A REVIEW ON MICROGRID AND ITS COTROL

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Abstract—Increasing electrical demand, economic constraints of generation expansion, quality control of supplied electricity and utilization of renewable sources led to the invention of microgrid. A Microgrid is the system comprising Distributed Generation (DG), energy storage devices, distribution network, loads and hierarchical control & management networks. To integrate the energy from DG to grid, power electronic interfaces are used with control strategies. This paper gives insight of microgrid control and discusses various aspects related it.

Index Terms—Distributed generation (DG), inverter, voltage source inverter, switching pulse generator, SVPWM.

I. Introduction

Electrical energy is produced in large scale using conventional methods utilizing the non-renewable resources like coal, diesel, gas etc. Due to increasing population, electrical energy is being extensively used and the reserves of these non-renewable sources are getting depleted. Also, power generation from these sources results in environmental pollution and amends the atmospheric conditions.The existing power grid technology became old and is now having many concerns like increasing demand, restrictions in planning, variable market and lesser scope of generation expansion. As a solution, the world is now looking towards development of efficient technologies which utilizes renewable sources and produces electricity. Electricity produced from these technologies may be smaller in magnitude, but it is clean.

Economically, it is not easy to extend a power system in terms of generation if the demand is increasing and it is a better idea to supply the excess demand using the distributed energy produced from the renewables like photo-voltaic, wind power etc., Energy which is generated at places where these renewables are obtained, integrated to the power system grid to supply the excess demands and reduce the burden on the grid. Some industries produce their own electricity so that the dependence on utility is reduced and such industries will supply the excess generated energy to main grid. This penetration of DG into main grid reduces the burden on main grid but adds new issues which are to be solved. Power generated from DG is intermittent in nature and hence power electronic devices are needed to regulate the voltage and frequency of the generated supply. Disturbances in DG side are reflected in all the stages of the multi staged main grid. In order to solve these issues and get the benefit of DG, the concept of microgrid was introduced. Maintaining quality and reliability of the supply is an important concern under all conditions which can be achieved through microgrid. Research is having a great scope in this area. A Microgrid is the system comprising DG (like solar photo-voltaic, wind turbines, fuel cells, micro-turbines, gas based generation, CHPs etc.,), distribution network, energy storage devices (fly-wheels, batteries etc.,), loads, power electronic interfaces and hierarchical control & management networks. Synchronous machine with regulator and governor control can also be a source in microgrids. There exists AC and DC microgrids out of which AC microgrid are more focussed as they operate in conjunction with main grid directly. DC microgrids are generally used in networks where communication is needed [1]–[7]. Objectives of the microgrid concept are increasing the reliability of the supply, reduce the transmission losses, provide electricity to remote places, reduce the environmental impact due to generation of electricity and reduce the power system expansion cost. A typical structure of a microgrid is depicted in Fig. 1.

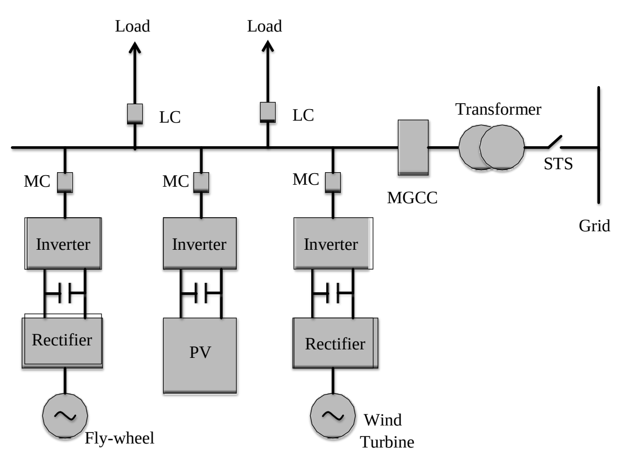


Fig. 1: Structure of a typical microgrid

As shown in Fig. 1, power electronic devices acts as interfaces between DG and utility grid. MGCC (Microgrid Central controller) is the main controller which controls MC (Micro-source Controller) and LC (Load Controller). Inverter is controlled as per load requirement and hence there should be a control scheme to regulate the power flow from the DG and maintain quality and reliability of supply. Motive behind any control scheme is accurate power sharing and required voltage and frequency regulation [8]. Various modes of operation and controlling of inverters are explained in further sections. Depending upon the mode under which a microgrid operates, control strategies are designed [9].

II. Modes of Operation

A Microgrid can operate in two modes.

1) Grid connected mode

In *grid connected mode/on-grid*, DG is connected to the utility grid at the PCC (Point of Common Coupling) through STS (Static Transfer Switch). The amount of active and reactive power to be injected by a DG is decided by the MGCC. MGCC issues commands to the MCs and LCs and these devices in turn control the local devices. Communication between MGCC, MCs and LCs is to transfer the small information related to set points of active and reactive power, reference voltage and frequency etc., PQ control is employed in this mode to regulate active and reactive power from inverter [10]–[12].

2) Islanded mode

When the microgrid is working autonomously, it is said to be in *islanded/stand-alone/off-grid* mode. Microgrids enter into this mode due to maintenance, outage or economic reasons [13]. Inverters acting as Voltage Source Inverters in this mode requires voltage and frequency set points which can be obtained by *centralized* or *decentralized* control. In centralized control, all the loads and sources are controlled by a hierarchical management system which issues the set-points to inverters through a communication link. This control is possible for low distance distribution networks only since it involves high capital cost and also unreliable. In [14], control strategy involving communication between MGCC, LC, and MC are discussed. For decentralised control, energy available in DG should be greater than the demand in the system. Inverters control the voltage and frequency of the grid in accordance to the load power requirement and share the demand. In this mode, LC's and MC's make their own control decisions [14], [15]. Droop control or *master-slave* control can be employed in this mode of operation [16]. But master-slave control is not preferred because of its low reliability [10], [12], [17]. In [18], both droop control and master-slave control schemes were implemented simultaneously in a system where, some inverters operating under PQ control while others as per droop control.

III. Background Math

Referring to Fig. 2, power flowing through the transmission line depends on voltage and frequency at sending and receiving end. Synchronous generators operate in parallel based on this power transfer theory of transmission line. Active and reactive power injected by sending end is described by the following equations [19].

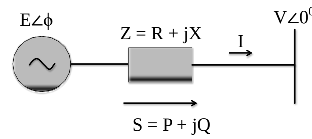


Fig. 2: Simple model for power transmission

$$S = P + jQ \quad (1)$$
$$= EI^* \quad (2)$$
$$= E\left(\frac{E - V}{Z}\right)^* \quad (3)$$
$$P = \left(\frac{EV}{Z}\cos\varphi - \frac{V^2}{Z}\right)\cos\vartheta + \frac{EV}{Z}\sin\varphi\sin\vartheta \quad (4)$$
$$Q = \left(\frac{EV}{Z}\cos\varphi - \frac{V^2}{Z}\right)\sin\vartheta - \frac{EV}{Z}\sin\varphi\cos\vartheta \quad (5)$$

assuming the line has negligible resistance i.e., $Z = X$ and $\vartheta = 90^0$

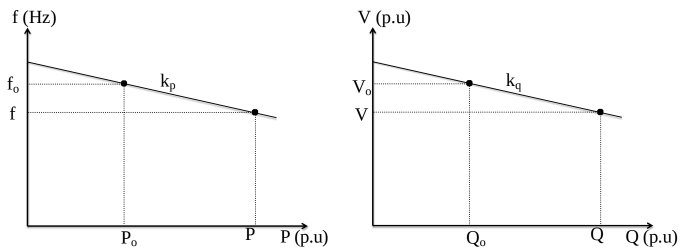
$$P = \frac{EV}{X}\sin\varphi \quad (6)$$
$$Q = \frac{EV}{X}\cos\varphi - \frac{V^2}{X} \quad (7)$$

IV. Control of Microgrid

A. Control of islanded microgrid

1) Droop Control: It is a decentralized control since it uses the local information only and the energy available in DG is more than demand. For a synchronous generator, if the active power output increases, its load angle increases thereby decreasing the frequency. Similarly, if the reactive power drawn increases, its terminal voltage decreases. This frequency and voltage droop characteristics are assigned to the inverters and they are made to imitate the behaviour of synchronous generator. For an inverter in a microgrid, if we require to increase the active power drawn from it, its frequency is reduced as per the frequency droop characteristic. The case is similar with reactive power also. The whole idea of this machine mimicking is to make the microgrid look more like a normal utility grid run by synchronous generators. In this mode, inverters will be working as Voltage Source Inverters (VSI) and operates in parallel with other inverters. Each system, i.e., each inverter is assigned with separate droop characteristics based on their generation capabilities and the total load is shared by the inverters based on their droop characteristics [5].

From (6) and (7), active and reactive power are decoupled for smaller values of φ. Therefore, active power depends on phase angle i.e., frequency and reactive power depends on voltage difference [4], [11], [12], [17], [20], [21]. This



(a) $P-f$ (b) $Q-V$

Fig. 3: Frequency and Voltage Droop Characteristics

dependence is described in the form of equations called droop equations (8) and (9) and the characteristics are shown in fig. (3a) and fig. (3b). Instead of frequency droop, angle droop can be used which gives reduced frequency deviation for a given margin of stability and droop gain values [22].

$$(f-f_0) = -k_p(P-P_0) \tag{8}$$
$$(V-V_0) = -k_q(Q-Q_0) \tag{9}$$

where k_p and k_q are droop co-efficients. These co-efficients should be choosen in such a way that inverters share load properly maintaining stability, voltage and frequency deviations [19], [23]. An adaptive feed forward compensation method is used to reduce the affect of droop coefficients on stability [24]. Droop control model is shown in Fig.4

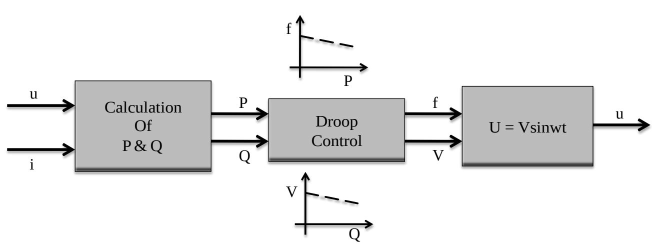


Fig. 4: Droop control model

When two sources are operating in parallel and if there is a change in active power demand, ratio of change of active power delivered by sources is inversely proportional to the ratio of their active droop coefficients. The same holds good for reactive power also.

$$\frac{\Delta P_1}{\Delta P_2} = \frac{k_{p2}}{k_{p1}} \tag{10}$$

In general, for n number of sources,

$$k_{p1}\Delta P_1 = k_{p2}\Delta P_2 = \cdots = k_{pn}\Delta P_n \tag{11}$$
$$k_{q1}\Delta Q_1 = k_{q2}\Delta Q_2 = \cdots = k_{qn}\Delta Q_n \tag{12}$$

Where, f and V are the frequency and voltage of inverter, P and Q are the active and reactive power from the inverter, k_p and k_q are slopes of the frequency and voltage droop characteristics [10], [19].

2) V/f control: During the power sharing process, the voltage and frequency deviates from their nominal values as per the droop characteristics of the inverters. *V/f* control helps in bringing back the frequency and voltage to their nominal values. It plays a vital role during synchronization i.e., switching between islanded mode to grid connected mode. This is done by a secondary loop which shifts the droop characteristics up or down as shown in Fig.5 as per the requirement. Considering Fig. 4, point A is the initial position where P_1, f_0 are nominal power and frequency. If the power delivered increases, frequency should decrease to f_1. Characteristic is shifted up to maintain the nominal frequency f_0 and point moves to position B. Similarly, if power demand decreases, frequency increases to f_2. Now, the characteristic is shifted down to maintain the frequency at nominal value.

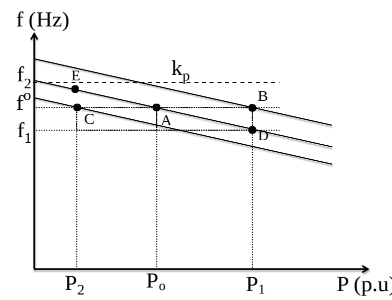


Fig. 5: V/f control or secondary control

B. Control of grid connected microgrid

In ON-grid control i.e., PQ control, inverter injects the available power in the DG into the grid. Based on the specified set values from MGCC, it injects the real and reactive power [10]–[12]. Inverter output power can be controlled by output current regulation or output voltage regulation [48]. In output current regulation mode, inverter is generally operated at unity power factor i.e. reactive power output is set to be zero and the real power reference value in few cases can be generated by the maximum power point tracking controller (PV,wind) or an energy manager. By using the current controlled technique, amplitude and phase of the output current is tracked and controlled to meet the desired active and reactive power as shown in Fig. 6.

In output voltage regulation, power flow is controlled by regulating the amplitude and phase of DG output voltage. Reference voltage is generated by reactive power controller and reference phase angle is generated by real power controller as shown in Fig. 8.

$$Q_{ref} = \frac{V_{ref}-V}{k_q} \tag{13}$$
$$P_{ref} = \frac{f_{ref}-f}{k_p} \tag{14}$$

Based on the values of V_{ref} and f_{ref}, active and reactive powers are delivered by the inverter satisfying (13) and (14).

Fig. 7 shows the variation of frequency reference required for corresponding variation in active power to be injected.

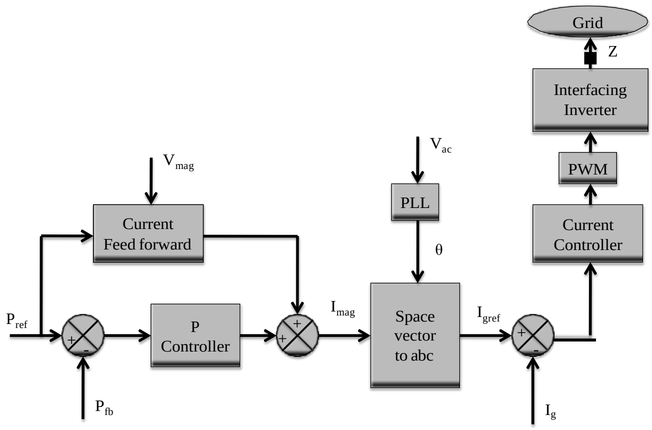


Fig. 6: Power control using output current regulation(UPF)

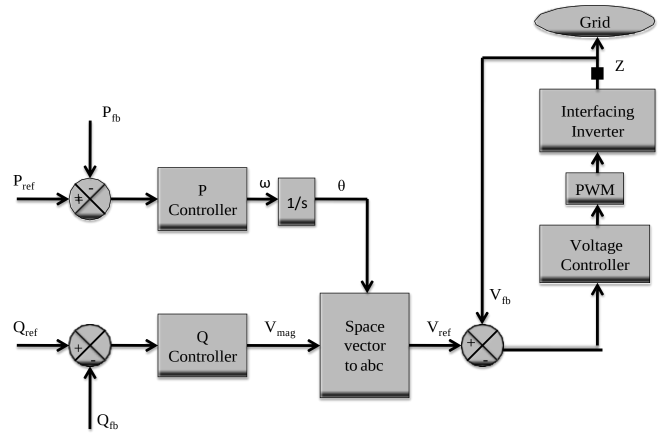


Fig. 8: Power control using output voltage regulation

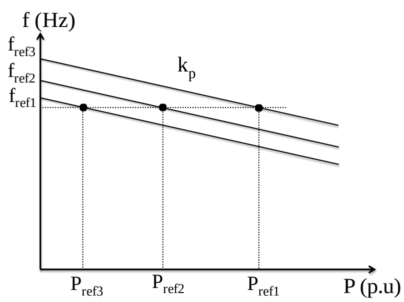


Fig. 7: Active power control in grid connected mode

Similarly, variation in voltage reference effects reactive power injection.

V. Control Aspects

Droop control explained in earlier section is called direct droop control and is valid for lines whose resistance is negligible. The characteristics are developed considering high X/R ratio and assumed resistance to be zero. But, a microgrid concept is generally implemented in distributed network, which is a low-voltage (LV) network [49]. For a LV network, X/R ratio is very less and therefore the inductance is assumed to be zero ($\vartheta = 0^0$). For this condition, the active power P depends on voltage and reactive power Q depends on power angle i.e., reverse to the direct droop case. Therefore the same equations are not valid for a LV network and they are to be modified considering the new conditions. This new implementation is called as indirect droop control [25], [26]. Some implementations use a orthogonal matrix to convert direct droop method into indirect method [27]. Instead of using indirect droop method, an altered Q-V method was proposed in [28], [29].

Power electronic devices are fast acting devices compared to mechanical systems. When gate pulses are given to an inverter, it instantaneously changes its frequency and voltage. But, in a synchronous generator, due to rotor inertia, it takes some time for its frequency to change and reach steady value. So, a

TABLE I: Typical line parameters

Type of line	R (Ohm/km)	X (ohm/km)	I_N (A)	R/X
Low voltage line	0.642	0.083	142	7.7
Medium voltage line	0.161	0.190	396	0.85
High voltage line	0.06	0.191	580	0.31

first order inertia is included in the control model to make the inverter behave exactly like a synchronous generator. Also this time constant helps in improving the stability but, decreases the dynamic response speed [19].

Output impedance of inverters affects the power sharing between the DG. If there are imbalances in inverter output impedance or line impedance, power sharing gets degraded and steady stage voltage is not constant. Closed loop impedance is not constant and depends on control strategy. To fix these problems, interface inductors can be included between inverter and grid but, they are heavy and bulky. So, we emulate the lossless resistors or reactors by drooping the reference voltage by the voltage drop produced by the output current in the emulated impedance as shown in Fig. 9. Soft start operation can be achieved by inserting high impedance during start and slowly reducing it to required value [27], [30]–[32].

Control structures for linear loads power distribution between the inverters are developed based on droop control method. Conventional droop control (direct droop control) works only when the loads are linear since the distorted power demanded by non-linear loads is not considered [28], [33]. In this sense, an extra loop is designed to share the non-linear loads. By emulating separate impedance for each harmonic, we can make the inverters share non-linear loads. Even a resistive output impedance method can make the inverters supply non-linear loads. During impedance variations, active power shared also varies which makes the steady state frequency to vary. An extra derivative term can be used in the droop characteristic so as to eliminate this deviation and improve

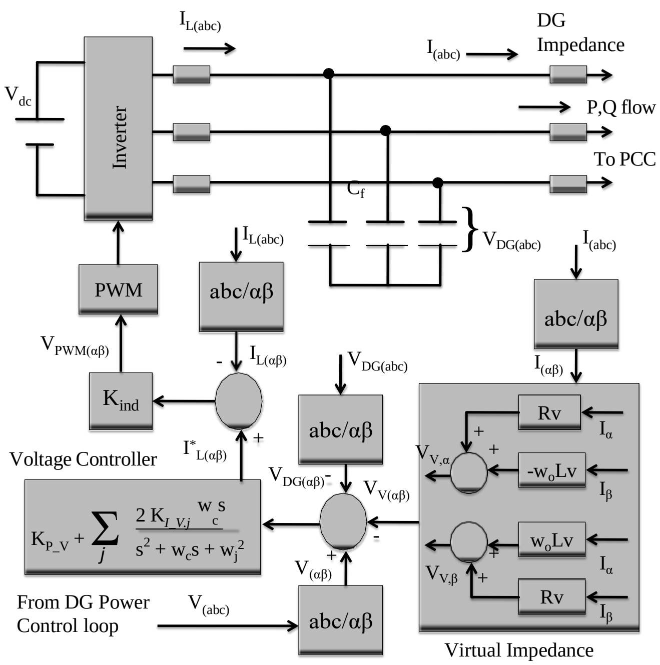


Fig. 9: Virtual output impedance implementation

dynamic performance as well. Harmonic Compensation using droop control technique was explained in [34]. Imbalances may occur due to faults on grid side or within the microgrid network and these imbalances results in nonlinear currents and distortion of voltage. In [35], a new control method for imbalance compensation using Q'-G droop has been proposed. It uses a new technique of controlling negative sequence current and positive sequence line voltage so as to make the inverters share these imbalances as shown in Fig. 10.

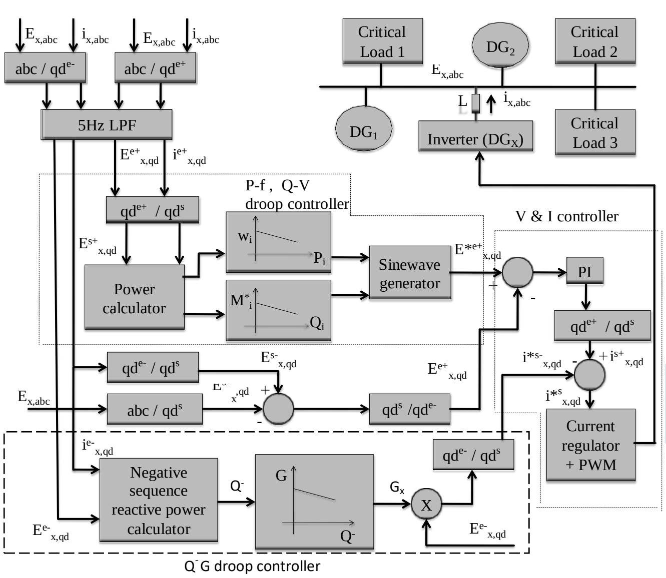


Fig. 10: Imbalance compensation using Q-G droop

In reference [36], a controller was proposed which adjusts the output voltage bandwidth to share non-linear loads. A controller which produces a droop in every harmonic voltage for corresponding harmonic current was discussed in [37]. This controller shows a slow dynamic response since it requires low-pass filters with reduced bandwidth for average power calculations. In [8], a controller was proposed which improves the dynamic performance of the system by adding integro-differential power terms in droop control. In [38], a decentralized control was implemented with resistive output impedance which makes the inverters share harmonic currents and allow good power sharing with very low sensitivity to impedance imbalances. It also minimises the circulating currents among the modules.

Frequency deviations and voltage deviations in a microgrid are dependent on each other and they can make the micro-grid to enter into unstable region even though the capacity of DG is more than demand. Therefore, loads voltage and frequency dependence should be considered while designing droop control method and impact of load on frequency and voltage deviations was discussed in n [39] .

When there is a short circuit happening at the inverter terminals, large magnitude currents will flow and they damage the system. In [27], a method for parallel operation of inverters is explained which has superior behaviour in terms of short circuit protection, voltage harmonics. Instead of controlling active and reactive power, it is advantageous to control active and reactive current in terms of short circuit protection.

Decentralized control doesn't guarantee the overall optimal performance. In [40], a hierarchical control method was proposed which has certain degree of decentralization and centralization which controls the lower levels as shown in Fig. 11. This Control method is composed of three individual controls *viz.*, primary, secondary and tertiary. Primary control corresponds to control of P and Q, regulation of frequency and voltage. Secondary control restores the frequency and voltage to nominal values after a demand change whereas tertiary control regulate the import and exports of the power flow as per economics [50]. Detailed structure of hierarchical control method is shown in Fig. 12.

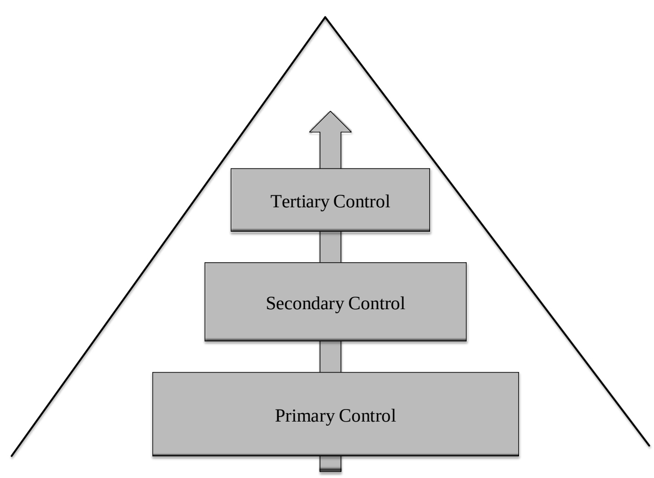


Fig. 11: Structure of multilevel control scheme

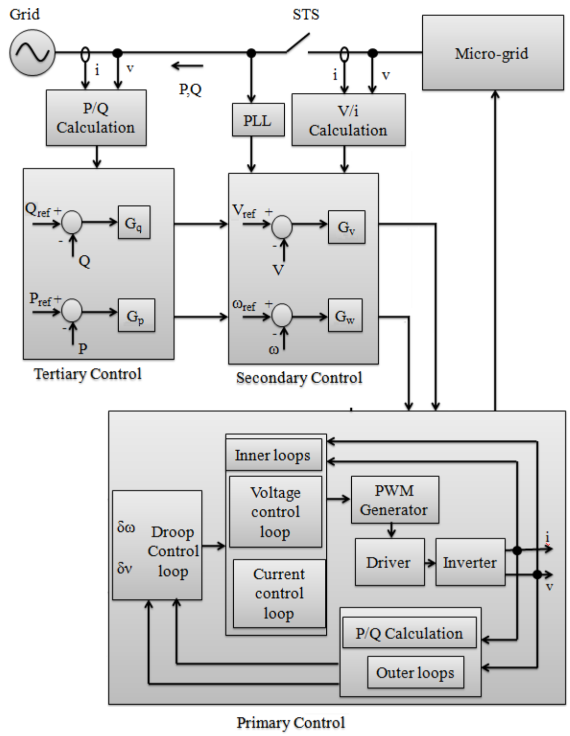


Fig. 12: Hierarchical control method

In [41], a control strategy which works along with P/V droop control was developed which controls the grid rms voltage's set value as a function of dc link voltage. This control avoids the frequent changes of the power which is delivered. It is a decentralized method which is beneficial in terms of transient stability and reliable issues. In [28], [42], P/V droop control is developed for VSI's working in parallel.

In [43] a Universal Inverter working was explained which works in both modes of operation i.e., grid connected mode and stand alone mode. It is applicable to both high voltage grids and low voltage grids by utilizing the orthogonal matrix which converts the the active and reactive power of direct droop method into indirect droop method. In [13] a generic method for modelling of a islanded droop controlled multi inverter system is proposed.

Energy storage systems in a microgrid plays a key role in maintaining the quality and reliability of supply. They are connected to the grid through power electronic converters just like a micro-source and they give or absorb power as per the requirement. When the microgrid is in grid connected mode, they import power and they export power to the network during islanded mode thereby improving the quality, dynamic performance and stability of the system [44].

The process of disconnecting loads as per priority to ensure the safe working of the system is called *load shedding*. When the microgrid is in grid connected mode, power absorbed or delivered by the main grid is the difference of DG and demand. When the microgrid is isolated due to any outage or economic reason, load demand is to be supplied by the

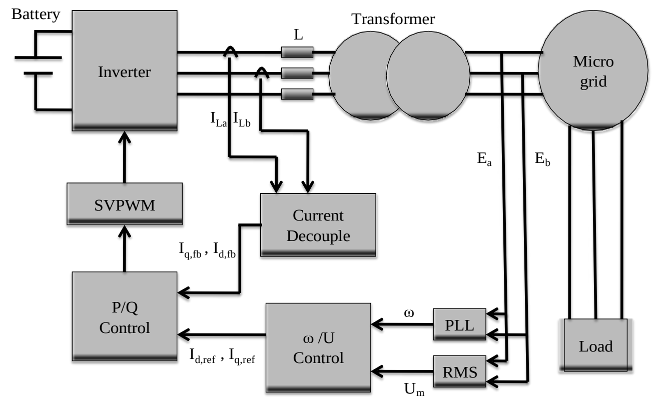


Fig. 13: Energy storage system in microgrid

DG. Power difference in this condition decides the voltage and frequency fall from their nominal values. This fall in voltage and frequency is used to detect whether the microgrid is in islanding mode or grid connected mode. Thus automatic load shedding is to be provided to maintain stability, voltage and frequency regulations as the demand is not constant all the times [9].

Distribution generation has become a new kind of business practice. Many industries are generating and selling the excess energy to grid. Microgrids acts as agents in the market under a Market Operator (MO), Distribution Network Operator (DNO) and there exists an optimal deal after negotiation between the generating agents and load agents [51]. Generating agents individually set their tariff at which they want to sell the energy and load agents always has a choice to select the least tariff charging agent as shown in Fig. 14, Fig. 15.

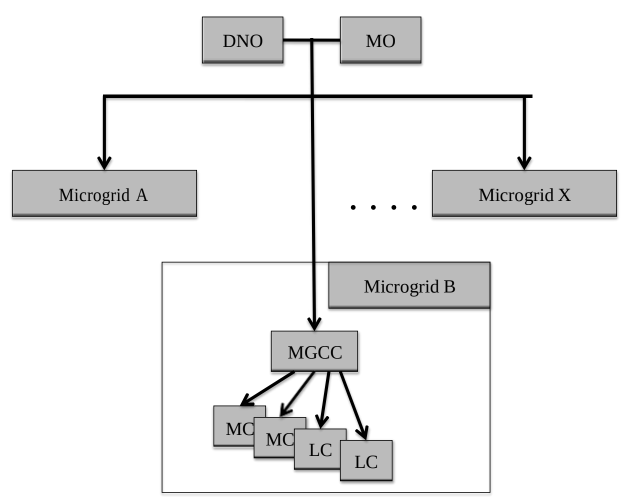


Fig. 14: Control levels in MAS based microgrid

This is done by *multi-agent system* which does a continuous monitoring of power requirements and optimal decision making of energy trade. It decides whether the microgrid should consume power from an agent or not. Smart-grids are developed for giving safe, controllable, economical and pollution free energy and microgrid is a component of it. Microgrids utilising the intelligent electronic devices for controlling and protection was explained in [46].

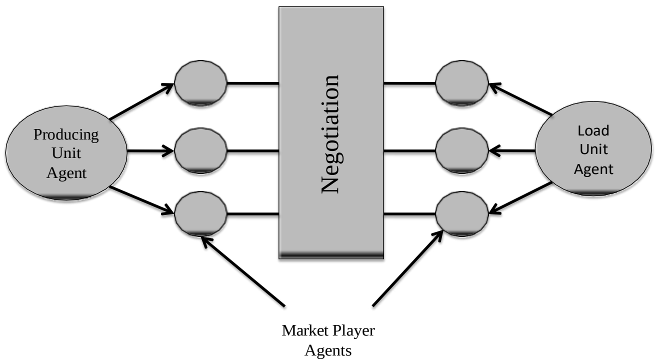


Fig. 15: Negotiation between market player agents

Communication greatly influence the reliability and stability of a microgrid. Information such as voltage, power etc., is to be passed with high speeds so as to run the system in real-time and necessary control actions. Therefore, a proper communication protocol is to be used such as *EtherCAT* which is capable of transferring the information in micro seconds [45].

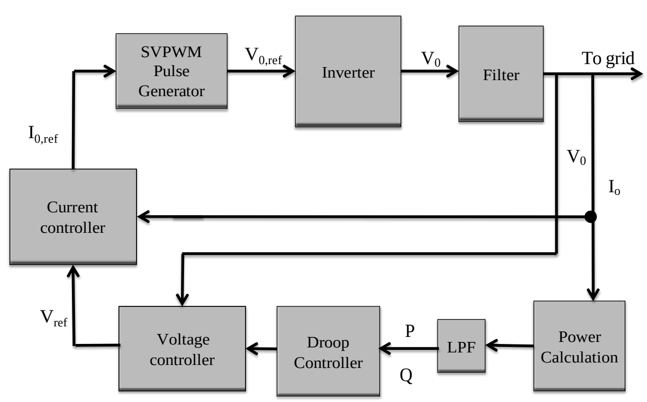


Fig. 16: control schematic showing inner and outer loops

A dual loop control schematic is shown in Fig. 16. Power calculation, LPF and droop controller forms the outer loop whereas, voltage controller and current controller forms the inner loop. P and Q are calculated using voltage and current through the inverter output and are sent to droop controller through a *low-pass filter*. Based on the droop characteristics, droop controller issues a command to a voltage controller where the voltage is compared and it in-turn issues a output current reference to the current controller. Both the voltage controller and current controller consists of PI controllers and feed forward paths with decoupling. Current controller issues output voltage reference to *SVPWM pulse generator*. According to the reference voltage, pulse generator generates switching pulses and required reference voltage is produced at the output. Here, the current controller protects the inverter from over currents. Droop control concept is developed based on the steady state inertia. The calculated power values consist of both fundamental and higher order harmonics. These harmonics are eliminated before entering the droop controller using a low-pass filter. The problem with the low-pass filter is the bandwidth required for it is of the order of $2Hz$ which is very low. Bandwidths of voltage controller and current controller are around $600Hz$ and $1.5kHz$. Comparatively, rise time required by low-pass filter for its operation is very high and this slow responding filter degrades the dynamic performance of the entire control structure. To improve the dynamic performance of the system, an adaptive droop controller was explained in [47].

VI. Conclusion

In this paper, details about the necessity, objectives, features, modes of operation and control aspects of a microgrid were discussed. Upcoming research will be in the areas of development of control methods which consider the intermittent nature of DG sources, load imbalance emulation and efficient design of controllers improving the stability and dynamic performance of the system.

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