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Adaptive virtual resistance load sharing for resistive microgrids

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ABSTRACT

This paper proposes an adaptive virtual resistance load sharing method in $\alpha\beta$ frame, where the α-component of the virtual resistance is used to share the active power and the β-component of the virtual resistance is used to share reactive power. Using the proposed method for photovoltaic systems makes the active and reactive power sharing sensitive to the varying nature of the solar energy. It will be shown that the proposed adaptive active power sharing significantly reduces the energy required from a fossil-fuelled auxiliary generator. The proposed adaptive reactive power sharing reduces the reactive power exchanged with the auxiliary generator and the switching stress on each distributed generator's converter through, seamlessly, reducing the reactive power contribution of the units with higher active power contribution. This is all achieved without any communication between distributed generation units. Whilst the proposed method is also applicable on inductive microgrids, this paper focuses on a resistive microgrid since most microgrids are likely to be located on the low voltage side of the grid (where the network is mainly resistive). Different load sharing methods in a resistive microgrid are also categorized and briefly reviewed to justify the chosen approach in the paper. MATLAB/SIMULINK simulations are used to validate the proposed method.

1. Introduction

Sustainable energy generation, and efficient energy storage and management are possible in well-controlled microgrids (MGs) enabling a global move from large centrally controlled power stations to a distributed generation approach where smaller renewable based generators can be successfully employed [1–4]. Thus MGs, consisting of a variety of distributed units, enable capacity and control flexibilities that provide energy security, system reliability and power quality gains [5–7]. The MG can be controlled to operate both in grid-connected approach or in islanded mode. Renewable energy generation is often complemented with dispatchable resources, such as auxiliary generator (AG) and energy storage systems, to balance demanded energy with generation in an MG [6]; the absence of such dispatchable resources can cause the malfunctioning of the inverter-based units [8–11]. Hybrid distributed generation networks comprising of renewable sources, energy storage systems and fossil-fuelled AG, are often employed to improve the flexibility and reliability of MGs [1–3,12]. In grid-connected MGs, local voltage and frequency are imposed by the grid; whereas, in islanded-mode, the inverter-based source must actively regulate the voltage and frequency for the stable and continuous operation of the MG [13–15]. In case of shortage of energy when islanded, a practical MG needs a fossil-fuelled AG to supply (at least) the essential loads. The operation of the AG, in this approach (which operates only as a back-up), is different to that of a master unit (in a master-slave paradigm) since the operations of other units are not reliant on the AG.

Most MGs are likely to be located at low voltage side of the grid, where the network is predominately resistive [16–18]. In resistive MGs, three main load sharing methods were identified in the literature:

1.1. P–V *and* Q–f *droop load sharing scheme*

In predominantly resistive systems, the droop slopes are defined as active power (P)–voltage (V) and reactive power (Q)–frequency (f). Similar to classical inductive networks, P and Q are used to regulate the voltage amplitude and frequency of the distributed generator (DG) [9,13,19,20]. In a resistive MG, P and Q are given by [20–22]:

$$P = \frac{V_o^2 - V_o V_t \cos\delta}{Z} \approx \frac{V_o}{R}(V_o - V_t)$$
$$Q = \frac{V_o V_t}{Z}\sin\delta \approx -\frac{V_o V_t}{R}\delta \qquad (1)$$

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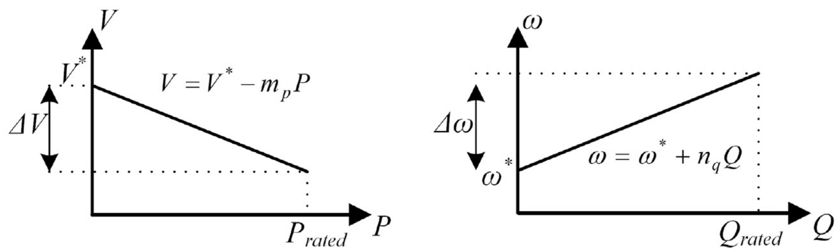

Fig. 1. Active and reactive power droop characteristic (in steady-state) in a resistive MG.

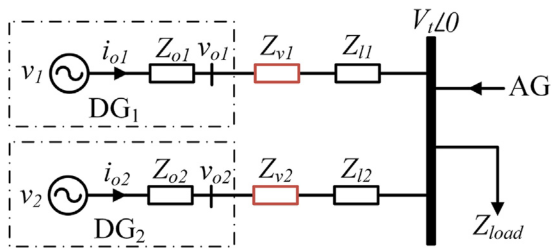

Fig. 2. Two parallel-connected DGs including virtual impedance.

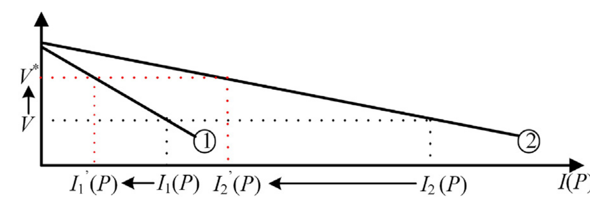

Fig. 3. Characteristics of static virtual resistance droop (*V*–*P*).

The droop equation (given in (1) and (2)) is normally adopted for the proportional sharing of *P* and *Q*; where *P* and *Q* vary according to the DG's voltage and frequency respectively [20–22]:

$$\begin{aligned} V_o &= V^* - m_p(P - P^*); \quad m_p = \frac{\Delta V}{P_{rated}} \\ \omega &= \omega^* + n_q(Q - Q^*); \quad n_q = \frac{\Delta \omega}{Q_{rated}} \end{aligned} \tag{2}$$

where $(V_o - V_t)$ is the difference in voltage amplitude; δ is the difference in phase angle between the DG's output voltage (V_o) and the voltage at the point of common connection (V_t); *R* is the resistance of the output feeder of the DG in the resistive network. ΔV and $\Delta\omega$ define the allowed voltage and frequency deviation. m_p and n_q define the droop coefficients (i.e., the gradient of droop lines in Fig. 1), which guarantee the preferred relative power sharing based on the rating of the inverter-based source (i.e., P_{rated} and Q_{rated}).

The droop slopes (in Fig. 1) are carefully selected to promote and ensure adequate load sharing between DGs while minimizing significant deviation in frequency and voltage at steady state [20].

1.2. P–f and Q–V droop with virtual impedance

References [16,19,23,24] have investigated the "Virtual Impedance" (VI) scheme to mitigate the coupling effect amongst *P* and *Q*, which is due to the relatively higher line resistance in a low voltage network.

Fig. 2 shows an equivalent circuit of two parallel-connected DGs with VIs, where v_{o1}, i_{o1}, Z_{o1}, Z_{v1}, and Z_{l1} are the output voltage, output current, output impedance, virtual impedance and line impedance of DG_1. v_{o2}, i_{o2}, Z_{o2}, Z_{v2}, and Z_{l2} are the output voltage, output current, output impedance, virtual impedance and line impedance of DG_2; V_t is the terminal bus voltage of the MG. The VI is usually wired in series with the resistive line impedance to make the overall output impedance of the DG inductive, this, in turn, improves the stability and transient performance of the system [25,26]. Since using the VI, the effective total impedance becomes inductive, the classical *P*–*f* and *Q*–*V* droops can be employed [22].

1.3. Virtual impedance load sharing scheme

The VI scheme is often used in inverter-based applications to shape the dynamic profile of DG. Power flow control and harmonic compensation can also be achieved via the VI scheme [19,24]. The VI scheme also has the potential to autonomously enhance current sharing between parallel-connected converters in an MG, this in turn eliminates the need for the classic droop controller [18,17,27]. It was shown in [17,18] that the VI, coupled with a synchronous reference frame phase-locked loop (PLL), could be used as an alternative option for load current sharing in parallel-connected DGs in an MG. Hence, the VI scheme help to eliminates some of the major drawbacks of conventional droop control schemes, i.e., inaccurate load sharing, instability problems as a result of load disturbance, poor transient response, steady-state error in line voltage, and frequency [16–18,27–29].

Out of the three above described approaches, the *P*–*V*, *Q*–*f* droops approach is the simplest. However, it has the disadvantage of relatively unstable operation in comparison with VI that improves the system stability [17,18,30,19,20,27,31]. Having both droops (*P*–*f* and *Q*–*V*) and VI, although possible, seems redundant as only VI can be used for load sharing. Therefore, the rest of the paper mainly concentrates on the VI load sharing approach.

In a microgrid consisting of several PV units, the solar irradiation on the units will not be necessarily the same even if they are located in a small geographical area. This can be due to the shadow of passing clouds or a nearby object such as trees. A common drawback of all of the previous arts in load sharing in resistive MGs (using any of the above approaches) is that the sharing ratio (between units) is not sensitive to the varying nature of renewable energy. Fig. 3 shows a conventional VI (*I*–*V*) load sharing scheme where a static voltage droop gain is determined regardless of the energy available from the renewable energy source. The DG's local voltage in this manner varies in relation to changes in either the load or line impedance, the voltage is usually constrained within the acceptable voltage drop, to maintain the DG's local voltage within acceptable limits [20]. In such cases, if the available power in a DG reduces from I_1 to I_1' (e.g., say there is a drop in solar irradiation), the local voltage (*V*) of the DG will shift to a new operating point (V^*). Subsequently, the other connected DG must comply with the new operating voltage (V^*), leading to its power drop from I_2 to I_2' (irrespective of its available generating capacity), which can increase the energy demanded from an AG.

Similarly, *Q* sharing, conventionally, is only sensitive to the inverter's rating (S_{rated}) of each DG, i.e., a unit with higher *P* contribution would also contribute more *Q*. This is obviously not an optimised sharing as it can increase the switching stress on the inverters as well as the *Q* exchanged by the AG.