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# Overview of the Microgrid Concept and its Hierarchical Control Architecture

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***Abstract*— The advent of the Smart Grid has enticed a lot of interest in the research of Distributed Generation (DG) thereby bringing into existence an intelligent electrical power distribution network. This distribution network is designed to possess desired characteristics such as reliability, security, stability and sustainability of energy. Distributed Generation (DG) employs various dispersed energy sources to generate electric power reliably and close to the load that is being served. The energy sources in DGs may include both renewable and non-renewable sources. The Microgrid (MG) concept is an integral part of the DG system and has been proven to possess the promising potential of providing clean, reliable and efficient power by effectively integrating renewable energy sources as well as other distributed energy sources. The energy sources include solar photovoltaics (PV), wind, fuel cell, micro-turbine, biomass, micro-hydro etc. Various architectures of MG are available and many more are still being developed. The architecture of an MG depends on a number of factors such as availability of renewable resources, geographical location of site, load demand etc. For effective and efficient operation, unlike the main grid, the Microgrid (MG) needs to employ special and proper control strategies. This is so because of the combination of conventional or traditional distributed energy sources and the high penetration of renewable energy sources most of which are intermittent in nature. As such, there is need for a control system that ensures proper sharing of the load among the distributed energy sources and also proper power flow between the microgrid and the main grid. The control system should be able to regulate the voltage as well as the frequency, both during islanded operations of the microgrid and grid-tied operation. This paper gives an outline of a microgrid, its general architecture and also gives an overview of the three-level hierarchical control system of a microgrid. The paper further highlights the importance of the Hierarchical control in the effective operation of the microgrid.**

***Keywords—Microgrid, Distributed Energy Sources, Hierarchical control, Droop control***

## *I. Background information on MG Concept*

Climate change has become a very prominent issue lately and is attributed to the massive use of fossil fuels. Most of society today is heavily dependent on high and growing fossil fuel consumption as a source of energy. As a matter of fact, all fossil fuels emit carbon dioxide when burnt, which is a proven major cause of global warming and climate change.

The possibility of weaning the world from this dependence cannot be achieved within a short time. This is mainly because most of the power that is generated from the centralized power system today comes from fossil fuels. However, global efforts are being made by concerned parties to reduce this dependence and also the levels of carbon emissions thus serving our planet Earth.

The deployment of renewable energy technologies increases the diversity of electricity sources and, through distributed generation, contributes to the flexibility of the system as well as its resistance and resilience to central shocks. The significance depends on a range of factors which include the market penetration of the renewables concerned, the balance of plant and the wider connectivity of the system as well as the demand side flexibility.

The main feature of the traditional centralized power system is that the whole grid is interlinked together forming a large grid, the advantage of which is the ability to fully enhance the efficiency of energy use. Despite being robust, the system suffers some drawbacks which include high cost implications and operational difficulties, as such encounters some difficulty in meeting users' increasing requirements for safety, efficiency and reliability [1].

The rapid and revolutionary changes in the regulatory as well as operational atmosphere of the main grid utilities and the emergence of micro-sources or smaller generating systems like micro-turbines, biomass, photovoltaics (PV) and fuel cells as already mentioned, have set up a new world of opportunities for electricity consumers in that it accords them an opportunity to generate electric power on site. Distributed energy resources (DER) or small power generators are typically located at sites where the generated energy is to be consumed. These are a promising option to meet the growing customer needs for cheap, economic and reliable electric power [2] supply.

The generation of power is evolving from the large centralized generators to smaller distributed generators (DG) usually powered by non-conventional sources and lately renewable sources have been heavily integrated. The smaller distributed generators, which were initially applied for back up purposes only, and not connected to the grid, are now taking the role of primary sources [3].

This evolutionary shift in the role of distributed generators (DG) from that of back up to that of primary sources is pioneered by a cluster known as a Microgrid (MG). The MG is a reliable power source in a small package which gathers distributed generation sources and forms a small power group to supply power in a moderately small area.

From one perspective, the MG can be thought of as a miniature version of the larger centralized system, including distribution and regulation of the flow of power to consumers but on a block and smaller scale.

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The MG, however, is an independent and decentralized system, which uses a lot of modern power electronic technology and employs small power sources such as micro-turbines, wind power, solar, biomass, fuel cells and energy storage devices which are directly connected to the user side.

In other words the MG is assumed to be a cluster of loads and micro-sources operating as a single controllable system providing both power and heat to consumers locally, near to the point of power generation. It offers integration of distributed energy resources (DER) with local elastic loads, and is designed in such a way that it can operate either in parallel with the grid or in isolation (island) mode. At the moment there is no agreed standard definition of the microgrid. However, many researchers and organizations have coined their own definitions in various ways. The Microgrid Exchange Group of the United States of America for example defines MG as a group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid [4].

It is therefore a distributed energy system having generation, storage and demand, all embedded within a single controlled network. It is this feature that makes a MG to operate in isolation (island mode) or connected to the grid [5] just as earlier highlighted. Another important feature of the MG is to flexibly and yet controllably, interface with the main grid.

The MG has many desirable features some of which are well outlined in reference [6].

A more comprehensive definition of a MG is one given by the Consortium for Electric Reliability Technology Solutions (CERTS) as an aggregation of loads and micro-sources operating as a single system providing both power and heat. The CERTS emphasizes that MGs must be power-electronic based to provide the required flexibility to ensure operation as a single aggregated system. This control flexibility allows the MG to present itself to the bulk power system as a single controlled unit that meets local needs for efficiency, reliability and security [7].

CERTS further states that a MG derives from its presentation to the main distribution grid as a single self controlled entity or power supply system. This implies that the grid should not be able to distinguish between the MG and other legitimate customer sites (loads). The large utility grid should view the MG as a single controlled cell or unit capable of responding quickly to the needs of the external transmission and distribution system of the grid [8-9].

This profile however, solely relies on the flexibility of the power electronics systems such as inverters for control of interface between micro-sources and the connected loads, as well as with the main grid. MG combines distributed power, loads, energy storage devices and control devices, forming a single embedded power supply system. This concept reduces feeder losses, and increases reliability of local power supply, and improves energy efficiency.

MG provides power to isolated rural communities, training institutions, industrial sites, office blocks thereby reducing energy dependence on the utility supply. MGs are mostly designed in such a way that they benefit both utility and consumers. On the part of the utility, MGs give scale benefits as they can be regarded as controllable entities, thus reduce transmission and distribution costs whereas for the consumers, they enable power delivery at better power quality and high reliability [10]. In the recent past the MG has become an integral part of smart distribution and smart grid, thus has attracted a lot of research. This is so because it is viewed to be the solution to the energy crisis, and also as a means of combating climate change due to its high penetration of renewable energy sources.

## II. GENERAL ARCHITECTURE OF A MICROGRID

The MG can be viewed as a microcosm or smaller version of the main grid. This is so because it contains all the necessary components to enable it operate in isolation of the grid (off-grid), but at a distribution level. Microgrids are formed by the hybrid interconnection of various units such as AC and DC energy sources, storage devices, AC and DC loads, AC/DC, DC/DC, or DC/AC converters. MGs may operate in grid-connected mode or islanded mode. The transition from grid-connected to islanded mode can either be intentional or unintentional. The smooth transition in either case requires implementation of accurate algorithms to facilitate the process. When operating in island mode however, the MG must supply the needed active power, reactive power and the frequency, and must operate within the specified range of voltages.

On the other hand, when operating in isolation from the grid (island mode) either intentionally or unintentionally, the MG sustains itself. The MG connects to the grid through the point of common coupling (PCC) as dictated by prevailing commercial or technical conditions. Therefore by virtue of being a self contained system, the microgrid is resilient to grid disruptions [5]. The resilience time frame varies from a grid independence system which can operate as long as fuel or renewable energy source is available, to a system which operates for short periods to protect against the devastating effects of grid failure.

The IEEE standard 1547 stipulates that MG is to be provided with automatic tripping system for the interconnected sources, so that it islands itself when the grid fails, and reconnects back when the fault is corrected. Reference [3] comprehensively explains this concept. The MG basic architecture consists of two critical components; the Static Transfer Switch (STS) and the micro-source. The micro-source comprises generators, storage system, load controller and power electronic interfaces, whereas the static transfer switch (Figure 1) is responsible for the connecting and disconnecting of the MG to and from the main grid respectively.

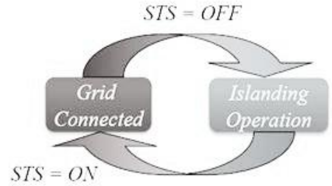


Figure 1: Function of Static Transfer Switch

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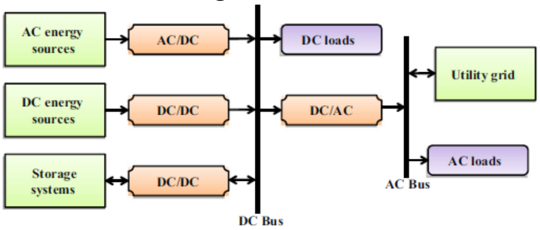
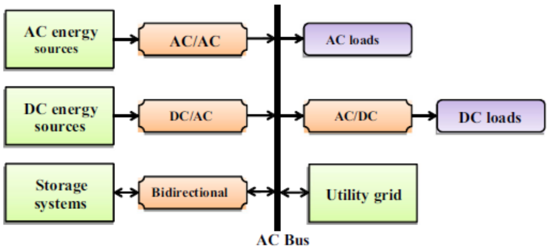
The selection of architecture for a particular location depends on a number of factors which may be geographical, economical, or technical [11]. It is very important to consider these factors as they determine which renewable energy resources are readily available in that location. Microgrid can be designed to operate as direct current (DC), alternating current (AC), high frequency alternating current (HFAC) or a combination of these three (i.e DC, AC, HFAC), depending on the need. Figure 2 below shows the general layout of typical DC and AC Microgrid architecture.




(a)




(b)

Figure 2. Layout of Microgrid (a) DC Microgrid
(b) AC Microgrid

The microgrid structure, as already stated, can consist of several types of distributed energy resources (DER) such as solar photovoltaics, wind turbines, fuel cell, biomass, microturbines etc each in the form of DG, including energy reserves from storage systems also known as distributed storage (DS) [12].

Various renewable energy sources give out different type of power. For instance, the outputs of fuel cell and solar power are low voltage DC that needs to be stepped up to a higher level DC power for processing using DC/DC converters. In contrast the output power of wind turbines is variable-frequency AC power, whereas the output for biomass generator is AC and that of micro-turbines is high-frequency AC power. Therefore for all these examples of classes of sources, the converters (DC/AC, AD/DC or AC/AC) are employed [13] to convert the generated power to DC or AC depending on the type of microgrid architecture. In the DC architecture, DG sources are connected to a uniform DC bus voltage including the DS. This facilitates plug-and-play capability by being able to store the DC power and use DC/AC converters to generate AC power.

## III. PRACTICAL APPLICATIONS OF MICROGRIDS

Generally, there are (but not limited to) five core microgrid applications which include Community Microgrids, Industrial Micrograids, Campus Micrograids, Off-grid Micrograids and Military Micrograids.

Community Micrograids are usually designed to supply power to a specific geographical location such as residential area or shopping complex. These are principally driven by affordability and security. Industrial Microgrids mainly apply to commercial centers and/or critical manufacturing zones, mining sites etc. These usually tend to be driven by security and affordability.

Campus Microgrids provide power to Schools, universities or even government offices. They offer the best short-term development opportunity.

Off-Grid Microgrid Systems also referred to as Remote micrograids are becoming very common especially in remote rural areas in third world countries. These supply power in far flung areas where there is no access to the central power grid. They represent the greatest number of micrograids currently operating globally, but having the smallest average capacity. They are however expected to continue to be a market segment driven by solar photovoltaics deployment in far flung or remote areas. Other forms of energy are projected to play a growing role in this type of micrograid as well.

Military Micrograids: These take up the smallest market segment, and were just recently developed. They are installed in military bases, military camps, prisons etc.

The MG enjoys a number of advantages some of which are outlined below.

*Independence or Autonomy:* Micrograids combine generation, storage and loads to seamlessly operate in an autonomous fashion, balancing out voltage and frequency challenges with the application of the latest power electronic technology. In the case of grid-tied MGs, when a disturbance occurs in the utility grid, they have the ability to separate and isolate seamlessly from the grid with little or no disruption to the loads they serve.

*Stability and controllability:* Control approaches are based on frequency droops and voltage levels at the terminal of each convertor device, allowing the entire network to operate in a stable manner, regardless of whether the larger grid is up or down.

*Compatibility:* Micrograids are completely compatible with the existing centralized grid, serving as a functional unit that assists in building out the existing system thus helping to maximize otherwise stranded utility assets.

*Flexibility and interactivity:* Expansion and growth rates do not have to follow any precise forecasts since lead times are short and build outs are incremental. Micrograids are also technology neutral and are able to tap a diverse mix of renewable and fossil fuels.

*Scalability and Diversity:* Micrograids facilitate the use of many small power generation sources, storage, and load devices in a parallel and modular manner in order to scale up to higher power production and/or consumption levels.

*Efficiency and effectiveness:* Energy management goals, including economic and environmental, can be optimized in a systematic fashion.

*Economics:* Droop frequency control techniques allow for the programming of economic decision-making into standard operating protocols.

Micrograids are already much more prevalent now, and their agent-based operation simplifies the adoption of diverse technologies. Micrograids are locally responsive so they can more easily fulfill their own purposes rather than integration

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based on far-off central offices. They also inherently have more options for balancing intermittent energy generation and intermittent consumption compared with larger complex grids. This is because the trade-offs are visible and local. Microgrids are today the proving grounds for consumer acceptance and site-based management of smart energy. Microgrids today are pioneering consumer-based transactive energy. The architectures described in this paper provide a means for these systems to assemble themselves into aggregates that can further aggregate themselves into larger microgrids or Smart grids.

## IV. HIERARCHICAL CONTROL (HC) ARCHITECTURE FOR MICROGRIDS

The MG control system is one of the very critical and challenging parts in the study of Microgrids. The principles involved differ quite significantly from those of centralized or traditional power system. For instance, when an out of balance situation occurs between the electric power source and the load in a traditional power system, the power is instantly balanced by the rotating inertia in the system, giving rise to a change in frequency [10], which is the underlying principal of the *P-f* droop control method [15].

For the MG however, this inertia is absent due to the fact that most sources in MG are renewable which are intermittent, thus making the control system design quite challenging. This is what led to the development of a new control strategy for controlling MGs known as Hierarchical Control (HC). HC comprises three levels; primary control, secondary control and tertiary control as summarized by Figure 3 below.

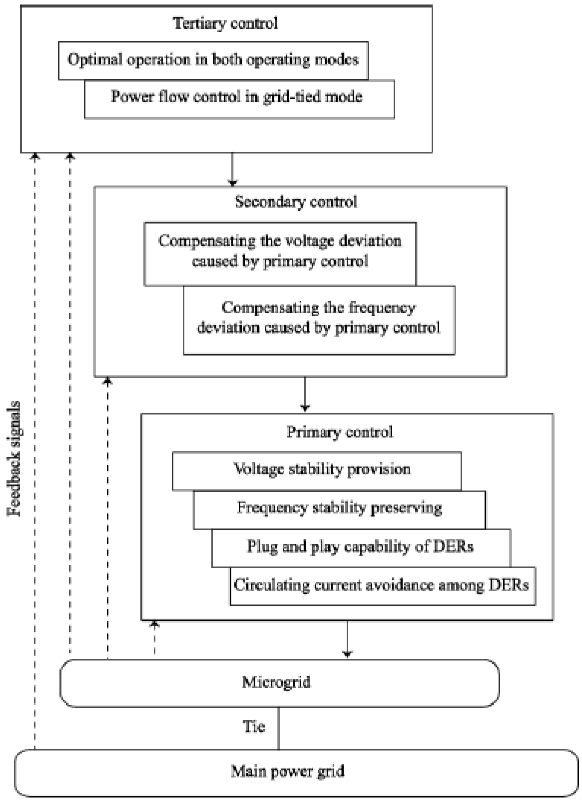


Figure 3: Diagrammatic representation of the basic Hierarchical Control Structure

In general the primary control is responsible for the local voltage control that allows each DG unit to operate independently and also for the reliability of the system. Thus the primary control deals with the inner control of the distributed energy sources by adding virtual inertias and controlling their output impedances as explained by reference [15], and depicted by figure 4.

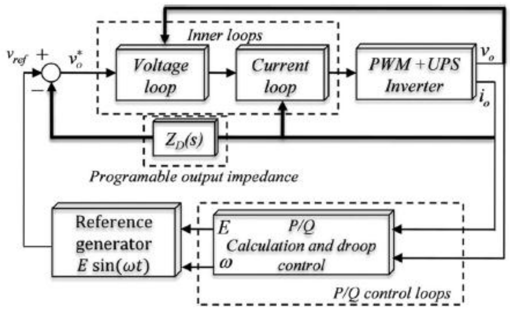


Figure 4: Virtual-impedance loop.

The primary control provides the reference points for the voltage and current loops of the MG sources, also called inner control loops. These are implemented in two modes: PQ mode and voltage control mode. In the former, the active and reactive power of distributed energy sources is regulated with regard to the preset reference points (figure 5(a)), whereas in the latter distributed energy sources operate as voltage controlled sources (figure 5(b)) in which the reference voltage is determined by droop characteristics (Figure 5(c)) [14 – 16]

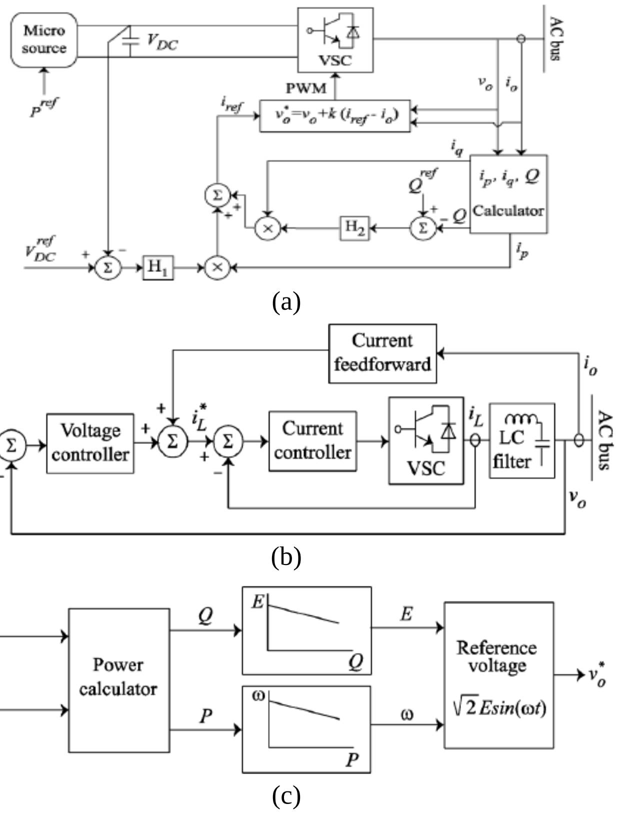


Figure 5: (a) PQ control mode with active and reactive power
(b) The voltage and current control loops in voltage control mode
(c) Determination of reference voltage for the voltage control mode

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The secondary and tertiary controllers are the main supporters of the microgrid operation. The function of the secondary control is to help the MG to achieve global controllability by restoring the frequency and amplitude deviations produced by the virtual inertias and output virtual impedances during primary control. This controller uses a Microgrid Central Controller (MGCC). The central controller holds the control intelligence that considers the MG as a whole and is able to optimize the operation of the entire microgrid. This is in contrast to the primary control whose operation is confined to the island mode only.

At times the MGCC may also include tertiary control. Tertiary control ensures economic optimization, based on energy cost and electricity market [10]. Tertiary controller enhances exchange of information or data with the distribution system operator in order to optimize the microgrid operation within the utility grid. In grid-tied mode, the tertiary controller manages the power flow between the main grid and the microgrid by adjusting the amplitude and frequency of distributed energy sources at the Point of Common Coupling. Figure 8 shows a summary of the secondary and tertiary control system of a microgrid.

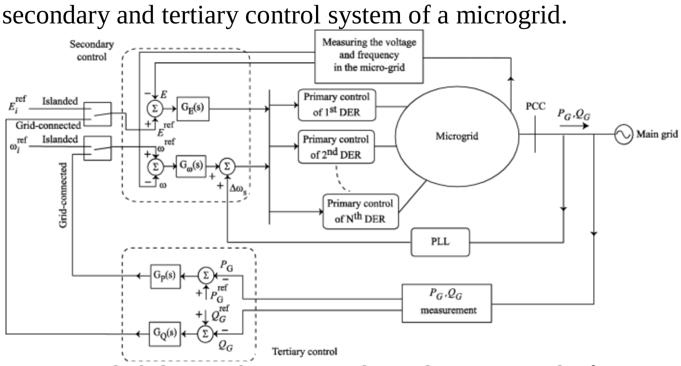


Figure 8: Block diagram showing secondary and tertiary controls of a MG [15]

Bidram et al in "Hierarchical Structure of Microgrids Control System" puts across very concisely extra details of secondary and tertiary control strategies. From the above overview, it can be seen that the effective control for proper operation of the microgrid can be attained by employing the hierarchical control architecture outlined in this research.

Hierarchical control is thus mainly carried out or executed by the master controller. The controller ensures the economical and secure operation of microgrids by maintaining the frequency and voltage in microgrids. In some cases it also employs the Supervisory Control and Data Acquisition (SCADA) to monitor and regulate frequency and voltage in microgrids according to the "Power-Frequency (*P-f)*" and "Reactive power-Voltage (*Q-V)*" droop characteristics, which lead to a very important concept called the droop control.

Droop control technique is a method that is used for load sharing in traditional power systems with multiple parallel generating sources. The load is shared by drooping the frequency of each distributed source with the real power delivered. This allows each source to share changes in total load in a pattern dictated by the droop characteristic. In the same way, a droop in the voltage amplitude/reactive power is used for reactive power sharing [13]. This technique is based on the theory that the flow of the active power and reactive power between two sources can be controlled by varying the power angle, and the voltage amplitude of each source. The active power is controlled by the power angle, whereas the reactive power is controlled by the magnitude of the voltage. This thus means that real power and reactive power can be controlled independently. The method is widely applied for power sharing in parallel connected distributed energy sources.

Research prospects for Microgrid control still stand especially in enhancing its effective and efficient operation considering the presence of renewables. A number of other areas in relation to microgrid technology need more research, such as the synchronization process during grid-connection and grid-disconnection, and the voltage/frequency control methods. The vast research in microgrid control technology currently going on globally will sooner or later lead towards the development of control concept that will help transform the current microgrid system into a more intelligent microgrid system which will be able to work autonomously and efficiently.

## V. CONCLUSION

The paper has highlighted the fact that Microgrids can comprise traditional sources as well as renewable energy sources. The integration of renewable energy sources, which are intermittent in nature, entails that special control methods have to be employed. It is this characteristic of renewable energy sources that led to the advent of the hierarchical control system that is introduced in this paper. The hierarchical control comprises three levels, each of which plays a crucial role in the effective operation of the microgrid. The three levels of hierarchical control presented in this paper are as follows; primary control level which deals with the inner control of the DG units, secondary control level which restores the frequency and amplitude deviations produced during primary control, and the tertiary control level which synchronizes power flow between the microgrid, and the main network at the point of common coupling (PCC).

Finally, some research prospects are also presented as a means of improving on hierarchical control systems for future microgrids.

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