MOHAMMAD REZA MIVEH, **MOHD FADLI RAHMAT** AND **MOHD WAZIR MUSTAFA** FROM UNIVERSITI TEKNOLOGI MALAYSIA AND **ALI ASGHAR GHADIMI** FROM ARAK UNIVERSITY IN IRAN DISCUSS CONTROL OF AUTONOMOUS MICROGRIDS

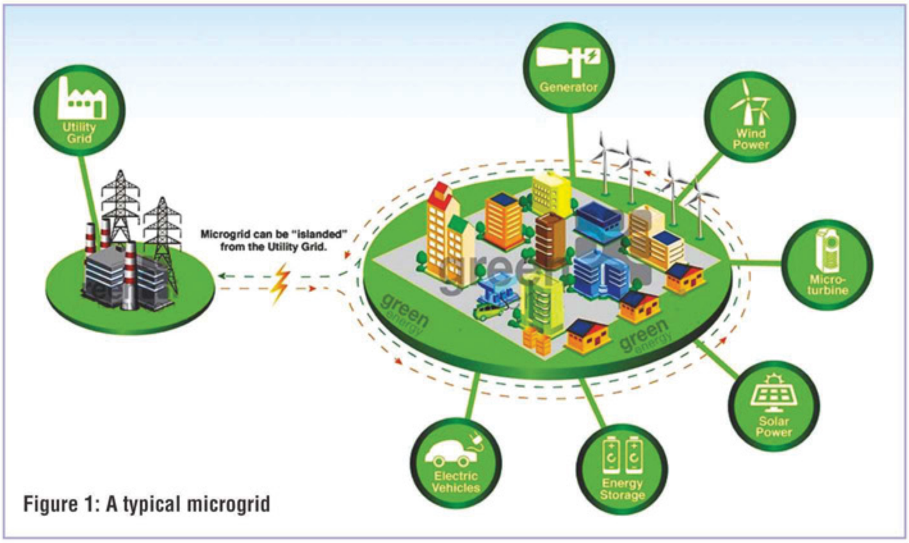

Figure 1: A typical microgrid

PROGRESS IN CONTROLLING AUTONOMOUS MICROGRIDS

A typical power system consists of equipment such as massive power plants, transmission systems and distribution networks to provide electricity to end consumers. Due to their availability and ability to generate huge amounts of electricity, fossil-fuel-based technologies have been the most common choice for generating electricity in these traditional power systems. Fossil-fuel generation technologies have improved our quality of life, but the advancements have come at a very high price. Moreover, they are the main cause of environmental pollution. Hence, for economic, technical and environmental reasons, it is essential to find energy alternatives that are renewable and environmentally clean.

With the recent focus on renewable and sustainable energies, integrating small power generating units such as wind turbines and photovoltaic systems has become a priority in the distribution network. Throughout the world, policies have been developed to increase the use of green-energy technologies. For instance, the US and Germany are planning some 30% of their electricity to be generated from green sources by 2020.

Green-energy technologies in general provide numerous benefits for the power system. But, to efficiently integrate these distributed energy resources (DERs) into the low-voltage distribution networks, a number of technical and operational challenges should be addressed. Indeed, not only should the potential advantages of renewable energies be harnessed, but also the present levels of reliability and controllability in the power system must be maintained and possibly improved.

Microgrids

The recently-developed microgrid is a reasonably attractive alternative for overcoming the challenges of integrating DERs into traditional power systems.

A microgrid can be defined as a cluster of distributed generators (DGs), loads, powered electronic devices and energy storage systems, which behaves as a controllable entity, see Figure 1, capable of operating in both grid-connected and autonomous modes. Moreover, it can handle the transitions between these two modes. In grid-connected mode, any deficit can be supported by power from the utility grid, while the excess power generated within the microgrid can be transferred to the utility grid. On the other hand, the power generated in the microgrid through DERs, in autonomous mode must be in balance with the demand of local loads. The ability of the microgrid to operate in islanded mode increases the reliability, controllability and security of the system, especially in emergency situations. Furthermore, it reduces the vulnerability of the power system to external attacks or power quality events.

The types of DERs in a particular microgrid can be varied based on the operating mode, type of generation technology and topology of the system. Generally, DERs and conventional large generators differ considerably not only in scale, but also in the way they generate electricity – basically, traditional large generators are synchronous machines with a fixed frequency.

Based on their technologies DERs may be categorized into three main groups, including variable frequency (e.g. wind turbines), high-speed frequency (e.g. small gas turbines) and direct energy

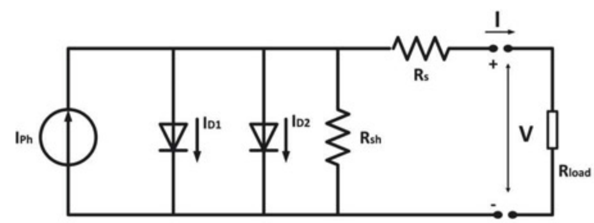

Figure 2: Electrical equivalent circuit of a two-diode PV cell

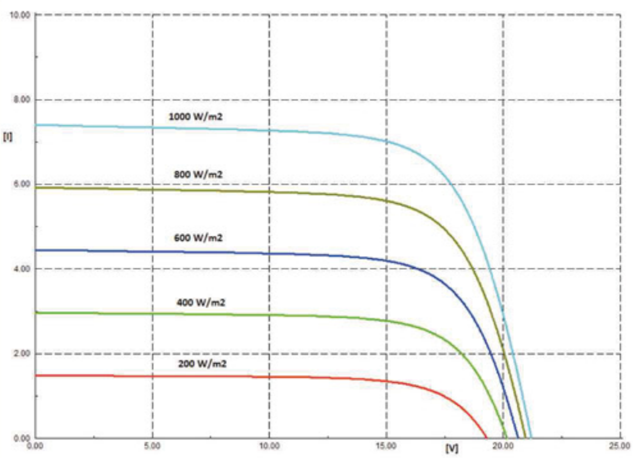

Figure 3: Electrical equivalent circuit of a two-diode PV cell

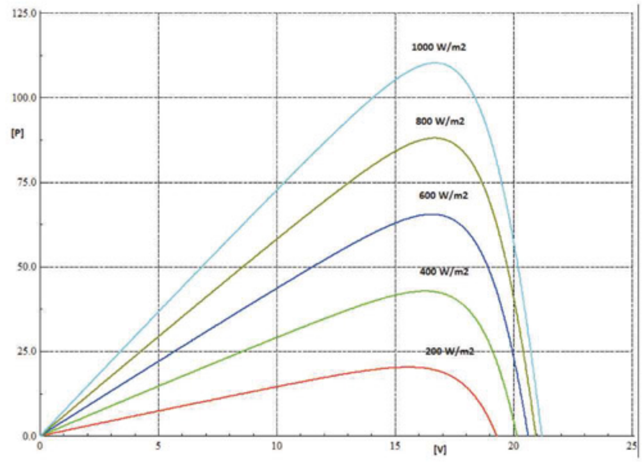

Figure 4: Output P-V characteristics with varying solar irradiation

conversion sources (e.g. photovoltaic arrays). Meanwhile, these units can be also classified based on dispatchability, containing non-dispatchable and dispatchable units. The output of non-dispatchable resources such as wind turbines and photovoltaic units is not controllable. In contrast, dispatchable units such as battery energy storage systems (BESS) can be fully controlled.

Modeling Of Solar Photovoltaic Array

For the purposes of our study, the dynamic model of a solar photovoltaic (PV) array was developed using the DIgSILENT power factory software.

The equivalent circuit model for a PV cell contains two diodes in parallel with an ideal current source, series resistance (R_s) and parallel resistance (R_{sh}) are shown in Figure 2. An ideal current source delivers current in proportion to the solar flux to which it is exposed. In a practical PV cell, a series resistance is offered by the semiconductor material, the metal grid, metal contacts and current collecting bus. These resistive losses are lumped together as series resistor (R_s). Similarly, a certain loss is associated with a small leakage of current through a resistive path in parallel with the intrinsic device. This can be represented by the parallel resistor, R_{sh}.

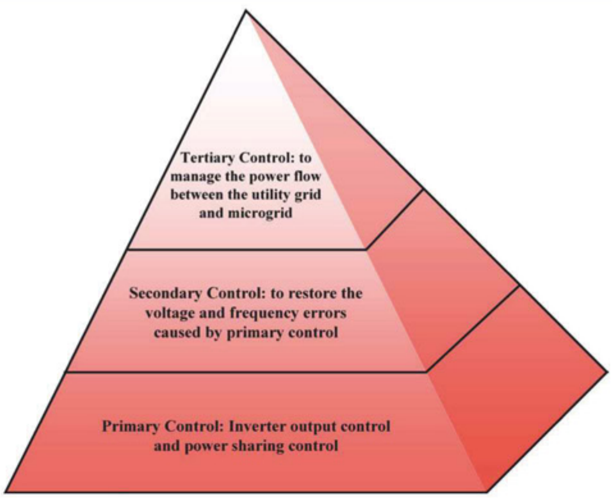

Figure 5: Hierarchical control levels of a microgrid

According to the equivalent circuit in Figure 2, the general PV panel current-voltage relationship for a specified illumination and temperature is given as:

$$I = I_{ph} - I_{s1}\left[EXP\left(\frac{V+R_S I}{N_S V_t}\right) - 1\right] - I_{s2}\left[EXP\left(\frac{V+R_S I}{2N_S V_t}\right) - 1\right] - \left(\frac{V+R_S I}{R_{Sh}}\right) \quad (1)$$

where I and V are the terminal current and voltage of the PV panel, I_{s1} is the saturation current due to the diffusion mechanism, I_{s2} is the saturation current because of carrier recombination in the space-charge region, N_s is the number of series-connected PV cells in the PV panel, R_s and R_{sh} are the series and shunt resistances, and V_t is the cell's thermal voltage.

Figures 3 and 4 show the I-V and P-V characteristics of the PV cell respectively under varying solar irradiation with constant temperature.

Islanded Operation

In autonomous mode, the microgrid operates as an independent entity. In this mode the need for a proper load sharing mechanism to balance sudden active mismatches leads to numerous operational and technical challenges. Therefore, autonomous mode is considerably more challenging than grid-connected mode.

> The main advantage of droop control is that it eliminates the need for communication

Since frequency and voltage of islanded operation are no longer supported by the utility grid, DER units are responsible for providing suitable control. Power balance also can be achieved through local controllers or by a central controller (CC). Local controllers operate based on local measurements, whereas CCs use communication links to guarantee that all units contribute to carrying the load in a pre-specified manner.

Changing the operating method of the power system through microgrids presents a number of operational challenges. Indeed, to ensure present levels of reliability and harness the full potential

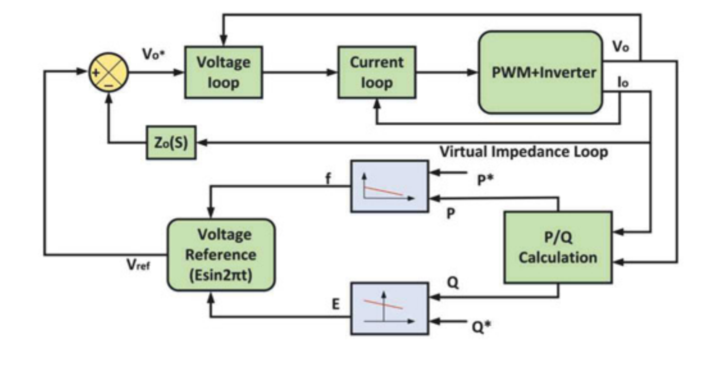

Figure 6: Primary control, including inner current and voltage loops, and droop control

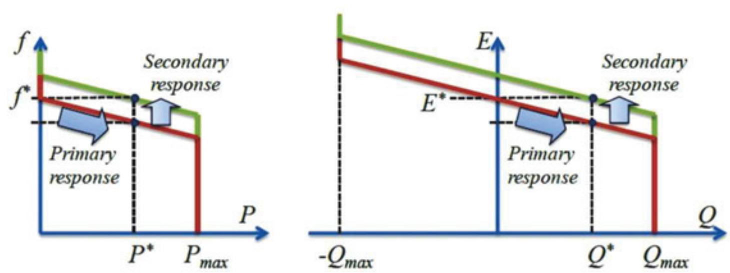

Figure 7: P_f and Q_E primary and secondary control actions

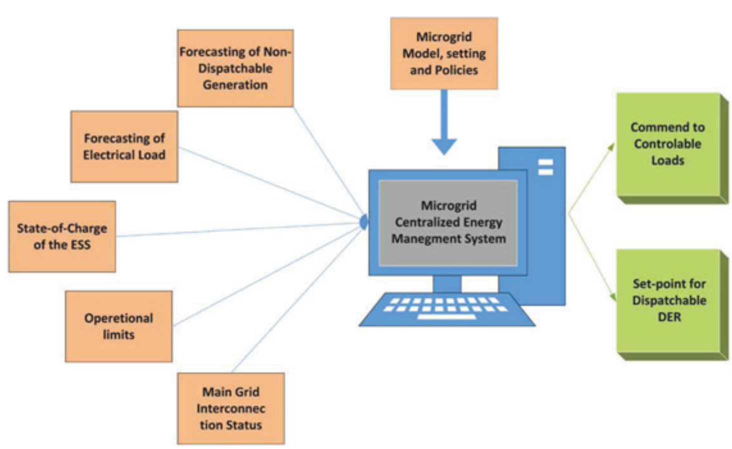

Figure 8: General structure of centralized secondary control for microgrids

advantage of DG units, some technical and operational issues in the design of a proper control system need to be considered, with the ultimate aim to ensure the reliable and economical operation of the microgrid.

Here, islanded operation is considered. Islanding operation requires adequate control and management systems to provide stable, autonomous operation. Voltage and frequency control, active and reactive power sharing, power quality control and optimizing operating costs together comprise the key principles of microgrid control structure in islanded mode. With respect to these requirements, hierarchical control can cover all these responsibilities.

Hierarchical Control Of Islanded Microgrids

In structuring a power system to accomplish these control actions, two different approaches – centralized and decentralized – can be used.

In a fully centralized technique, a CC performs the control actions for all units based on extensive communication links. On the other hand, in a fully decentralized approach, each control unit operates based on local measurements. For microgrid applications, implementing either fully centralized or fully decentralized control is impossible, due to the large number of controller units and stringent performance requirements.

A possible solution to these limitations can be achieved by introducing a hierarchical control scheme, a compromise between fully decentralized and centralized approaches, which includes three different levels. These levels, based on infrastructure requirements and speed of response, can be classified into primary, secondary and tertiary controllers; see Figure 5.

Primary control is the fastest level, responsible for inverter output control and power sharing, subsequent to the islanding process. Secondary control restores voltage and frequency deviations of islanded mode caused by the primary control. Indeed, it is responsible for mitigating the steady-state errors produced by the power-sharing unit.

At primary level, the main task of the inverter output controller is to regulate the electrical signals of the autonomous microgrid. Normally, inverter output control includes an external loop for voltage control and an inner loop for current regulation. The power-sharing controller is also used to manage active and reactive power sharing.

Typically, power sharing is done using active power-frequency and reactive power-voltage droop controllers without the need for communication links. Figure 6 shows primary level, including inner current and voltage loops, and droop control.

Secondary level is also used to correct the frequency and voltage deviations caused by the primary level. In some circumstances, the frequency or voltage of the microgrid increase, due to an unexpected reduction on the demand side. As shown in Figure 7, to match demand with generation, the frequency or voltage of an islanded microgrid must be correctly changed through at primary level.

As can be seen, the voltage or frequency in autonomous mode even after operation of the power-sharing unit is below the rated value. In such a situation, the main target of secondary control is to restore the operating point.

Researchers have recently started using multi-feedback loops in conjunction with the droop method for operating two or more voltage source inverters (VSIs) in an islanded microgrid. This comprises an outer voltage loop for voltage control and an inner current loop to generate the gate signals of the PWM (pulse width modulation).

Proper design of these control loops can be achieved using various controllers in different reference frames. Use of a proportional-integral controller in the synchronous reference frame with an additional feed-forward compensation path is a common approach, extensively used to improve performance of the regulators. Multi-variable control methods are another approach, widely used for the design of the control loops.

Power-Sharing Control

Power-sharing control is the second stage within the primary level. It can be implemented either using the droop concept or the CC. Indeed, this level can be classified into two different approaches: droop-based and non-droop-based.

Droop-based method

The concept of droop comes from the balance of power in conventional synchronous generators used in traditional electrical power systems. In this concept, whenever an imbalance between the mechanical power of the generator and its output electric active power occurs, the rotor speed will change, causing frequency deviation.

Similarly, output reactive power variations cause deviation in voltage magnitude. This concept can be artificially applied to inverter-based DG units in islanded microgrids. The main idea of this technique is to mimic the behaviour of a synchronous generator by reducing the frequency when the active power increases. The relationship between active power/frequency and reactive power/voltage can be written as:

$$\omega_o = \omega^* - K_P (P_o - P^*) \quad (2)$$

$$V_o = V^* - K_Q (Q_o - Q^*) \quad (3)$$

where ω^* and V^* correspond to the reference values for angular frequency and voltage respectively, and ω_o and V_o correspond to the measured output frequency and voltage of the DG system, respectively.

Non-droop-based methods

Non-droop-based methods use parallel converter configuration based on a communication link. Over long distances, communication links are vulnerable and expensive. Concentrated control, master/slave, instantaneous current sharing and circular chain control methods are the main examples of non-droop-based approaches.

Secondary Control In Islanded Mode

Secondary control is the highest level of hierarchical control in islanded mode. It is responsible for the reliable and economical operation of microgrids by restoring the frequency and voltage deviation caused by the primary level. Secondary control can be implemented either in centralized or decentralized way. The performance of secondary control in centralized manner significantly depends on the operation of the CC, while in decentralized approach various units can decide to interact with the microgrid.

The general structure of centralized secondary control for microgrids is shown in Figure 8. As can be seen, the CC uses information from DERs units, loads, the network and forecasting systems to provide proper set-points for dispatchable DERs and appropriate commands for controllable loads. As can be observed, the input variables may include forecasted power output of non-dispatchable energies and local loads, state of charge of the BESS, operation limits of dispatchable DGs, the utility grid interconnection status, security and reliability constraints of the microgrid and forecasting of grid energy price. The output variables of the CC are used as reference values for the next level to cope with the selected control objectives.

On the other hand, in the decentralized approach, the energy management challenges are handled by providing the highest possible autonomy for DG units and loads. Indeed, control of variables is done locally. Although decentralized secondary control has difficulty providing high levels of coordination for the microgrid, it can easily incorporate new DG units without needing to change the controller's settings.

Trends

The progress of microgrid control schemes in autonomous mode has evolved very buoyantly in numerous ways relating to the aspects discussed here.

But despite the numerous advantages of energy storage systems, such as power quality enhancement and microgrid islanded operation, they have not been fully utilized. The main cause of this limitation is the lack of proper control and management; further work needs to be done to develop control strategies for various energy-storage technologies, such as pumped hydro and compressed-air energy storage.

Even though a considerable amount of literature exists on the development of microgrid output control strategies, several questions still remain unanswered. The following areas can benefit from further research: improving robustness to topological and parametric uncertainties; improving the controllers' transient response; obviating the need for complex communication infrastructure; accounting for imbalance and harmonics; enhancing the control schemes' scalability; and developing control schemes that function for both grid-tied and islanded modes.

The main advantage of droop control is that it eliminates the need for communication. Moreover, in this approach, the control action is based on only local measurements. This gives droop control significant flexibility in that, as long as the balance between generation and demand is maintained, there is no interdependency between the local controllers.

However, the conventional droop control method has several challenges that need to be addressed: poor transient performance or instability owing to the use of average values of active and reactive power over a cycle; ignoring load dynamics that can result in failure subsequent to a large or fast load change; requiring special provisions for system restoration; poor performance when adopted for distribution networks; and unsuitability for nonlinear loads since it does not account for harmonic currents, among others. ●