac{1}{k_p}\frac{X}{Z}(f - f_0) - \frac{1}{k_p}\frac{R}{Z}(V - V_0) \tag{5}$$

$$Q - Q_0 = \frac{1}{k_q}\frac{R}{Z}(f - f_0) - \frac{1}{k_q}\frac{X}{Z}(V - V_0). \tag{6}$$

The result is a droop control for grid voltage and frequency. When the grid voltage deviates from its nominal value, the active and reactive power injection is altered accordingly. A few remarks and simplifications can be made regarding (5) and (6).

2.1. Neglecting frequency differences

The frequency of the network is not easily controlled by a DG unit. Unlike the grid voltage which is affected locally, the frequency is a global parameter and is primarily controlled by large power plants. In this paper, the DG unit is grid-following and thus frequency droop control is omitted.

2.2. Grid impedance ratio R/X

In order to fulfil the active and reactive power control, it is required for the grid impedance $R + jX$ to be known. Although the two variables R and X appear separately in (5) and (6), they do not have to be separately known. It is sufficient to know the ratio R/X. If the grid impedance ratio $\alpha = R/X$ is used, then the following equations arise:

$$\frac{X}{Z} = \frac{X}{\sqrt{R^2 + X^2}} = \frac{1}{\sqrt{\left(\frac{R}{X}\right)^2 + 1}} = \frac{1}{\sqrt{\alpha^2 + 1}} \tag{7}$$

$$\frac{R}{Z} = \frac{R}{\sqrt{R^2 + X^2}} = \frac{1}{\sqrt{1 + \left(\frac{X}{R}\right)^2}} = \frac{\alpha}{\sqrt{\alpha^2 + 1}}. \tag{8}$$

Substituting (7) and (8) in (5) and (6), together with the omission of frequency droop and introducing a per unit notation, the following active and reactive power droop control results:

$$p = -\frac{\alpha}{\sqrt{\alpha^2 + 1}}\frac{1}{k_p}(v - v_0) + p_0 \tag{9}$$

$$q = -\frac{1}{\sqrt{\alpha^2 + 1}}\frac{1}{k_q}(v - v_0). \tag{10}$$

2.3. Dependency on time

The parameter v is measured instantaneously at the sample rate of the Analogue-to-Digital Converter (ADC). The maximum