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# Power quality in micro grids with electric vehicles

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# *Dedication*

*Self-efforts and*
*guidance of caring Elders were required to surpass*
*this challenging work.*

*I dedicate this modest work to my sweet and loving*
*Mother and my family members whose affection,*
*love, encouragement and prayers made me able to*
*get such success and honor.*
*Along with all my friends, hardworking and*
*respected Teachers.*

*Oussama Abd Elkayoum Bensalem*

# *Dedication*

*It was a great pleasure to dedicate this humble work*

*To my Beloved Family,*

*To all my Friends and*

*Teachers from primary school to my last year of university*

*And to all with whom I spent wonderful moments.*

*Merzouk Haniche*

# *ACKNOWLEDGEMENT*

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*We would like to express our deepest and sincere gratitude to our project Supervisor Pr. A.RECIOUI. It was a great honor to work and study under your supervision, we would like also to thank the other teachers for their precious help during our work.Thank you very much.*

*Last but not least, we are infinitely grateful to our family members, particularly our parents for their patience, and continuous encouragement and support throughout our whole life. Every step we took and every success we made is because of them being beside us.*

*Finally, a special thanks go to all IGEE members.*

# Abstract

Plug-in electric vehicles are becoming more practical and popular in developing countries being efficient and more environmentally friendly. They can act as loads as well as sources using a technique known as Vehicle-to-Grid which adds key features to a micro grid in the form of primary frequency regulation. In this work, a method called Decentralized Vehicle-to-Grid Control for Primary Frequency Regulation Considering Charging Demands is studied and modeled under MATLAB Simulink for different scenarios to see the impact of these electric vehicles on the micro grid's frequency.

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| | |
|---|---|
| BEVs | Battery electric vehicles |
| BPL | Broadband power |
| BSH | Battery state of charge holder |
| CCHP | Combined cooling, heat, and power |
| CFR | Charging with frequency regulation |
| CRS | Congressional Research Service |
| CSTs | Coordinated strategies |
| DER | Distributed energy resources |
| DG | Distributed generation |
| DMS | Distribution Management Systems |
| DVC | Decentralized Vehicle-to-Grid control |
| EVs | Electric vehicles |
| FCVs | Fuel cell electric vehicles |
| HEVs | Hybrid electric vehicles |
| IC | Interface converter |
| MAS | Multi agent-based control system |
| PCC | Point of common coupling |
| PFC | Primary frequency control |
| PQ | Power quality |
| SLM | Smart load management control |
| SOC | State of charge |
| SS | Static switch |
| THDs | Total harmonic distortion |
| USTs | Uncoordinated Strategies |
| V2G | Vehicle-to-Grid |
| VUF | Voltage unbalance factor |
| WGs | Wind generators |

# General introduction

In the coming decades, the widespread usage of electric vehicles (EVs) which are considered as non-linear loads will place additional strain on the distribution system' ability to operate safely and efficiently and cause some power quality issues such as voltage and frequency fluctuations [1]; on the other hand, EVs can be used to help the micro grid to mitigate the issues it may face using a method known as Vehicle-to-Grid. These smart appliances, such as PEVs, will soon be able to "speak" to the grid to determine how best to work and autonomously plan their activity based on available generation. The role of electric vehicles in the form of vehicle-to-grid technology has recently increased especially with the development of the micro grid concept in the power grid. The V2G enables bidirectional energy exchange between electric vehicles and the micro grid, allowing the power system to benefit from a variety of services such as grid control, spinning reserve, peak load shaving, load leveling, and reactive power compensation. Optimization approaches are often used since the deployment of vehicle to grid technology is a complex unit commitment issue with several competing aims and restrictions.

Frequency fluctuations is one of the power quality issues facing the micro grid when EVs are integrated. The simulation model of the Decentralized Vehicle-to-Grid Control (DVC) is studied in this work, as well as its contribution in primary frequency regulation taking charging demands into considerations for different scenarios. The simulation system is modeled under Simulink which is a MATLAB-based graphical programming environment for modeling, simulating and analyzing multi domain dynamical systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries

This study is divided into three main chapters:

**-Chapter one:** presents an overview of smart grids followed by a full discussion of micro grids, including the most popular definitions, characteristics, components, operation, and so on. This chapter is critical to understand the notion of V2G and the interplay between the micro grid and EVs.

**-Chapter two:** deals with the major power quality issues that a micro grid may face when EVs are integrated providing the suggested mitigation strategies.

**-Chapter three:** illustrates the data required and the design model, as well as the effect of the Decentralized Vehicle-to-Grid Control for primary frequency regulation considering charging demands in different scenarios. The simulation is performed using MATLAB Simulink.

# *CHAPTER1*

## ∴ *Microgrids*

∴ *Introduction*

∴ *Micro grids and smart grids*

∴ *Characteristics of microgrids*

∴ *Micro grid structure and components*

∴ *Micro grid architecture*

∴ *Types of micro grids*

∴ *Micro grid operation, control and protection*

∴ *Advantages*

∴ *Conclusion*

# Micro grids

## 1.1 Introduction

We all rely on energy to light our lives and power our world but how that energy is generated and delivered is changing fast ,one way that is happening is through smart grids and micro grids, the traditional centralized utility grid is a big interconnected network that takes energy from large far away energy generation plants and transmits it over long distances to consumers, as technologies and policies continue to evolve, communities and businesses can choose to supply their own energy locally by building their own micro grid.

## 1.2 Micro grids and smart grids

A micro grid is considered as a subset of a smart grid.

### 1.2.1 Definition of a smart grid

The smart grid is a new electric power grid infrastructure; a network made of transmission lines, substations, transformers with uniform renewable and alternative energy sources integration, through modern communications technologies and automatic control, it aims to combine intelligent technologies with electricity in order to improve the convenience, efficiency, reliability and safety of the whole electricity, it allows modern network management strategies ensuring their effective grid integration in distributed generation (DG) for demand side management and storing energy for load balancing [2].

### 1.2.2 Definitions of a micro grid

Some definitions are shown as follows:

#### a. Definition from a comprehensive study on micro grid technology of Eklas Hossain

A micro grid is a modern group of power sources and loads using sustainable local energy resources designed as part of various smart grid initiatives, it operates like a single controlled unit which is in synchrony with the conventional centralized grid (macro grid), but can be disconnected and operates independently as physical and/or economic conditions dictate [3] [4].

#### b. Definition of the Lawrence –Berkeley laboratory

The US department of micro grid exchange group characterizes micro grids in this manner:

A micro grid is a modern group of interconnected loads and distributed energy resources (DER) within a clearly defined electrical boundaries that operates like a single controlled unit with respect to the grid, it can connect as it can be disconnected from the grid to make it able to function in both grid-connected or island-mode.

### c. Definition of the Congressional Research Service

The Congressional Research Service (CRS) presents a micro grid definition in [5]**:**

Any small or local electric power system that does not depend on the bulk electric power network can be considered as a micro grid, it can be either a combined heat and power system based on a natural gas combustion engine (which cogenerates electricity and steam from water used to cool the natural gas turbine), or diesel generators, renewable energy, or fuel cells. A micro grid can be used to provide electricity to data centers, colleges, hospitals, industries, military bases, or entire communities.

## 1.3 Characteristics of micro grids

The micro grid has the following characteristics [6]:

### 1.3.1 Local

The micro grid generates local energy for nearby consumers and this is what makes it different from the traditional centralized grids.

Central grids transmits electricity from power generation plants over long distances via transmission and distribution lines, it is inefficient to deliver power from that far due to electricity dissipation in transit _eight to fifteen percent_so the micro grid overcomes this inefficiency by producing power near to those it serves; the generators are close to or within the building, or on the roof in the case of solar panels.

### 1.3.2 Independent

The micro grid can function independently and disconnect from the centralized grid, this capability is called island mode that allows the consumers to be provided by power when a storm or other calamity causes an outage on the power grid. For example in the US, the traditional grid is most likely to experience outages due to its size and interconnection. – more than 5.7 million miles of transmission and distribution lines [6], a falling tree on a power line can knock out power in several states, even across international boundaries into Canada but this failure can be avoided by using micro grids .Even if the micro grids can operate independently, but most of the time they do not and remain connected (unless they are in an isolated area where there is no central grid). As long as the central grid works properly, both functions in a sort of symbiotic relationship.

### 1.3.3 Intelligent

The micro grid is intelligent and this intelligence comes from what is called the micro grid controller which is the central brain of the system that coordinates every part of the micro grid from generators, batteries to nearby building energy systems with a high degree of sophistication. The controller manages a lot of resources by either increasing or decreasing the use of one of them in order to fulfill the energy goals set by the customers and these goals can be: clean energy, low price, great electric reliability or other outcomes.

## 1.4 micro grid structure and components

A micro grid is mainly built up of variety of distributed generators, energy storage devices, different types of loads, interfaced distributed energy resources as shown in fig1.1.

### 1.4.1 Distributed generators

There are two main types of generation technologies that may be used for micro grid design which are renewable distribution generation (photovoltaic (PV), solar thermal, wind, fuel cell, hydro, biomass, biogas, etc.), and non-renewable distribution generation (diesel engine, steam turbine, gas engine, induction and synchronous generators, etc.) [4] [7].

#### a. Photovoltaic (PV) system

Generating electricity from solar energy by a PV cell, is free and inexhaustible.

The performance of a PV system depends on these factors:

1 geo-location and resource information like solar intensity, cloud cover and temperature.

2 PV modules, DC-DC converters and inverters efficiency.

#### b. Wind turbines

Wind power system which converts wind energy to electricity is composed of two main parts: one of them is mechanical and the other one is electrical.

In the mechanical part, the kinetic energy coming from the wind extracts the rotational energy which is then converted into electric energy in the electrical part.

#### c. Micro-hydro

Generation technology of electricity from water flow is known as micro-hydro which mainly depends on the area's topography and annual precipitation.

The system may experience large variation of water flow due to unequal rainfall, resulting a variation in generation in the absence of a hydro storage.

### 1.4.2 Energy storage devices

Energy storage devices are one of the most important key components to count on for a micro grid's proper functioning. The primary role of energy storage devices in a micro grid application is to balance power and energy demand with generation [7].

#### a. Batteries

During charging, batteries store energy in a chemical form and discharge it in an electrical form when connected to a certain load.

Batteries are quiet popular and suitable as micro grid storage system specially, lead-acid batteries since they are very cheap compared to other storage devices and provide a large current for a short time interval.

#### b. Flywheel

Flywheels are mainly used for power quality improvement, or as a central storage for the whole system, they store kinetic energy in a rotating mass and releases it by converting the kinetic energy to electrical energy when needed.

#### c. Super capacitors

The energy is stored in the form of their electrostatic field and because of their structure of liquid and porous electrodes, a very high surface area is created, also, a distance less than 1 μm is obtained between the electrode and electrolyte, which facilitate the development of a very high capacitance between hundreds to thousands times larger than electrolytic capacitors.

### 1.4.3 Interfacing distributed energy resources

The term "distributed energy resources" (DER) encompasses both DG and energy storage technologies, the majority of upcoming DER systems require an inverter interface to transform energy into grid-compatible ac power, this connection may include both a converter and an inverter or merely an inverter. The power electronic interface will include filters and the appropriate protective mechanisms, these DER devices support micro grid operation because of the converter's ability to adjust voltage and frequency.

### 1.4.4 Micro grid loads

A micro grid system has various kinds of loads which play a vital role in its operation, stability and control.

A micro grid might serve a wide range of consumers, including residential, commercial, and industrial which are often described as critical/sensitive loads that require a high level of power quality and dependability. This load categorization is critical in the micro grid setup to accomplish the desired operating strategy:

1 Facilitate load/generation shedding to stabilize the voltage and frequency in the autonomous operation.

2 Boost the power quality and reliability of important loads

In order to accomplish the previous operating strategies in a micro grid, a portion of the non-sensitive loads can be utilised as controlled loads (electric vehicles) [8].

### 1.4.5 Interconnection of micro grids

The micro grid generally operates in grid-connected mode, according to the operational philosophy, if a disruption happens or maintenance is scheduled in the utility grid, it may be smoothly disconnected at the point of common coupling (PCC) and continue to run in island mode, and vice versa.

Micro grids most of the time connect at the distribution level with limited energy handling capability due to RES usages and heat wasting.

Because of the limitation in the rated peak power of the micro grid, the connecting relay that connects the micro grid to public service is critical, and the switching control technique of this component influences the effectiveness of transition management across the grid [9].

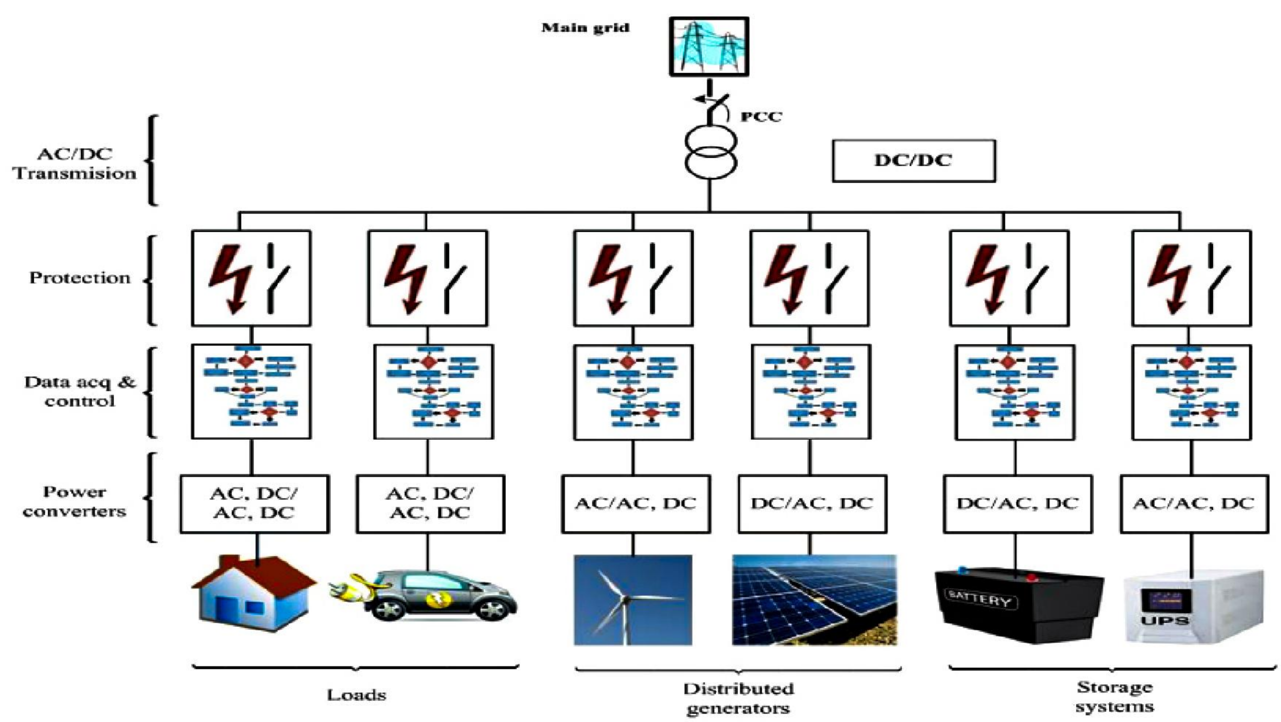



**Figure1.1**micro grid structure [4]

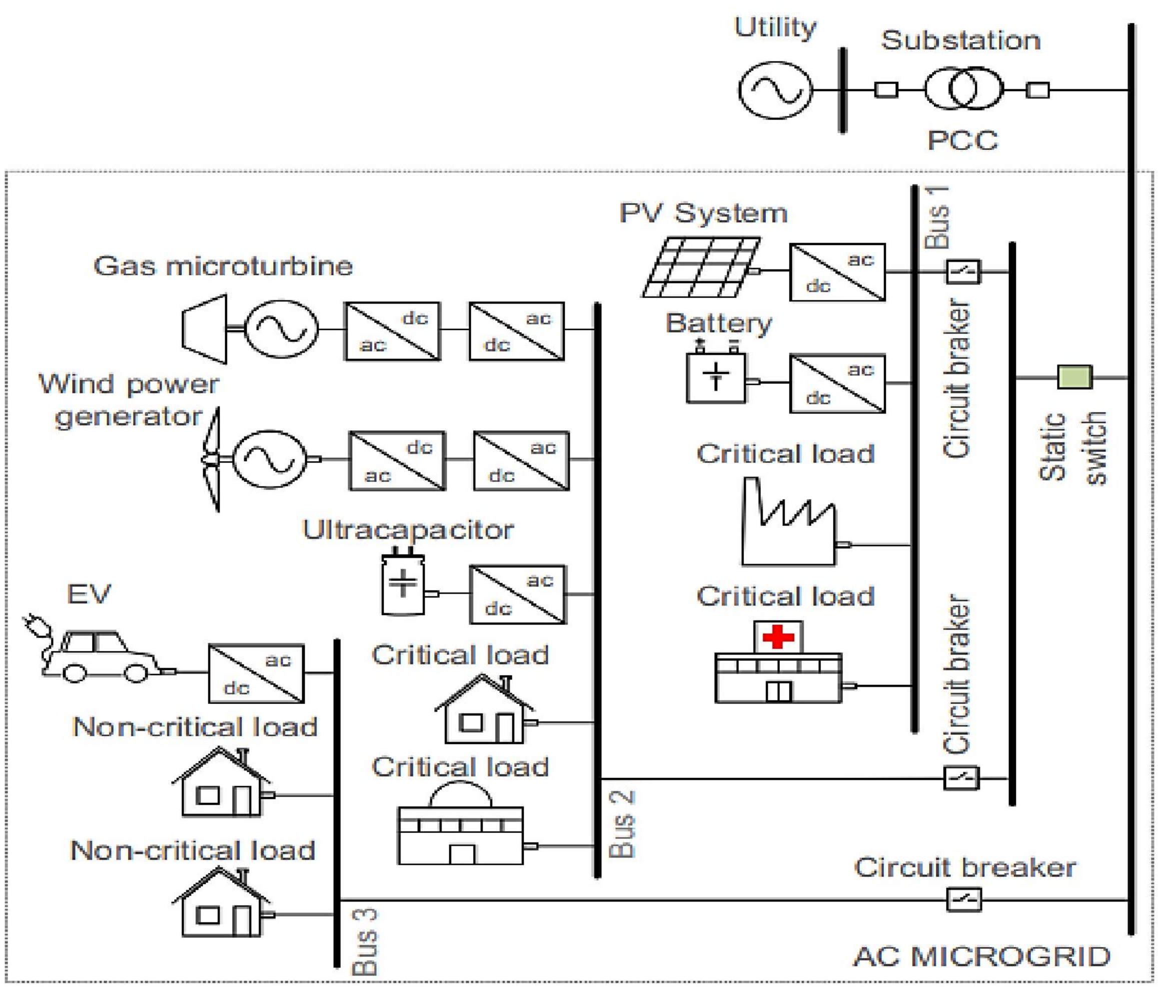
## 1.5 Micro grids architecture

In order to manage the flow of energy from different types of sources into the electrical grid, architectures are needed; thus, the micro-grid can be classified into three main categories, namely: AC micro grid, DC micro grid, hybrid micro grid.

### 1.5.1 AC micro grid

Power sources with AC output are interfaced to AC bus through AC/AC converter or AC/DC then DC/AC converter which will transform the AC variable frequency and voltage to AC waveform with another frequency at another voltage. While power sources with DC output use DC/AC converters (inverters) for the connection to the AC bus as shown in figure 1.2.

In the example below, the micro grid contains three AC feeders, two of them have critical loads, distributed generators, energy storage devices while the other one contains only non-critical loads.Through the circuit breaker, the micro grid can adapt generation and demand to any operating conditions by just changing its topology.The main role of the static switch is to connect the micro grid with the utility and disconnect it when the power quality is poor, leaving it in islanded mode, this maintains high quality and reliable supply to the critical loads which are fed from both distributed generators and energy storage devices [10].



### 1.5.2 DC micro grid

From the example of the DC micro grid shown in figure1.3, the most important power electronic converter is the bidirectional AC/DC interface (IC) because it allows the DC micro grid to be connected at the PCC with the AC utility grid, and permits power exchange in both ways since it is bidirectional, also it regulate the DC bus voltage providing an extremely high power quality for the micro grid regardless the utility grid quality.

Distributed generators and energy storage devices are connected to DC bus through power electronic interface DC/DC (choppers) or AC/DC (rectifiers).

DC micro grid have a simpler structure and a lower system costs and an improved efficiency compared to the AC micro grid [10].

Figure1.3 shows the diagram of the DC micro grid.

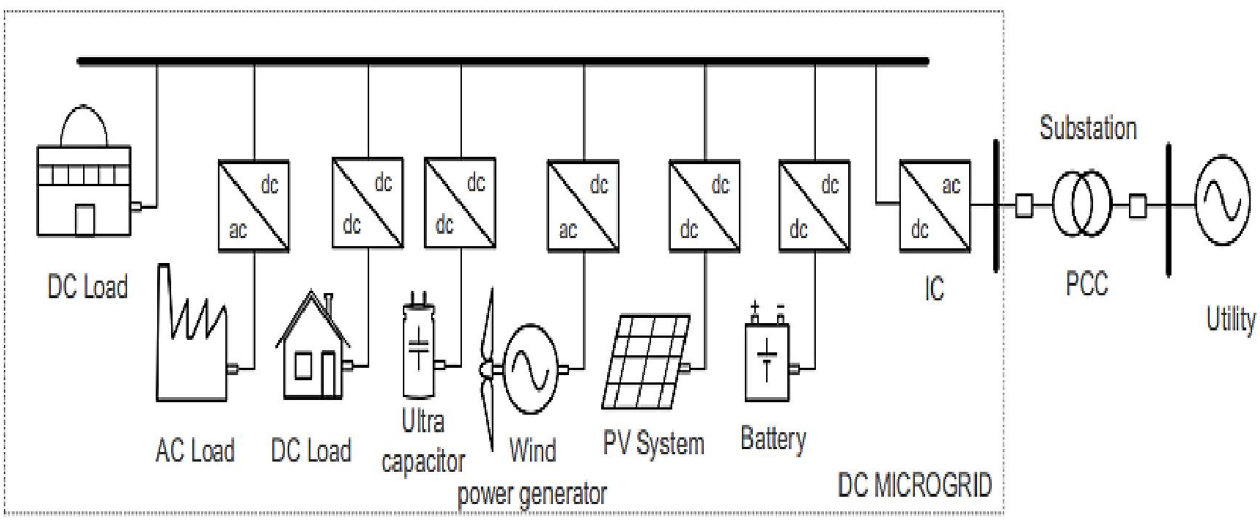



**Figure1.3** DC micro grid [10]

### 1.5.3 Hybrid micro grid

It combines both AC and DC architectures in the same distribution grid.

The AC and DC grids are connected via the AC/DC bidirectional converter while the AC and DC loads are linked respectively to the AC and DC buses using a power converter.Distributed generators and energy storage devices can be either connected to DC or AC buses.The architecture of the hybrid micro grid makes the electronic interfaces very simple, it helps also to reduce conversion stages so that it minimizes energy losses [10].

The diagram of the hybrid micro grid is shown in figure1.4.

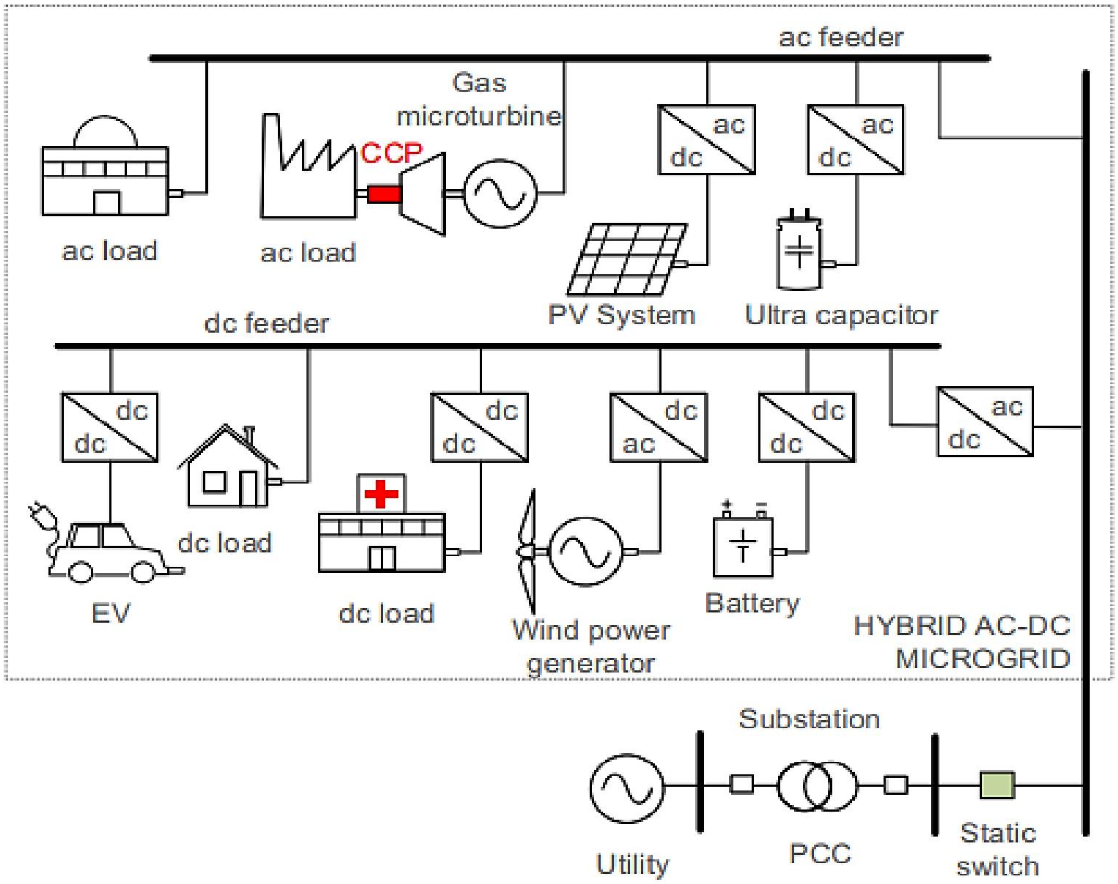



**Figure1.4** Hybrid micro grid [10]

## 1.6 Types of micro grids

Many types of micro grids are distinguished [7] [11]

### 1.6.1 Campus or institutional micro grids

Campus micro grids focus on onsite current generation aggregation, particularly in a combined cooling, heat, and power (CCHP) application to support various loads located in a tight geographical area where they can be easily managed by the owner.

So far this type of micro grids has been a successful model containing the largest micro grids, with capacities ranging from 4 to more than 40 MW.

### 1.6.2Community or utility micro grids

They are able to serve thousands of customers and support the penetration of local energy (electricity, heating, and cooling).

In a community microgrid, some houses may have some renewable sources that can supply their demand as well as that of their neighbours within the same community.

**Figure1.5** Community Micro grids change the future one neighborhood at a time

### 1.6.3 Remote off-grid micro grids

Due to some economic issues and geographical position, this type of micro grids are not able to operate in grid-connected mode, they are never linked to the utility grid and instead they always function in an island mode.

An "off-grid" micro grid is often built where there is a need to electricity but no access to a wide-area electrical grid. Running an off-grid micro grid in rural areas that are dominated by renewable sources reduces the cost of energy production during the life of such micro grid operations.

Such micro grids are built to be energy self-sufficient, intermittent RES and their unexpected variations can lead to an unexpected power shortfall or excessive generation in those micro grids which cause an undesired voltage or frequency deviation in the grid, so in order to avoid such situations, it is recommended to interconnect such microgrids temporary to a neighbouring micro grid for exchanging power and improving the voltage and frequency deviations.

### 1.6.4 Military micro grids

These micro grids are being actively deployed with focus on achieving cost-effective energy security for military facilities which is the capability of an installation to obtain reliable supplies of electricity and fuel and the means to be used in order to protect and deliver sufficient energy to meet critical operations during an extended outage of the local utility grid.

**Figure1.6**military base micro grid in US

### 1.6.5Commercial and industrial (C&I) microgrids

Unlike other types of micro grids, commercial and Industrial (C&I) micro grids focus on meeting the requirements of businesses and corporations, means that their main role is making a profit for only those establishing the micro grid, by lowering the cost of the company's energy consumption and avoiding productivity losses caused by a power outage. They can be optimized to consume supplied power from the utility grid until the energy price rises, at which they move to produce their own energy.

## 1.7 Micro grid operation, control and protection

### 1.7.1 Micro grid operation

The micro grid can operate in two operation modes:

**1.** Grid-connected mode: the micro grid is linked to the utility grid through a point of common coupling (PCC) and receive all or some of the energy by the main grid (depending on the power sharing). On the other side, the main grid can also receive power excess from the micro grid in case when the total production is greater than power consumption.

**2.** Island Mode: the micro grid can disconnect from the utility grid and move to islanded operation mode when the utility is having a problem, or there are some planned maintenance actions. Conflicting interests among various stakeholders involved in power supply, such as system/network operators, DG owners, DER operators, energy suppliers, customers or users, may have an impact on the micro grid's operation [12] [13]

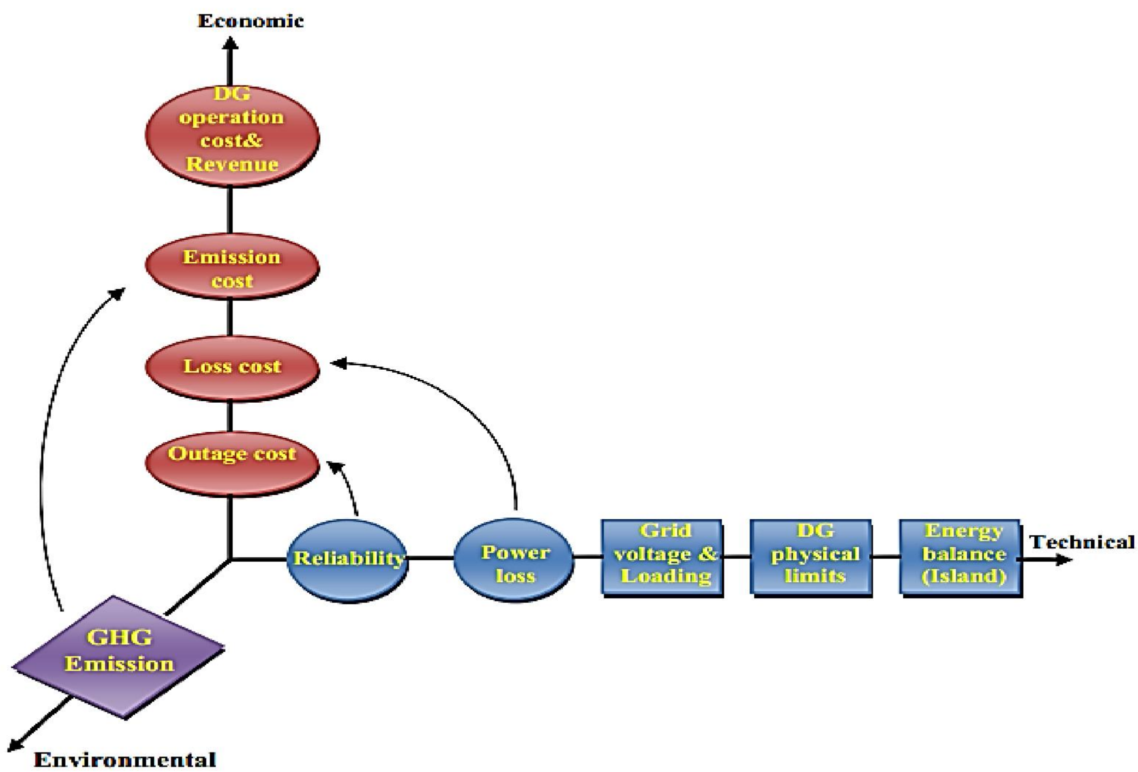



**Figure1.7** micro grid operation strategies [13]

There exist four micro grid operation strategies presented in figure1.7 [13].

## a. The economic option

The main goal is to reduce total costs of DER operation and Revenue. This option includes lost cost and emission obligations. The constraints are described as the physical constraints of DER and energy balance [13].

## b. The technical option

The objective function of this option is to minimize the power loss while the constraints are the voltage variation and device loading, DER physical limits and energy balance.

## c. The environmental option

DER units with lower specified emission levels will be the preferred objective, regardless of cost or technological considerations. The goal of this option is to reduce the emissions cost.

## d. The combined option

This option addresses a multi-objective issue by taking into account all of the economic, technical and environmental considerations, the economic and the economic equivalents of the technical and environmental are the main objective, in the other hand the voltage variation and loading, DER physical limits and the balance energy are considered as constraints.

## 1.7.2 Micro grid control

There exist a lot of control techniques that are shown in figure1.8 which help to manage the component level of a distribution system [4] [14].

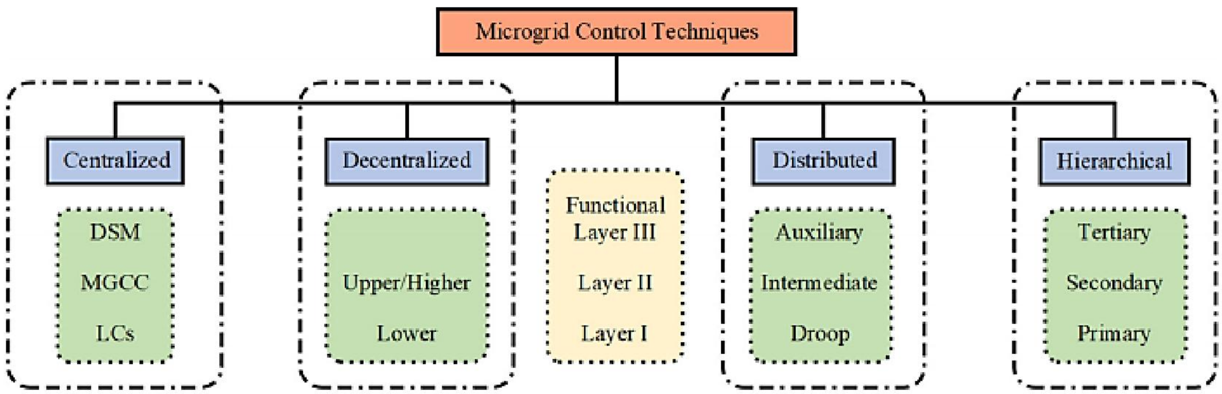



**Figure1.8** Classification of micro grid control techniques and functional layer system [14]

## a. Centralized control system

The system's intelligence is obtained from a certain central point, depending on the type of the network, it may be a switch, a server, or a router controller.

A centrally-controlled system is very simple to be used, because it provides the operator who is in charge of the entire system with an increased control; in order to achieve power necessities this feature enables the managers to create wide control techniques, however, the centralized control system requires only a single control device that handles every collected data by measurement.

Various communication issues, as well as several malfunctions that could shut down the entire system may arise due to this unique controller.

## b. Decentralized control system

In opposition to a "master" controller, the decentralized controller enables a system in which all devices may operate themselves autonomously. For example, a decentralized controller can require operation or not from a distribution point, where such a solution boosts the overall system's communication speed.

The manager may lose control, affecting the entire micro grid because the whole decisions are made in the distribution level, this is why a well-organized control system is required to be built with high installation costs than that of the centralized control system, the optimum solution, is proposed by some researchers to perform a decentralized control and known as the multi agent-based control system (MAS) which combines the characteristics of both the centralized and decentralized control systems.

## Comparison of methods

Among the other types mentioned above, MAS-based decentralized control has various advantages as shown in table1.1.

**Table1.1** Study on centralized and decentralized control techniques

| Characteristic | Centralized | Agent-based control (MAS) |
|---|---|---|
| Power management | Better power management ability | Power management ability is good |
| Access of information | It is not possible to obtain all the data by MGCC | MAS provides each independent control with information about its neighbour |
| Data communication structure | A significant flow of data is required to produce similar results (Global & synchronous communication) | Localized network and data exchange is required for MAS communication (Local & asynchronous communication) |
| Real time functionalities | Difficult and expensive | Comparatively easy and inexpensive |
| Plug & play capability | MGCC must be programmed | Can be achieved without any modification in the controller |
| Configuration | Expensive | Cheap |
| Grid model | Global grid model | Local grid model |
| Efficiency | More efficient | Less efficient |
| Fault tolerance ability | Poor fault tolerance ability | Better fault tolerance ability |
| Flexibility & modularity | Reconnection is required for additional DERs | MAS able to install modular and scalable system with high precision |
| Complexity of the control | Implementation of complex controllers is somewhat easier | Implementation of complex controllers is hard |

### c. Distributed control system

The distributed control architecture has a three-layered structure: droop/lower, secondary/intermediate and auxiliary/upper, it is considered as an improvement on the decentralized approach, in which each local controller communicates with its nearby ones through channels in a collaborative way in order to get some of the intended benefits of the centralized design for the entire MG.

Each device is managed based on local measurements taking into consideration the reaction of neighbours, it not only protects each controller's autonomy but also fulfills the global goal at the same time.

### d. Hierarchical control system

The hierarchical control system is based on the mismatch in time scales of distinct control requirements, it is divided into a three-level structure: primary, secondary and tertiary, the primary layer functions in a time interval of seconds and milliseconds to control voltage and frequency, the secondary layer operates within minutes which is a little bit slower than the first one in order to eliminate steady state deviations caused by the primary layer activity while the tertiary layer regulates the power flow with the main grid (utility grid) in a time interval of minutes to an hour which is the slowest among the previous layers.

## 1.7.3 Micro grid protection

Protection of a micro grid is currently one of the most critical challenges that face micro grids implementation. Once a micro grid is formed, it is mandatory to make sure that all the components such as loads, lines, energy storage devices and the distributed generations on the island are well protected [15].

Locating faults quickly and precisely is so important for economy, safety and reliability of power system so when a problem arises in both the micro grid and the utility grid, the micro grid protection system must respond rapidly.

If a disturbance occurs in the utility grid, the protection must be tripped as fast as possible to separate the micro grid from the main grid allowing it to operate in island mode, and this is done by a rapid semiconductor switch known as a static switch (SS).

In case the problem (fault) occurs within the microgrid, it is eliminated by isolating the smallest possible section of the distribution feeder by the protection system.

The traditional protection in the distribution system is based on short-circuit current detection. Short-circuit currents will be increased by directly connected rotating-machine-based micro sources. Inverter fault currents are restricted by the ratings of the silicon devices to roughly 2p.u. rated current. The magnitudes of fault currents in islanded inverter-based micro grids may be insufficient to apply typical over-current prevention strategies. This potential necessitates a more comprehensive defense plan [16].

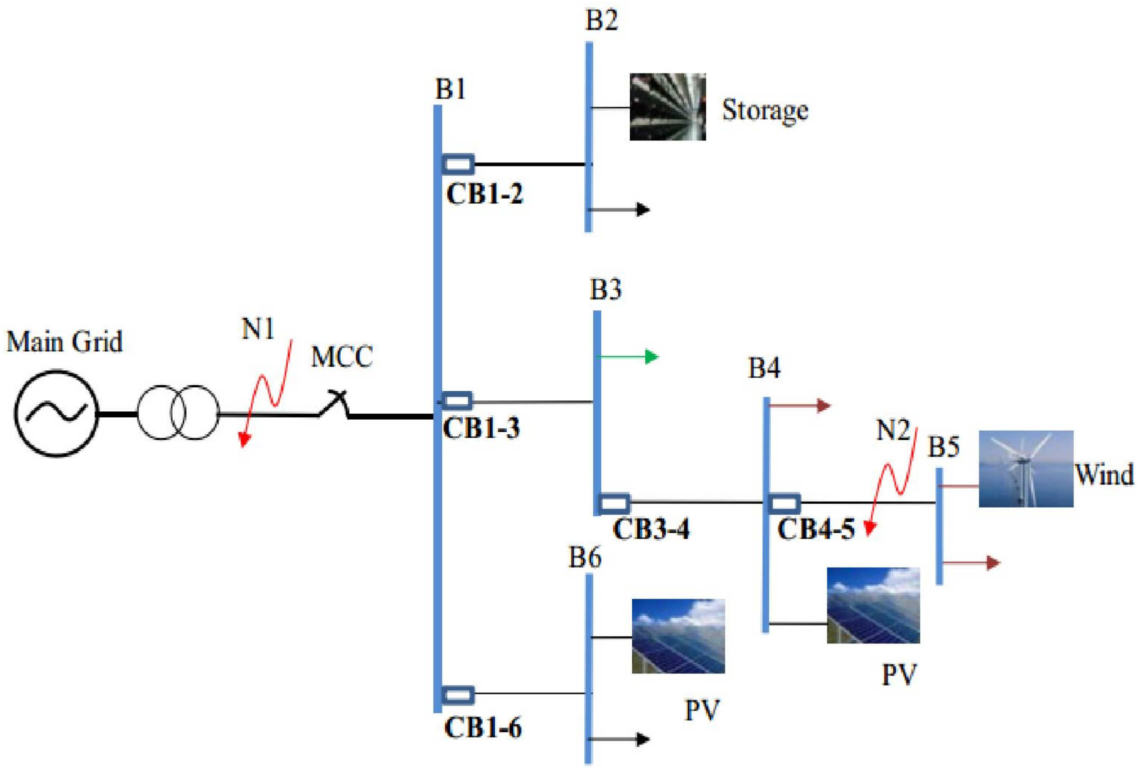



**Figure1.9**external and internal fault scenarios in a micro grid [16]

The fault occurs at N1 is an external fault since this point lies in the utility grid; the static switch (SS) at MCC opens to disconnect the micro grid from the utility grid, after that, the micro grid will operate in the island mode.

In case the fault is internal and appears at N2, and in order to isolate the smallest possible section of the distribution feeder, the circuit breaker CB4-5 would open but the CB 3-4 would operate normally, the source at the bus B5 has to be shut down while the other remaining sources will continue their function.

The automatic adaptive protection is considered currently as a new solution, it was mentioned in [12]. The change of protection settings depends on the micro grid configuration based on pre-calculated or on real-time calculated settings.

## 1.8 Advantages

Some of the advantages of a micro grid are:

A micro grid not only provides a secure backup for the utility grid in case of emergencies, but can also be used to save energy costs since its efficiency is very high.

A micro grid has the ability to disconnect and isolate itself during disturbance from the utility smoothly with little or no disruption to the loads within the micro grid.

A micro grid allows communities to be more energy independent (self-sufficient) and in some cases more environmentally friendly because the greenhouse gas emissions are reduced and carbon footprints are lowered.

As energy becomes ever more critical in our daily lives, micro grids will enable us to shift from central power generation to local flexible reliable forms of sustainable power and thermal energy, so when disaster strikes we will still have all the energy we need to power our life [17].

## 1.9 Conclusion

A micro grid is very important to power our world since it is local, independent and intelligent; however, it may face some power quality issues when EVs are integrated and this is what will be discussed in the next chapter, as well as the suggested solutions to mitigate these issues.

# *CHAPTER 2*

## ∴ *Power quality and EVs reviews*

- ∴ *Introduction*
- ∴ *Definition of power quality*
- ∴ *Power quality progression*
- ∴ *Types of power quality*
- ∴ *Power quality issues*
- ∴ *An overview of electric vehicle technology*
- ∴ *Impact of integrating EVs with micro grid*
- ∴ *Conclusion*

# Power quality and electric vehicles overview

## 2.1 Introduction

In recent years, there has been an increased emphasis and concern for the quality of the power delivered to factories, commercial establishments and residences due to the increasing usage of harmonic-creating non-linear loads like adjustable speed drives, switched mode suppliers as well as electric vehicles (EVs). In this chapter, the most common power quality issues and the solutions to mitigate them are going to be discussed.

## 2.2 Definition of power quality

Power quality could be a term which means diverse things to distinctive individual. The Institute of Electrical and Electronic Engineers (IEEE) defines power quality as "the notion of powering and resting sensitive electronic equipment in a way suited for the outfit" [18]. The limiting of power quality to "sensitive electronic gear" may be open to debate, as appropriate as this description may appear. Electrical gear that is susceptible to control quality, or more accurately, that is in need of control quality, would fall into an ostensibly limitless domain.

When subjected to one or more power quality issues, all electrical equipments are vulnerable to failure or malfunction. An electric engine, a transformer, a generator, a computer, a printer communication gear, or a domestic machine might all be examples of electrical devices. Depending on the inflexibility of problems, all of these and other equipment react poorly to power quality concerns [19].

## 2.3 Power quality progression

The use and transmission of electricity have all progressed rapidly since the discovery of electricity 400 years ago [19].The mechanical revolution was fueled by new and inventive ways to create and use electricity, and since then, researchers, engineers, and experts have contributed to its continued growth. Electrical equipment and devices in the beginning were crude at best, but in any event quite useful. They invested a lot of energy and performed admirably. The machines were constructed conservatively with toll issues in mind since they were auxiliary to execution considerations. They were probably unable to control quality irregularities that existed at the time, but the consequences were not immediately apparent, partly because to the machines' vigor and partly due to a lack of practical means to measure power quality parameters [20] [21].

## 2.4 Types of Power quality

There are several sorts of power quality problems, each of which is classified by a distinct feature. Some of them categorize the events as of: “steady-state” and “non-steady-state” phenomena [22]. In [23] the duration of the event is the most crucial component. Other standards (e.g., IEC) use the frequency range of the event for the classification. Whereas IEC 61000-2-5 uses the frequency range and divides the problems into three main categories: Low frequency (9 kHz), High frequency (9 kHz), Electrostatic discharge phenomena. Each frequency range is separated into disturbances that are "radiated" and "conducted."

## 2.5 Power quality issues

The main classification of the PQ issues is represented in Fig2.1.

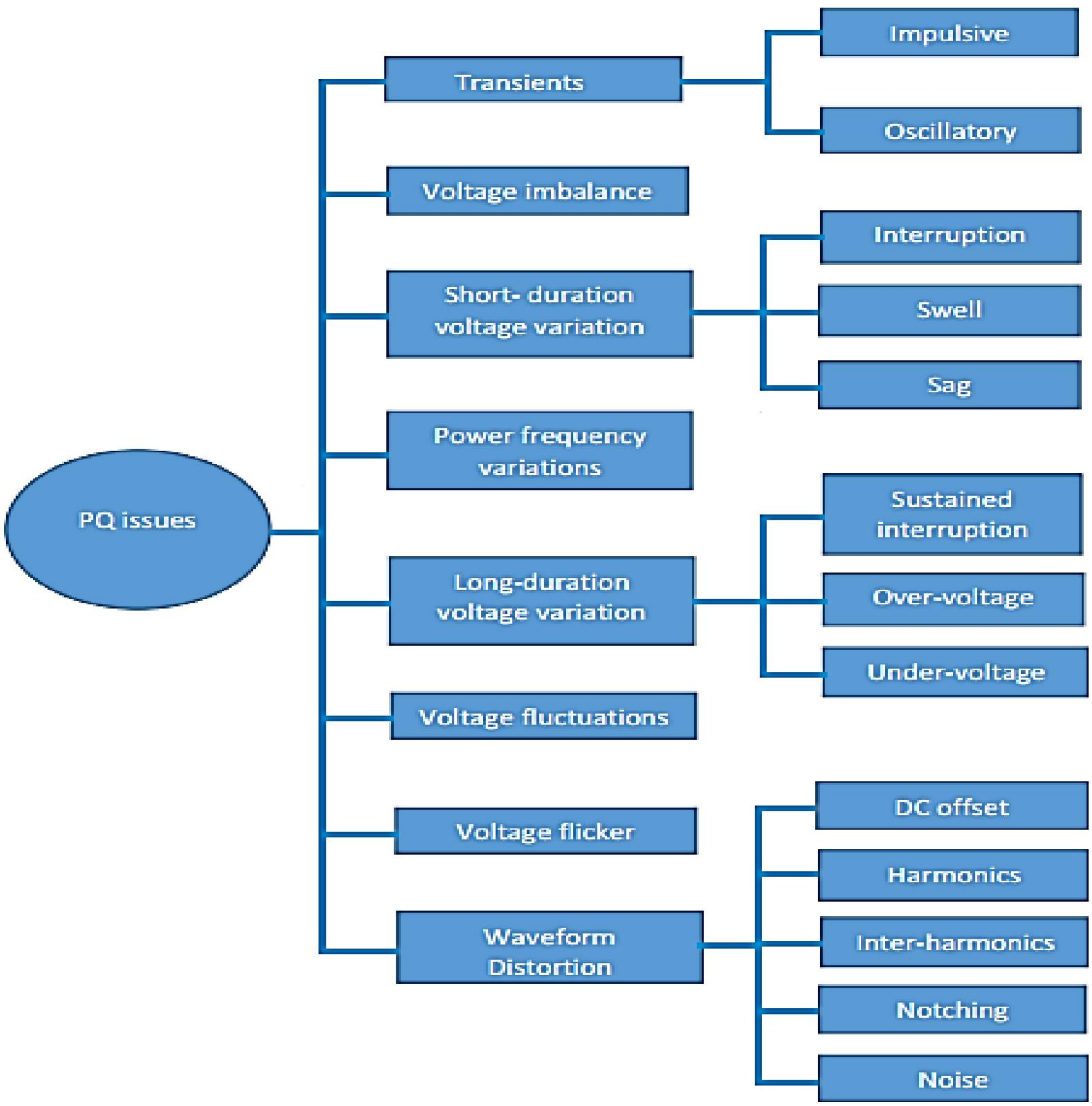



**Figure2.1** PQ issues classification [24]

### 2.5.1 Transients

Transients in the power system are undesired, fast- and short-duration phenomena that cause distortions. Their features and waveforms are determined by the generation method and network settings.

Many characteristics of transients may characterize it, including amplitude, duration, rising time, ringing polarity frequency, energy delivery capabilities, amplitude spectrum density, and frequency of occurrence.

Impulsive and oscillatory transients are the most common types of transients [25].

#### a. Impulsive transient

An impulsive transient is a unidirectional polarized, non-power frequency change in the steady-state condition of voltage, current, or both (primarily either positive or negative) [26].

#### b. Oscillatory transient

An oscillatory transient is a voltage or current whose polarity varies quickly at its instantaneous value. Its spectral content (predominant frequency), duration, and magnitude are used to define it. There exist three categories of frequency spectral content high, medium, and low [26].

### 2.5.2 Short duration voltage variation

Fault circumstances, the energisation of big loads that demand high starting currents, or periodic loose connections in power wiring are usually the causes of short-duration voltage changes. The problem can induce transient voltage spikes (swells) or voltage reductions (sags), or a full loss of voltage, depending on the fault location and system circumstances (interruptions) [22].

#### a. Interruption

According to [27], an interruption occurs when the supply voltage or load current drops to less than 0.1 Pu for a period of time not exceeding 1 minute.

Power system faults, equipment failures, and control issues can all cause interruptions. Because the voltage magnitude is always less than 10% of nominal, the interruptions are quantified by their duration [28].

#### b. Sags (dips)

Short-duration drops in the RMS voltage between 0.1 and 0.9 Pu [29] are known as sags. The duration of sag is not well defined, however it is often between 0.5 and 1 minute.

The most common reasons of voltage sags are [19]:

• Energization of heavy loads.

• starting of large induction motors.

• Single line-to-ground faults.

• load transferring from one power source to another.

### c. Swells

Swell is the rise in voltage magnitude between 1.1 and 1.8 Pu. The most common swell duration is between 0.5 cycles and 1 minute [30].

The amplitude of a swell is likewise determined by its residual voltage, which is always more than 1.0 in this situation. Swells, like voltage sags, are frequently linked with system failure circumstances, but they are far less common [26].

A swell can occur due to:

• Switching off of a large load.

• Energizing a capacitor bank.

• Voltage increase of the unfaulted phases during a single line-to-ground fault.

## 2.5.3 Long duration variations

RMS deviations at power frequencies lasting more than 1 minute are referred to as long duration fluctuations. When the ANSI limitations are exceeded for more than 1 minute, they are declared present. Depending on the cause of the change, long-term variations might be either overvoltage or undervoltage [21].

### a. Overvoltage

Overvoltage can occur as a result of load switching (for example, turning off a heavy load) or changes in the system's reactive compensation (e.g., switching on a capacitor bank). Overvoltage occur when a system's voltage regulation capabilities or controls are inadequate, it can also be caused by incorrect tap settings on transformers [31].

### b. Undervoltage

Undervoltages are caused by events that are the polar opposite of those that produce overvoltage. An undervoltage can occur when a load is turned on or a capacitor bank is turned off until the voltage regulation equipment on the system can restore the voltage to within tolerances [32].

### 2.5.4 Sustained interruptions

The most severe and oldest power quality event is sustained (or long) interruption, in which voltage goes to zero and does not automatically restore. The duration of a persistent interruption is more than 3 minutes according to the IEC standard, but more than 1 minute according to the IEEE definition. The number and duration of long interruptions are critical factors in determining a power system's capacity to provide service to consumers [33].

### 2.5.5 Voltage imbalance

The ratio of the negative or zero sequence components to the positive sequence component is known as voltage imbalance (or unbalance). The negative or zero sequence voltages in a power system generally result from unbalanced loads causing negative or zero sequence currents to flow [34]. In other words, voltage imbalance arises when the magnitudes of the voltages in a three-phase system are not similar and/or the phase differences between them are not exactly 120 degrees.

### 2.5.6 Waveform distortion

Waveform distortion is a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation [35].

There are five primary types of waveform distortion as follows:

#### a. DC offset

Dc offset refers to the presence of a dc voltage or current in an AC power system. This can happen as a consequence of a geomagnetic disturbance or as a result of the half-wave rectification effect [36].

#### b. Harmonics

Sinusoidal voltages or currents with integer multiples of the frequency at which the supply system is meant to operate are known as harmonics (termed the fundamental frequency; usually 50 Hz or 60 Hz). Waveform distortion is caused when harmonics mix with the basic voltage or current. The nonlinear properties of devices and loads on the power system cause harmonic distortion [37].

#### c. Interharmonics

Interharmonics may be observed in all voltage classes of networks. They might take the form of discrete frequencies or as a wide-band spectrum. Static frequency converters, cyclo-converters, induction motors, and arcing devices are the principal sources of interharmonic waveform distortion [38].

### d. Notching

Notching is a periodic voltage disturbance caused by the normal operation of power electronics devices when current is commutated from one phase to another. Voltage notching is a unique situation that exists between transients and harmonic distortion [38].

### e. Noise

Unwanted electrical signals having a wideband spectral content of less than 200 kHz superimposed on power system voltage or current in phase conductors, or detected on neutral conductors or signal lines, are referred to as electric noise [39]. Faulty connections in transmission or distribution systems, arc furnaces, electrical furnaces, power electronic devices, control circuits, welding equipment, solid-state rectifier loads, improper grounding, turning off capacitor banks, adjustable-speed drives, corona, and broadband power line (BPL) communication circuits can all cause electric noise. The problem can be mitigated by using filters, line conditioners, and dedicated lines or transformers. Electric noise impacts electronic devices such as microcomputers and programmable controllers [40].

## 2.5.7 Voltage fluctuations

Voltage fluctuations are random voltage changes or systematic variations of the voltage envelope that do not generally exceed prescribed voltage ranges (e.g., 0.9 to 1.1 Pu as stated by ANSI C84.1-1982) [41]. Voltage fluctuations can be classified into two types:

- Step-voltage changes, regular or irregular in time
- Cyclic or random voltage changes produced by variations in the load impedances [31].

## 2.5.8 Power frequency variations

The deviation of the power system fundamental frequency from its specified nominal value (e.g., 50 or 60 Hz) is defined as power frequency variation [42]. The rotating speed of the generators on the system is directly connected to the frequency of the power system. The frequency is determined by the balance between the load and the capacity of the available generation at any given time.

## 2.6 An overview of electric vehicle technology

In 1834, the electric vehicle (EV) was created by a variety of firms in America, the United Kingdom, and France. During the last decade of the nineteenth century electric vehicles (EVs) have been on the market and they were quite popular and sold successfully until around 1918 [43]. Due to battery limitations, EVs are currently only employed for small cars and limited distance applications [44].

The electric vehicle is mainly characterized by its state of charge which is the capacity of the battery, it has a limit which cannot be exceeded in order to extend its life.

### 2.6.1. Characteristic of EVs

Table2.1 presents a comparison of the interesting characteristics of three types of EVs

**Table 2.1** Characteristics of BEVs, HEVs, and FCVs [44]

| **Type of EVs** | **Battery EVs** | **Hybrid EVs** | **Fuel cell EVs** |
|---|---|---|---|
| Energy system | -Battery<br>-Ultracapacitor | -Battery<br>-Ultracapacitor<br>-ICE generating unit | -Fuel cells<br>-Need battery/ Ultra capacitor to enhance power density for starting |
| Energy source and infrastructure | -Electric grid charging facilities | -Gasoline stations<br>-Electric grid charging(for plug in hybrid) | -Hydrogen<br>-Hydrogen -production and transportation infrastructure |
| Characteristics | -Zero emission<br>-High energy efficiency<br>-Independence of crude oils<br>-Relatively short range<br>-High initial cost | -Very low emission<br>-Higher fuel economy as compared with ICE vehicles<br>-Long driving range<br>Dependence on crude oil<br>-Higher cost as compared with ICE vehicles<br>-The increase in fuel and reduce in emission depending on the power level of motor and battery | -Zero emission or ultra-low emission<br>-High energy efficiency<br>-Independence on crude oil<br>-Satisfied driving range<br>-High cost |
| Major issues | -Battery and battery management<br>-Charging facilities | -Multiple energy sources<br>-Battery sizing and management | -Fuel cell cost /cycle life and reliability<br>-Hydrogen infrastructure |
| Propulsion | -Electric motor drives | -Electric motor drives<br>-Internal combustion engines | -Electric motor drives |

### 2.6.2 The concept of V2G

Users of plug-in electric vehicles can sell electricity stored in their batteries back to the power grid, allowing utilities to manage demand peaks more effectively [45].

A vehicle-to-grid (V2G) system would take use of the fact that most automobiles are parked 95% of the time. During these moments of inactivity, the stored electricity in the batteries might be transferred from the PEV to the power lines and then back to the grid. In the United States, this return to the grid is anticipated to cost utilities up to $4,000 per car each year [46].

In a V2G system it would also be expected that battery electric (BEVs) and plug-in hybrids (PHEVs) would have the capability to communicate automatically with the power grid to sell demand response services by either delivering electricity into the grid or by throttling their charging rate [47].

### 2.6.3. Charging strategies

The following diagram categorizes all different charging methods into 14 main strategies. Where they are divided into two main groups: Uncoordinated Strategies and Coordinated Strategies.

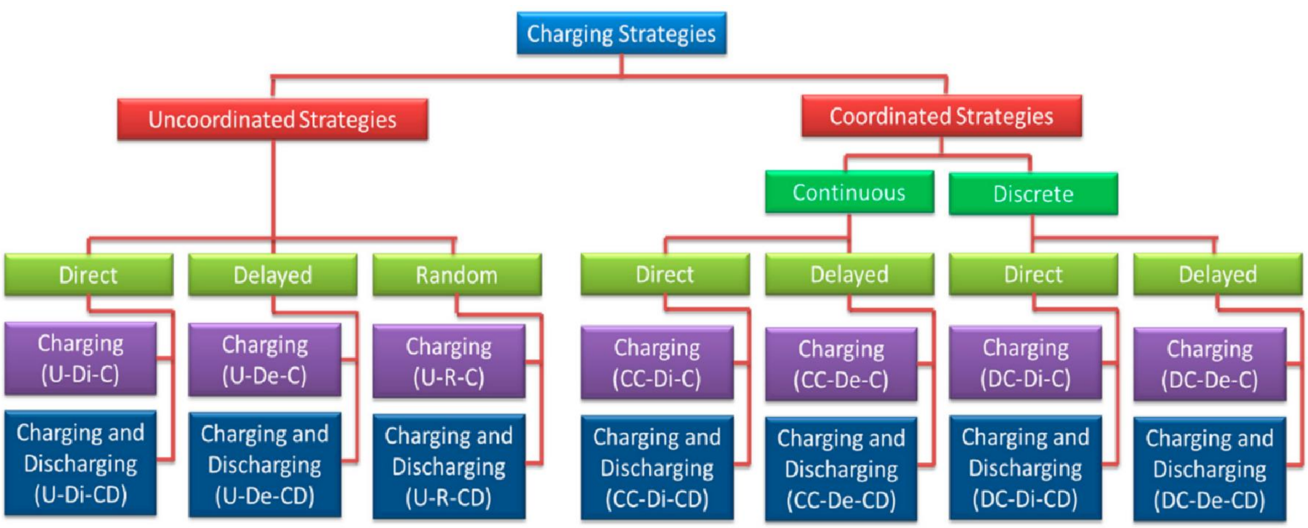



**Figure 2.2** Coordinated and Uncoordinated Strategies [48]

### a. Uncoordinated Strategies

Uncoordinated Strategies (USTs) are defined as the "charging" or "charging and discharging" processes (also known as modes) of a single or a fleet of electric vehicles that take place in an irregular situation, without scheduling, optimization algorithms, or coordination between different EVs on the same transformer. As shown in Figure 3.1, this category includes three alternative charging and discharging techniques as well as six basic strategies [49] [50].

## b. Coordinated Strategies

CSTs are described as the "charging" or "charging and discharging" modes of a single or a fleet of EVs that occur in a coordinated way, with scheduling, utilizing optimization approaches, with or without coordination between various EVs on the same transformer, and according to price systems [49] [50].

"Continuous" and "Discrete" Charging Strategies are the two primary branches of this category.

## 2.7 Impact of integrating EVs with micro grids

Electric cars will reach new levels of limitless possibilities. These cars assist not only to reduce pollution, but also to save natural resources researches are attempting to mitigate hybrid technology into electric cars which will result in higher power and efficiency; however, in order for electric vehicles to become a reality, a sufficient infrastructure should be in place, from car construction, to charging stations, all must be created in a methodical manner. Electric cars must be charged in a regular basis, as a result, suitable charging stations must be constructed in regular intervals. These charging stations for electric vehicles have a number of difficulties that might cause harm as well as shortening their life spam and affecting the power quality, harmonics, voltage lag, losses and other power quality issues as shown in table2.2 [51].

**Table2.2** methods to mitigate the impact of EV integration on PQ [24]

| **impacts** | **Methods** |
|---|---|
| Impact of EV integration on voltage profile | -Charging discharging of EVs (smart load management control SLM ) -Active power curtailment/ Reactive power support |
| Impact of EV integration on voltage imbalance | -EV charging /discharging management -A phase reconfiguration approach |
| Impact of EV on power loss | -Coordinating EV charging /discharging ( real time scheduling method ) |
| Impact of EV on harmonic | -Absorbing or injecting harmonic currents coordinating with wind generators |
| Impact of EV on frequency | -Primary frequency control considering charging demands |

## 2.7.1 Impact of EV integration on voltage profile

PEV chargers are large and unpredictable loads that might have a negative influence on distribution grid performance. Utilities are worried about the potential overloads, strains, and voltage instability that residential PEV charging activities, as well as newly emergent charging stations, may cause in distribution networks. As a result, alternative techniques for mitigating the impact of EV integration on voltage profile are suggested.

## a. Charging management of EVs

New smart load management (SLM) approach for the coordination of multiple plug-in electric vehicle (PEV) chargers in distribution feeders is proposed

## Smart load management control (SLM)

The new SLM control technique is mainly designed to coordinate PEV charging based on peak demand shaving, voltage profile improvement, and power loss minimization. Furthermore, the proposed SLM technique uses a priority selection mechanism to take into account the PEV owner's chosen charging time zones. PEV charging stations and average daily household loading patterns are also taken into account.SLM is supposed to work as part of a distribution feeder's DMS to schedule PEV battery chargers intelligently while taking distribution system performance into account. This method takes into account human inputs by allowing the PEV owner to choose the priority of PEV charging.

As an alternative to PEV chargers randomly and immediately operating when first plugged in, or after some fixed time delay, the proposed SLM will decide which PEVs will commence charging and at what time. PEV charger control can be achieved through the forthcoming smart grid communications infrastructure by sending and receiving signals to individual PEV chargers. This means that PEV charging control would be taken out of the hands of the owner and scheduled automatically.

The proposed SLM will perform peak shaving, loss minimization and voltage regulation based on the system constraints. Furthermore, it also takes into consideration existing load variations over a 24 h cycle, while factoring PEV owner preferences for charging time zone and priority.

The designed SLM allows PEV owners to choose their favorite charging time zone, and it will make every effort to respect their preferences in charger scheduling while keeping the peak shaving and loss reduction goals in mind [52].

## b. Active power curtailment

This method is to reduce the EV charging power or PV production power upon grid congestions like typical big voltage drop (for EV) or voltage increase (for PV). Because of the resistive feature of low voltage grid (i.e. line resistance is typically larger than line reactance) the active power reduction can relieve the voltage deviation effectively. Though it is effective in terms of voltage regulation, the main drawback of this method is that it will lead to longer charging time for EVs or less production for PVs [53].

### c. Reactive power support

This method is to adjust reactive power output of EVs or PVs to compensate the line voltage drop or rise caused by them. The effect of this method is limited due to the fact that low voltage grid is typically resistive, and reactive power does not have significant impact on the voltage variation. The additional burden of this method is also obvious by the fact that the ratings of the power electronic interfaces of EV or PV have to be larger to perform reactive power support ability. Also the line losses become larger due to this additional reactive power flow [53].

## 2.7.2 Impact of EV integration on voltage unbalance

From the distribution system operator point of view, the power losses during charging are an economic concern have to be minimized and transformer and feeder overloads have to be avoided. Not only power losses, but also power quality (e voltage profile, unbalance, harmonics, etc.) are essential to the distribution grid operator as well as to grid customers. Voltage deviations are a power quality concern. Too large voltage deviations cause reliability problems which must be avoided to assure good operation of electric appliances.

Overnight recharging can also increase the loading of base-load power plants and smoothen their daily cycle or avoid additional generator start-ups which would otherwise decrease the overall efficiency [54].

### a. Phase reconfiguration approach

From the viewpoint of a PEV owner, the PEV's batteries must be charged overnight so that the driver may drive away with a completely charged battery the next morning. This opens up the possibility of intelligent or smart charging. The charging might be coordinated remotely in order to shift demand to periods of lower load use, so avoiding higher power consumption peaks [54].

### Charging periods

Three major charging times are suggested. The first charging time occurs at night and in the evening. From 21h00 until 06h00 in the morning, the majority of the vehicles are at home. When some PHEVs get home from work, they're immediately plugged in so they'll be ready to go for the rest of the evening. As a result, the second charge period occurs between 18h00 and

21h00. This charge time corresponds to the evening's peak load. During this time, the number of cars that will be taxed is likely to be lower. Another pricing time is considered, which is between the hours of 10 a.m. and 16 a.m.

## Uncoordinated charging

Because no smart metering system for PHEVs is currently available, the vehicles will be charged without coordination. Uncoordinated charging means that when the vehicles' batteries are plugged in, they either start charging instantly or after a user-adjustable set start delay. Vehicle owners now lack both the incentive and the necessary information to schedule battery charging in order to optimize grid consumption. The fixed start delay was implemented to allow car owners to begin charging utilizing off-peak electricity tariffs.

## Coordinated charging

Smart metering and transmitting signals to specific cars will allow for direct charge coordination. In general, by flattening peak output, coordinated charging of plug-in hybrid electric vehicles can reduce power losses and voltage variations. When charging durations are chosen randomly, however, the influence of the PHEV penetration level is significant. The expense of implementing coordinated charging is not insignificant.

## b. EV charging /discharging management

In distribution systems, the location of household loads and their consumption at each hour are varied, that leads to change VUF of network.

In case PEVs were absent, VUF can be only affected via connection phase and demand of household loads. For this condition, VUF can be controlled in the allowable range only by changing the customer’s load connection point and their consuming power.

In the case where PEVs are connected to grid with uncoordinated charging method, they can cause to increase VUF and threat the network. In this state, PEVs are connected to each phase without any scheduling program and VUF depends on PEVs connection phase, location and network loads situation.

Due to wide spread distribution of PEVs in the network and enough number of PEVs, they have good potential to improve VUF if the coordinated charging and discharging method is applied.

The charging and discharging variable rating power with bidirectional power flow have more effects on VUF reducing. In coordinated charging and discharging, each PEV is connected to grid based on scheduling program and different parameters have effect on VUF such as time of connection, the charging and discharging power rate, PEV point of connection, and etc.

In the single direction power flow (from grid to vehicle or only charging mode) with constant power, the maximum VUF is lower as compared to uncoordinated charging. In this mode, the accepted PEVs depend on the network loads.

The impact of discharging capability of EVs (V2G) besides their charging. Using this property, some PEVs can supply a part of household loads and cause to reduce voltage unbalance.

The best condition to reduce VUF is using coordinated charging/discharging of PEVs with variable rating power that VUF can be reached to its minimum value.

In other words, the bidirectional power flow can decrease VUF in comparison with only charging mode. Similar to charging mode, variable-bidirectional power flow leads to lower VUF [55].

### 2.7.3Impact of EV integration on harmonic

Wind generators (WGs) and electric vehicles (EVs) that employ power-electronic interface cause harmonic disturbances in the power system. Higher penetration and uncoordinated WG and EV operation can result in voltage and current harmonic distortions that may exceed IEEE limitations. It's worth noting that WGs and EVs have several harmonic characteristics in common. As a result, when EVs are linked to the grid, the quantity of wind power injected into the system can help to lessen the harmonic pollution EVs cause, and vice versa [56].

### a. Absorbing or injecting harmonic currents coordinating with wind generators

EVs and wind power have capability to help reduce the emissions and depletion of fossil fuel. Despite the benefits integration of EVs and wind generators (WGs) in the power network also causes adverse impacts because of the increased load from EV charging and intermittency of wind power [57] [58].

Uncoordinated charging of a large number of EVs impacts the overall residential load curve, and also increases harmonics in the power grid due to non-linearity; however, power losses and voltage THDs are found much less in the case of coordinated charging of EVs.

Low EV penetration is not a worry for voltage THDs, as the THDs are less than 5%, which is within the IEEE's guidelines. Low EV penetration, on the other hand, has been demonstrated to have a major influence on current THDs. Furthermore, significant EV penetration has been demonstrated to have negative effects on current and voltage THDs. When WGs are used in a test feeder with EV loads, it is shown that they can assist reduce THDs at some nodes while increasing THDs at others. This showed that WGs can help to alleviate THDs produced by EVs;

however, the appropriate dispatch of WGs is to be determined in order to achieve the benefits of WGs to reduce THDs.

### 2.7.4 Impact of EV integration on power loss

When considering the potential demand produced by incremental PEV grid integrations, power system losses become a big problem. Off-peak charging might result in energy losses of up to 40% for 62 percent of PEV market penetration. With rising PEV penetration, network power losses increased sharply, almost regardless of location. This, however, is countered by the fact that network losses are dependent on load location.

According to recent research, distributing PEV charging demand over a longer time period can significantly minimize system losses. PEV, like any other high-demand load, increases network power flow, resulting in substantial system losses. Off-peak charging, appropriate phase balancing methods, and serving the PEV load with local distributed generators are some of the ways to mitigate this impact.

### a. Coordinating EV charging /discharging

One of the main places where EVs will be charged is at home. Many recent studies have shown that random unscheduled EV charging at home may significantly put 3-stress on the low-voltage residential distribution system [58]. The associated problems include increased peak load and losses, excessive voltage drop and branch overloading.

These studies also pointed out that, by properly scheduling and controlling EV charging, the existing network infrastructure should be able to accommodate a much higher EV penetration level.

A real-time scheduling scheme for EV charging in low-voltage residential distribution feeder is proposed. This scheme schedules EV charging either to minimize system losses or to avoid voltage dropping below the lower limit during the charging period, depending on whether the EV penetration level is sufficiently high to make the voltage drop become the binding constraint

### Real-time scheduling

Real-time scheduling deals with random arrivals and departures of EVs. Whenever an EV is plugged-in or out at a certain node, the scheduling shall be performed to update the charging plan. Owner's to respect the EV autonomy, an EV owner can specify his/her expected departure time and desired final SOC. If the desired final SOC cannot be satisfied before the expected departure time even if the EV is charged at the maximum allowable power, this EV is classified as unschedulable, schedulable; otherwise, it is unschedulable EVs take the maximum allowable charging rate and are treated as part of the base load in the scheduling. The schedulable EVs are further divided into groups. EVs belonging to a certain group have the same or very close expected departure time. The next step of scheduling is to calculate the .V levelled using the latest expected Devi tot, t departure time. The scheduled charging capacity is then distributed to the EV groups discriminately. For example, suppose that there are three groups of EVs. The group with the earliest expected departure time is given sufficient scheduled charging capacity in time interval 1h–(1802 h). Subsequently, the group with the second earliest expected departure time is assigned sufficient scheduled charging capacity from the remains in time h– interval 1 and 2 (1804 h). Finally, the group with the latest expected departure time utilizes the remaining h– charging capacity in time interval 1, 2 and 3 (18 06 h). As a result, in each time interval, a proportion which group's dictates the respective EV share of the scheduled charging capacity can be determined [59].

### 2.7.5 Impact of EV integration on frequency

Generation and load in electric power systems must be equal in real time; otherwise, the grid frequency will deviate from the standard value. If the grid is subjected to a high charging load from EVs, more power generation will be required to keep the grid frequency within the permitted range [60]. In addition, the departure and arrival times of electric vehicles are subject to uncertainty. As a result, power systems are likely to face increasing demand-side uncertainty.

EVs can also be used as mobile storage and controllable loads. Vehicle-to-grid (V2G) technology, which allows bidirectional power transfer between EVs and a power grid, will open up new possibilities for power system optimization. The provision of frequency regulation services is one of the most essential uses of V2G. When the frequency of the system drops, EV charging load reduction or EVs operating as power providers can prevent the frequency from dropping any further. EVs, on the other hand, might absorb power from the grid to avoid additional frequency increases. This sort of V2G control has been found to be suitable for providing regulation services in energy balancing markets [61][62].

### a. Primary frequency control considering charging demands

When the remaining battery energy is low, the customer has to charge the EV to a higher SOC level. On the other hand, if the residual SOC is sufficiently high in the day time, the EV customer is generally willing to maintain the SOC and recharge the EV in the night considering the low off-peak electricity price. Therefore, except for frequency droop control, it is necessary for the V2G control strategy to include both maintaining the SOC and achieving charging demand.

Vehicle-to-grid (V2G) control has the potential to provide frequency regulation service for power system operation from electric vehicles (EVs). In the next chapter, a decentralized V2G control (DVC) method is proposed for EVs to participate in primary frequency control considering charging demands from EV customers.

When an EV customer wants to maintain the residual state of charge (SOC) of the EV battery, a V2G control strategy, called battery SOC holder (BSH), is performed to maintain the battery energy around the residual SOC along with adaptive frequency droop control. If the residual battery energy is not enough for next trip, the customer needs to charge the EV to higher SOC level. Then, a smart charging method, called charging with frequency regulation (CFR), is developed to achieve scheduled charging and provide frequency regulation at the same time. Simulations on a two-area interconnected power system with wind power integration have shown the effectiveness of the proposed method [63].

## 2.8 Conclusion

The main power quality issues and their suggested solutions were presented, as well as the impacts of EVs integration on voltage and frequency. In the next chapter, a detailed simulation on primary frequency control strategy is done with the obtained results that are discussed and compared in parallel with similar works.

# *CHAPTER 3*

## ∴ *Results and discussions*

- ∴ *Introduction*
- ∴ *Description of the DVC*
- ∴ *Simulation system*
- ∴ *Simulations and discussions*
- ∴ *Conclusion*

# Simulation results and discussions

## 3.1 Introduction

Any power system is mainly characterized by two parameters : voltage and frequency, so in order to keep the expected operating conditions and avoid unexpected disturbances that affect the connected loads and cause the system to fail, it is necessary to control these parametrers within predefined limits.

Power generation and load must be equal in the real time; otherwise, the grid frequency deviates from the standard value (Fn±0.1 Hz) where the nominal frequency (Fn) is 50 Hz (Europe and most of Asia) and 60 Hz (North America) [64].

With the high integration of electric vehicles, the grid is imposed to high charging load, so more power generation would be required to maintain the grid frequency within the permitted range and this can be achieved using a method called “Decentralized Vehicle-to-Grid Control”.

## 3.2 Description of the DVC

The DVC is a method that achieves bidirectional power flow between EVs and a power grid to offer frequency regulation service and achieve charging demands which are the two main concerns to be handled. EVs can act as mobile storage devices and produce power to avoid further drop in frequency, also they can act as controllable loads and absorb the power from the grid in order to prevent further increase in frequency.

The main challenge facing the DVC is to balance between frequency control and requirements from EV users which are: maintaining battery SOC (Type I) and achieving charging demands (Type II) since these EV customers care about battery state of charge (BSOC) more than frequency regulation. The EV customer tends to charge the EV to a higher SOC level if the remaining battery energy is low; On the other hand, if the residual SOC in the day time is sufficiently high for the next trip, the customer is generally willing to maintain the SOC and recharge the EV at home considering the low off-peak electricity price in the night [63].

### 3.2.1 BSOC holder (BSH)

The BSH is designed for EVs willing to maintain their BSOC while joining in primary frequency regulation with an adaptive droop depends on the real time SOC and the initial SOC.

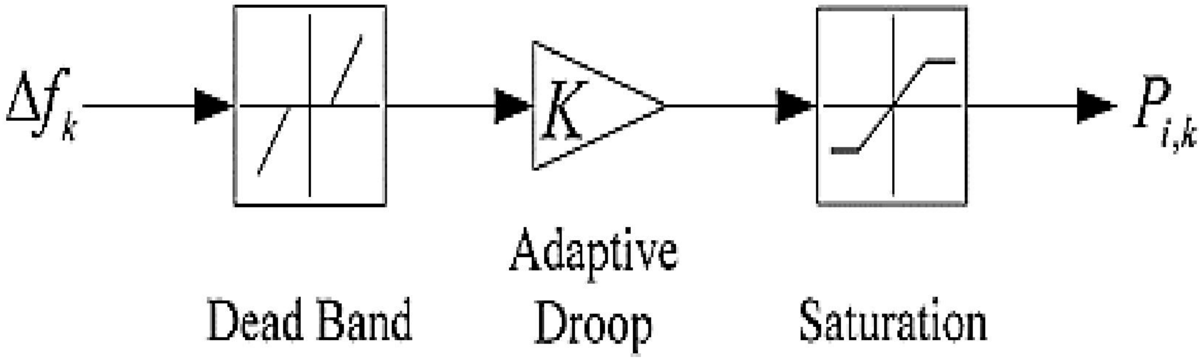



**Figure3.1** Adaptive droop control loop of the BSH for the EV charging/discharging power

The adaptive droop can be calculated as follows:

**1**. If $SOC_{i,k} \leq SOC_i^{min}$, then:

$$K_{i,k}^c = K^{max} \qquad (3.1)$$

$$K_{i,k}^d = 0 \qquad (3.2)$$

**2**. If $SOC_{i,k} \geq SOC_i^{max}$, then:

$$K_{i,k}^c = 0 \qquad (3.3)$$

$$K_{i,k}^d = K^{max} \qquad (3.4)$$

**3.**If $SOC_i^{min} < SOC_{i,k} \leq SOC_i^{in}$, then:

$$K_{i,k}^c = \frac{1}{2} K^{max} [1+\sqrt{((SOC_{i,k} - SOC_i^{in}) / (SOC_i^{min} - SOC_i^{in}))}] \qquad (3.5)$$

$$K_{i,k}^d = \frac{1}{2} K^{max} [1-\sqrt{((SOC_{i,k} - SOC_i^{in}) / (SOC_i^{min} - SOC_i^{in}))}] \qquad (3.6)$$

**4**. If $SOC_i^{in} < SOC_{i,k} < SOC_i^{max}$, then:

$$K_{i,k}^c = \frac{1}{2} K^{max} [1-\sqrt{((SOC_{i,k} - SOC_i^{in}) / (SOC_i^{max} - SOC_i^{in}))}] \qquad (3.7)$$

$$K_{i,k}^d = \frac{1}{2} K^{max} [1+\sqrt{((SOC_{i,k} - SOC_i^{in}) / (SOC_i^{max} - SOC_i^{in}))}] \qquad (3.8)$$

From the above equations the following relationship can be deduced:

$$K_{i,k}^c + K_{i,k}^d = K^{max} \qquad (3.9)$$

Adaptive droop of the BSH for maintaining the initial SOC is illustrated in figure3.2.

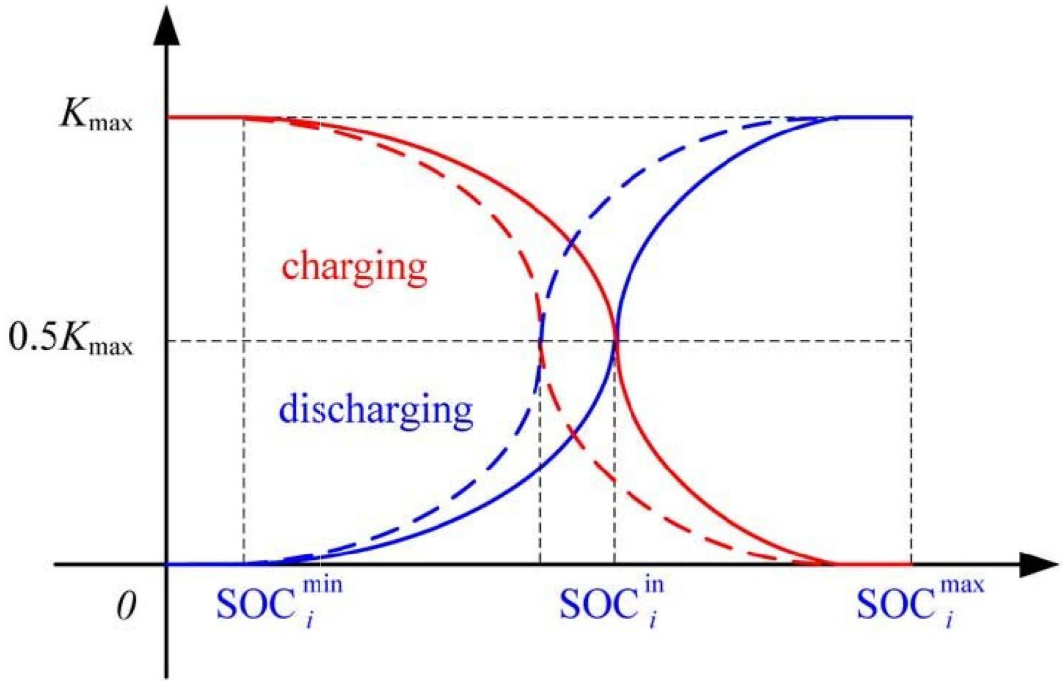



**Figure3.2** Adaptive droop K of the BSH for maintaining the initial SOC [63]

The BSH with adaptive droop is illustrated in fig3.3.

In order to eliminate frequency fluctuation, the power is exchanged between the EV and the power grid in the following cases:

1. When the system frequency deviation $\Delta f_k$ is below the predefined dead-band, the EVs inject power to the grid (discharging).

2. When the system frequency deviation $\Delta f_k$ is above the predefined dead-band, the EVs absorb power from the grid (charging).

With the change of the real-time SOC, adaptive droop will rotate around point 1/2 between zero and $K^{max}$ to adjust the charging/discharging power.

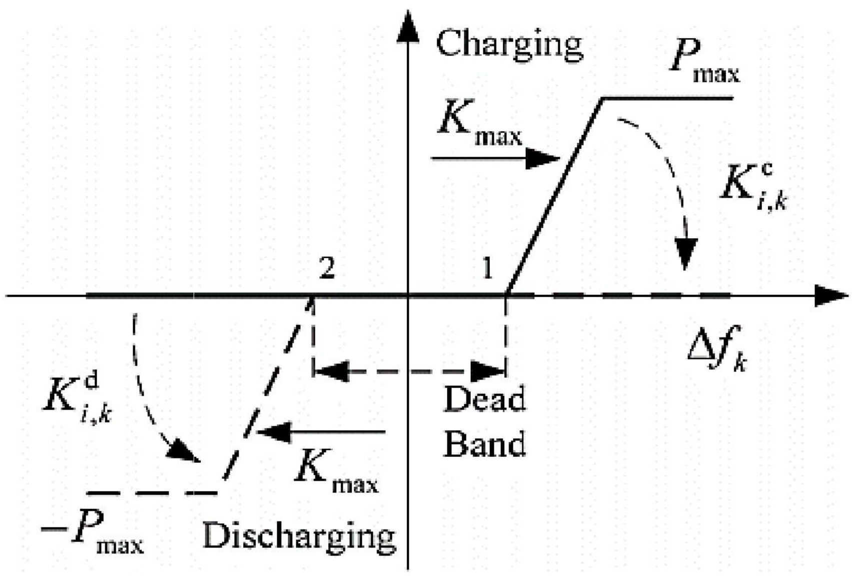



**Figure3.3** BSOC holder with adaptive droop control [63]

If the real-time SOC is greater than the initial SOC, the adaptive droop will block the increase of the BSOC so the charging droop ($K_{i,k}^{c}$) will be smaller than the discharging droop ($K_{i,k}^{d}$) so more power will be injected to the grid; otherwise, the adaptive droop will impel the increase of the BSOC so the charging droop ($K_{i,k}^{c}$) will be larger than the discharging droop ($K_{i,k}^{d}$) so more power will be absorbed from the grid [66].

### 3.2.2 Charging with frequency regulation (CFR)

The CFR is designed for those EVs that need to charge their batteries to a higher SOC level, since the remaining SOC is low and not sufficient for next trip. The CFR is proposed so that it achieves charging demands while suppressing frequency deviation at the same time.

As indicated in fig3.4, the CFR consist of frequency droop control that is used to improve frequency quality, and scheduled charging power to meet charging demand.

Constant scheduled charging power at the battery side of the *i* th EV for achieving charging demand can be described by the equation below with expected SOC and plug-out time provided by the EV customer:

$$P_i^c = (SOC_i^e - SOC_i^{in}).E_i^r \,/\, (t_i^{out} - t_i^{in}) \qquad (3.10)$$

It should be noted that an EV may not join the primary frequency regulation (PFC) in case when the scheduled charging power $P_i^c$ is equal or larger than the maximum charging power.

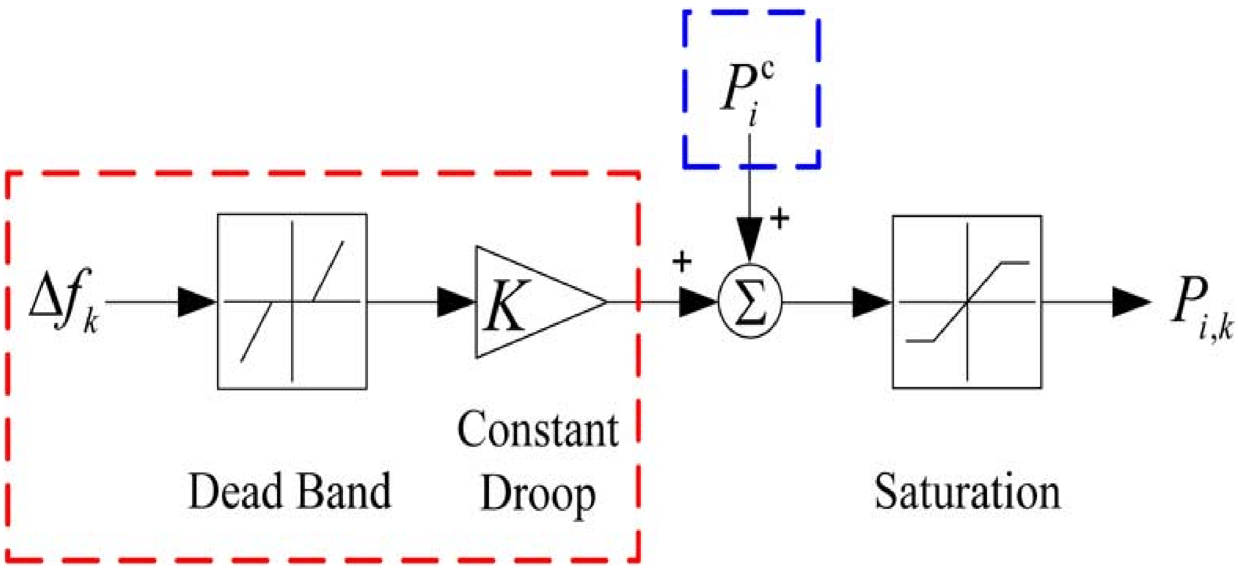



**Figure3.4** Droop control loop of the CFR (red part represents frequency droop control and blue part is scheduled charging power) [63]

In case the frequency deviation $\Delta f_k$ is within the predefined dead-band, so no frequency regulation is required this means that only scheduled charging power works. Once frequency deviation is out of the dead-band, both scheduled charging power and frequency droop control will work.

Taking the charging and discharging efficiencies into account, the power at connecting point of a charging/discharging device from/to the power grid can be expressed by the following equations:

$$P_{i,k}^{p} = P_{i,k}/\eta^{c}, \quad P_{i,k} \geq 0 \qquad (3.11)$$

$$P_{i,k}^{p} = P_{i,k} * \eta^{d}, \; P_{i,k} < 0 \qquad (3.12)$$

The CFR has the ability to switch automatically to the BSH tin order to keep the battery state of charge (BSOC) around the expected SOC when the charging demands are achieved and the EV battery is filled to the required level before the schedule duration or the actual plug out time [63].

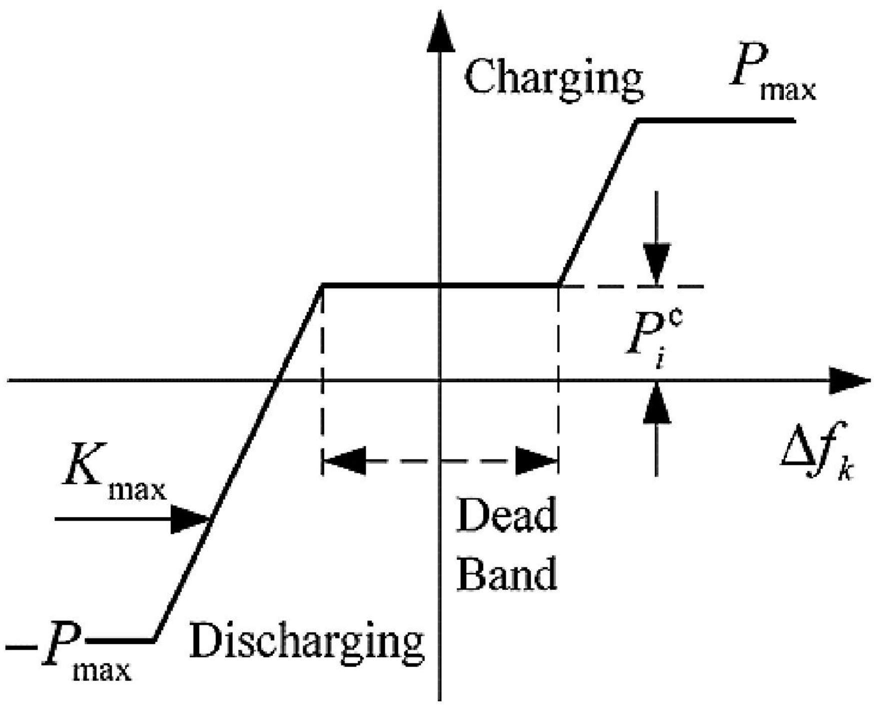



**Figure3.5** Charging with frequency regulation with maximum V2G droop [63]

## 3.3 Simulation system

The simulation system for the decentralized vehicle-to-grid control (DVC) for primary frequency regulation considering charging demands is illustrated in figure3.6. The simulation system consists of a two area inter-connected power system which are area A and area B.

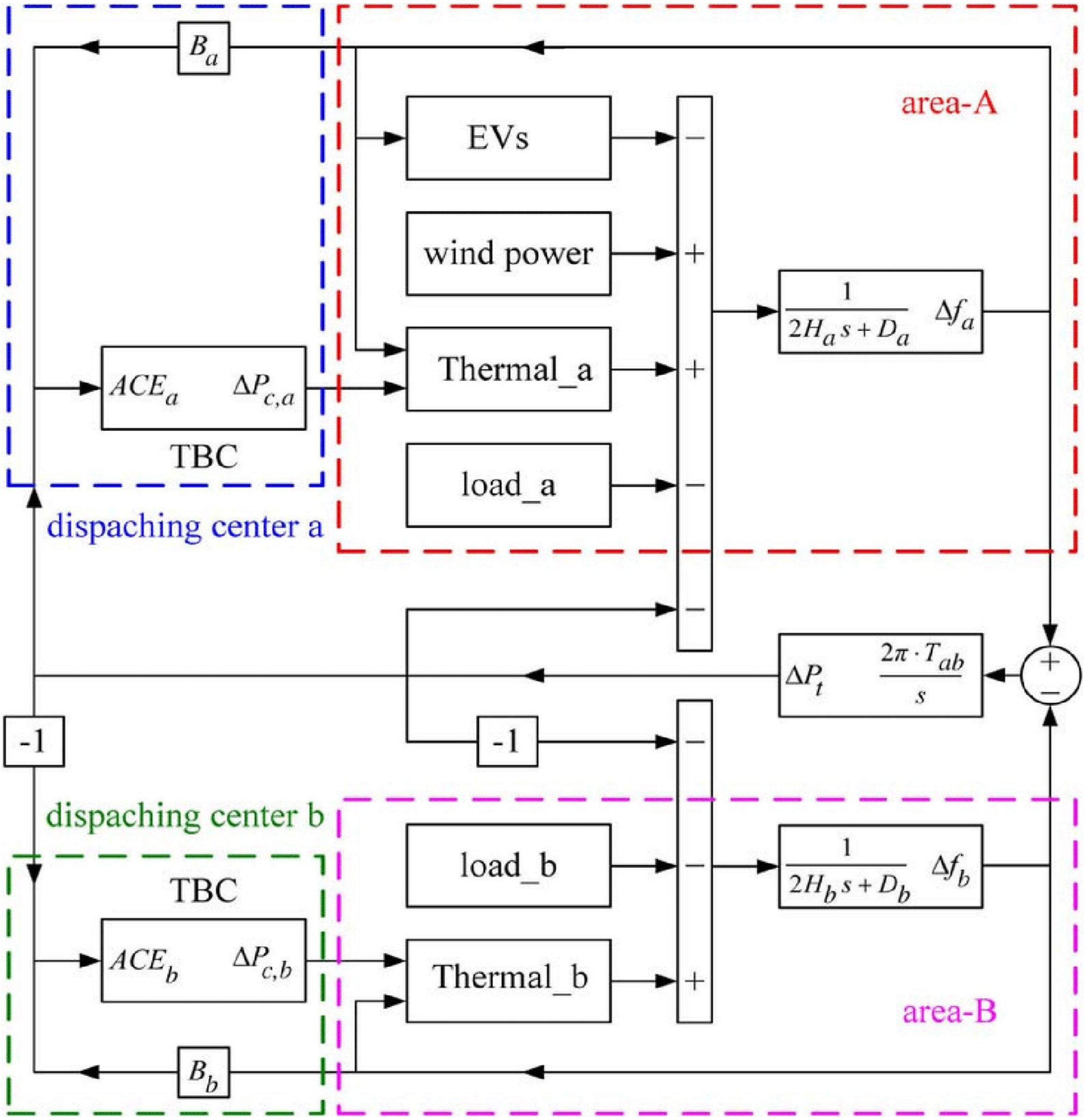



**Figure3.6** simulation system for DVC [63]

The “thermal  power  plant” and “EV V2G control” blocks used in the simulation system are shown in fig3.7 and fig3.8 respectively.

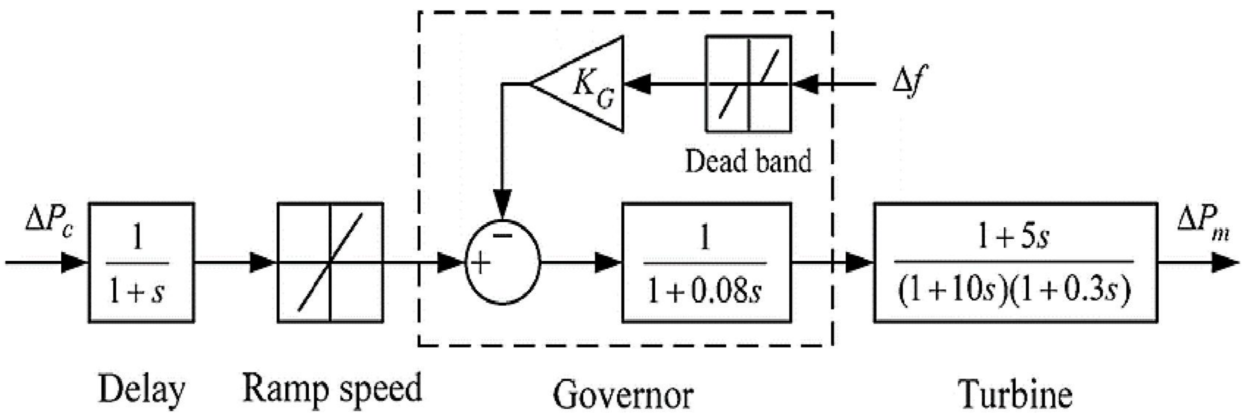



**Figure3.7** Thermal power plant block for frequency regulation [63]

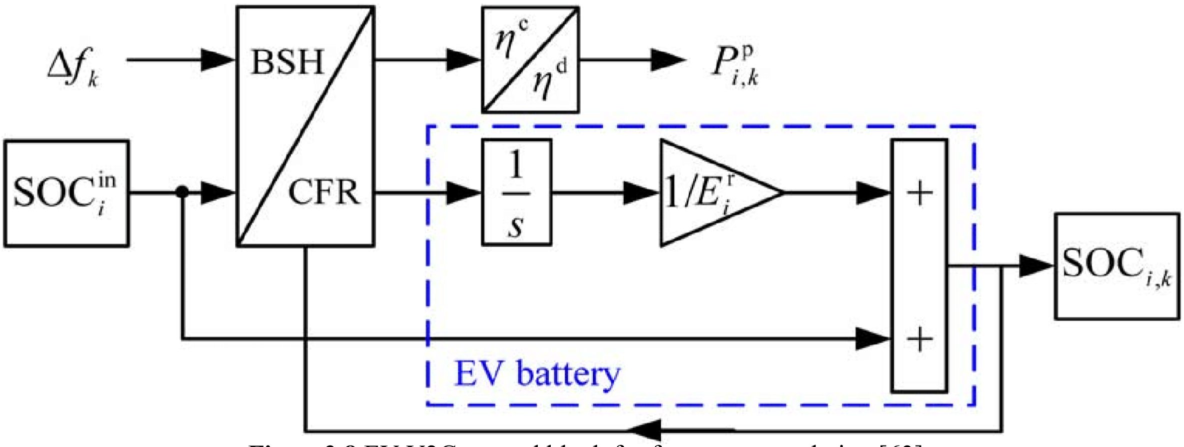



**Figure3.8** EV V2G control block for frequency regulation [63]

The battery energy variation $\Delta Ei$ and The BSOC at time k $SOC_{i,k}$ can be expressed as:

$$\Delta Ei = \int_0^k Pi(k)dk \qquad (3.13)$$

$$SOC_{i,k} = SOC_i^{in} + \Delta Ei.(1/E_i^r) \qquad (3.14)$$

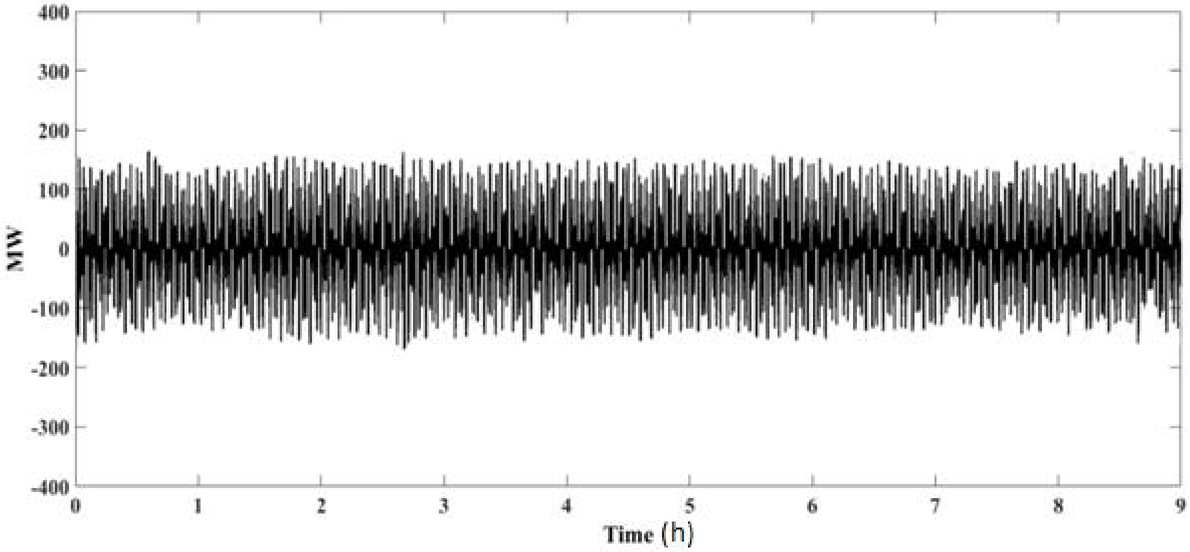



**Figure3.9** data for random load a

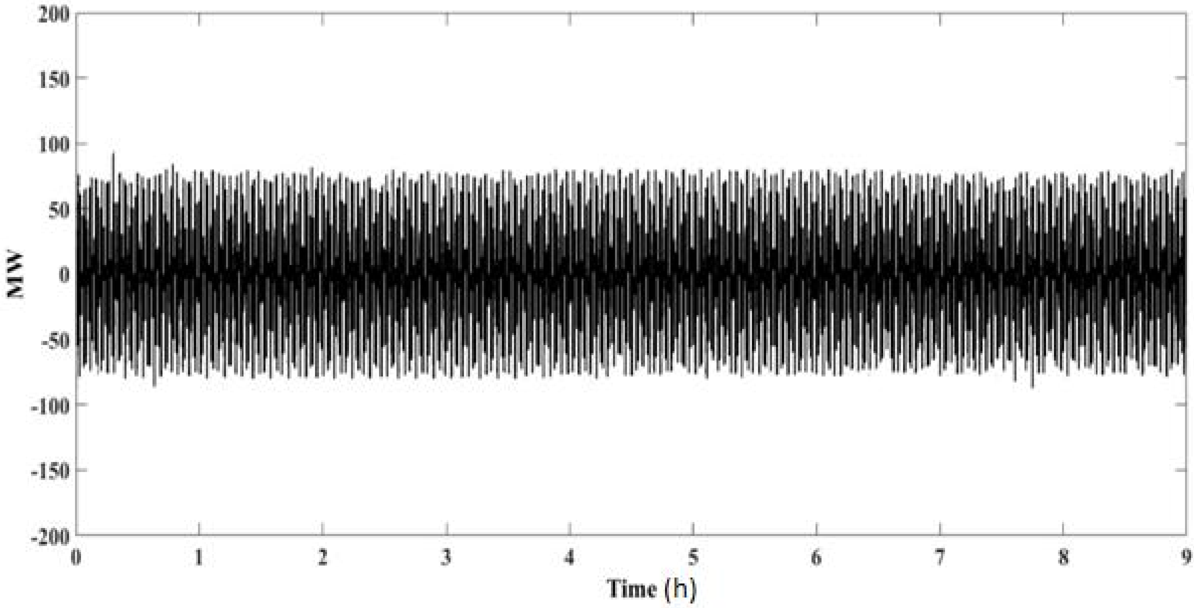



**Figure3.10** data for random load b

Fig3.9 and 3.10 show respectively random loads (load a and load b) used for frequency regulation simulation.

Wind power data which are taken from a real historical data is illustrated in fig3.11.

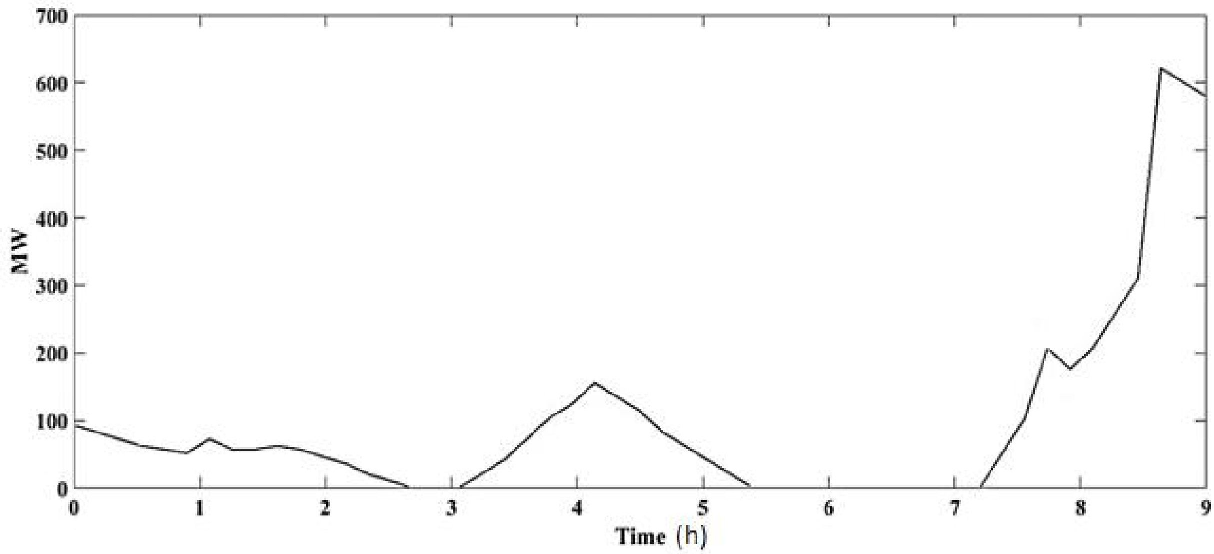



**Figure3.11**data for wind power generation

The detailed parameters of the power grid model are summarized in Table3.1 where it can be noticed that the values of inertia constant and load damping coefficient are kept constant to simplify the work.

**Table3.1** Parameters of power grid model [63]

| Parameters/area | Area A | Area B |
|---|---|---|
| Maximum load capacity (Mw) | 20000 | 10000 |
| Proportional and integral gains | 1, 0.01 | 1, 0.01 |
| time constant for LFC (s) | 4 | 4 |
| Frequency bias factor B (Pu/Hz) | 0.15 | 0.075 |
| Inertia constant H (Pu.s) | 0.32 | 0.16 |
| Load damping coefficient D (Pu/Hz) | 0.04 | 0.02 |
| Synchronizing torque coefficient $T_{ab}$ (Pu/Hz) | 0.04 | 0.04 |
| Dead band of primary frequency control (Hz) | 0.033 | 0.033 |
| Time constant for frequency detection (s) | 0.1 | 0.1 |
| Communication delay (s) | 1 | 1 |
| Dead band of area control error (Mw) | 20 | 20 |
| Ramp speed (Mw/min) | 400 | 200 |
| time constant for wind power fluctuation (s) | 1 | 1 |

The V2G simulation parameters are listed in table3.2 where Type 1 refers to maintaining BSOC and Type 2 for achieving charging demands.

**Table3.2** V2G simulation parameters [63]

| Parameters | Type 1 | Type 2 |
|---|---|---|
| EV number | X | X |
| Battery capacity (Kwh) | 32 | |
| Dead band of frequency (Hz) | [-0.01, 0.01] | |
| Charging/discharging efficiency $\eta^c/\eta^d$ | 0.92/0.92 | |
| Maximum V2G power $P_{max}$ (Kw) | 7 | |
| Maximum V2G droop $K_{max}$ (Kw/Hz) | 120 | |
| Maximum/minimum SOC (Pu) | 0.9/0.1 | |

## 3.4 Simulations and discussions

A Monte Carlo Simulation method is performed first before simulating the DVC system under MATLAB Simulink.

### 3.4.1 Monte Carlo simulation

The basis for Monte Carlo simulation is the ability to generate a sequence of independent random numbers having a given distribution with finite mean $\mu$and variance $\delta$ [65].

Table3.3 shows the battery SOC which is normally distributed within the specified range. Since the mean $\mu$ and the variance $\delta$ are given {SOC~$N(\mu, \delta)$}, then the SOCs of any given number of EVs is easily obtained by Monte Carlo Simulation method using EXCEL or any other Software, and then modeled under a Simulink environment.

**Table3.3** simulation scenarios of the EVs with normally distributed SOC [63]

| | Type 1 | Type 2 |
|---|---|---|
| Initial SOC (Pu) | SOC~$N(0.7, 0.01)$<br>SOC $\in$[0.6, 0.8] | SOC~$N(0.4, 0.01)$<br>SOC $\in$[0.3, 0.5] |
| Expected SOC (Pu) | \ | SOC~$N(0.7, 0.01)$<br>SOC $\in$[0.6, 0.8] |

### 3.4.2 Different scenarios

The main concern is in area A where EVs integration and wind power are as shown in fig3.6; thus, in order to observe the effect of the decentralized V2G control strategy and examine how increasing or decreasing the number of EVs affects the frequency, the DVC is subjected to different scenarios.

## A. First scenario

An assumption is made, so that the plug-in duration of EVs is 9 hours (note that it does not mean that the simulation will run for 9 hours in real time, just that the provided data are used as if provided for 9 hours period).

The simulation is run for 10000 EVs with normally distributed SOCs divided randomly as follows:

**Table3.4** distribution of SOCs for 10000 EVs

| | **Type 1** | **Type 2** |
|---|---|---|
| EV number | 7000 | 3000 |

Fig3.12 displays the result of the first simulation, where the red line represents the frequency fluctuations without using the V2G and the blue line indicates the frequency deviation in case of using the proposed charging schedule considering primary control (DVC).

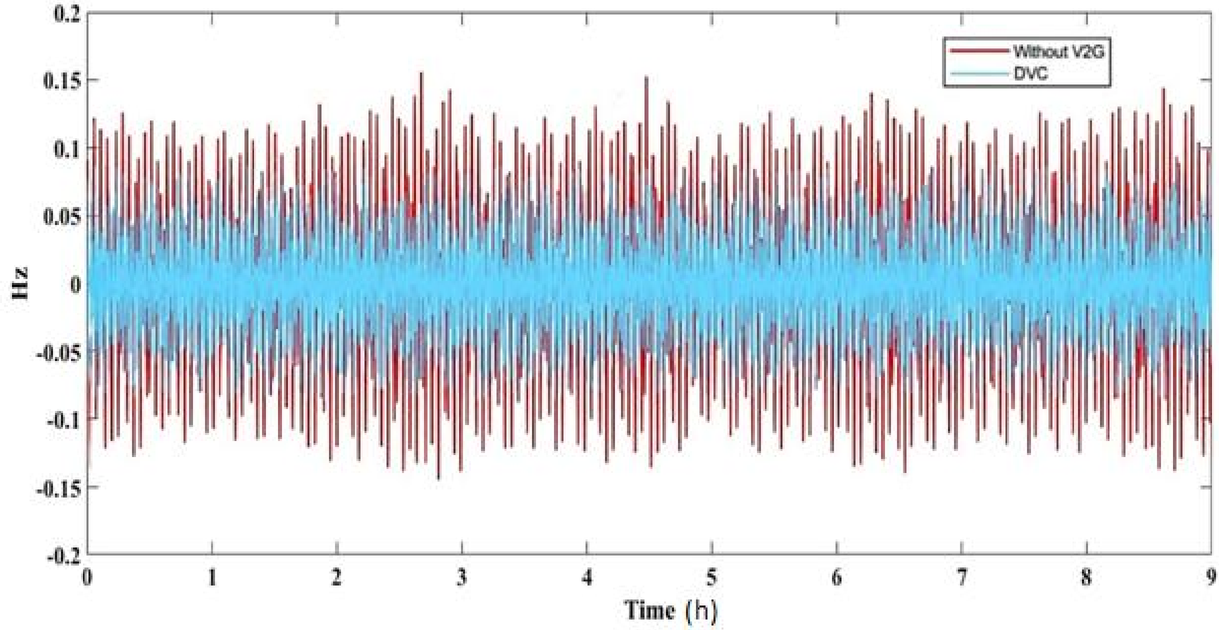



**Figure3.12** frequency deviation in area A: (a) without V2G, (b) with 10000 EVs in area

The maximum and the minimum values in Hertz of the simulation result are reported in table3.5.

**Table3.5** reported values: (a) without V2G, (b) with 10000 EVs in A

| | **Maximum (Hz)** | **Minimum (Hz)** |
|---|---|---|
| Without V2G | 0.158 | -0.145 |
| 10000 EVs in area A | 0.0782 | -0.092 |

Before using the V2G control, the frequency deviation in area A $\Delta f_a$ was out of the previously mentioned range which is [-0.1, 0.1] Hz as seen in table3.5, and this may cause the system to fail. When the DVC is used, the frequency deviation $\Delta f_a$ became within the range; hence, the system frequency quality is improved and stabilized due to the fast adjustments of charging/ discharging power of EVs. EVs in micro grid contribute in frequency regulation and improve the stability when a disturbance occurs. The regulation is provided in terms of active and reactive power through bidirectional flow.

## B. Second scenario

For the second scenario the number of EVs is increased further to 20000 with SOCs divided as shown in table3.6.

**Table3.6**distribution of SOCs for 20000 EVs

| | **Type 1** | **Type 2** |
|---|---|---|
| EV number | 15000 | 5000 |

Simulation result is displayed in figure3.13.

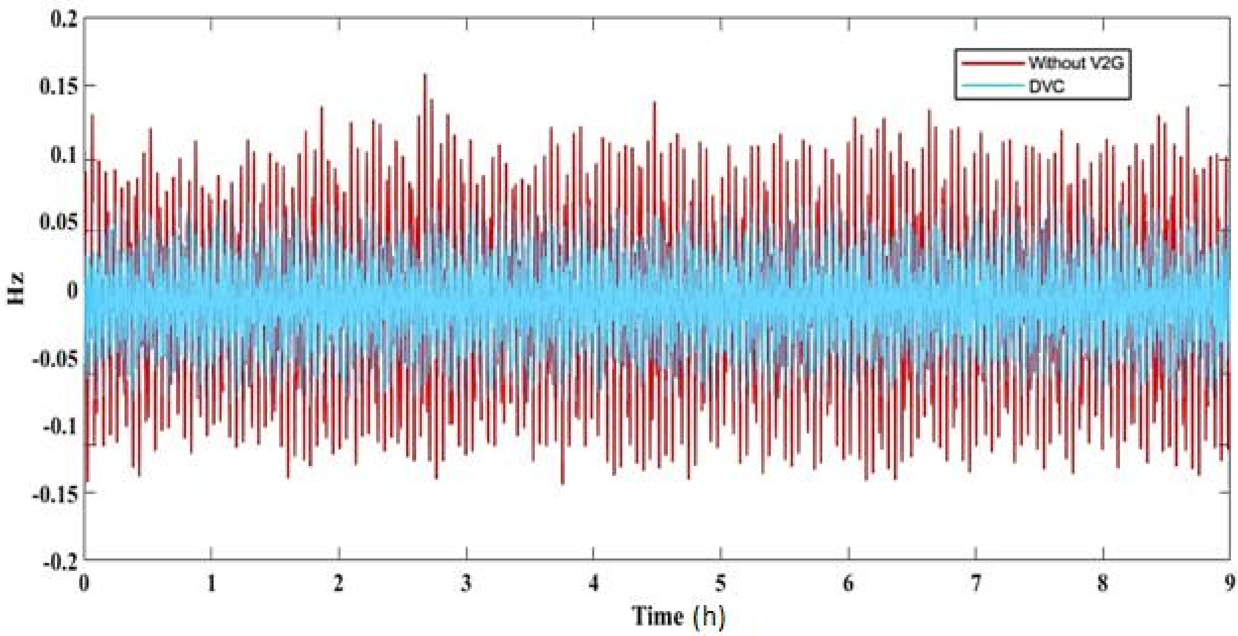



**Figure3.13** frequency deviation in area A: (a) without V2G, (b) with 20000 EVs in area A

Initially only 10000 EVs were considered in the V2G control, then the number of EVs is increased to 20000. These two scenarios are compared with a similar work done in [66], in which 50000 EVs were used.

**Table3.7** comparison between different scenarios

| | Maximum (Hz) | Minimum (Hz) |
|---|---|---|
| Without V2G | 0.158 | -0.145 |
| First scenario (10000 EVs) | 0.0782 | -0.092 |
| Second scenario (20000 EVs) | 0.0757 | -0.09 |
| 50000 EVs in area A [66] | 0.0693 | -0.092 |

From table3.7 it can be deduced that when the number of EVs is increased, then it further stabilizes the frequency and improve it. The more EVs joining primary frequency regulation, the more energy reserve added to the micro grid.

## C. Third scenario

In the third scenario, EVs are integrated into area B where there is no wind power while keeping the number of EVs 20000.

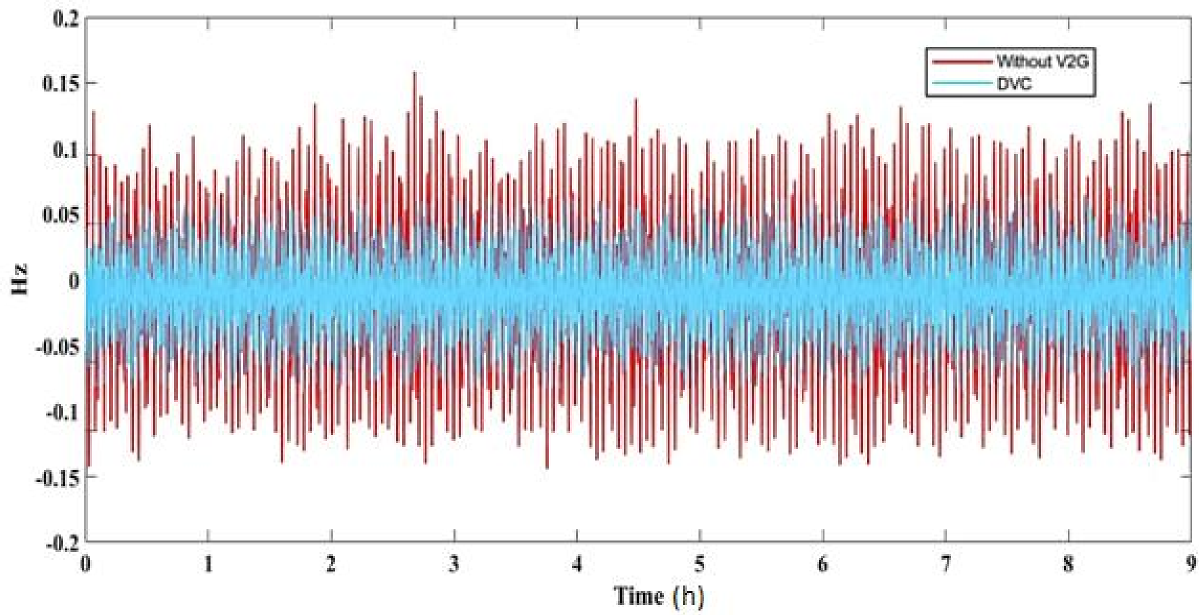



**Figure3.14** frequency deviation in area A: (a) without V2G, (b) with 20000 EVs in area B

**Table3.8** reported values: (a) without V2G, (b) with 20000 EVs in area B

| | Maximum (Hz) | Minimum (Hz) |
|---|---|---|
| EVs integrated in area B | 0.0752 | -0.088 |
| Without V2G | 0.158 | -0.145 |

From figure3.14 and table3.8, it can be observed that even when EVs are integrated into area B, the frequency fluctuation sourced in area A is suppressed by the V2G. When EVs and wind power are in different areas, the tie-line power change between area A and area B is increased hence, the system's frequency quality is improved.

## D. Fourth scenario

Three EVs in type 1 with random SOCs are chosen. As displayed on fig3.15, all of the SOCs are maintained at a certain level with an approximately similar curves since the V2G control is decentralized which means it may operate itself autonomously using the BSH; hence, it regulates the charging/discharging power of each EV independently according to the real-time change of its SOC and the system frequency deviation.

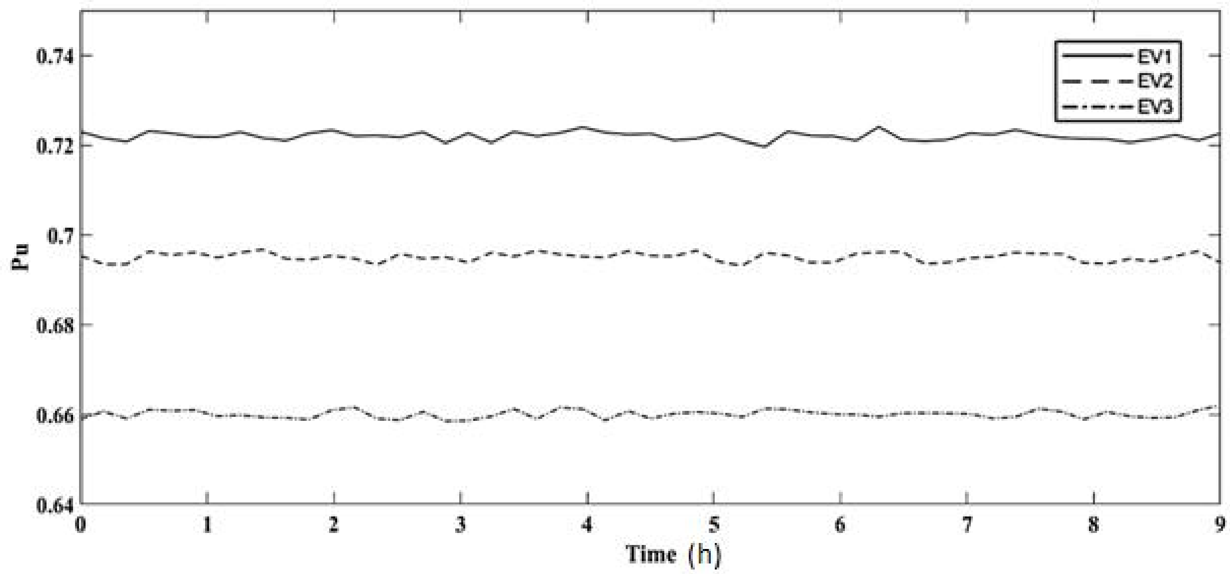



**Figure3.15** real-time SOCs of three randomly chosen EVs in type 1

As illustrated in figure3.16, the power is exchanged between the micro grid and the EVs according to the change in real time SOC for the sake of suppressing frequency fluctuations and keeping the BSOC around the expected level. When P >0 W, this means that the power is absorbed from the power grid by the EVs (charging); otherwise, the EVs deliver power to be absorbed by the grid (discharging) to satisfy the above mentioned purposes. It can be noticed that the amount of the injected and absorbed power by EVs is approximately equal.

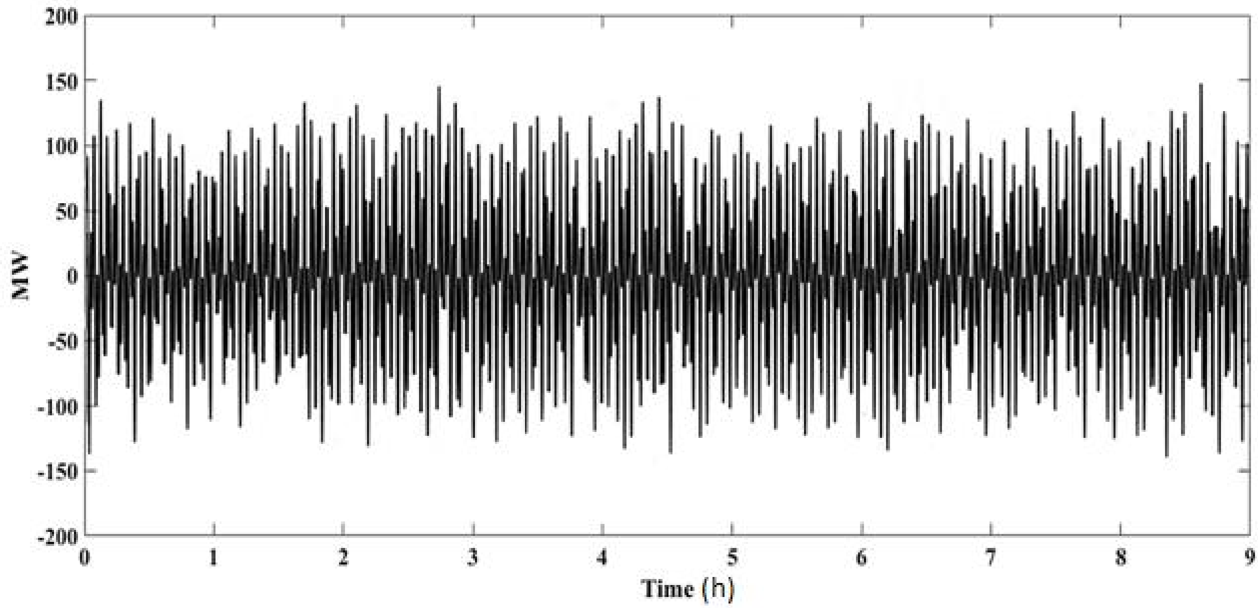



**Figure3.16** total V2G power at the power grid side of type 1

## E. Fifth scenario

Another three EVs in type 2 are randomly chosen for illustration shown in figure3.17 and figure3.18.The role of the CFR is to lift the battery energy from the initial SOC level ($SOC_i^{in}$ ∈ [0.3, 0.5]) to the expected SOC level ($SOC_i^{e}$ ∈ [0.6, 0.8]). Once the BSOC is filled to the required level and charging demands are satisfied, the scheduled charging reaches its end time; hence, the CFR is automatically switched to the BSH to maintain the BSOC.

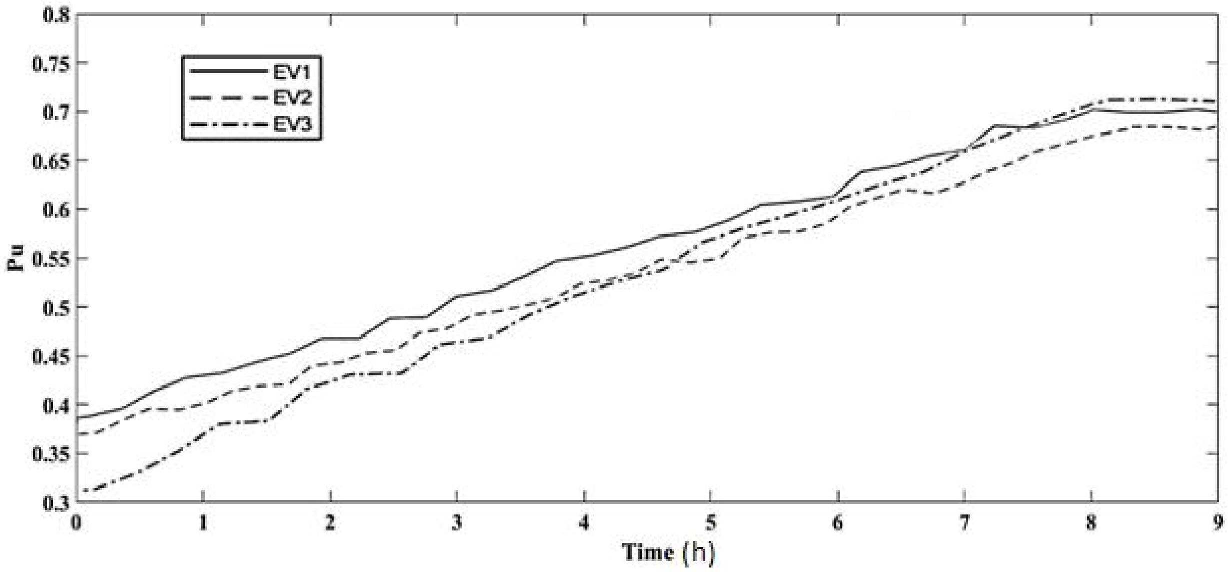



**Figure3.17** real-time SOCs of three randomly chosen EVs in type 2

During the scheduled charging, it is observed that the curve is shifted up which means that the amount of power absorbed by the EVs is greater than the delivered power which lead the EV battery to charge in parallel with frequency regulation. At the end of the scheduled charging, the V2G power of the DVC is released and kept at equilibrium in order to maintain the battery energy around the expected SOC since charging demands are achieved.

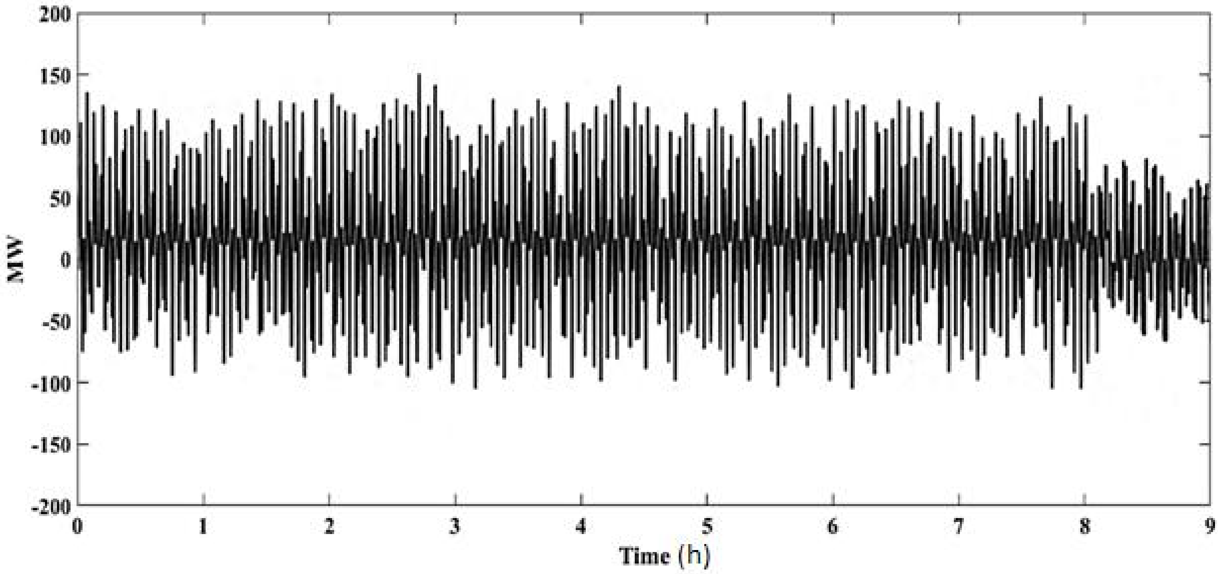



**Figure3.18** total V2G power at the power grid side of type 2

## 3.5 Conclusion

This chapter studies the impact of the Decentralized Vehicle-to-Grid Control (DVC) and the contribution of EVs in primary frequency regulation taking charging demands in consideration. The DVC consists of the BSH to maintain the residual battery energy and hold different initial SOCs altogether with frequency regulation and the CFR to achieve charging demands. Different scenarios have been simulated and the results prove that the DVC achieves frequency regulation within the acceptable range as well as satisfying charging demands. Frequency regulation improves even further by increasing the number of EVs as more vehicles participate to grid regulation mode.

# General conclusion

This report addressed an essential subject in energy fields, which is the effect of EVs on power quality when integrated in micro grids.

A micro grid is an essential modern group of interconnected loads and distributed energy resources (DER) to light and power our world; however, with high EVs integration, the micro grid systems will suffer from additional strain and some power quality issues. A method known as Decentralized Vehicle-to-Grid Control (DVC) is proposed to suppress frequency fluctuations and achieve the requirements from EV customers which are: either maintaining the battery SOC, or charging the battery to a higher SOC level. The DVC system is simulated under MATLAB Simulink.

After the simulation, it can be noticed that the proposed DVC is flexible and effective to improve frequency quality as well as satisfying charging demands. Moreover, the following points can be concluded concerning the proposed method:

1. The more EVs joining the PFC, the further the frequency is regulated.
2. The BSH can hold different initial SOC levels altogether with frequency regulation.
3. The CFR is flexible to achieve charging demands of each EV.

For enhancing more the performance of the DVC, the CFR can be improved further in order to achieve charging demands in a shorter time.

Future studies on power quality improvements in micro grids like solutions for renewable energy intermittency problems using V2G technologies are recommended. Another future challenge concerning PQ improvements using EVs is to design cost-effective on-board EV chargers that can offer provisions for additional services. These services include voltage and frequency regulation, reactive power compensation, and harmonic reduction while the EV operates in either V2G or G2V mode. This requires additional current measurement Sensors which must be considered in the next generation of the EV chargers.

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