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Modeling and control of microgrid: An overview

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Abstract

A microgrid (MG) is a building block of future smart grid, it can be defined as a network of low voltage power generating units, storage devices and loads. System of systems (SoS) is another concept involving large scale integration of various systems. In this paper, we provide an overview of recent developments in modeling and control methods of microgrid as well as presenting the reason towards incorporating MG into the existing grid. Various SoS control strategies when applied to MG are discussed.

1. Introduction

The burden on the transmission network is increasing at an unexpected pace due to the increasing demand of power. Since updates to the transmission network are economically challenging, micrograds have evolved to become an economically viable alternative. In microgrids, generating units are commissioned within the scope of the conventional distribution network so that power can directly flow from the generators to the load without having to pass through the transmission network. The other advantage of using such an architecture is that loads can be served even if the transmission network is down due to a fault, increasing the overall reliability of the system. A Microgrid is generally known as the system consisting of small distributed generating stations along with the loads which is capable of going into islanded operation at times of need [1].

Among the many benefits of having a microgrid, one is that it facilitates distributed generation (DG) and high penetration of renewable energy sources [2–4]. They increase power quality and

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reliability of electric supply. A microgrid having renewable energy sources will help to alleviate some of the environmental issues related to burning fossil fuels. There is an extensive literature on the various challenges posed by microgrids. Despite having some benefits of microgrid architecture in the grid environment, there are some challenges related to this also. Implementation is an issue. Microgrid protection is also considered one of the most important challenges facing the implementation of microgrids. Once a microgrid is formed, it is important to assure that the loads, lines, and DGs on the island are protected because conventional unidirectional power flow protection method is no longer viable [5]. Solid regulatory base is another issue related to microgrids. It is known that energy related industries established policies and 'solid regulatory base' in place which became important for the growth in market. Government organizations should ensure that these regulatory policies should include guidelines and schemes to implement microgrid technologies

Control of the voltage and frequency during islanded operation of DGs is also a major challenge. A method for intentionally islanding a single DG to feed a local load was proposed in [6]. A much more complex and challenging task is to operate more than one DG on the island. With more than one DG on the island, it is necessary to regulate the voltage during microgrid operation, which could be achieved by using a voltage versus reactive power droop controller [7]. There needs to be an algorithm that should complete the resynchronization process once the grid is restored. A supervisory control mechanism will monitor the overall process and provide information to the local controller to respond accordingly.

The concept of power grid is based on the technology introduced around 120 years ago. It is facing lot of issues in keeping up with modern challenges. One of the main challenges is to guarantee electricity supply to customers and maintaining long-term energy security. Therefore increased reliability/efficiency is very much needed in today's world where the demand of electricity is ever-growing. Microgrids (MG) incorporate various distributed generator (DG) units into the utility grid and solve many problems of existing power systems. It is also the vital building block of the future Smart Grid [7].

On another front, the concept of system of systems (SoS) is gaining rapid interest in the field of research and can also possibly lead to a new branch of engineering known as SoS Engineering. This branch is related to systems engineering and deals with the optimization of a network of interacting systems. Any large scale integrated system or any complex system can be viewed as an example of SoS [8,9]. A microgrid can be viewed as a system of system (SoS).

In this paper, motivation towards development of MG and an overview will be presented on the two key aspects, modeling and control, of MG. Recent developments in these two key aspects will be presented. A better control strategy, by viewing MG as a special case of SoS, will be discussed.

2. Distributed generation: applications and issues

The existing grid has small number of producers, long distribution ways and high maintenance cost, it is also difficult to achieve load balancing. Moreover, the depleting fossil fuels and the adverse effect on environment by its consumption have gain multi-national interest in reducing the excess use of nonrenewable energy resources and many nations are keeping tap on CO_2 emissions [10].

The main concerns with the existing centralized power system grid are summarized below [11]:

- Increasing demand and lack of high reliability.
- No scope of expansion on power system expansion.
- Limitations of centralized power system planning.

- Risks of volatile bulk power markets.
- Security threats.
- Limited power quality.
- Environmental effect (release of CO_2, nuclear waste etc.)

All the above issues urges the need to incorporate Distributed Generating (DG) units into the existing power systems [12]. The concept of DG is of early 1990s, it has multiple advantages for both source and consumers [13]. In the literature, there exists various definitions of DG which are summarized in [14]. DG is defined as, "*Generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in the power system*" [15].

DG units are the emerging micro-generating technologies such as microturbines, fuel cells, internal combustion (IC) engines. It also makes use of renewable energy sources such as photo voltaic (PV) arrays and wind turbines. The DG units have low emission rates, environment friendly and are economical. The introduction of DG units should reduce the pressure on central power grid principally but in technically speaking, penetration of distributed generation into the power grid creates a new class of issues different from those found in traditional power sources. Random applications of DG units will cause as many issues as it may solve [16]. Some of the problems are discussed below:

- First of all, DG units operate close to the distribution voltage level of 480 V as it is geographically located near the loads and provides a DC or variable frequency AC output and hence require power electronic devices in order to interface with the power-grid/load. The power electronic interface leads to development of new control strategies [17].
- The output of renewable energy systems fluctuates with conditions of weather which is also a debatable issue when DG units are connected to power grid [18].
- The existing power grid follows a multi-level flow of power from transmission to distribution network, any change in power flow causes problems because DG units behavior is different than a conventional load [10].
- Finally, the initial energy balance for a new load is taken care by the power stored in the generator inertia and the micro generating units are inertia less. This lack of inertia is the major problem leading to power imbalances between the generation and load. There are also number of barriers in the form of technical, business and regulatory issues when it comes to connecting DG's to electrical grid [17].

To overcome these issues and to utilize the potential of distributed generation, the concept of MicroGrid was introduced in [17]. Using power electronic devices in addition with *Distributed Energy Resources* (DER), integration of DG into the utility grid is possible. Power electronic devices improve the flexibility and adaptability of the system by converting the power from source to a fixed frequency AC power. They also provide various ancillary services to the grid [19,20].

3. Microgrid: definition and applications

A microgrid can be defined as, '*A network of low voltage power generating units, storage devices and loads capable of supplying a local area such as suburban area, an industry or any commercial area with electric power and heat*'. The components of Microgrid are interfaced through quick response power electronics and present itself as a single entity and therefore can be connected to traditional power grid or can also be operated in stand-alone mode as a self-sustained power system [7].

As stated in [17], "*The heart of the microgrid concept is the notion of a flexible, yet controllable interface between the microgrid and the wider power system.*". Microgrid acts as a *Good Citizen*, that is, ideal conventional load behavior towards the grid which is less troublesome than distributed generation system. It also has environmental benefits because it uses renewable energy sources.

Different countries around the world adopt various topologies and structure based on their priorities on functionality offered by microgrid. The research on microgrid is more active in US, Canada, Europe and Japan. Several demonstration projects and laboratory facilities are developed and a lot of research is in progress concerning various issues in the microgrid [21,22]. Various objectives which can be achieved by the use of microgrid are listed below, ride through capability provided by energy-storage is a common objective of microgrid:

- Reliability of power supply.
- Reduction of environmental impact of electric supply.
- Reduction of investment in plant, equipment and cost.
- Increase of energy efficiency stable.
- Ensure diversity of energy supply.
- Power supply to a remote site.
- Ride-through capability provided by energy storage.

The future *smart grid* is expected to be a well organized plug-and-play integration of microgrids connected via dedicated highways for exchange of command, data and power. The emerging standards, research, development and demonstration are also discussed in [23].

4. Microgrid: components and formation

A generalized structure of microgrid is shown in Fig. 1. The microgrid can be connected to the utility grid through single Point of Common Coupling (PCC). The isolating device is used to isolate the microgrid from the utility grid.

The Distribution Generation (DG) unit is responsible for generation of electricity. It consists of rotating type and inverter type generating devices. Rotating type includes IC engines, gas turbines, microalternator etc. whereas the inverter type includes photovoltaic, fuel cells and wind turbines, etc. Both rotating and inverter type requires power electronic converters for their interface. The power range of DG unit components is small-scale ranging from 4 KW to 10,000 KW [11].

Energy storage unit is essential to balance the flow of power at the onset of islanding mode of operation. It is also used to control the flow of power to and from the main grid. They help in improving the quality of power and assist in voltage control. Batteries, flywheels, super-capacitors, superconducting magnetic energy storage, etc. can be used to store the energy. All these devices again require power electronic devices for their interface [11].

There has to be a *control system* for the safe operation of microgrid in various modes of its operation. This system can be based on a central controller or distributed controller. The selection of controller depends mainly on the operation mode of microgrid and its requirements [24]. Various control strategies will be discussed in this paper in other sections.

The purpose of microgrid is not obtained until the customer is served with nominal voltage and frequency by a stable system during all the modes of operation [24].

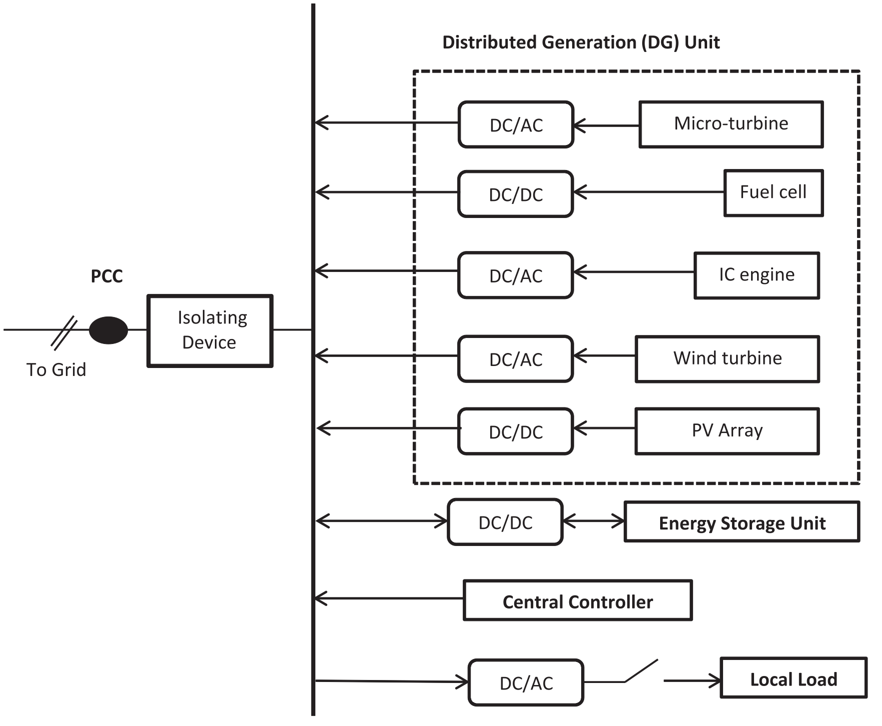

Fig. 1. Generalized microgrid structure.

5. MG: modes of operation

Microgrid can operate autonomously and can also be connected to the utility/main grid. In case any fault occurs while operating in grid connected mode, microgrid has an ability to disconnect itself from grid and operate independently supplying its local load [25]. Therefore, the microgrid modes of operation can be classified into grid connected, islanded, transition between grid-connected mode to the islanded mode and vice-versa [26]. In any mode of operation, the heat generated by some of the micro-sources can be used to supply the heat demand of the local load.

When functioning in parallel with the utility (main) grid, it acts as a model or good citizen and the voltage and frequency are controlled by main grid. Depending on the load of the main grid, it will either supply or absorb power and act as either controllable load or controllable source. If any fault or disturbance occurs in the main grid, microgrid has an ability to disconnect and operate autonomously. This ability of microgrid increases the quality of power to its local customer by providing local voltage control. In this mode of operation, the points to be noted are:

- The frequency and voltage magnitude are controlled by utility grid.
- DG units supply the total or a part of the load.

Islanding of microgrid can be due to unplanned faulty events discussed in [26] and can also be due to planned actions like maintenance, etc. The microgrid controls the voltage and frequency in autonomous mode by continuously adjusting the output active and reactive power. This is a very common mode of operation. In this mode, it supplies a local load which is closely located geographically. The local load can be a small village, a university, an industry or a commercial building, etc. The main issue which the microgrid should address in this mode is the management of voltage and frequency, Quality of Power (QoP), balancing between load and supply, communication among its components, etc. In this mode of operation, the points to be noted are:

- The DG units control the frequency and voltage magnitude.
- It supplies active and reactive power to the load.

6. Microgrid: overview of modeling

A microgrid integration of various units. Basically, it consists of DG unit, energy-storage unit, controller unit and conventional load. The DG unit again compromises of various micro-generating devices. Therefore, microgrid modeling varies from one configuration to other depending on the components used. Various approaches for the modeling and control of microgrid can be found in the literature [27]. We will discuss the different models available in the literature.

A small signal dynamic analysis of an autonomous hybrid system is performed in [28]. The configuration of the system is shown in Fig. 2.

The dynamics of all the DG units are approximated by a first order linear model with a time constant and a gain factor while the network is neglected [28,29]. The transfer functions of various components are obtained and time domain analysis is performed by considering various components at each time. The transfer functions of various components are given as follows and Fig. 3 shows the configuration in one of the cases:

$$\text{Wind turbine}: \; G_{WTG}(s) = \frac{K_{WTG}}{1 + sT_{WTG}}$$

$$\text{PV system}: \; \frac{K_{PV}}{1 + sT_{PV}}$$

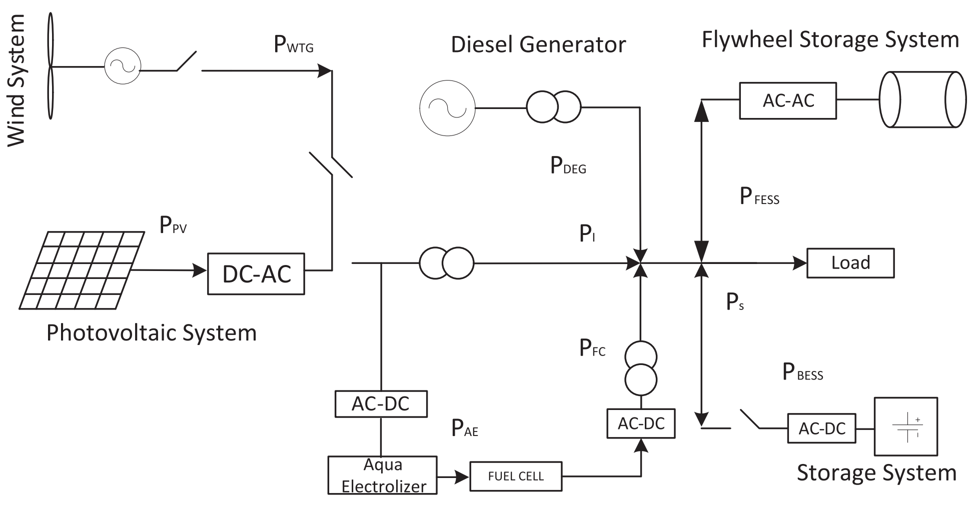

Fig. 2. Configuration of a microgrid system [28].

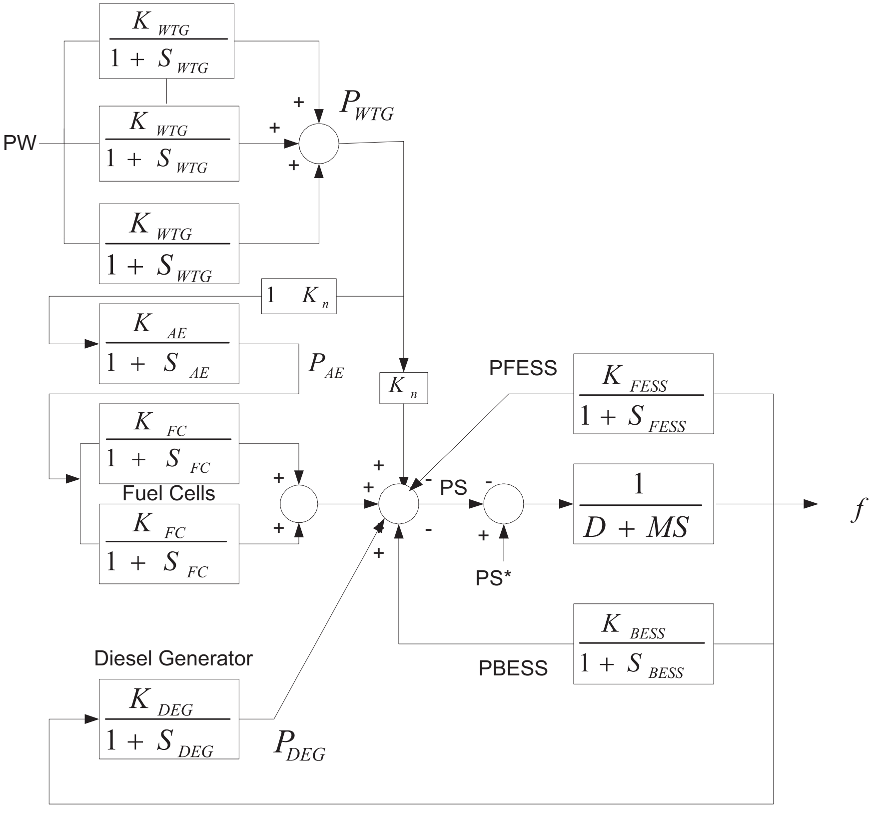

Fig. 3. Block diagram of a microgrid.

$$\text{Fuel cell}: \frac{K_{FC}}{1+sT_{FC}}$$

$$\text{Diesel engine generator}: \frac{K_{DEG}}{1+sT_{DEG}}$$

$$\text{Aqua electrolyser}: \frac{K_{AE}}{1+sT_{AE}}$$

$$\text{Storage system}: \frac{K_{sto}}{1+sT_{sto}}$$

Since a MG is a power generating unit, it can be represented by a DC source. This concept of modeling a MG with an RLC load in islanded mode is proposed in [30,31]. As shown in Fig. 4, MG is represented by a DC source connected to a voltage-sourced converter (VSC). The MG is connected to the grid by means of a *R–L* filter, step-up transformer and a circuit breaker. The circuit breaker is open when the MG is islanded. The load which is passive RLC type is connected on the high voltage side of the transformer. A control system is used to control the VSC.

The dynamic model of Fig. 4 is represented by the following nonlinear equations:

$$\frac{di_{td}}{dt} = \omega i_{tq} - \frac{R_t}{L_t} i_{td} - \frac{v_d}{L_t} + \frac{v_t d}{L_t}$$

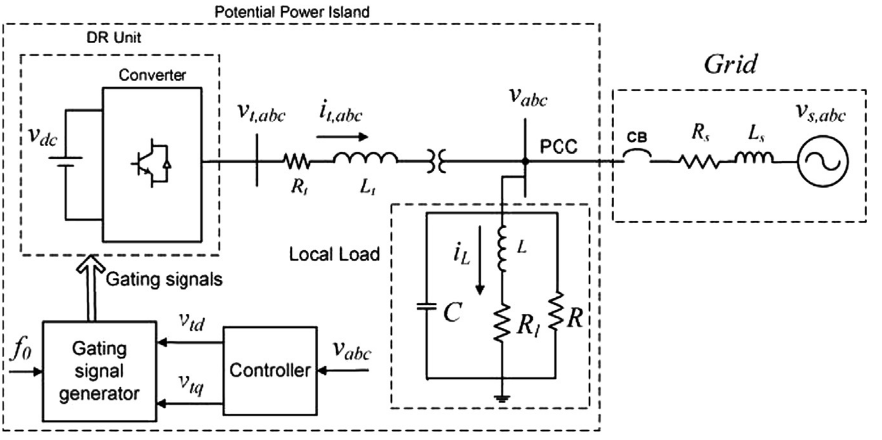

Fig. 4. Model of MG in [30,32,33].

$$\frac{dv_d}{dt} = \frac{1}{C} i_{td} - \frac{1}{RC} v_d - \frac{i_L d}{C}$$
$$\frac{i_L d}{dt} = \omega i_{Lq} + \frac{v_q}{L} - \frac{R_l}{L} i_{Ld}$$
$$\frac{i_t q}{dt} = -\omega i_{td} - \frac{R_t}{L_t} i_{tq} + \frac{v_{tq}}{L_t}$$
$$\frac{i_L q}{dt} = -\omega i_{Ld} - \frac{R_l}{L} i_{Lq}$$
$$\omega C v_d = i_{tq} - i_{Lq}$$

After performing the linearization, whose details can be seen in [30,32,33], the state space matrices are obtained as mentioned below. The overall test system was simulated in the *Matlab Simulink* and *ATPDraw* environment:

$$A = \begin{bmatrix} -\frac{R_t}{L_t} & \omega_0 & 0 & -\frac{1}{L_t} \\ \omega_0 & -\frac{R_l}{L} & -2\omega_0 & \frac{R_l C \omega_0}{L} - \frac{\omega_0}{R} \\ 0 & \omega_0 & -\frac{R_l}{L} & \frac{1}{L} - \omega_0^2 C \\ \frac{1}{C} & 0 & -\frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$
$$B^T = \begin{bmatrix} \frac{1}{L_t} & 0 & 0 & 0 \end{bmatrix}, \quad C = [0 \ 0 \ 0 \ 1]$$
$$X^T = [i_{td} \ i_{tq} \ i_{Ld} \ v_d]$$

This concept of representing MG as a combination of DC source with VSC is also presented in [34,35]. This paper models the islanded operation of MG consisting of two parallel DG units. Again the local load is a passive RLC network located at the PCC. The schematic diagram of such an arrangement is shown in Fig. 5. The MG structure is used for the application of decentralized control and hence there is a separate controller for each DG unit.

By applying KVL and KCL and further application of frame transformation gives the below dynamic equations governing the MG:

$$\frac{dV_{dq}}{dt} = -\frac{1}{RC} V_{dq} - \frac{1}{C} i_{t,dq1} - \frac{1}{C} I_{L,dq} + \frac{1}{C} I_{t,dq2}$$

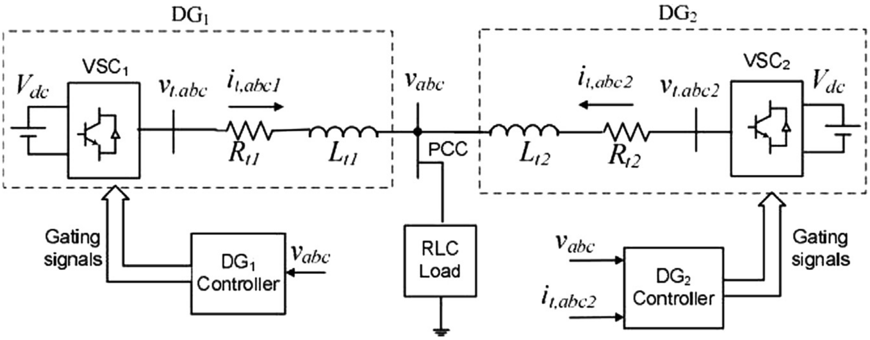

Fig. 5. Radial configuration of DG's used in [34].

$$
\begin{aligned}
&\frac{I_{t,dq1}}{dt}+j\omega_0 I_{t,dq1}=-\frac{1}{L_{t1}}V_{dq}-\frac{R_{t1}}{L_{t1}}I_{t,dq1}+\frac{1}{L_{t1}}V_{t,dq1}\\
&\frac{I_{L,dq}}{dt}+j\omega_0 I_{L,dq}=\frac{1}{L}V_{dq}-\frac{R_l}{L}i_{L,dq}\\
&\frac{i_{t,dq2}}{dt}+j\omega_0 I_{t,dq2}=-\frac{1}{L_{t2}}-\frac{R_t2}{L_t2}i_{t,dq2}+\frac{1}{L_t2}v_{t,dq2}
\end{aligned}
$$

The model is then represented in state space which is simulated using *Matlab SimPowerSystems* toolbox [34].

A microgrid consisting of only inverter based DG's is modeled in [36,37]. Typical structure of such microgrid is shown in Fig. 6. The modeling approach considered the full dynamic model of the complete network rather than algebraic equations.

The approach of modeling was divided in to three modules namely inverter, network and loads. The inverter model compromises of dynamics of controller, output filter and coupling inductor. The state equations of network and load are represented on one of the inverters reference frame which is assumed to be common reference. Then using the transformation technique [38], all the other inverters are transformed to this common frame. Each sub-module is modeled in state-space form and combined together on this common reference frame. Block diagram of state space model of the MG is shown in Fig. 7.

By combining individual sub-modules, the overall state-space model of MG is given below. The subscript represents states of inverter, network and load. Detailed derivation and information on the state-space matrices can be found in [36]:

$$
\begin{bmatrix}\Delta\dot{x}_{Inv}\\ \Delta\dot{i}_{networkdq}\\ \Delta\dot{i}_{loaddq}\end{bmatrix}=A_{mg}\begin{bmatrix}\Delta x_{Inv}\\ \Delta i_{networkdq}\\ \Delta i_{loaddq}\end{bmatrix} \tag{1}
$$

A small signal dynamic model of MG which includes synchronous generator based DG and power electronically interfaced DG is presented in [39]. Fig. 8 shows the single line diagram of the MG. DG1 is a synchronous machine (diesel or gas-turbine generator) with excitation and governor control system whereas DG2 is a dis-patchable source (micro-turbine or wind generator, etc) equipped with a Voltage-Source Converter (VSC). The system parameters are given in [26]

To obtain the linearized mathematical model of the above system the following steps are followed:

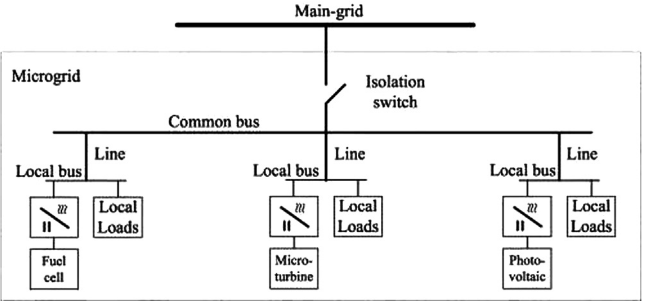

Fig. 6. Inverter based MG structure in [36].

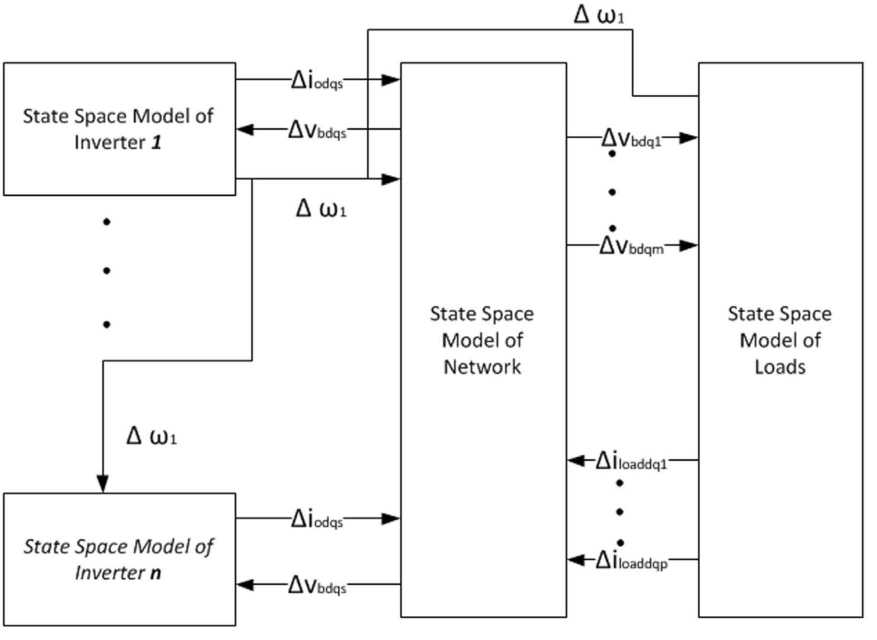

Fig. 7. State-space model of MG in [36].

- The ordinary differential equations (ODE) of DG units including network components are developed in their respective local *dq0* reference frames.
- The obtained equations are transformed to the global *dq0* frame of MG.
- Linearized about a nominal operating point and arranged in the state space form.

The dynamic model of DG1 in its local reference *dq0* frame is obtained from [40] and the dynamic model of DG2 can be found in [41,42]. The electrical network modeling is carried out on the basis outlined in [43] and can be found in [42]. The overall system model is represented by the block diagram in Fig. 9. The small signal model was validated in the *PSCAD/EMTDC* environment.

The same MG structure is taken into account in [26] and the stability analysis for various transient conditions such as energizing load, transition from grid-connected mode to islanded

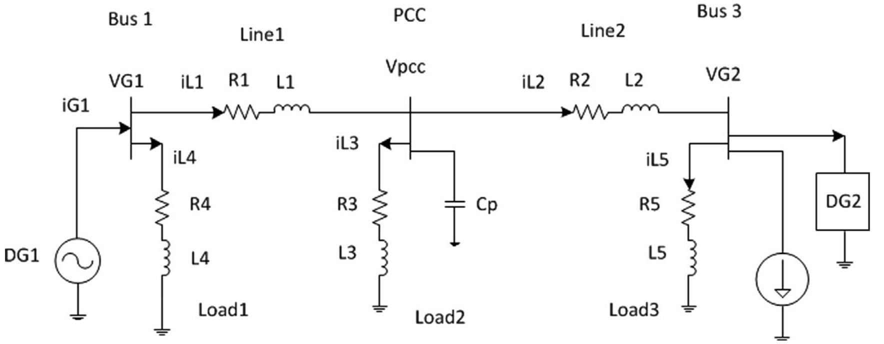

Fig. 8. Small signal of synchronous generator model [39].

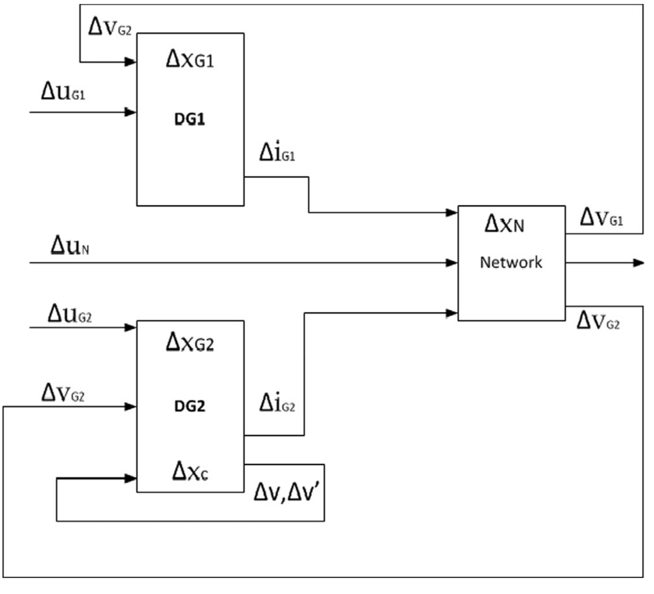

Fig. 9. Block diagram of MG model [39].

mode and vice-versa is performed. An operational architecture developed within EU R&D microgrids projects [44,45] is adopted in [46]. This concept is shown in Fig. 10. It is a multi-level type control and management scheme supported by a communication infrastructure.

The head of this multi-level control system is MicroGrid central controller (MGCC) installed at the MV/LV substation and centrally controls the MG. Load controllers (LC) and microsource controller (MC) form the second level of Hierarchy and exchange information with the MGCC. LC acts as an interface to controllable loads and MC controls the active and reactive power of each microsource. Both LC and MC receive their set-points from MGCC.

The dynamic modeling of each DG components was picked from different literature. The dynamic model of solid oxide fuel-cell (SOFC) is described in detail with the values of each parameters in [47,48]. A gas turbine (GAST) was used for the primary unit of microturbine. The dynamic model of GAST is adopted from [47]. A fifth-order induction generator was connected

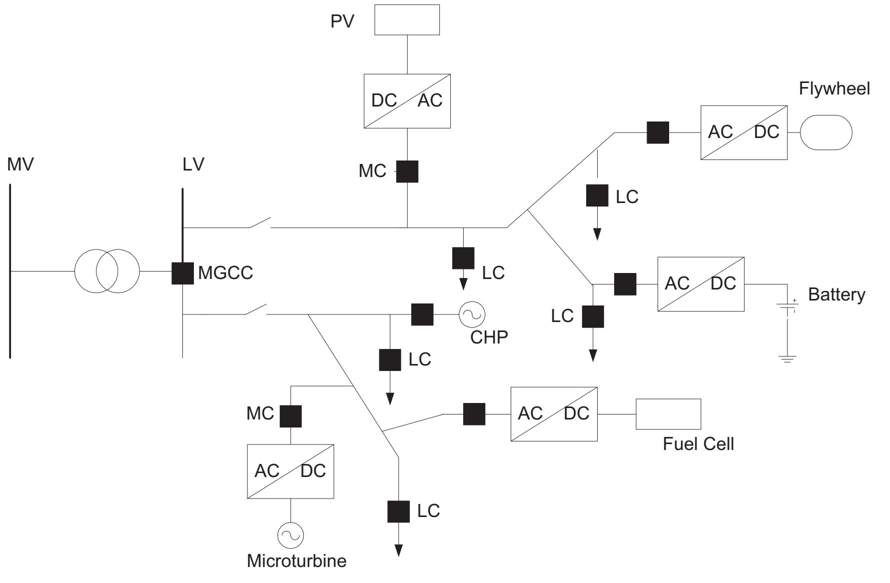

Fig. 10. MG structure in [46].

directly to the network serves as a wind generator. This model was available in *Matlab Simulink* toolboxes. An empirical model for the PV generator based on experimental results was adopted from [49].

Flywheels and batteries are used for the modelling of storage devices. They were modeled as a constant dc voltage sources and were coupled to the electrical network using power electronic interface.

The inverter modelling can be derived as per two control strategies, PQ inverter control modeling [50] and Voltage Source Inverter Control (VSI) model [51,52]. Inverters are modeled based only on their control functions for the purpose of analyzing the dynamic behavior of MG [26,53–56]. Two types of loads were considered, one is constant impedance load and other is motor load.

An LV test network was built in *Matlab/Simulink SimPowerSystems* environment. The implementation of this network is shown in Fig. 11 whose detailed description can be found in [57] and [58].

A low voltage MG with three unbalanced phases was proposed in [59], Fig. 12 shows the *Matlab Simulink* implementation of the structure used. Inverters droop controls were used to interface DG's and loads were modeled as constant power. Simulations were carried out for both grid connected and isolated modes. This model has an advantage of modeling small unbalanced networks but lacks the analytic details required for stability analysis.

A new method to form the system matrices of large MG's in islanded mode is discussed in [60]. The MG under consideration has DG's power electronically interfaced and hence the dynamics are similar to that shown in [36]. There were two types of DG's, one was *PQ* regulated and other was *Vf* regulated which are introduced in [39].

The proposed modeling approach is based on four defined complex vectors. These vectors allow for complex-valued system matrices to be formed in a quite automated way. Moreover, a convenient partition of the system matrices is proposed, which in turn allows fast and easy

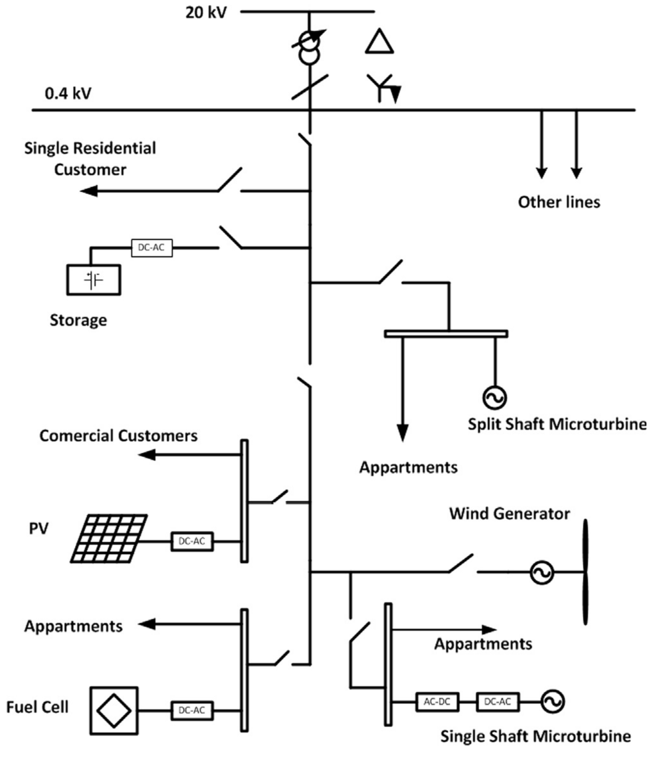

Fig. 11. Implementation of MG on LV network.

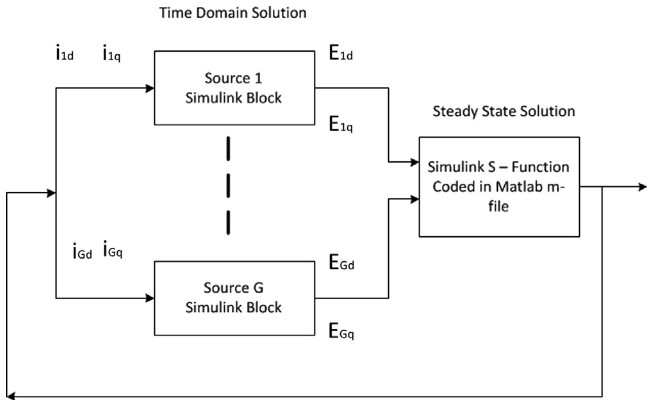

Fig. 12. MG network and *Matlab/Simulink* structure used in [59].

modifications. Additionally, a multivariable methodology is proposed to simultaneously determine the control system gains in an optimal sense.

An alternative approach is based on the "hub model" for microgrids [61] in which the couplings between an integrated electricity and natural gas system to yield optimal operation are modeled by energy hubs. It turns out that this concept serves as an interface between the loads and the transmission infrastructures and supports the application of distributed control schemes.

Similarly, hybrid modeling control techniques are applied to a two generator power system connected to the grid and the plant consists of a solar field and a secondary power source formed by an electrolyzer, hydrogen tank and fuel cell stack. It is shown that the system has essentially hybrid dynamics, as it can operate in four distinct modes, depending on the power circuit configuration and the fuel cell stack state [62]. With focus on bulk power flow of microgrids, research investigations are reported in [63,64] in which an optimal design of an electrical microgrid and sizing of its components is sought to balance capital investment with expected operational cost while meeting performance requirements. In [65], a comprehensive review on current control technology is presented with emphasis on challenges of microgrid controls. The impact of frequency and voltage regulation on the optimal design of an autonomous military microgrid comprised of a solar panel and vehicles as power sources, with each vehicle incorporating a battery and generator, is developed in [66,67].

7. Microgrid – overview of control

The control strategies for microgrid depends on the mode of its operation. The aim of the control technique should be to stabilize the operation of microgrid. When designing a controller, operation mode of MG plays a vital role. Therefore, after modelling the key aspect of the microgrid is control. In this section we will discuss the various control paradigms.

7.1. Microgrid control: grid-connected mode

In grid connected mode, microgrid acts as a controllable load/source. It should not actively regulate the voltage at the point of common coupling (PCC). Its main function is to satisfy its load requirements with good citizen behavior towards main grid. The balance between generation and demand, control of the parameters of the system is taken care by the utility grid. The voltage and frequency reference of the microgrid is also set by the main grid. Therefore the main task of a DG unit is to control the output real power (P) and reactive power (Q) [68,69]. The P, Q generated by a DG can be controlled either by current-based or by voltage-based power flow control [70].

7.2. Power flow control by current regulation

The control scheme for *power flow control through current regulation* is illustrated in Fig. 13. It is desired to control both the real and reactive powers. The real power control loop is used to obtain the synchronous frame d-axis reference current and reactive power control loop is used to obtain the q-axis current. The synchronous $d-q$ frame current can then be controlled in a closed loop manner [69].

7.3. Power flow control by voltage regulation

The other method to control the power flow is based on the output voltage of DG. Therefore it is know as *power flow control through voltage regulation*. It can be shown that real power (P) flow is proportional to the voltage phase angle (δ) and reactive power (Q) flow is proportional to voltage difference ($V_l - V_g$), where V_l is DG voltage and V_g is PCC voltage and δ is the phase angle difference between these two voltages. Therefore the flow of P can be regulated using δ and flow of Q can be regulated using $V_l - V_g$. This scheme is illustrated in Fig. 14. To improve

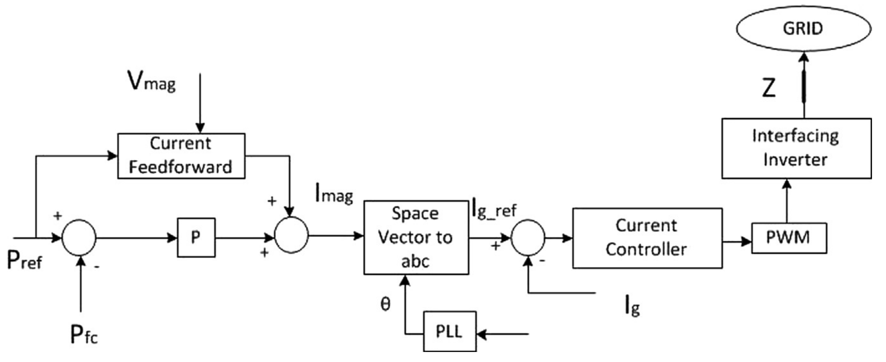

Fig. 13. PQ power control through output current regulation [70].

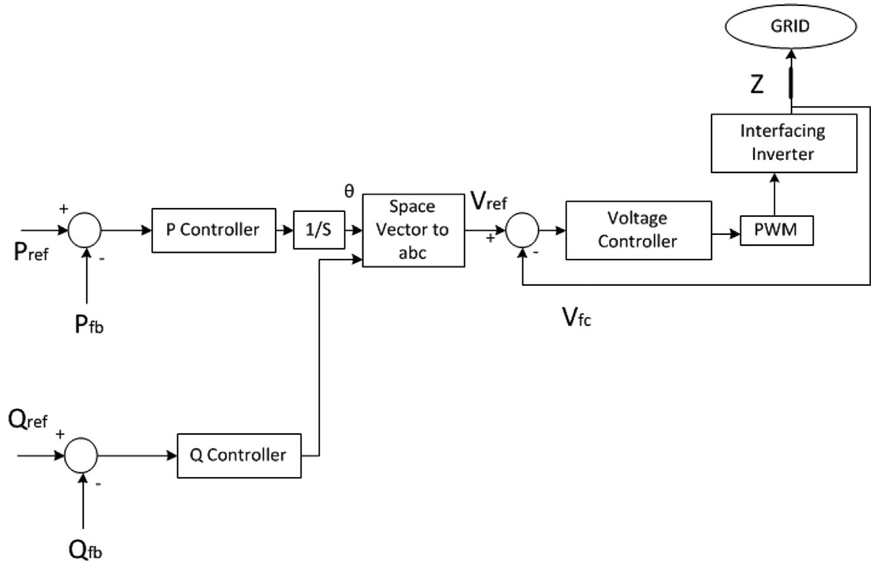

Fig. 14. PQ power control through output voltage regulation [70].

the accuracy of reactive power control, integral control can be included into the reactive power controller [68,71,72].

Power control through voltage regulation is more sensitive than current regulation to the line impedance between the DG and the PCC.

7.4. Agent based control

Microgrid management system was developed using agent based technology in [73]. Microgrid agents were developed on JADE (Java Agent Development Framework). The proposed system has several functionalities like SCADA system, selling bids managing system, load shifting system, etc. The software architecture of the management system is shown in Fig. 15.

Microgrid agent platform consists of following components:

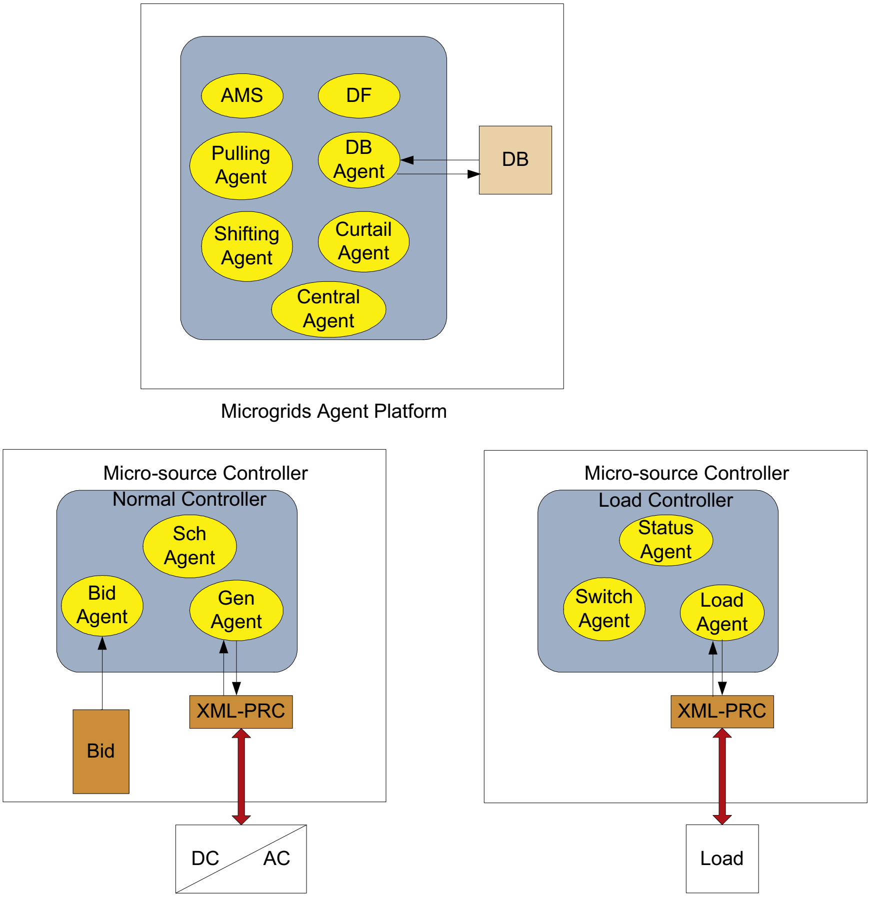

Fig. 15. Architecture of management system.

(1) Microgrid central controller (MGCC): It includes pulling agent, database agent, control agent, shifting agent and curtailment agent.
(2) Microsource controller: it includes generator agent, schedule agent and bid agent.
(3) Load controller: it includes load agent, status agent and switch agent.

The effectiveness and applicability of the introduced software have been evaluated on a laboratory environment.

7.5. MAS based distributed control

A distributed control approach based on Multi Agent System (MAS) for microgrids is proposed in [74], where advantages of MAS technology is utilized for controlling microgrids. As shown in Fig. 16, a fully decentralized approach is adopted with 3 distinguished control level.

Distribution Network Operator (DNO) and Market Operator (MO) are at medium voltage level and do not belong to microgrid. DNO refers to the operational functions of the system and is

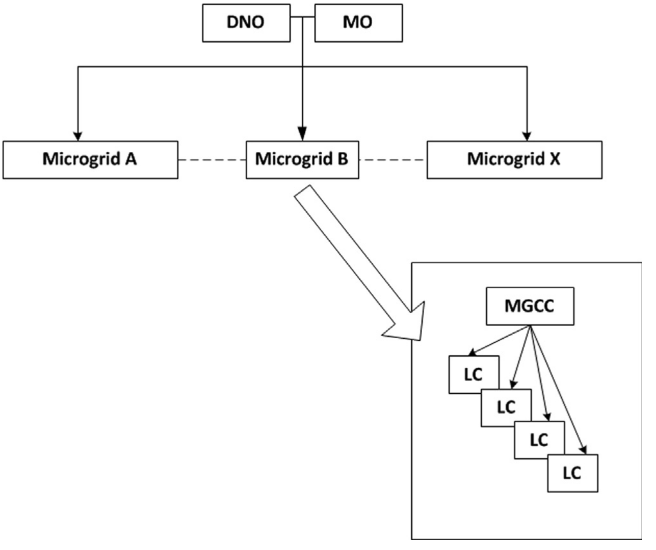

Fig. 16. Control levels of MAS environment.

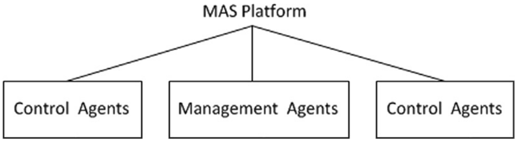

Fig. 17. Types of MAS agents.

responsible for technical operation of one or more microgrids whereas one or more MO are responsible for market functions of the area.

Microgrid Central Controller (MGCC) is the main interface between DNO/MO and the microgrid. Its main function is to optimize the operation of microgrid and coordinate the local controllers.

On the lower level, Load Controllers (LC) control the DG, production, storage and some of the local loads.

Using MAS technology, model of the system is obtained in detail where every agent uses the exact piece of information it needs, leaving the technical details for the agents that are below it in the organization chart. The paper proposes three types of agent. *Control agent* which controls physical units of the system directly. *Management agents* which manage the microgrid and take the decision. *Ancillary agents* which perform tasks like communication and storage of data. The proposed MAS platform is depicted in Fig. 17.

In [74], internal operation of the microgrid and its participation in energy market were focused particularly. The algorithm is proposed so that the every DER or controllable load decides what is best for it.

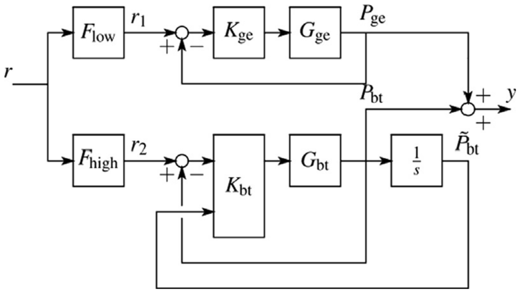

Fig. 18. Structure of MG [75].

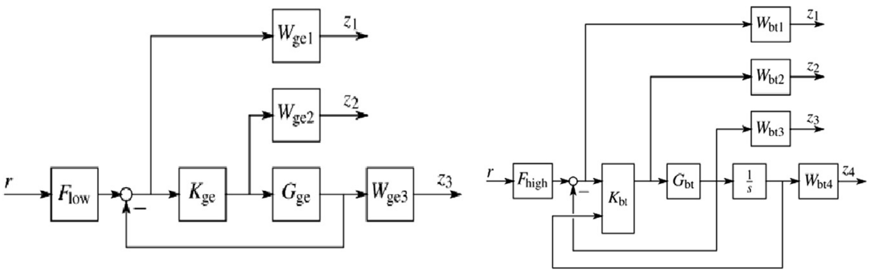

Fig. 19. Design of H_∞ controllers [75].

7.6. H_∞ control

A new power balancing method based on H_∞ control theory is proposed in [75]. The power fluctuations were considered as the disturbances added to the MG. Fig. 18 shows the block diagram of MG structure.

Where G_{ge} and G_{bt} are the first order transfer function representation of gas turbine [76] and K_{ge} and K_{bt} are controller gains for gas turbine and battery, respectively. F is the low/high pass filter gain.

Using the Robust Control Toolbox of *MATLAB*, the controller gains K_{ge} and K_{bt} were determined as standard controllers. Fig. 19 shows the block diagram of these controller designs, where W with subscript 1, 2 and 3 are weighing functions for tracking performance, gain margin of the microgrid system, and robustness for power fluctuations, respectively.

In [77], technical challenges and stability of DG's when connected into the distribution system are detailed. Since high penetration of the DG's can be considered as a microgrid the same technical challenges can be assumed correct for a grid connected microgrid.

7.7. Microgrid control: autonomous/islanded mode

In the autonomous or islanded mode of operation, microgrid supplies its local load and is not connected to the utility grid. The main challenges in this mode are:

(1) Voltage and frequency control
(2) Balance between supply and demand
(3) Power quality
(4) Issues relating to microsources

(5) Communication among microgrid components.

Lot of research has been done on control of microgrid in autonomous/islanded operation [78] which will be discussed in this section. The two main control strategies *PQ* and *VSI* control are discussed first, detailed description and explanation on these two controls can be found in [55].

When connected to grid, all the DG's can operate in PQ control mode because the voltage and frequency are dictated by the utility grid but at least one DG has to follow VSI control in islanded mode since the voltage and frequency reference is set by the MG.

7.8. PQ and VSI control

The aim of *PQ control* is to provide constant active and reactive power at a desired power factor [46,60]. The reference values of power are defined by a local controller or centrally from the MGCC. This scheme can be implemented as a current controlled voltage source or voltage controlled current source as discussed earlier in Section 7.1. Current or voltage components in direct (I_d or V_d) and in quadrature (I_q or V_d) with inverter terminal voltage are computed based on method given in [50].

Fig. 20 shows the control block for this strategy using current control. The direct component (I_d) of the current is used for the control of active power and the quadrature component (I_q) is used for the reactive power control.

Voltage source inverter (VSI) matches the behavior of a synchronous machine controlling the voltage and frequency on the ac system [53,79,50]. It acts as a voltage source whose output voltage's magnitude and frequency are controlled through *Vf* droop characteristics which are shown in Fig. 21. Hence, this method is also known as *Droop Method*.

In VSI control, voltage is related to reactive power ($V-Q$) whereas frequency/phase shift is related to active power ($f-P$) by the following equations:

$$f = f_0 - K_p \Delta P$$
$$V = V_0 - K_q \Delta Q$$

where K_p and K_q are the respective slopes of droop characteristics and f_0 and V_0 are the idle

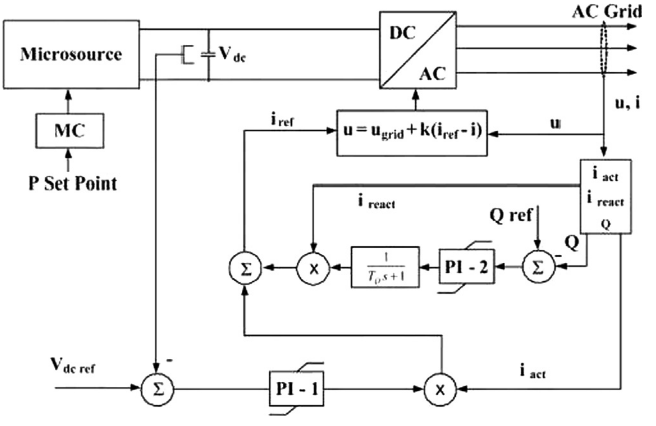

Fig. 20. PQ control scheme [46].

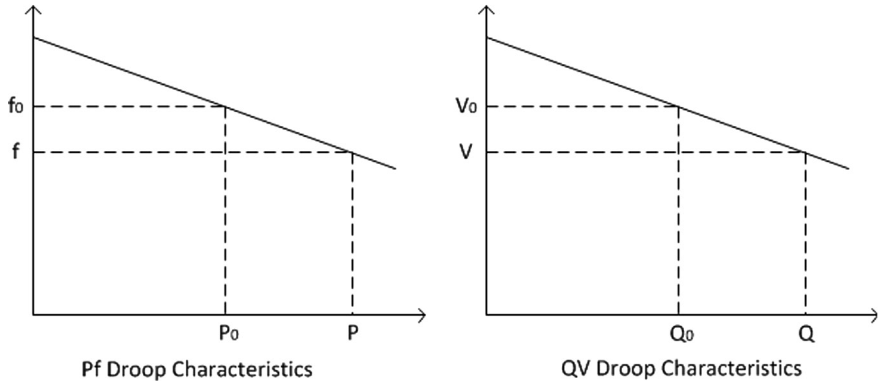

Fig. 21. *V* and *f* characteristics.

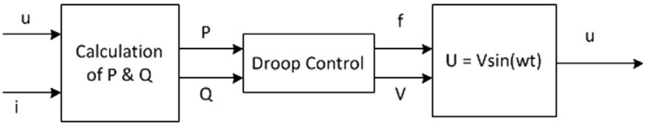

Fig. 22. Model of a VSI.

values of frequency and voltage, respectively [51]. 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).

A VSI model is shown in Fig. 22 [51,52]. The active and reactive powers are computed using the VSI terminal voltage. The output voltage frequency f is determined by the active power droops and magnitude V is determined by reactive power droops. The output voltage is the reference signals which control the VSI switching sequence.

The key point to be observed here is that VSI uses the local measurements at its terminals and reacts to any system disturbances quickly and hence does not require any communication infrastructure [53,79]. But there will be a communication infrastructure within the DG for the optimal management [46].A complete review of *Vf* control strategies can be found in [80] and validation of *Vf* control in both grid and islanded mode is performed in [24].

7.9. Autonomous control

The concept of utilizing *VQ* and *Pf* droops for controlling the microgrid is also proposed in [12,16,81]. They propose an autonomous control for the *peer-to-peer* and *plug-and-play* model of the microgrid components. The concept of peer-to-peer allows the continuous operation of microgrid even with the loss of any component/DG because there is no master controller or central storage unit. The concept of plug-and-play ensures that any component can be added at any point in the system without re-engineering the controls.

Microsource controller based on droop characteristics is shown in Fig. 23. *P*, *Q* and *V* are calculated and then the droops are implemented in two separate blocks. Then the controller generates the voltage at desired magnitude and frequency at the inverter terminals.

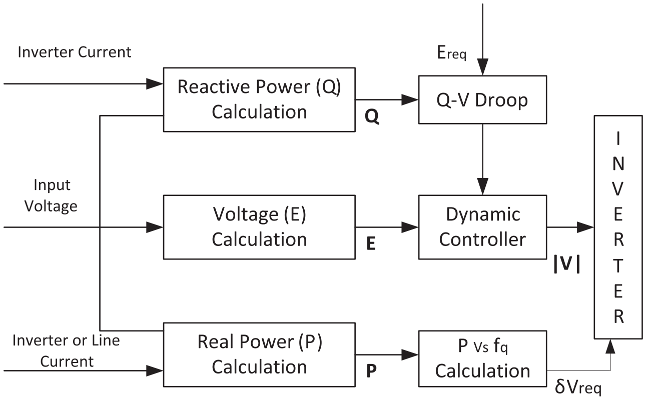

Fig. 23. Microsource controller using droops.

7.10. New $Q-\dot{V}$ droop control

In islanded mode, the reactive power sharing is highly dependent on impedance of power line. Due to the different distances among DERs interface converters (DICs), the equivalent transmission line impedance could be unequal [51]. *Pf* and *QV* droop characteristics are used in DER interface converters for power sharing operations [82,81]. The *Pf* droop control provides an accurate real power sharing among the DIC's but the problem arises in *QV* droop control. Because of these unequal impedance load sharing performance of *QV* control can be affected. Various control methods addressing this issue have been proposed [83–85] but with some constraints.

Therefore a new droop control method for the islanded operation of MG is proposed in [86] to overcome the effect of line impedance on the reactive power flow, this method is known as Q–$\dot{V}$ droop control method where $\dot{V}$ represents the rate of change of voltage. By regulating the voltage with $\dot{V}$, the reactive power sharing can be made independent of the line impedance. The operation principle of the proposed method is shown in Fig. 24.

7.11. Control design based on transfer function

Controller based on the transfer function of the plant is designed in [30,33], this is adopted from the classical feedback control approach presented in [87].

For the islanded mode of operation, Fig. 25 shows the structure of controller. Reference angle is provided by a three phase PLL. The q component of load voltage is set to zero and d component is regulated to the desired peak value. Regulation of v_d is done by comparing with reference signal and the error is applied to the controller. The controller then provides inputs to the gating signal generator of the VSC (Fig. 4). More details can be found in [30,33].

Instead of using frequency droops, an internal oscillator is used to design a multivariable controller in [32]. The function of this oscillator is to control the frequency in open loop way. The robust servomechanism controller was designed using the parameter optimization methods [88,89] in addition with non-conservative robustness constraint [90].

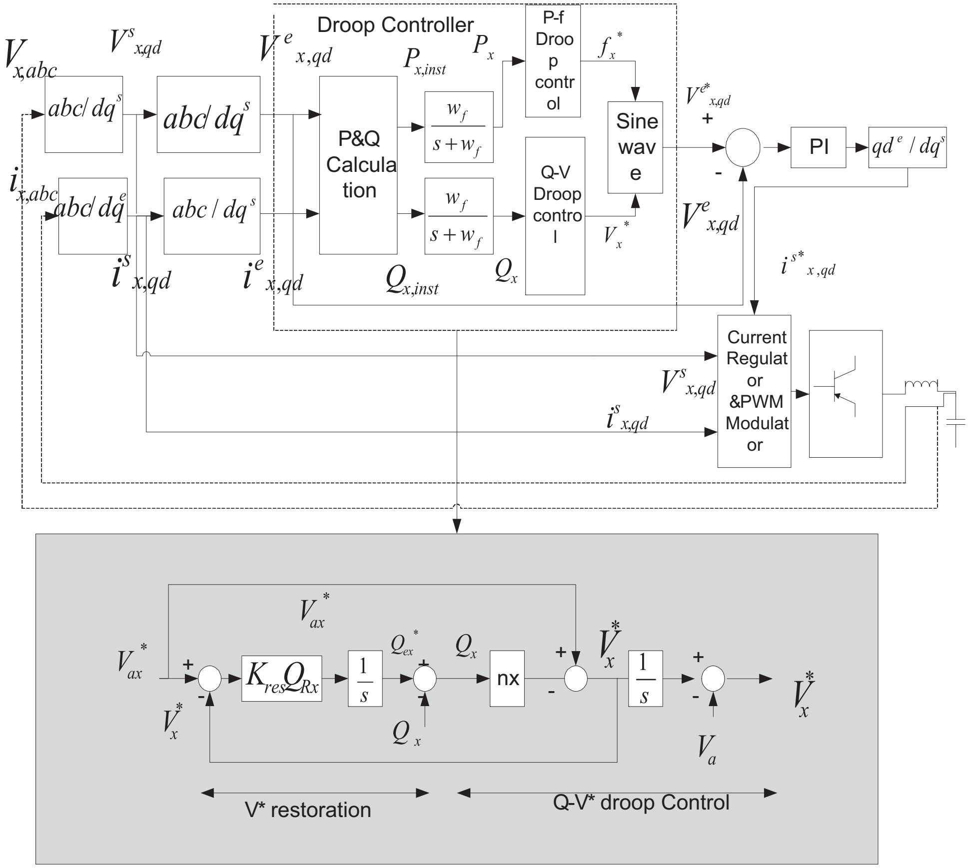

Fig. 24. Block diagram of DIC with $Q\dot{V}$ droop control [86].

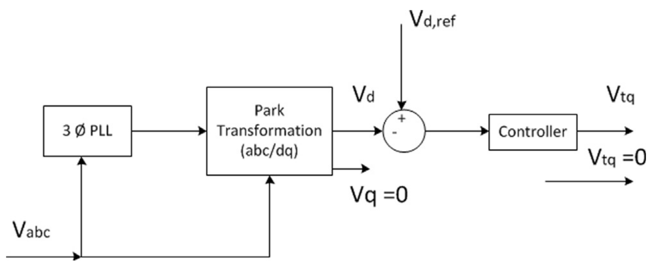

Fig. 25. Control strategy [30,33].

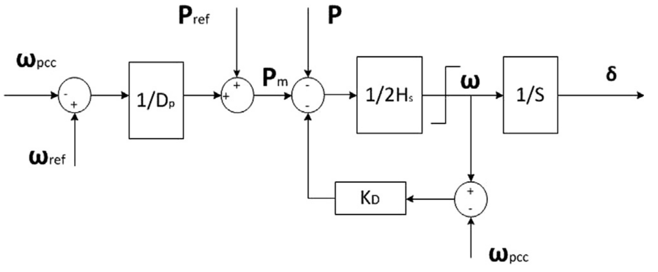

Fig. 26. Block diagram for the *frequency* control [31].

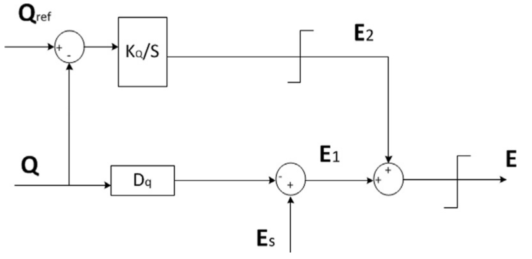

Fig. 27. Block diagram for the *Voltage* control [31].

8. MG – control in both modes

A novel control strategy which can be applied to MG in both the modes is introduced in [31]. This scheme of control allows a DG to control its real and reactive power components in grid-connected mode and to control the voltage and frequency in autonomous mode.

The proposed VSC frequency control is similar to that of a synchronous machine and is shown by the block diagram in Fig. 26. In grid-connected mode, the frequency at PCC (ω_{pcc}) is equal to the grid frequency and hence has no impact on the system dynamics and only the output real power reference has to be set. In autonomous mode, it is same as VSC frequency determined by the droop characteristics.

The block diagram in Fig. 27 shows the proposed voltage control scheme. During grid-connected mode, output reactive power of VSC at PCC is set while in autonomous mode, the DG has to supply the load with reactive power, which is achieved by setting E_2 to zero and only E_1 remains effective.

9. System of systems – introduction

To understand the concept of system of systems (SoS) or cyberphysical system (CPS), let us consider an airplane which is an example of large scale complex system. Various parts of airplane are operated by different systems but the plane flies only when all its systems operate collectively and does not fly if they operate individually. Therefore, a SoS is the large-scale integration of many systems that combine their capabilities together to form a more complex system offering more functionalities than the individual sum of the constituent systems [91].

SoS is inherently multidisciplinary. The synthesis of multi systems requires the study of their interdependency because each effects the other. This will result in different problems ranging from modeling to control. Therefore almost all the key issues of systems engineering have to be revised. The methodology of developing models, tools and control of SoS is typically referred to as system of systems engineering. SoS methodology finds large number of applications in the defense sector but recently it is also being used in auto transportation, space exploration, search and rescue and many other non-defense areas [92].

For SoS engineering branch, all aspects of systems engineering have to be revised. But the main problem arises in the two key aspects which are modeling and control. The challenge in modeling point of view lies in the indirect effects, the cause and effect need not be directly related, any change *here* can produce effect *over there* because of their interdependency. It is clear that these systems are very large and pose unpredictable behavior which is difficult to model. SoS models available so far are still immature and there should be focus on additional development. These models are quite complex and needs a multidisciplinary approach [92–96].

Control is perhaps the most critical challenge facing SoS designers. Due to the difficulty or impossibility of developing a comprehensive SoS model, either analytically or through simulation, SoS control remains an open problem and is, of course, different for each application domain. Moreover, real-time control which is required in almost all application domains of interdependent systems poses an especially difficult problem [97,98].

10. SoS control – application to MG

The key issue of SoS, which is control, faces a main challenge of developing a comprehensive SoS model, analytically or by simulation. Availability of a proper model is necessary to design a controller. If a proper mathematical model is available then there are several available control strategies. Also control strategy for each system is not only dependent on its own sensory information but also on the communication links among its neighboring systems or components, this is another difficulty which rises from the control point of view. Control of SoS, which is different for each application domain, is still an open research area. In this section we will discuss several potential control strategies.

10.1. Decentralized control

Another control lacking real-time consideration is *decentralized control* [92]. In this scheme of control, SoS is assumed to be having multiple input and output variables. The control design aims at assigning proper inputs for proper controller which can observe a set of outputs. Thus there are multiple controllers, each one controls a particular operation of SoS. As it can be seen in Fig. 28, this scheme avoids storage of data.

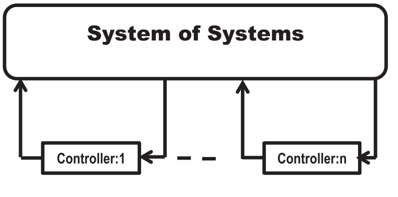

Fig. 28. Decentralized SoS control scheme.

10.2. MG – decentralized control

A robust decentralized control strategy is proposed in [34] for the islanded operation of a MG. The proposed model of MG is shown in Fig. 5. It is shown that the MG can be represented by an interconnected composite system consisting of two subsystems [99] and each subsystem can be controlled using the local controllers.

The dynamic model of the MG is decomposed into two subsystem as follows:

- Master subsystem,
- Slave subsystem.

Since the two subsystems are controllable and observable, it is shown that the composite system is stabilizable by using only local controllers i.e., decentralized control strategy can be applied.

For the master subsystem, an H_∞ controller was designed to meet the robust characteristics [100]. This control strategy fulfills the voltage and frequency requirements of the load. The configuration of H_∞ control is shown in Fig. 29. *Matlab LMI* toolbox is used to synthesize H_∞ controller [101].

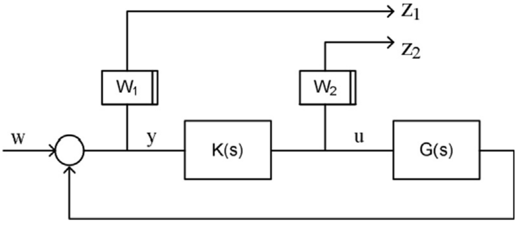

Fig. 29. H_∞ Control for master subsystem [34].

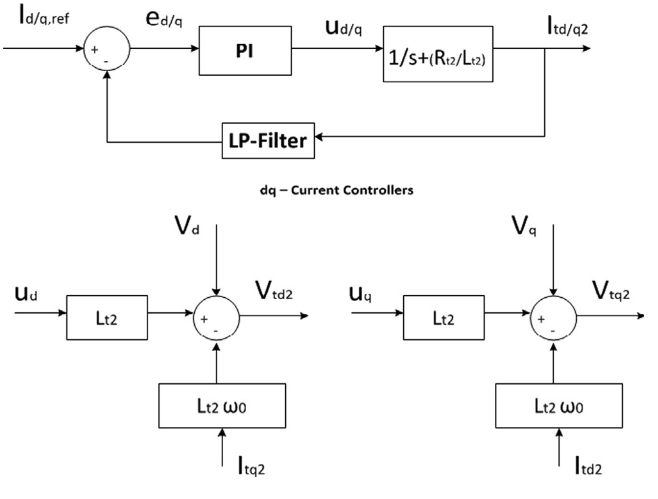

Fig. 30. *dq* current control method for slave subsystem [34].

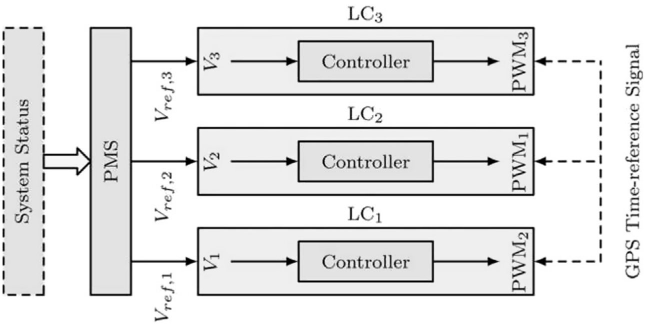

Fig. 31. PMS and control scheme in [104].

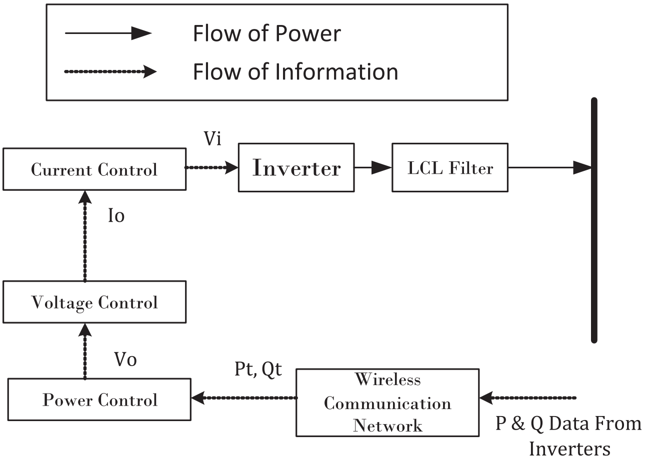

Fig. 32. Inverter control scheme in [105].

A simple PI controller was designed for the slave subsystem using the conventional *dq* current control method [102,103]. This is depicted in Fig. 30. The overall model and its controllers were simulated in *Matlab/SimPowerSystems* toolbox.

A fundamental concept of Power Management System (PMS) and robust decentralized control strategy for the islanded MG is proposed in [104]. The schematic diagram of proposed control is illustrated in Fig. 31. It consists of a PMS, local controller (LC) for each DER and MG frequency control and synchronization scheme.

A low bandwidth communication system is used to supply the instantaneous values of real/reactive power of each DER unit and load to the PMS. The PMS determines the set points of real, reactive power and voltage for the PC buses and transmits to LC's which measures the magnitude of voltage at its PC bus provides voltage tracking based on the received reference set point.

A decentralized inverter control based on wireless communication is proposed in [105]. wireless communication is used to enhance the stability of droop based decentralized inverter control. A wireless network is developed so that each inverter can communicate with a certain set of inverters. Fig. 32 shows the block diagram on inverter control.

Droop based inverter control scheme is adopted [106,36]. The controller of each individual inverter consists of three parts, i.e., the power controller, voltage controller, and current controller. Only the stability of power controller is considered whereas the voltage and current controllers are based on traditional PI controllers. A fully decentralized communication is considered which implies that any inverter only needs to communicate with its immediate neighbors to calculate the total power generation of all DG units. Stability analysis with and without incorporating communication delay is presented.

A novel decentralized controller for load sharing among parallel connected inverters in an islanded MG is proposed in [107]. The controller has 3 nested loops:

(1) Inner loop
- Regulates the output voltage of inverter.
- Voltage gain is responsible for good output voltage tracking.

Resistive output impedance loop
- Reduces the impact of line impedance unbalance.

(2)
- Used to fix the output impedance of the inverter in terms of magnitude and phase.
- The output impedance presented to harmonic components can be fixed.

P/Q sharing outer loop
- Used to obtain proper P/Q sharing.

(3)
- Droop/boost control scheme is used.

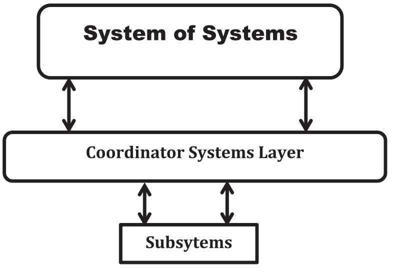

Fig. 33. Multilevel SoS control.

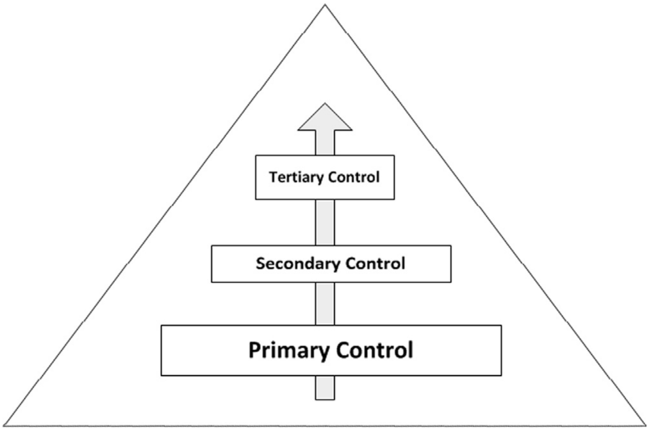

Fig. 34. Structure of multilevel control scheme.

10.3. Multilevel control

As discussed earlier SoS is integration of large-scale systems and large-scale systems that can be decomposed into subsystems. *MultiLevel control* assumes that SoS is characterized by N finite set of subsystems coordinated by system coordinator as shown in Fig. 33. By employing any optimal control method the subsystems can be optimized and repeatedly performing the modeling, the interactions between the coordinator and subsystems can be converged to an optimal solution. In the literature, multi-level control is obtained by classical steady state approach but lot issues has to be dealt while its implementation in real time [92–96] (Fig. 34).

10.4. MG – multilevel control

In this scheme of control there are three main levels namely primary control, secondary control and tertiary control as shown in Fig. 33 [108,109].

The key points related to *primary control* are listed below:

(1) Used to share load between converters.
(2) Improves the system performance and stability.
(3) Regulate the output frequency and voltage magnitude.
(4) *Droop-control* method is often used.
(5) Can also include virtual impedance control loop to provide proper output impedance.

The key points related to *secondary control* are listed below:

(1) Restores the f and V to nominal values whenever load change occurs.
(2) Removes any steady-state error introduced by the droop control.
(3) During transition from islanded to grid-connected mode, this control can perform synchronization to the main grid before interconnection.
(4) Makes use of low bandwidth communication.
(5) More global responsibilities.

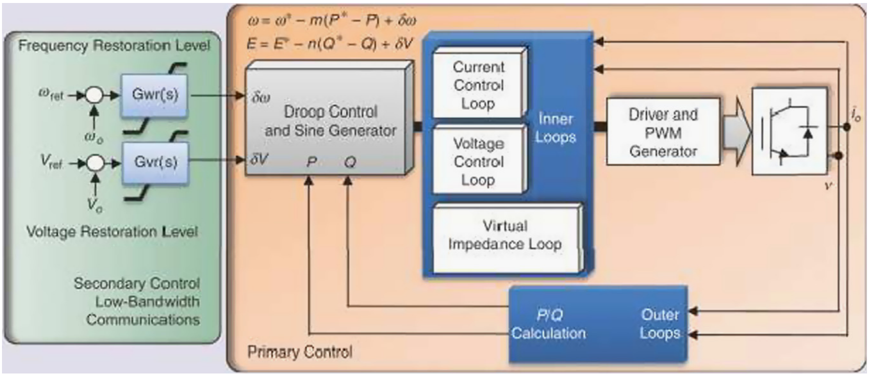

Fig. 35. Primary and secondary control.

The primary control loop makes use of only local output voltage and current to perform calculations of droop control method whereas the secondary control level consists of an external centralized controller to correct the errors produced by the primary control. Both controls are depicted in Fig. 35.

The tertiary control level comes into play mainly when the MG interacts with the utility grid. The key points related to *tertiary control* are listed below:

(1) Controls the power flow between MG and the utility grid.
(2) Send the frequency and voltage references to the secondary control.
(3) Can perform islanding detection or voltage harmonic reduction.
(4) Can also improve the quality of power at PCC.

The proposed multilevel control scheme allows the system to integrate more and more MG's and with this scheme of control microgrids can operate in both grid connected and islanded mode.

10.5. Networked control systems

In modern control systems, we find more and more application of networks owing to impressive advancements in network technology. One such example is *Networked Control System* (NCS). In NCS, the feedback channel is closed using a real time communication network and all the data among the components of system are exchanged through this communication network [110]. In [111], NCS is properly defined as "*Network Control Systems* (*NCS*) *are spatially distributed systems in which the communication between sensors, actuators and controllers occur through a shared band limited digital communication network*". This definition explains that the components of NCS are distributed and may operate asynchronously to reach some overall objective [112].

One of main issues in NCS is the transmission delays and packet dropouts, therefore the challenge in NCS for SoS is to develop an SoS distributed control system which can overcome these issues. As mentioned in [113], these communication infractions can be compensated by:

(1) Adjusting control power and controlling distances between systems (power control).
(2) Trading off modulation, coding, and antenna diversity versus throughput (adaptive modulation coding).
(3) The (non-wireless) intra-feedback (on-board hardware) loop of the autonomous control within S_i is lower latency than the inter-wireless distributed control loop between S_i and S_j or the inter-wireless system of systems controller and the S_i controller.

Another way to check on these communication is to design a wireless network control system (WNCS) taking account of all the aspects of the ad hoc network [114]. In this design, the distributed control will generate two components at each sampling period, one is local controller which is classical or modern control and the other is correction component of the controller which compensates for the ad hoc network quality of service (QoS) parameters. As shown in

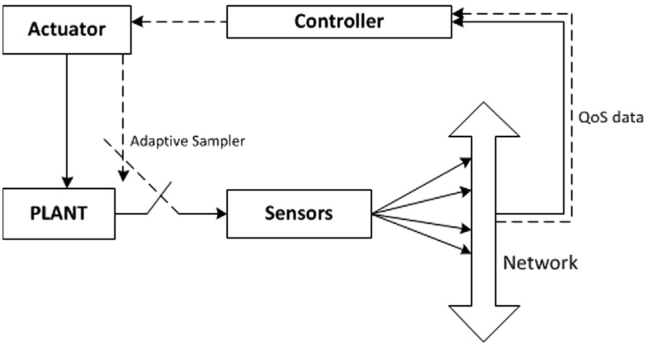

Fig. 36. NCS for SoS with sampler.

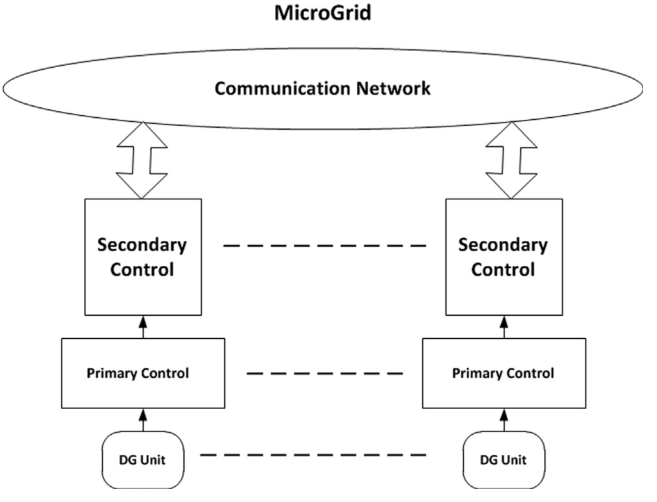

Fig. 37. Networked controlled microgrid [115].

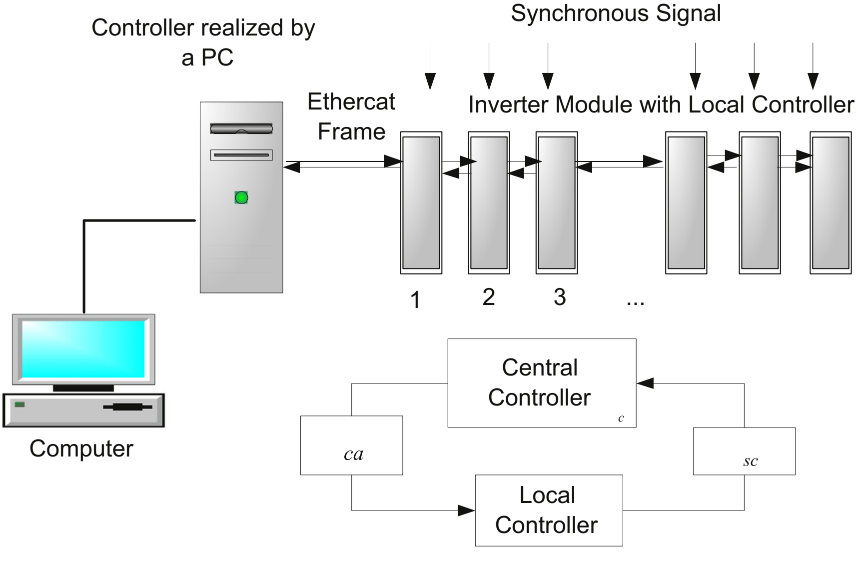

Fig. 38. Control of parallel multi-inverter system [116].

Fig. 36, with the combination of a local controller, correction component and adaptive sampler the stability and robustness will be enhanced.

10.6. MG – networked control

In the previous section multilevel control scheme for MG is discussed. The primary and tertiary control levels are decentralized and centralized, respectively, because one aims at the control of DG and other at global optimization of MG. Conventionally secondary control is implemented in the MGCC but recently a new distributed control scheme for the secondary known as *networked control system* (NCS) is proposed in [115] which is shown in Fig. 37.

This strategy is proposed for power electronically based MG's. The primary and secondary controls are implemented in DG unit. The primary control which is generally droop control is

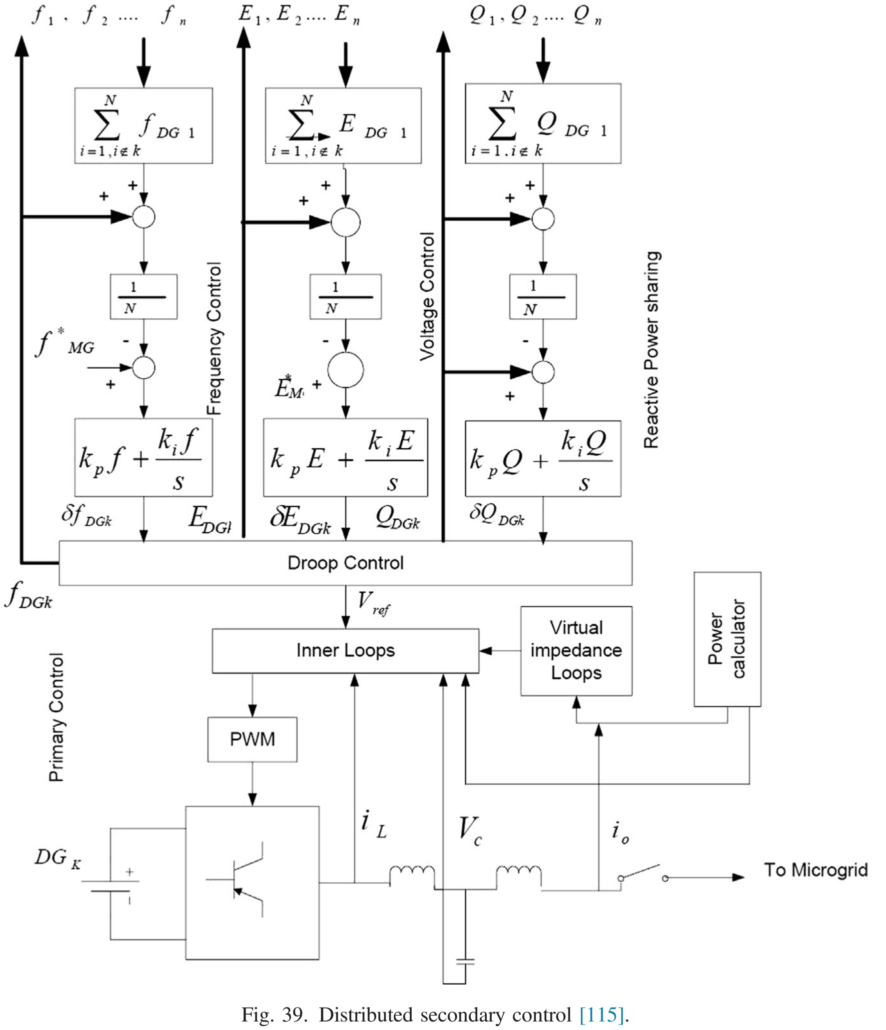

Fig. 39. Distributed secondary control [115].

already discussed in Section 7. The secondary control has frequency, voltage and reactive power controls in a distributed manner. The secondary control gathers all the measurements from DG units using the communication system, average them and generates the proper control signal for the primary control level. The schematic diagram of this proposed control scheme can be seen in Fig. 39 and the detailed explanation can be found in [115].

In another approach, a real time network is used for the control of parallel multi-inverter system [116]. Microgrid makes use of this type of inverter connections to deliver energy.

The considered system is shown in Fig. 38. It consists of a central controller, communication network and inverters with their local controllers. The control strategy is as follows: local

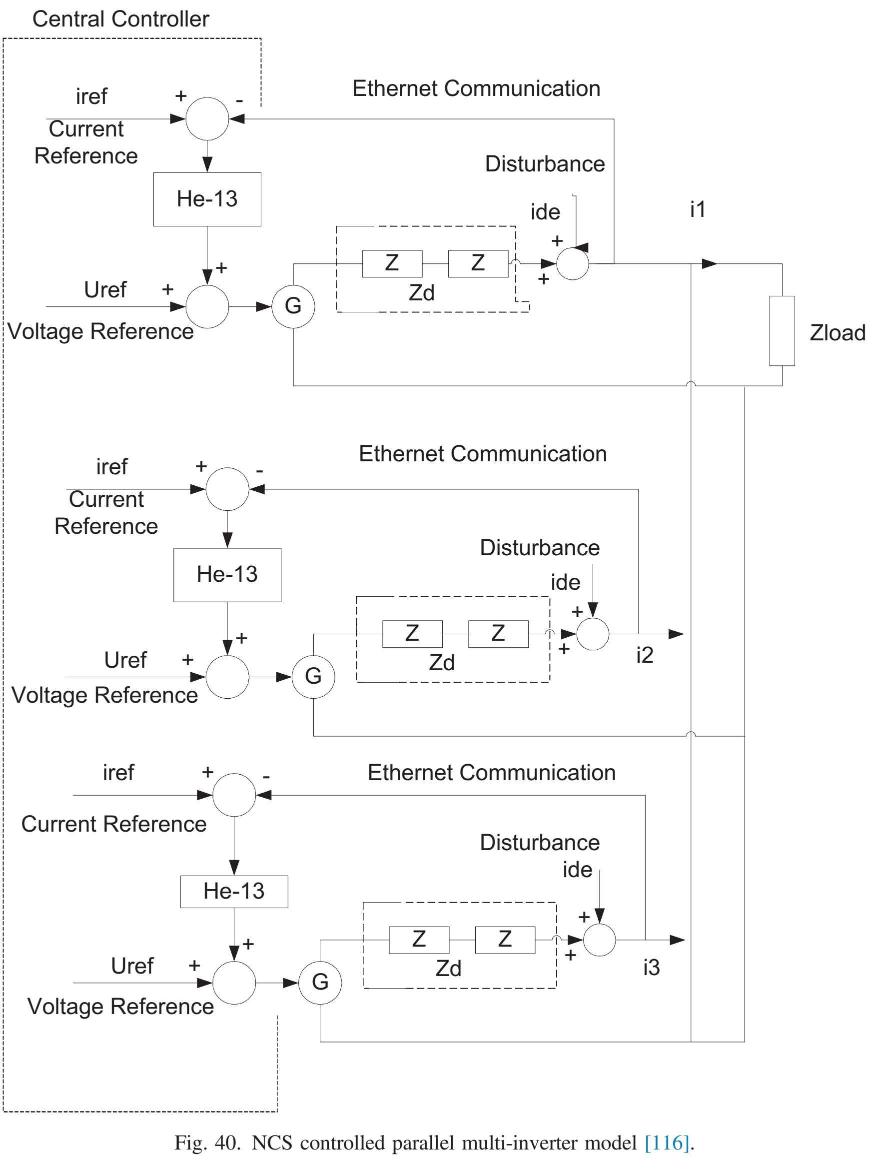

Fig. 40. NCS controlled parallel multi-inverter model [116].

controllers send the voltage and current measurements to the central controller via network frame. A closed loop control inside the central controller produces the satisfactory PWM duty ratio for each inverter module and sends it back to local controller via another network frame. This is a centralized control strategy where central controller has all the central information.

A PID controller is used to achieve better inverter performance [117] and D-partition method is used to determine the stability region of PI controller [118]. It was found that network induced delay brings about a considerable effect on closed loop control of a single inverter. The practical model implementing the NCS is shown in Fig. 40.

11. Comparative analysis

After discussing the control techniques, it is worth performing the comparative analysing of the control techniques which are most commonly used. In this section, we will classify the control techniques considering vital aspects for the purpose of simplification and better

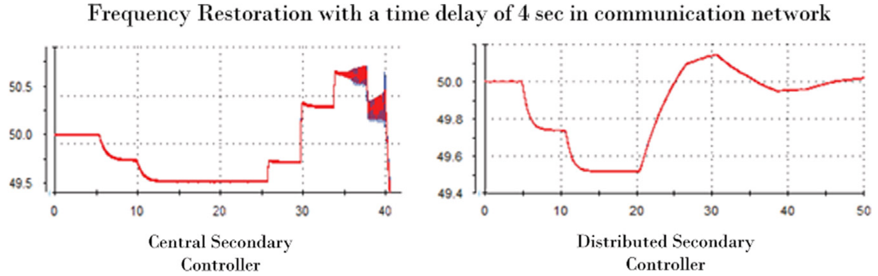

Fig. 41. Performance analysis of centralized and distributed controllers.

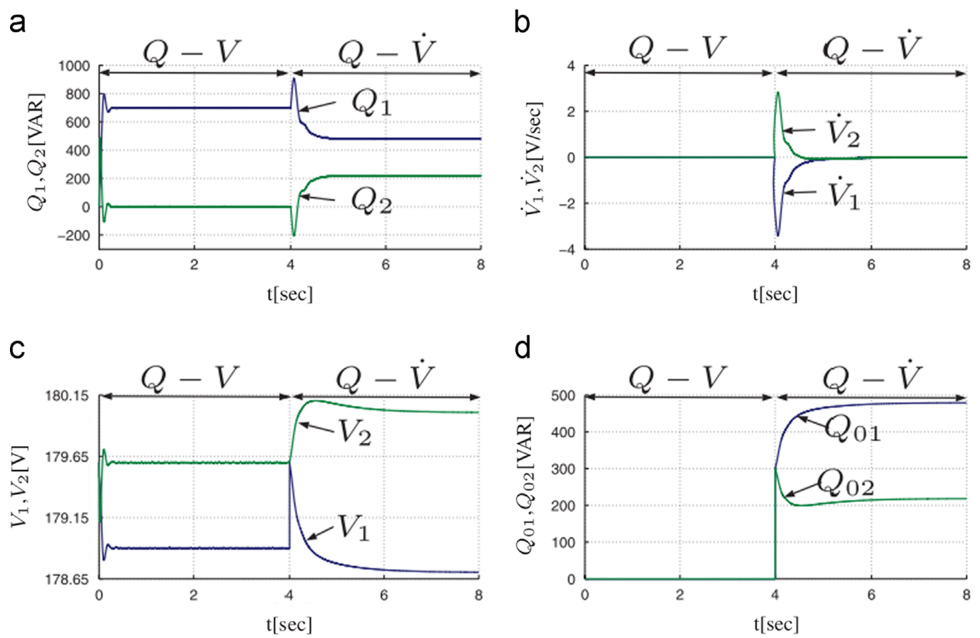

Fig. 42. Performance analysis of primary controllers.

understanding. Control strategies for MG are very vast and detailed comparison of each techniques with another is out of scope of this paper.

MG control (depending on architecture) can be generally classified into two main streams namely centralized, distributed (or decentralized). Multi-level control is also most widely used one but again depending on the architecture of control levels, even this control techniques falls in former mentioned categories. For instance in multi-level control, the secondary control level can be single (centralized) [109] or it can be implemented in a distributed way [115]. Fig. 41 shows the performance of the controller when implemented in centralized and decentralized manner. The time delay in the communication network is taken in account here. It is obvious from the figure that, the control implemented in distributed way is better.

Depending on the power sharing, the methods available in the literature can be broadly divided in to two groups, one using communication medium and another is non-communication based. Because of their inherent advantages, only communication-less control which is also known as Droop-based Control is used. It was initially proposed in [79] and since then there were many variations performed keeping the basic idea droop control [71,10,86]. One such comparison is shown in Fig. 42. A modified droop control technique, designed to improve the reactive power sharing among the DG units, is proposed and analysed with the conventional one [86].

12. Conclusions

The role of Microgrid in penetration of DG's in the present utility network is discussed. Modeling of microgrid is a key aspect and the recent developments in the modeling of microgrid are presented in both grid-connected and autonomous mode. The control techniques of microgrid available in the literature for various modes of operation are also discussed. The microgrid can be viewed as a special case of SoS. It can be concluded that using networked control system, a better control of microgrid can be obtained.

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