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A Review of Control Strategies for Microgrids

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Authors' contributions

This work was carried out in collaboration between both authors. Author MAA conceived the study, performed initial literature survey and wrote the first draft of the manuscript. Author KS reviewed the literature survey, validated the literature searches and reorganized the draft manuscript to increase its visibility. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Global demand for electrical energy has never been higher than it is currently. This high demand for electricity has driven need for innovative and sustainable power production schemes. The current power system is therefore challenged with the need for quality, reliable and sustainable power production. In most countries, the system is aging, making it require more resources to meet contemporary challenges, coupled with the requirements to maintain a clean environment and mitigate environmental disasters. These lead to the microgrid concept. Deployment and use of the microgrid comes with new challenges - control and protection. In this paper, some of the most obvious control challenges of microgrid operations have been articulated. Nine (9) of the recent control strategies in literature have also been presented in this paper, including a brief explanation on the fundamental principles of the proposed strategies. Finally, this paper also presents a comparison of the strengths and weaknesses associated with the control strategies in literature.

Keywords: Microgrid; control; distributed; generation; droop.

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1. INTRODUCTION AND MOTIVATION

The current high demand for electrical energy is historical. This has driven the need for sustainable energy production processes - the microgrid [1-3]. A microgrid is a power system comprising of small (micro-), distributed generators (DGs), and controllable loads, with an option of energy storage systems, operated as a single controlled and coordinated unit such that it could operate in an autonomous or non-autonomous mode [4-7]. Consequently, the primary interest of a microgrid is to supply quality, reliable and sustainable power to a local load, resulting in occasional bidirectional power flow [8-10]. Fig. 1 shows a simplified microgrid connected to the main (utility) grid at the Point of Common Coupling (PCC).

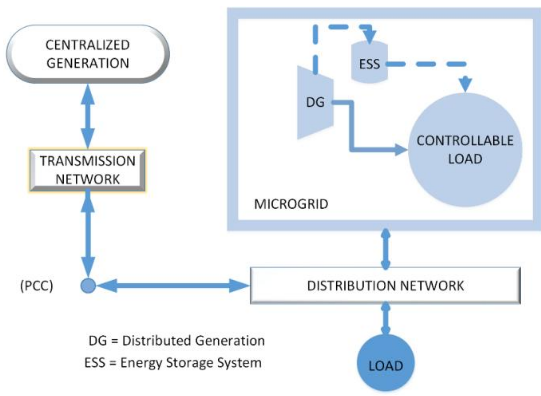

Fig. 1. A simplified utility-connected microgrid

This paper therefore seeks to provide an up-to-date review of research efforts in microgrid control systems.

2. CHALLENGES OF MICROGRID OPERATION

The operation of microgrid faces a number of challenges, including large difference between the fault current level in the grid-connected mode and the autonomous mode, caused by the fact that the short circuit levels of power electronic-interfaced microsources are limited to about less than four times their rated capacities by their controllers [11-15]. In addition, in a microgrid the operating control strategy dictates the values of critical network parameters such as voltage and current magnitudes and angles. When the microgrid is in non-autonomous mode, its control is dictated by the grid; when it is in autonomous (islanded) mode of operation, its control is dictated by factors such as net capacity of microsources installed, types of microsources installed, available energy storage capacity, connected load type and ownership of microgrid components. The operational control strategy determines the fault current and other parameters [8,16-18]. Full scale deployment of microgrids has been challenged by some of the following:

1. Design of protection systems due to;

   a) bidirectional power flow,
   b) network topology change - meshed or ring network,
   c) converter interfacing - Power Electronic (PE) interfaced microsources incorporate controllers which are current limiters, even when the system is stressed.

2. Reliable stand-alone mode of operation - lack of rotating inertia in PE interfaced microsources (MSs), resulting in poor transient stability during disturbances. This results in inability to meet Low Voltage Ride Through (LVRT) and other grid codes.
3. Seamless transition from islanded mode to grid-connected mode and vice versa - disconnection and reconnection provoke voltage fluctuation and frequency oscillations.
4. Seamless integration - plug and play, and peer-to-peer.
5. Dominantly resistive low voltage (LV) distribution networks - challenging decoupled and independent control of active power, P, and reactive power, Q.
6. Uncertainty in dispatch and reserves - intermittent nature of primary energy source and high cost of large storage systems [19-22].

3. MICROGRID CONTROL STRATEGIES IN LITERATURE

A control strategy where the real power, P, and reactive power, Q, are regulated to remain fairly constant is called PQ control. In such control strategy the microsource behaves as a voltage-controlled current source. Its terminal quantities (voltage, current, or power) are measured in a suitable reference frame, compared with a reference set-point and a control action taken to regulate the output quantity [23-26]. In this section, the control strategies in literature are presented.

3.1 Power Output Control

This strategy was proposed in [27] by Alfred Engler and Nikos Soultanis. In this method, the microsources behave like conventional rotating sources when the microgrid islands. The output active power, *P*, and reactive power, *Q*, of the microsources vary as the microgrid frequency, *f*, and voltage, *V*, vary, respectively. A microsource generates more active power, ΔP, when the microgrid frequency drops by Δf and vice versa, in accordance with the droop characteristic shown in Fig. 2a. Similarly, a microsource generates more reactive power, ΔQ, when the voltage of the microgrid drops by ΔV, and vice versa, as shown in Fig. 2b.

3.2 Pure Droop Control

In this strategy, as proposed by Georgakis et al. in [28], all microsources and storage devices capable of regulating their outputs switch to droop control as soon as the microgrid islands. They jointly control the voltage and frequency of the microgrid in islanded mode of operation such that the resultant droop characteristics determine the aggregate voltage and frequency of the microgrid. As an illustration of this strategy, consider a microgrid with two microsources and two energy storage devices importing power, P_{imp}, from the utility, as shown in Fig. 3. In grid-connected mode, the output power of the microsources are P_{ms1} and P_{ms2} respectively, while the output power of storage devices are P_{s1} and P_{s2} respectively. Once the microgrid islands, the microsources and storage devices augment the local demand through provision of additional power to meet the power originally imported from the utility, as given in (1) [1,29-31].

$$\Delta P_{imp} = \Delta P_{ms1} + \Delta P_{ms2} + \Delta P_{s1} + \Delta P_{s2} \tag{1}$$

The aggregate P/f droop characteristic determines the new microgrid frequency, f_{new}, as shown in Fig. 3(a). Similarly, the new microgrid voltage, V_{new}, is determined by the aggregate V/Q droop curve, as shown in Fig. 3(b).

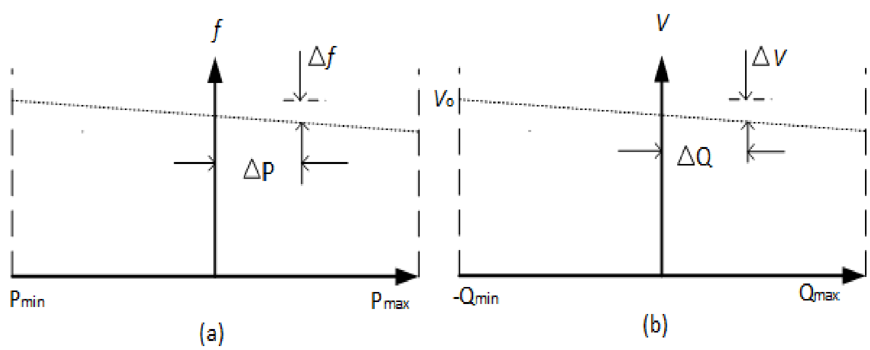

Fig. 2. *f* / *P* and *V* / *Q* droop characteristics

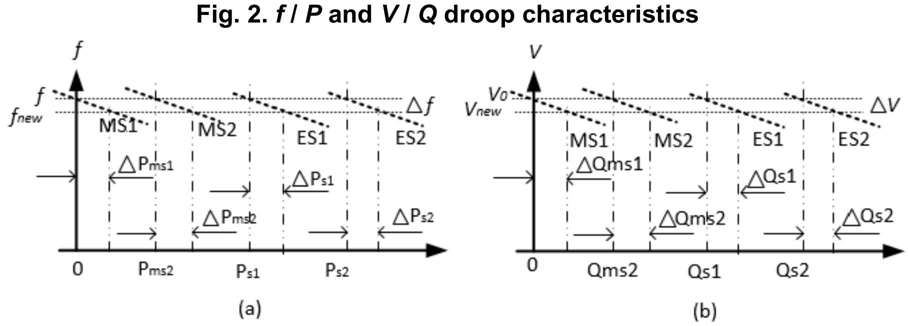

Fig. 3. Pure droop control - (a) f/P control and (b) V/Q control

3.3 Inverter Modes Control

This control strategy was proposed by Pecas Lopes et al. in [32,33]. In their proposal, while the microsource remains in PQ control, the energy storage shifts to droop control as soon as the microgrid islands. Then, a Proportional-Integral (PI) controller included in the microsource determines the pre-island real power set-point, as shown in Fig. 4. The controller forces the microsource to generate sufficient power to maintain the pre-island frequency. This ensures that the energy storage does not contribute to the overall power demand. However, if energy storage is installed in the dc bus of the microsource inverter, it could shift to droop mode and contribute to overall voltage and frequency regulation.

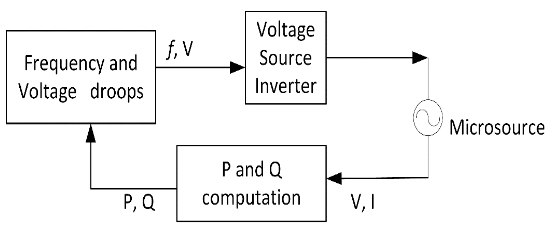

Fig. 4. Inverter modes control

The voltage is also controlled using droop control as shown in Fig. 3(b).

3.4 Primary Energy Source Control

This approach was proposed by Pecas Lopes et al. in [34]. In their proposal, when the microgrid islands, the storage device and microsource maintain pre-island voltage and frequency by shifting to droop control. Consider that the storage device is generating zero real power and reactive power, as shown in Fig. 5.

Assuming the microgrid is importing real and reactive power P_{grid} and Q_{grid} , respectively from the grid just before islanding (Point A). When the microgrid has islanded, the frequency and voltage drop to new island values, f_{isl} and V_{isl} (Point B). Then, the microsource and storage device shift their operating droops to the right (Point C), thereby producing the required real and reactive power to maintain pre-island frequency and voltage.

3.5 Reverse Droop Control

This strategy was proposed by Laaksonen, et al. in [35] because of the resistive-dominance of low-voltage (LV) distribution network. In this strategy, the inverter of the storage device or microsource shifts to droop control when the microgrid islands. The droop characteristic is implemented such that the microgrid frequency is regulated by controlling its inverter reactive power, while its voltage is regulated by controlling its inverter active power, as shown in Fig. 6.

3.6 Autonomous Control

This strategy was proposed by Lasseter and Piagi in [36]. In their approach, they suggested exclusion of a single failure point like MicroGrid Control Center (MGCC) in the microgrid. They proposed a peer-to-peer and plug-and-play model which controls the microsource (in islanded mode) using either or combination of two configurations - Unit Power Flow or Feeder Flow.

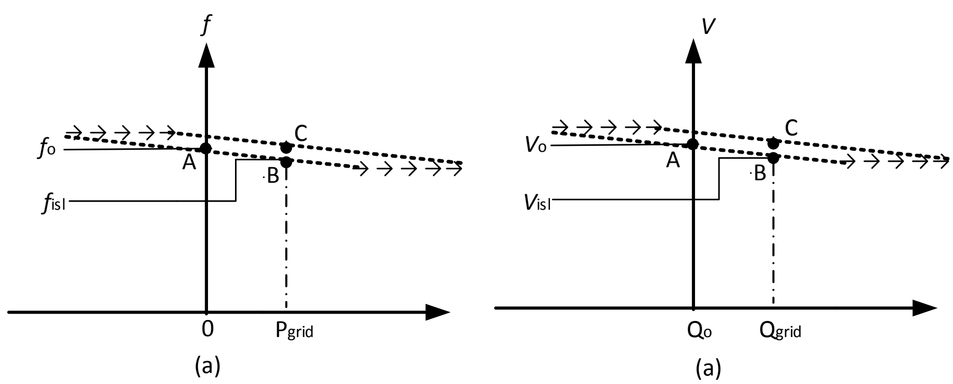

Fig. 5. Droop curves of primary energy source control

The output power of a microsource is constant when the microgrid is grid-connected since the grid dictates its frequency. The microsources operate in droop control in both grid-connected and islanded modes of operation when in unit power flow configuration. In this configuration, when the microgrid islands, its frequency is determined by the droop curves as described in Fig. 2(a).

When the microgrid is in feeder flow configuration, it controls a particular feeder frequency by regulating the amount of power it wheels into the feeder. Fig. 7 shows the relationship between the amount of power flowing through a feeder, *F*, and the feeder frequency, *f*. Consequently, the microgrid. frequency is determined by the aggregate *F/f* curves of all the microsources when it islands.

3.7 Multi-agent Based PQ Control

This strategy was proposed by Oyarzabal, et al. in [37]. It requires all microsources to remain in PQ control after islanding so that the storage device shifts to droop control, generating or absorbing power to ensure power balance at all times. The storage device therefore controls the voltage and frequency of the microgrid. In every 30 seconds, the MicroGrid Control Center (MGCC) computes the output power set-point of each microsource and sends it back to the microsource for comparison with a reference set-point, thereby controlling the scheduling operation of each microsource [38-41].

3.8 Fictitious Impedance Control

This method was proposed by Engler et al. as published in [42]. The strategy aims to decouple the *P/f* and *Q/V* control channels in a power electronic (PE)-interfaced microsource. This changes the behavior of the inverter and leads to a system with inductively coupled sources, since resistively coupled sources in LV network provokes instability. This method is inspired by the fact that in PE-interfaced microsources, the output converter lacks the output impedance inherently found in synchronous sources. Therefore, paralleling of inverter outputs results in coupling of the *P/f* and *Q/V* droops, making independent control of P and Q challenging.

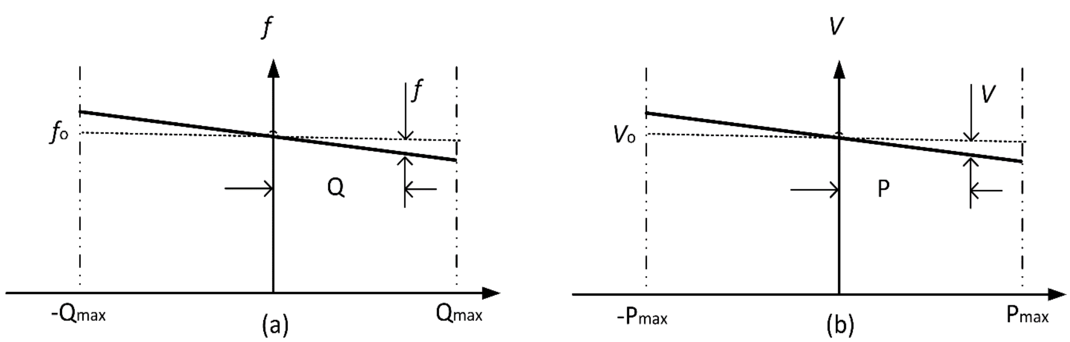

Fig. 6. Reverse droop control

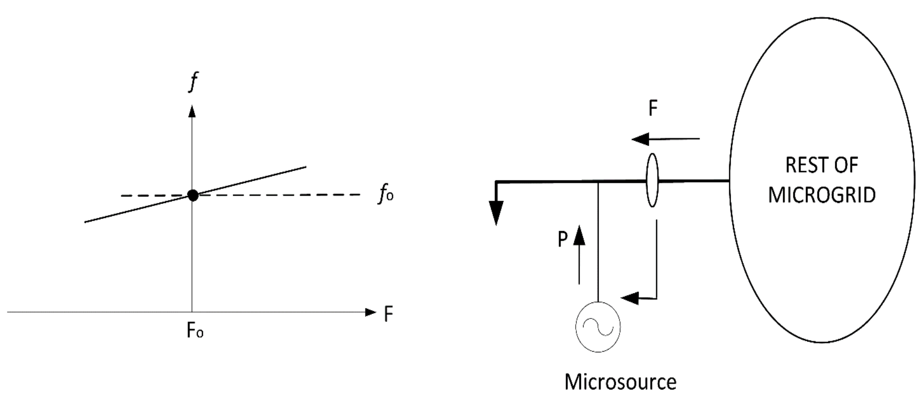

Fig. 7. Feeder flow configuration

3.9 Power Sharing Control

This method was proposed by Ferreira et al. as published in [43]. It controls active power through droop coefficients and reference frequencies. This method was inspired by the fact that the LV distribution network, under certain scenarios, is not dominantly resistive, but complex and inductive. For this condition of impedance, their experiments showed that inductive droop control is better for controlling the active power. Their method used the abc reference frame for computation, rather than the dq or $\alpha - \beta$ used in previous studies. This makes the dynamic system response of their method faster than methods based on dq or $\alpha - \beta$ as previously reported.

4. CHOICE OF CONTROL STRATEGY

When the microgrid is grid-connected, its control strategy is dictated by the utility. When in islanded mode of operation, its control strategy is determined by factors including net capacity and type of microsources, available energy storage capacity, load type and ownership of the microgrid components [44-46].

4.1 Net Capacity and Type of Micro-sources

The choice of control strategy should depend on the types of microsources installed in the microgrid. If intermittent (wind, solar or Combined Heat and Power (CHP)) microsources are installed, at least one of the microsources should perform load following since the primary energy sources are stochastic. Wind and solar are intermittent in nature while CHP generates power only when heating is needed. In order to balance instantaneous generation and demand, the load follower adjusts its output power accordingly. If the microgrid has large storage capacity installed, the best control strategy is pure droop or fictitious impedance, since the load following is shared among microsources and storage device. However, if installed storage capacity is small the best control strategy is the inverter modes or multi-agent based PQ control, since other than the dedicated load follower, remaining microsources are forced to perform load following. This limits the risk of overcharging or over-discharging the storage device [47]. The drawback of the multi-agent based PQ control is its vulnerability to communication failure.

4.2 Available Energy Storage Capacity

The capacity of the storage device depends on the services it will provide in the microgrid. If the storage device will only provide short-term energy, its capacity can be small. If, however, it will provide long-term energy support, its capacity should be large. For microgrids with small energy storage, the inverter modes or multi-agent based control strategy is recommended, since the storage provides only quick reaction to imbalances between generation and demand during sudden change in generation or demand. On the other hand, in microgrids with large storages which participate in the system net power generation, the pure droop, primary energy source, reverse droop or fictitious impedance strategy is recommended. This is because the storage device outputs or absorbs active power for a longer duration [42,48].

4.3 Load Type

The fundamental function of a controller is to regulate voltage fluctuation and frequency oscillation. The magnitudes of voltage fluctuation and frequency oscillation depend on the magnitude and frequency of load fluctuations. Significant over- and under-voltages are caused by large load swings, while frequent load swings cause frequent over- and under-voltages. These lead to operating the microgrid beyond preset frequency and voltage limits. In the pure droop, reverse droop, fictitious impedance and autonomous controls, the range of power exchange between loads and generators, and slope of the droop curves determine the voltage and frequency extremes. Consequently, if the connected loads are not power quality-sensitive (e.g. PE-interfaced or constant impedance loads), then the best control strategy is pure droop, reverse droop, fictitious impedance control or autonomous control. However, if the connected load is power quality-sensitive, the best strategy is inverter modes, primary energy source or multi-agent based PQ control. These strategies provide high quality power and small deviation in voltage and frequency [47,49].

4.4 Ownership

In an islanded microgrid, the ownership of the system components dictates the control strategy. In a single-owner microgrid, the primary interest of the system will be to satisfy local demand continuously while maximizing overall system profit. In such case, the best control strategy is dependent on factors mentioned in section 4.1 to

4.3. This is in contrast to a multi-owner microgrid where system operation is to satisfy individual component owner's interest. In such a situation, the recommended control strategy is the multi-agent based PQ control or autonomous control [47].

5. CONCLUSION

This paper presents nine [9] strategies for control of microgrid in islanded mode of operation. The fundamental operating principles of each of the strategy has been highlighted. Net capacity and type of microsources, available energy storage capacity, load type and ownership have also been articulated as factors which determine choice of optimal control strategy in an islanded microgrid. Consequently, this work has provided a state-of-the-art review of research efforts in microgrid control systems.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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