Distributed Control Techniques for Next-Generation Power System

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***Abstract*—Distributed energy resources (DERs) are playing the key role in meeting the energy requirement of the modern industrialized era. However, due to the dissimilarities of integration parameters such as voltage and frequency, etc., DERs create compatibility and power quality problems when connected to the current grid system. So, proper monitoring and controlling mechanisms are needed to overcome these problems. Smart grid is considered as a next-generation power grid which is expected to solve these monitoring and controlling problems. Moreover, the microgrid is the building block of the smart grid. It has distributed control capability which is essential for efficient operation of the power system. This paper gives an overview of distributed control techniques of the microgrid. It also discusses the different hierarchy of control layers and applications of distributed control of microgrid.**

***Index Terms*—Microgrid, smart grid, distributed control, hierarchical structure, microgrid management system (MGMS), multiagent system, model predictive control, consensus-based techniques, decomposition-based techniques.**

I. INTRODUCTION

DUE to industrialization, energy demand is increasing day by day. The traditional fossil fuel-based energy generation systems are not sufficient to meet this huge demand due to their limited resources. Moreover, the fossil fuel-based system creates a greenhouse effect that leads to an environmental hazard. Renewable energy sources such as solar, wind, biomass, tidal waves, and geothermal sources have shown a huge potential to incorporate into the conventional electrical grid system. However, concern for power quality, reliability and security increases as the new distributed renewable systems are being integrated [1]. System failures occur frequently due to inadequate monitoring and controlling infrastructure in the old grid system. Smart Grid: the next generation power grid is the solution to these problems.

While the traditional grid system focuses on centralized energy generation process, smart grid focuses on distributed generation (DG) process by integrating renewable energy resources (RES). Although DG brings many advantages, control and optimization of DG units are difficult due to many scattered generation sites. Thus, centralized control for DG is not the best option. Main drawbacks of centrally controlled DGs are as follows [3]:

1. Dedicated control operator is not available;
2. High-performance computer infrastructure requires due to complex problems;
3. The requirement of a costly communication protocol;
4. Privacy issue due to the exposure of customer's data in the network;
5. System's reliability and resiliency issue because of a single point of failure.

With the intelligent control system, reliability and distributed energy resource (DER) management, microgrid become the core element of the Smart Grid [2]. Distributed schemes of the microgrid are better to meet the functionality of the system. Each unit has a different task based on the global objective. Control layers are separated in different time frame called control hierarchy.

This paper illustrates the control hierarchy and distributed control techniques of the microgrid. As the part of the process, section II describes the definition and characteristics of the microgrid. Moreover, section III briefly explains the different types of microgrids. In addition, section IV tells the control functions of the Microgrid Management System (MGMS). Furthermore, section V provides a comparison between centralized and distributed control of microgrid. It also discusses the three hierarchical structures of control layer of the microgrid. Ultimately, section VI gives an overview of the distributed control techniques and their features.

II. DEFINITION OF MICROGRID

The increment of distributed generation (DG) during the last decade lead to comprehensive study regarding control and maintaining desired voltage and quality of power. However, integrating DG in the conventional system put stress on the power grid due to the dissimilarities of integration parameters. Thus, control and management systems are necessary for properly integrating DGs and coordinating loads. For distributed control architecture and power flow in a bidirectional manner, distribution grids are becoming active from passive linking customers demand with power generation requirement and operating the grid optimally. This concept paved the way to employ the smart grid. As per European Technology Platform of Smart Grid, a smart grid allows incorporating all forms of electrical network and consumers in an intelligent network that provides monitoring, controlling, communication and self-healing technologies. The smart grid is constituted by microgrids that is the part of the active distribution network. Microgrid usually connected in low voltage local distribution system [1], [2].

Microgrid has the following characteristics [1]:

1. It is capable to operate in both islanded and grid-connected mode by the self-dependent control mechanism or by an external control system. In other words, an intelligent microgrid can intentionally isolate itself as a standalone system. Moreover, a grid-connected microgrid can disconnect volatile RES and dispatch electricity during an emergency black-start situation.
2. Nearby or local loads are the main beneficiary of a microgrid.
3. As microgrid can provide an optimal solution for power flow to all the connected system, it can satisfy all sorts of grid owners.

Usually, different DERs such as solar photovoltaic (PV), wind turbines, and micro-hydroelectric turbines etc. along with storage elements such as batteries, flywheels, and storage capacitors, etc. constitutes microgrid. Moreover, power electronics interfaces, connected loads, and a point of common coupling (PCC) are the main elements of microgrid [2], [5]. Elements of microgrid are briefly discussed in the next section.

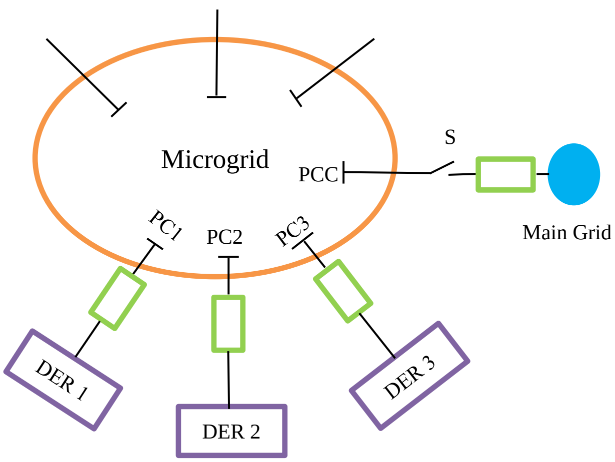

Fig. 1. Generic multiple DER connected microgrid system [3]

We can distinguish between normal to advanced microgrid by the capability to integrate DERs, profitable grid operation, and participation in the market etc. An advanced microgrid can dynamically balance between the load demand and generation. Moreover, it increases the grid reliability and resiliency. It is becoming a part of virtual power plants (VPPs) as more DERs are being integrated into the conventional system. Point of common coupling (PCC) is the electrical connection point through which current power grid is connected to microgrids as shown in Fig. 1. A microgrid can import power from or export to the existing grid system through PCC as a part of VPP [2].

III. Elements of Microgrid

With the advancement of power electronic technology, people are more leaned towards the DC-based network rather than AC based network. Despite being an integral part of the power distribution system, AC power system proses power quality and synchronization problems. As a result, AC microgrid faces the problem with controlling its elements and operating efficiently [5]. There are three types of microgrids: A) AC microgrid, B) DC microgrid, and C) Hybrid microgrid.

A. *Elements of AC Microgrid*

Most of the current grid networks are designed based on the principle of the AC system. AC microgrid can operate in both grid-connected and islanded mode. Conversion of DC DERs such as PV is done though DC-AC power electronic converter. On the other hand, AC-AC converters are used for AC DERs such as wind turbines. This system has an energy storage unit to store additional energy and support during an emergency. All the systems are connected to an AC bus. Finally, the AC bus is connected to the utility grid through a PCC. A typical AC microgrid system is shown in Fig. 2. [5].

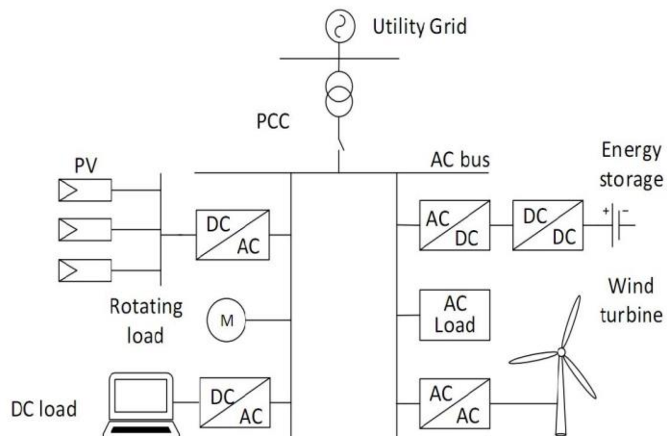

Fig. 2. AC microgrid architecture [5]

B. *Elements of DC Microgrid*

DC microgrids are getting more popular because of the emergence of DC loads. Unlike AC microgrids, energy conversion requirement is less for DC microgrids. Thus, DC microgrid architecture is considered simpler and more trustworthy. Nonetheless, DC microgrids are not free from demerits. High investment cost and voltage conversion efficiency are the main concerns while designing a DC microgrid. A typical DC microgrid architecture is shown in Fig. 3. [5].

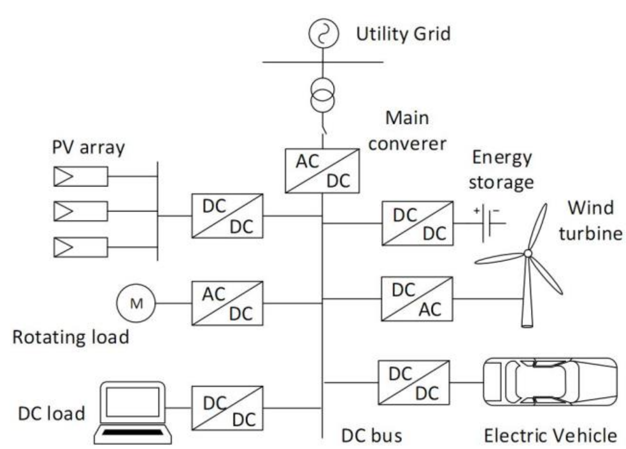

Fig. 3. DC microgrid architecture [5]

C. Elements of Hybrid Microgrid

In a hybrid microgrid, although AC and DC systems are connected, DC system works as a subsystem of the AC system. The DC system is connected to the AC system through a DC/AC converter as illustrated in Fig. 4. While a hybrid microgrid is considered as a form of AC microgrid, its efficiency is better than that of the AC microgrid [5].

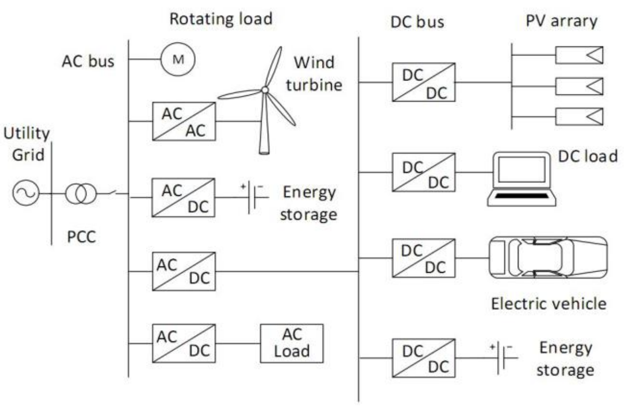

Fig. 4. Hybrid microgrid architecture [5]

IV. Control Functions of the Microgrid Management System (MGMS)

Microgrid management system (MGMS) is the key player that makes a microgrid a truly advanced intelligent microgrid. MGMS assist to coordinate protective devices, improve power quality and optimally dispatch power according to the load [2]. In Fig. 5, we can see the overall control function of the MGMS.

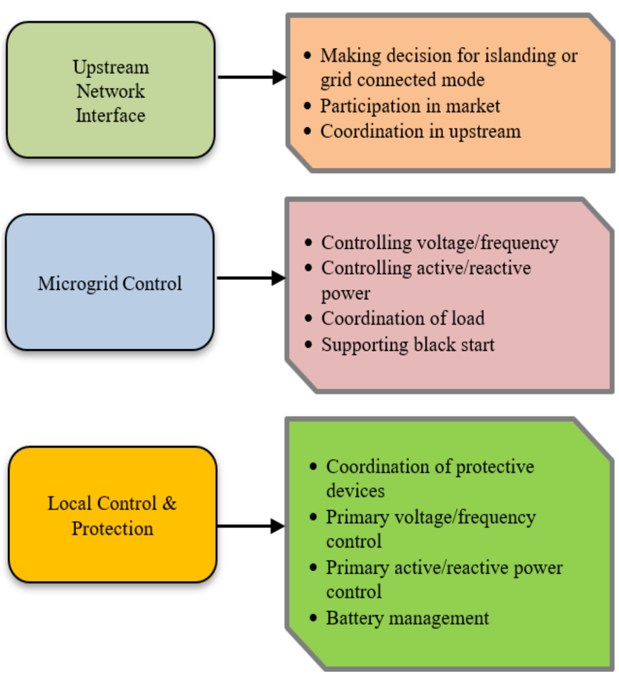

Fig. 5. Overall control functions of microgrid MGMS [1]

V. Control Structures of MGMS

A. Centralized vs Distributed Control of Microgrid

MGMS conventionally works in a centralized way by relying on a microgrid central controller (MGCC). MGCC supports operator to monitor microgrid's voltage and frequency through a supervisory control and data acquisition (SCADA) system. Balancing demand and generation as well as forecasting and optimization are done under MGMS in MGCC. However, MGMS can also be implemented in a distributed way. Fig. 6. shows the control structure of MGMS in both centralized and distributed way. In the distributed configuration, each element is connected to each other and MGMS separately [2]. Cooperation among all controllers in the distributed system through a peer-to-peer (P2P) communication system eliminate the necessity of the MGCC. This P2P communication network can be established easily through the Ethernet or a wireless network conforming IEC 61850 standard which promotes object-oriented P2P communication [2]. The distributed control system has the following advantages compared to the centralized MGMS system [1] – [3]:

1. It is cost effective as requires less computing power.
2. System blackout does not occur due to single failure as there are several controllers available to support the system during an emergency.
3. As decisions are made locally, it put less stress on communication infrastructure.
4. More suitable for alteration and future extension.
5. Provides more privacy through storing information locally.

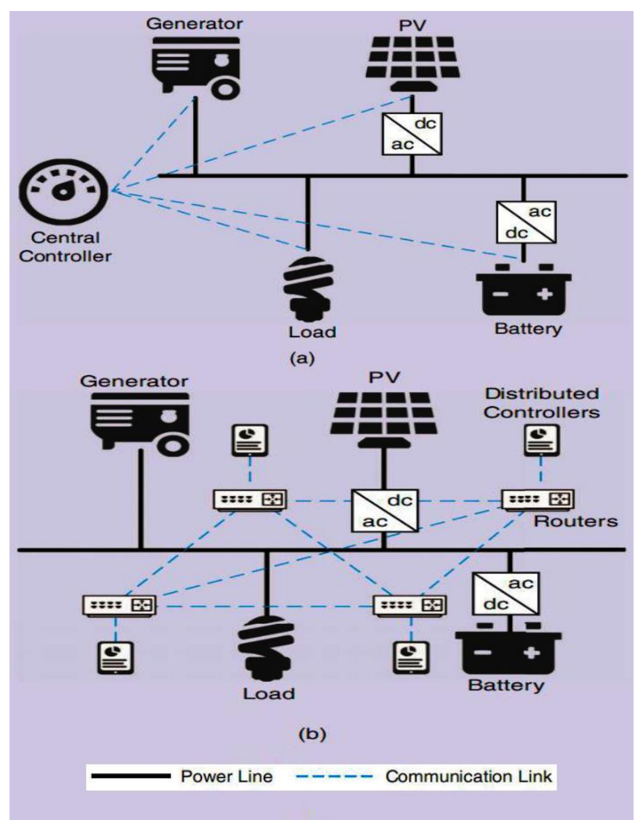

Fig. 6. a) A typical MGMS central control system, b) A typical MGMS distributed control system [2]

B. Microgrid Control Hierarchy

The main concept of distributed control is to allocate different control tasks to each individual unit of a microgrid. Based on the hierarchical structure, there are three control levels of microgrid namely: primary, secondary, and tertiary [1] – [6].

1. ***Primary Control:*** Primary control layer provides the fastest response time in the millisecond range. Local management functions such as voltage swing regulation, frequency deviation control, and islanding recognition are done in primary control layer through the voltage source inverter (VSI) interface. Although local management cannot change the control function of these inverters, they can define set points for voltage, frequency, real and reactive power. Each inverter interacts with the primary controller for sending system parameters and gaining control signals [2]. Even though most of the primary controllers do not require any communication infrastructure, some entities use the communication system to share active power for ensuring proper transient response and reduction of harmonics [3].

Energy storage units utilize the primary control mechanism to transfer power during the disturbance. Power sharing control scheme controls the generation of a certain system while maintaining the system's voltage and frequency at the set point. Depending upon the communication protocol, control of power sharing can be as follows [2], [3], [7]:

a) ***Concentrated Control:*** It uses synchronizing signal and power-sharing modules to coordinate and compensate real and reactive power. Moreover, it also ensures the power quality and economic stability. Each inverter shares the voltage and phase angle to their phase lock loop and power-sharing module monitors load current constantly to ensure the system's stability.

b) ***Master/Slave Control:*** This system has two unit: master and slave. Master unit works in voltage control mode while sending the current reference to the slave unit for current distribution.

c) ***Distributed Control:*** Consensus-based communication, distributed observer or droop control are the techniques which are used for power-sharing at the primary control level. Among these techniques, droop control is prevalent. Like the parallel operation of synchronous generators which is used to share loads equally among them, the droop control method shares loads among all connected inverters to regulate voltage and frequency according to the amount of generation of different DERs in an islanded microgrid. However, droop control has several disadvantages as follows:

1. Droop control has poor transient performance;
2. It ignores load dynamics;
3. Requires certain arrangement to black start after the system failure;
4. Due to the uncertainty of output impedance, accurate power sharing is not possible among DERs through droop control;
5. Real and reactive power can only be coupled partially.

Researchers are currently studying several variations of droop control methods such as virtual impedance control, virtual frame transformation method, adaptive droop control, compensated droop control, synchronized reactive power compensation, droop control-based synchronized operation, and multiagent based droop control, etc. [2].

2. ***Secondary Control:*** Secondary control layer of MGMS works to operate microgrid economically and reliably. Automatic generation control and energy management of microgrid are the main control function of the secondary control layer. With the help of the droop control method, the secondary controller adjusts voltage and frequency and create a set point from the data of microgrid energy management system (EMS) to stabilize the system at the PCC in the islanded mode. EMS can reduce the operation cost and increase the reliability of microgrid. The cost function of EMS works with respect to the economic aspects of fuel cost, maintenance cost, battery degradation cost, etc. On the other hand, the cost function about reliability contains the cost of the loss of loads. Moreover, through a narrow band communication channel, EMS is directly connected to the distributed management system (DMS). Furthermore, synchronization between the microgrid and the main grid is done through the secondary control layer. Secondary control layer can be both centralized and decentralized [2], [3].

a) Centralized Secondary Control: Usually secondary controller relies on microgrid central controller (MGCC) for controlling power flow and compensation of harmonics. From the Fig. 7., we can see that primary controllers control DGs and each of the primary controllers is connected to one central secondary controller. This secondary controller collects local measurement variables using low bandwidth communication system, compares with a reference signal, and sends the control signal back to each unit of the primary controller. As peer-to-peer (P2P) communication is required for this type of secondary controller, it adds a communication burden and reduces the reliability of the system [6].

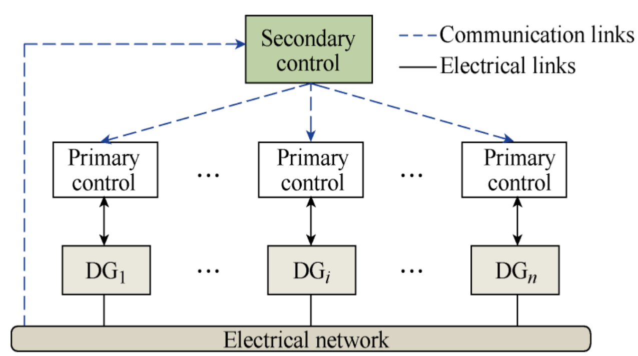

Fig. 7. A typical control scheme of centralized secondary layer [6]

b) Distributed Secondary Control: As distributed secondary controller reduces the system complexity, communication burden and increases the reliability, it is gaining more acceptance. In the distributed secondary control system, primary controller shares information with its counterparts through a band limited distributed communication protocol to achieve the local variable state. Droop regulated converter are the base for this system, although other mechanisms also can be used. The secondary controller compares the gained signal with the reference signal and adjusts the set point for the primary controller to remove the steady-state error. Communication among DGs is the main ingredient to achieve the control goal. In this way, the centralized control mechanism can be avoided. Fig. 8. shows a typical control scheme of distributed secondary controller [6].

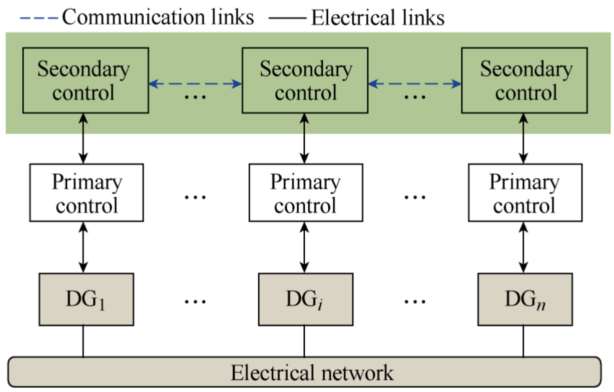

Fig. 8. A typical control scheme of distributed secondary layer [6]

Due to the distributed control nature, secondary control has slower time response compared to the primary control layer, usually in minute range to 1) differentiate between the primary and secondary control system, and 2) minimize the required bandwidth for communication among components [3].

3. ***Tertiary Control:*** Highest level of MGMS which takes part in the cooperation task among neighboring microgrids is called the tertiary control layer. Functions of tertiary control are real and reactive power support, supplementary services, and emergency disconnection from the grid, etc. According to some research, tertiary control is not considered as a part of MGMS [2].

Due to the limitation of communication infrastructure and distance among DERs, highest level does not usually have the local information. However, with recent technologies, microgrids can be connected to a cluster-based system. In that system, one microgrid works as a leader for other microgrid and take decision for the optimization problem. This function is the essential feature of MGMS tertiary control layer [2].

VI. DISTRIBUTED CONTROL TECHNIQUES

A. Multi-Agent System (MAS)

In the distributed control system, microgrid needs to be autonomous and react for each different entity to control generation, storage, and load management system. As each agent in a multi-agent system (MAS) is responsible for separate unit and has "plug-and-play" feature, it is suitable for large complicated power system where different units require to communicate with each other [3], [4].

MAS has the following characteristics [1], [4]:

1. MAS can perform the specific action in a physical or virtual environment such as generation control of a wind turbine or send a control signal to the software to participate in the electricity market. Each agent's task is different than other agents.
2. Cooperate with each other at the local level. For instance, in the wind power system, wind turbine and battery have separate agents to work properly. Wind turbine's agent must communicate with the battery's agent to store the energy in the battery.
3. Determine the system's condition and take the decision at the local level without involving MGCC. For example, MAS can govern the level of fuel, and state of charge of batteries, etc. based on the unit's specification.
4. Ultimately, agent's objective is to determine parameters such as voltage and frequency at its local bus to avoid the computational burden and represent themselves partially not as the whole system.

Based on these features, MAS agents are divided into two different categories: reactive agent and intelligent agent [1].

1. ***Reactive Agent:*** Agents or units that can represent themselves partially, perform a certain action, and act independently for fulfilling the goal requirement are reactive.
2. ***Intelligent Agent:*** Agents that can determine the system's current condition, store information, and take decision according to the stored information are called intelligent agents.

Agents can be classified into three categories based on the control hierarchy as follows [3]:

1. ***Centralized Agent System:*** Has only one agent;
2. ***Decentralized Agent System:*** Contain several agents that do not use communicating infrastructure;
3. ***Hierarchical Agent System:*** Constitute with agents in several layers which can communicate with each other. Agents send local information to the higher level and gain load information from the higher level to the local level as shown in Fig. 9.

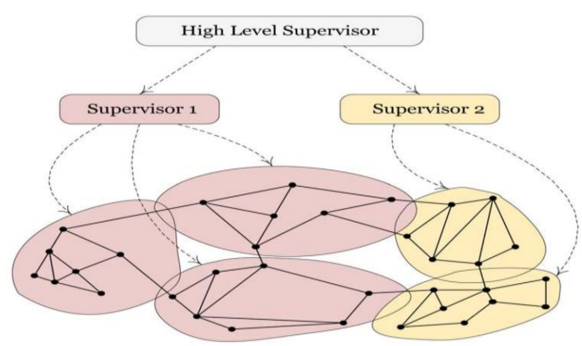

Fig. 9. A hierarchical structure of the multi-agent system [3]

New studies are being conducted to improve the efficiency of MAS. Development of agents in the multi-agent system is done through a software called Java Agent Development Framework (JADE) confirming the standard of Foundation of Intelligent Physical Agent (FIPA). FIPA regulate the standards and promote agent-based system [1]. A power system with a communication protocol is necessary to simulate the agent-based power system. Now, researchers are using

PSCAD/EMTDC along with custom Java module for communication-based simulation. Neighbor-to-neighbor three-step communication system also shows a promising result to implement MAS based architecture in the microgrid. Moreover, the multi-level hybrid control system can dynamically stabilize voltage and ensure the profitability of microgrid [3].

B. Model Predictive Control Techniques (MPC)

Model predictive control (MPC) is another distributed control technique of microgrid. Due to the capability of the solving control problem with multivariable and the ability to tune parameter easily, large processes are usually controlled with MPC techniques [3].

From Fig. 10., we can see that as a part of the distributed control scheme, reduction of the cost function which is related with the system performance over a finite number of future time steps can determine the control order of the system. System state deviation can be minimized through the cost function set points. A distinct time step of MPC contains the computation of control sequence for N future time steps, where N is called the prediction horizon for minimizing the weighted sum of errors. In the MPC system, the first input is utilized, and others are modified in future steps. This process continues as a loop for each consecutive time step [3].

MPC algorithm allows decomposing the optimization problem to control DG units of a microgrid into transient and steady-state subproblems. As a result, it can work under a slower time frame and reduces the necessity of complex calculation. Moreover, the MPC system can be used to forecast the voltage profile for regulating voltage and reactive power in an unbalanced microgrid. [3].

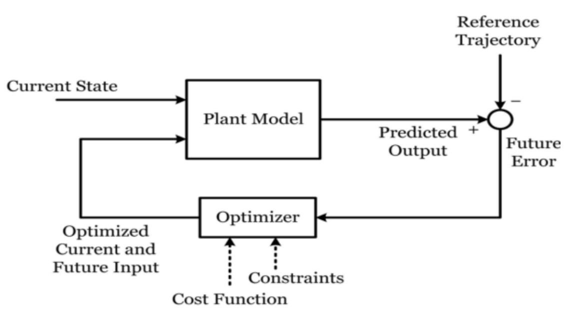

Fig. 10. The concept of model predictive control [3]

C. Consensus-Based Techniques

The microgrid can be controlled in a distributed fashion through another alternative methodologies called consensus-based techniques. These techniques depend on distributed optimization where each unit knows their global objective function. It can flexibly formulate the optimization problem and offer scalability. Several DER units can be converted into a single unit through the consensus-based technique. Each agent communicates with the neighboring agent through time-varying peer-to-peer (P2P) communication system for achieving the global optimization goal. With ensuring certain communication standard, a global agreement can be achieved despite having delayed time-varying connection. Thus, a dedicated central controller is not necessary [2], [3].

D. Decomposition-Based Techniques

The decomposition-based system also decomposes the microgrid optimization problem into smaller problems. These problems are solved repeatedly until the scheme get one desired solution for the problem. Even though we can divide the problem into different areas based on how the system can react and control requirement of electrical buses, availability of information is the critical issue for separating microgrid problems [3].

VII. Conclusion

Integration problems of DERs with current grid system created the idea of the microgrid. Now, microgrid turned into established technology from an emerging technology. Moreover, it became the constituent of the next generation power system namely the smart grid. Researchers are doing extensive research to find the different control mechanisms of the microgrid. Novel algorithms, such as the Particle swarm algorithm and Genetic algorithms, Lagrangian relaxation, and Primal-dual gradient descent methods can be utilized to solve optimization problems [2] - [6]. Distributed control of microgrid is suitable compared to the centralized control system not only for reducing the system’s complexity and communication burden but also for increasing reliability and resiliency. This article discusses the elements and hierarchy of microgrid such as primary, secondary and tertiary. Moreover, it shows the different control function of the MGMS. In addition, a discussion has presented related to the comparison of centralized and decentralized control of microgrid. Finally, different distributed control techniques are presented in the last section of this paper.

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