A Survey of Techniques Used to Control Microgrid Generation and Storage during Island Operation

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ABSTRACT

A microgrid is a cluster of interconnected distributed generators, loads and intermediate storage units that co-operate with each other to be collectively treated by the grid as a controllable load or generator. Power quality events and pre-set conditions will make the microgrid disconnect from the main grid and operate as a separate island. This paper enumerates and discusses the issues concerning the island operation of microgrids. The microsources and storage device should co-operate with each other to maintain the integrity of the islanded microgrid. Six co-operation approaches proposed by various authors are presented. The strategies are then compared based on their applicability to different control requirements.

1. INTRODUCTION

A microgrid is a cluster of interconnected distributed generators, loads and intermediate energy storage units that co-operate with each to be collectively treated by the grid as a controllable load or generator [1]. It is connected to the grid at only one point, the point of common coupling or PCC. The main objective of its conception is to facilitate the high penetration of distributed generators without causing power quality problems to the distribution network. Another important objective is to provide high quality and reliable energy supply to sensitive loads. The components that constitute the microgrid may be physically close to each other or distributed geographically.

Figure 1 depicts a typical microgrid. The microsources are the primary energy sources within the microgrid. They may be rotating generators or distributed energy (DE) sources interfaced by power electronic inverters. The installed DE may be biomass, fuel cells, geothermal, solar, wind, steam or gas turbines and reciprocation internal combustion engines. The overall efficiency may be improved by using combined heat and power sources (CHP).

The connected loads may be critical or non-critical. Critical loads require reliable source of energy and demand stringent power quality. These loads usually own the microsources because they require a continuous supply of energy. Non-critical loads may be shed during emergency situations and when required as set by the microgrid operating policies.

The intermediate energy storage device is an inverter-interfaced battery bank, supercapacitors or flywheel. The storage device in the microgrid is analogous to the spinning reserve of large generators in the conventional grid. They ensure the balance between energy generation and consumption especially during abrupt changes in load or generation. The microgrid in Figure 1 has a dedicated storage device. Another method of integrating energy storage to the microgrid is to install battery banks in the dc links of the inverters of the microsources [2].

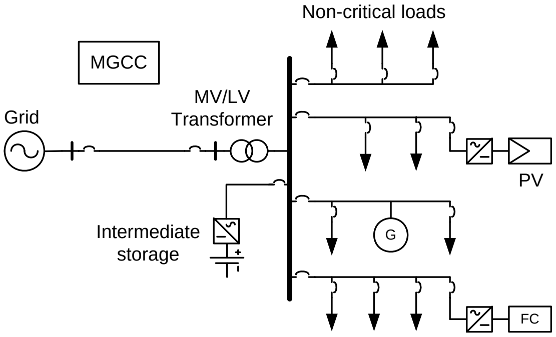

Figure 1: An example microgrid

The microgrid can operate in grid-connected mode or in island mode. In grid-connected mode, the microgrid either draws or supplies power to the main grid, depending on the generation and load mix and implemented market policies. The microgrid can separate from the main grid whenever a power quality event in the main grid occurs [3].

The microgrid components are controlled using a decentralized decision making process in order to balance demand and supply coming from the microsources and the grid. The degree of decentralization may vary from a fully decentralized approach or using hierarchical control (Hatziargyriou, Dimeas et al. 2005). The latter makes use of a central controller (microgrid central controller or MGCC) that controls the actions of all components of the microgrid (Hatziargyriou, Jenkins et al. 2006). The MGCC optimizes operation by maximizing the value of the microgrid. It is also capable of implementing demand side management.

2. ISLAND OPERATION OF MICROGRIDS

When a microgrid is grid-connected, it behaves as a controllable load or source. It should not actively regulate the voltage at the PCC [6]. Furthermore, the harmonics and dc current it injects to the grid should be below the required levels. During this mode of operation, the primary function of the microgrid is to satisfy all of its load requirements and contractual obligations with the grid.

The microgrid should disconnect when an abnormal condition occurs in the grid. It shifts to island mode of operation, and the microgrid is faced with the following issues:

1. Voltage and frequency management

The voltage and frequency are established by the grid when the microgrid is connected. When the microgrid islands, one or more primary or intermediate energy sources should form the grid by establishing its voltage and frequency, otherwise, the microgrid will collapse. Both voltage and frequency should be regulated within acceptable limits. If the frequency has dropped to excessively low levels, loads may be shed to hasten its recovery towards the nominal value [7].

2. Balance between supply and demand

If the microgrid is exporting or importing power to the grid before disconnection, then secondary control actions should be implemented to balance generation and consumption in island mode. If the connected load exceeds the available generation, demand side management should be implemented. Also, there should be enough energy storage capacity to ensure initial balance after an abrupt change in load or generation.

3. Power quality

The microgrid should maintain an acceptable power quality while in island operation. There should be an adequate supply of reactive energy to mitigate voltage sags. The energy storage device should be capable of reacting quickly to frequency and voltage deviations and injecting or absorbing large amounts of real or reactive power. Finally, the microgrid should be able to supply the harmonics required by nonlinear loads.

4. Microsource issues

A major difference between the primary energy sources in the grid and microsources connected to the microgrid is that the latter has no inertia [1]. The microgrid does not have the spinning reserves that are inherently present in the conventional grid. Most microsources (e.g. turbines and fuel cells) have slow response or ramp-time when implementing secondary voltage and frequency control. The intermediate storage units and microsources with built-in battery banks are therefore expected to deliver the benefits that should be derived from spinning reserves. The power electronics interface enabled these devices to respond quickly to abrupt command signals and changes in the power flow levels.

The types, ownership and combination of connected microsources also complicate the control of a microgrid during island operation. Microsources relying on renewable energy like wind and solar are operated at their maximum outputs to maximize production, and require forecasting methods to predict their output. CHP sources are only operated when their heat productions are required. Some microsources may be required to meet the energy demands of specific loads before they should provide for other loads.

4. Communication among microgrid components

The availability of communication infrastructure between the microgrid components is another aspect considered when choosing the control approach on an islanded microgrid. The microgrid should have a plug-and-play architecture so that the microsources will rely on locally available information to control their generated power [1]. If communication between components is required (e.g. MGCC sending setpoints to microsources or negotiation between agents controlling the microsources), the delay within the communication network should not present problems.

The microsources and storage device should co-operate with each other to maintain the integrity of the islanded microgrid. This paper enumerates and discusses six different co-operation approaches proposed by several authors. The approaches differ on how the microsources and storage device will co-operate when the microgrid is islanded. The strengths and weaknesses of each approach will be examined. Perceived implementation issues will also be discussed. Finally, the scenarios where these approaches are suited will be suggested.

3. CO-OPERATION OF MICROSOURCES AND STORAGE DEVICES

The first part of this section describes how the output power of the microsources is controlled. The second part enumerates the island mode co-operation techniques of the microsources.

3.1. POWER OUTPUT CONTROL

A microsource may be controlled so that its real and reactive power output is constant. This type of control is called PQ control [8]. The microsource behaves like a voltage-controlled current source. The terminal voltage is measured and broken down to its direct and quadrature components. The direct and quadrature components of the output current are computed from the voltage components and required real and reactive power output. Figure 2 shows how the output current is controlled.

The droop control of microsources proposed in [9] emulates the operation of a rotating generator in a conventional grid. The output frequency and voltage of the inverters follow the droop characteristics as shown in Figure 3. The microsources will change their output by ΔP (or ΔQ) when the frequency (or voltage) changes by Δf (or Δv) from the nominal values f_0 (or v_0).

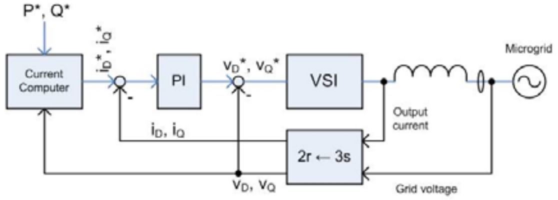

Figure 2: PQ control of microsources

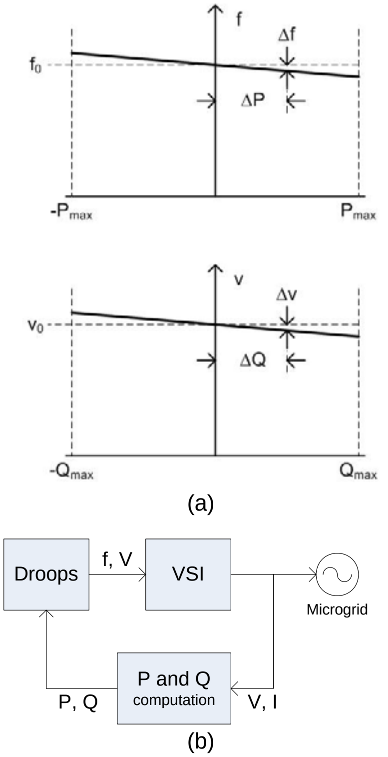

Figure 3: (a) Droop characteristics. (b) Inverter with droop characteristics.

3.2. CO-OPERATION OF MICROSOURCES

Six co-operation methods will be presented. Five of which apply to microgrids with dedicated energy storage while one applies to microgrids which microsources have installed storage capacity.

In the first four approaches, all microsources and storage device are in PQ control when the microgrid is grid-connected. The output power setpoints are determined by the MGCC or by the owners. The real power output of the storage device is zero. PV and wind microsources are operated at maximum output levels. For purpose of identification in this paper, the subsection heading will be used as name of the described co-operation technique.

3.2.1. PURE DROOP CONTROL

In the approach presented by Georgakis, etal in [10], the storage device and all microsources capable of regulating their power outputs switch to droop control when the microgrid islands. These devices will control the voltage and frequency of the microgrid. The resulting voltage and frequency are determined by their droop characteristics. As example, consider a microgrid with two microsources and one storage device that is importing power (P_{grid}) from the grid. The output power of the storage device and two microsources are zero, P_1, and P_2, and the frequency is f_0. When the microgrid islands, the microsources and storage device will provide the power originally imported from the grid. The individual droop characteristics will determine the new frequency, f_{new}, as shown in Figure 4(a). The storage device and microsources will output additional powers ΔP_0, ΔP_1 and ΔP_2, where

$$\Delta P_0 + \Delta P_1 + \Delta P_2 = P_{grid} \qquad (1)$$

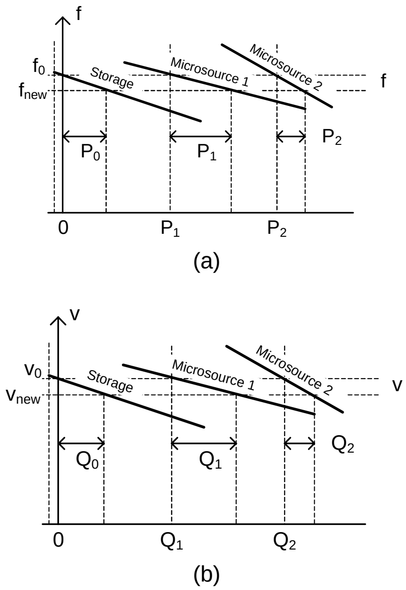

Figure 4: Pure droop control, (a) frequency control and (b) voltage control

The new microgrid voltage is determined by the individual Q-v curves as shown in Figure 4(b).

3.2.2. INVERTER MODES CONTROL

The co-operation approach proposed by Pecas Lopes, etal in [7, 8 & 11] is called microgrid operation based on inverters control modes. In their approach, the microsources remain in PQ control when the microgrid islands and the storage device shifts to droop control. A PI controller in the microsources compute the real power setpoint (P* in Figure 2) so that the frequency will return to the pre-island values. This action forces the microsources to produce the right amount of power so the storage device will not contribute to the overall generation. The voltage is controlled using droop control as shown in Figure 4(b).

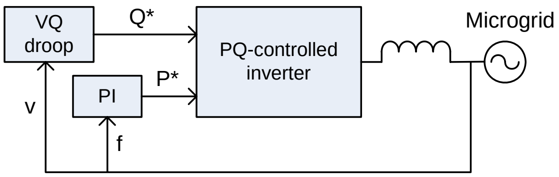

Figure 5: Microsource controller for inverter modes control.

This operation is called single master operation because only one inverter (the one associated with the storage device) regulates the frequency and voltage in the microgrid. If battery banks are installed in the dc bus of the microsource inverters, these microsources can also shift to droop control and participate in the regulation of the frequency and voltage. This is now called multi-master operation [8].

3.2.3. PRIMARY ENERGY SOURCE CONTROL

Another approach proposed by Peças Lopes etal in [11] is called microgrid operation regarding primary energy source control. When the microgrid islands, the storage device behaves like a synchronous generator: it performs secondary control actions to restore the voltage and frequency to pre-island values. The secondary actions involve the shifting of the droop characteristics.

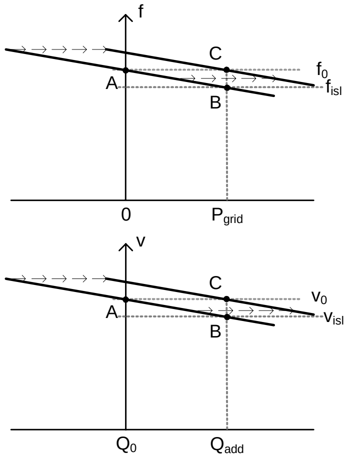

Figure 6: Primary energy source control

Figure 6 shows how frequency and voltage are regulated. Assume that the storage device is generating no real power and Q_0 reactive power, and the microgrid is importing real (P_{grid}) and reactive (Q_{add}) from the grid (point A). When the microgrid islands, the storage device should produce the real and reactive powers imported from the grid, so the frequency and voltage will drop to f_{isl} and v_{isl} (point B). The frequency and voltage are restored to the pre-island values (f_0 and v_0) by shifting the droop curves of the microsources to the right (point C).

3.2.4. REVERSE DROOP CONTROL

In the approach presented by Laaksonen, etal in [12], all microsources remain in PQ control and the storage device shifts to droop control when the microgrid islands. The droop control of the storage inverter, however, regulates the microgrid voltage by controlling the output real power, and the frequency is regulated by controlling the output reactive power. They proposed this droop relationship because of the resistive nature of LV distribution lines. In this paper, this co-operation approach will be called reverse droop control. The droop characteristics are shown in Figure 7.

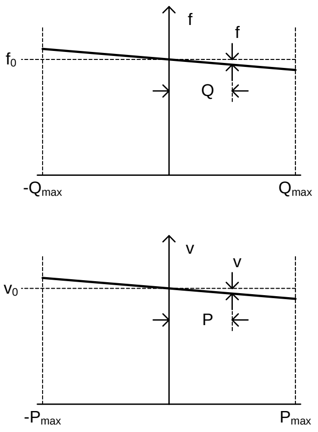

Figure 7: Reverse droops control.

3.2.5. AUTONOMOUS CONTROL

The approach proposed by Lasseter and Piagi in [2] is called autonomous control of microsources. They emphasized that the microgrid should follow a peer-to-peer and plug-and-play model. They avoided the installation of a single point of failure like MGCC and dedicated storage units, so the microsources have integrated storage (battery bank in the dc bus of the inverter). The microsources are controlled using unit power control configuration, feeder flow control configuration or combination of both.

In unit power flow configuration, the microsources assume droop control in both grid-tied and island modes of operation. The output power of a microsource is constant when the microgrid is grid-tied because the grid sets the frequency. When the microgrid islands, the microgrid frequency is determined by the droop curves as described in Figure 3(a). In feeder flow configuration, a microsource regulates the real power flowing through a particular feeder in the microgrid. It controls the amount of power it is generating to regulate the amount of power flowing through the particular feeder. Figure 8 shows the relationship between the power flowing through a feeder, F, and frequency, f. The microgrid frequency is determined by the F-f curves of the microsources when the microgrid islands.

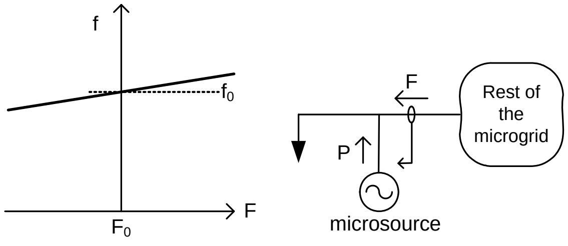

Figure 8: Feeder flow configuration

3.2.6. MULTI-AGENT BASED PQ CONTROL

The approach proposed by Oyarzabal, etal in [13] commands all microsources to remain in PQ control while the storage device shifts to droop control. The storage device will control the voltage and frequency of the microgrid. The output power setpoints of the microsources are computed by the MGCC and sent to the microsources every 30 seconds. The storage device acts as a load following unit: it generates or absorbs power to ensure energy balance at all times. Intelligent agents are used to manage the microgrid, and a control agent in the MGCC takes charge of the scheduling of the operation of the microsources.

4. COMPARISON OF CO-OPERATION STRATEGIES

The fundamental requirement of a microgrid in island operation is the presence of an inverter or rotating machine that will establish voltage and frequency and keep these values within acceptable limits. The slope of the droop curves, and the range of power exchange between generators and loads determine the voltage and frequency extremes in the pure droop, reverse droop and autonomous control. Furthermore, the frequency and magnitude of frequency and voltage fluctuations depend on the frequency and magnitude of load fluctuations. Frequent and large load swings will cause frequent and significant over- and under-voltages and operation beyond frequency limits. These control approaches may be adopted if the connected loads can tolerate the fluctuations (e.g. constant impedance loads and loads with power electronics front end). On the other hand, the inverters mode, primary energy source and multi-agent based PQ control guarantee that the voltage and frequency would not deviate much from the nominal values, resulting in high quality of power. The approaches are applicable to microgrids that drive power quality-sensitive loads.

The services required from the storage device determine the storage capacity required by the microgrid. Small capacity is required if it only provides quick reaction to imbalances between supply and consumption during abrupt changes in generation or load. The inverter modes and multi-agent based co-operation schemes may used for microgrids with small storage capacity because the storage device only functions as a fast power absorbing or generating unit but does not output power for extended periods. In contrast, large storage capacity should be installed if the storage device will participate in the overall power generation of the microgrid. The pure droop, primary energy source or reverse droops co-operation approaches demand large storage capacity because the storage device directly participates in frequency control. It is required to output or absorb real power for prolonged periods of time. The microgrid or storage device owner should have means of recovering the installation costs of the storage device. As suggested in [14], the storage device can participate in the market operation of the microgrid the latter is grid-connected.

All co-operation strategies except the multi-agent based PQ control will not require a communication infrastructure between microsources, storage devices and controllers during island operation if the inverters are capable of island detection. The storage devices and microsources with island detection capability can automatically transfer from PQ control to droop control and vice versa. However, if the microsources rely on the central controller in determining the state of the microgrid, a fast communication line should be installed between the controller and the microsources.

The multi-agent based PQ control needs a communication infrastructure like a LAN because the generation setpoints are periodically sent by the central controller. The success of multi-agent based control depends on the reliability of communication exchange between the agents.

Communication between the central controller and loads are required if load shedding is implemented especially when the connected load exceeds the generation capacity or the frequency dropped to excessively low levels immediately after disconnection. Black starting will also require communication among the microgrid components, however, the black start procedure may be executed by the operators using a telephone.

The choice of co-operation strategy should take into account the types of installed microsources. If intermittent (solar or wind) or CHP microsources are present, there should be at least one microsource that would act as a load following unit. A load following unit is required because of the stochastic nature of the intermittent sources and CHP sources operate only when heating is required. The load following microsource simply adjusts its output power to balance the instantaneous generation and consumption. If the installed storage capacity is small, the inverter modes and multi-agent based PQ control are best choices because the other microsources are forced to assume the load following function, and there is no risk of depleting or overcharging the storage device. If the installed storage capacity is large, pure droop control is the next best option because the load following responsibility is shared by the storage device and microsources. Reverse droop control may be also chosen if the other microsources will also assume reverse droop characteristics. The primary energy source control is the worst choice because the storage device is solely responsible in load following. If autonomous control is chosen, the feeder flow configuration should be used on the feeder where the intermittent source is connected. The microsource associated with the feeder flow configuration acts as the load following unit.

The ownership of the microgrid components also affects the choice of co-operation approach. If the microsources have several owners, they tend to operate the microsources in a way that will maximize their individual profits. All approaches may be used if the microgrid is normally importing power from the grid. When the microgrid islands, the microsources will remain operating at their maximum levels and some loads are shed to achieve balance between generation and consumption. However, if the microgrid is normally selling power to the grid, the shortage of consumers would force the microsources to decrease generation levels. They must compete on who will supply energy to the connected loads. The multi-agent based PQ control is best suited for this situation. Autonomous control may also be used for this case, but the consumers and microsource owners should pre-arrange through contracts the amount of energy that will be exchanged.

As mentioned earlier, the storage device is a critical component of an islanded microgrid because it establishes the voltage and frequency. Therefore, its owner must be compensated for providing this important service. This dilemma is avoided if the entire microgrid has only one owner.

All co-operation approaches may be used if the microgrid has only one owner. Having one owner implies that the microsources do not have to compete and the objective of the microgrid controller is to maximize the value of the entire microgrid, and not the value of individual components.

5. CONCLUSIONS

This paper presented six co-operation approaches for the microsources and storage device when the microgrid is in island operation. All approaches addressed the issues concerning island operation of microgrids. Factors like power quality and stability, installed storage capacity, requirement of a communication infrastructure, types of installed microsources and microgrid ownership affect the choice of co-operation strategy.

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