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Distributed Generation, Storage and Active Network Management

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1. Introduction

Power systems are changing due to global drivers such as climate change and environmental issues as well as increasing dependency on electricity. Therefore, there are needs for (i) large-scale integration of renewable, low-emission (CO_2) energy sources in high-, medium- and low-voltage (HV, MV and LV) networks, (ii) improving energy efficiency of the whole energy system and (iii) enhance electricity supply reliability. In Fig. 1 the main impacts A)-D) of these changes on power systems are presented.

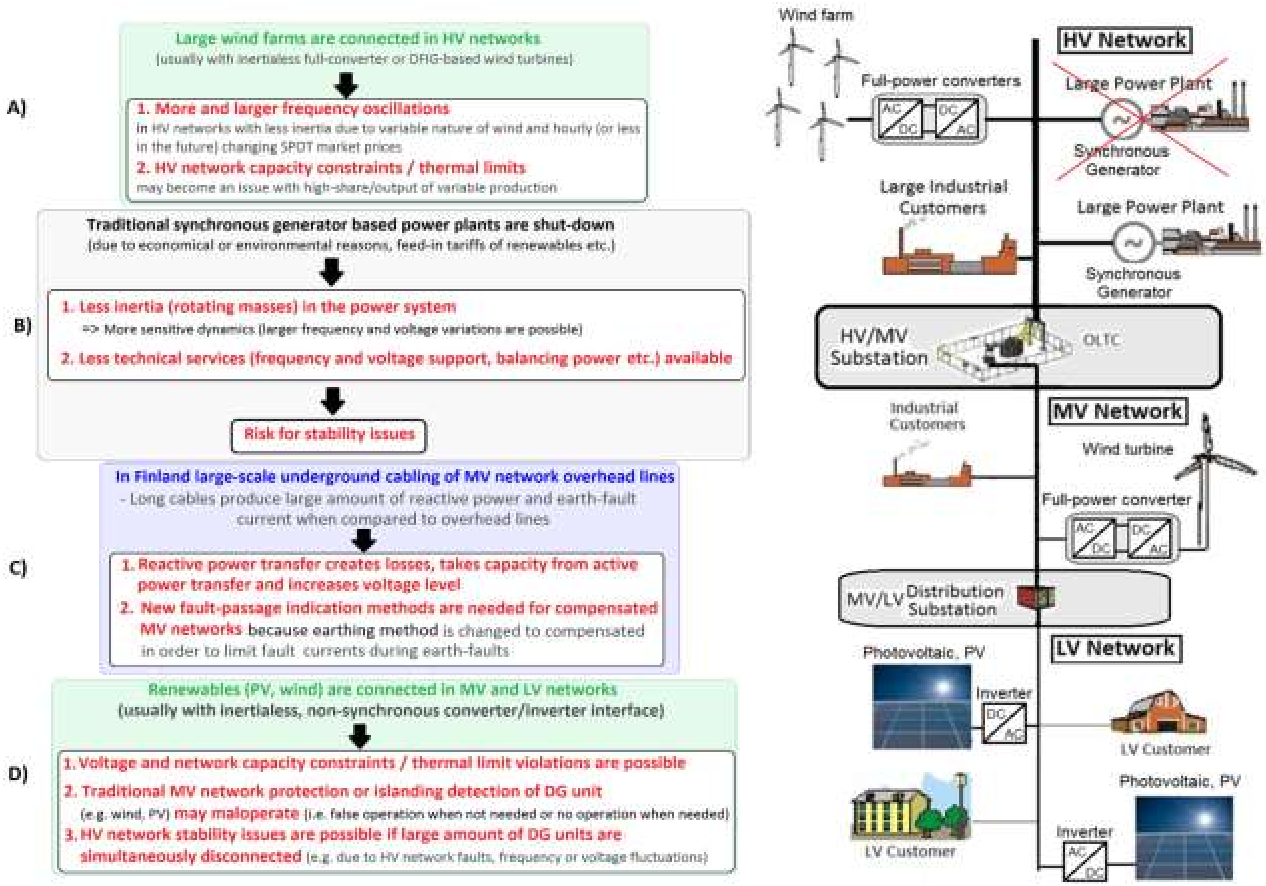


Figure 1. Main impacts of ongoing changes on power systems

Previously distribution grid connected renewable energy sources (RES) and other distributed generation (DG) units were usually required to be disconnected during faults and disturbances. Recent technological advances along with social acceptance have led to an increase in the number of DG units in the electricity distribution networks. Due to constantly increasing number of connected DG units, HV grid stability has become a central issue, and could get worse if, for example, large share of the DG units are disconnected during HV grid faults or frequency disturbances. Therefore, supply reliability and quality with integration of RES is tried to be ensured by setting stricter grid code requirements for the RES and other DG units connected at different voltage levels (HV, MV and LV). These grid codes define, for example, the required HV grid stability supporting functionalities like voltage and frequency fault-ride-through (FRT) requirements of the DG units during HV grid faults and frequency disturbances. These DG unit grid code requirements have been made mainly from HV grid stability point of view and less attention has been paid on distribution network effects (like protection and islanding detection). However, in the future this is not enough. In addition, there is a need for flexibility from distributed energy resources (DER), because DER (controllable generation units, energy storages, controllable loads and electric vehicles) at different voltage levels (HV, MV, and LV) has potential to,

a) Provide different local (corresponding voltage level) and system-wide (whole power system / HV network) technical flexibility services by active (*P*) and reactive (*Q*) power control which could, in addition to grid codes and regulations, be realized by future technical ancillary service / flexibility markets

b) Simultaneously improve energy efficiency i.e. reduce the demand for distribution network capacity (coordinated voltage control and congestion management), reduce losses and increase reliability of electricity supply to the customers (intended island / microgrid) operation

But this potential of DG units and full integration of RES cannot be realized without active management of the distribution grids and flexibilities connected in distribution grids. For example, different types of energy storage systems (ESSs) have been deployed extensively as flexible energy resources aiming to increase the flexibility at different levels of the power system including local (distribution network) and system-wide (transmission network) levels. In order to effectively integrate DGs and ESSs and exploit their maximum flexibility potential, appropriate management and control structures are needed. The recent advances in ICT have enabled active participation of these resources, accommodate all DG generation and energy storage options, and also facilitate optimal management of these resources.

Most efficient way to meet energy demand with increasing integration of RESs in the distribution networks is to incorporate innovative solutions, technologies and grid architectures. Developing economically viable yet innovative grid architectures becomes essential with the increased role of non-dispatchable and DGs based on RES. Such solutions are realized by active control of the DGs as part of Active Network Management (ANM) schemes. Smart grids provide the platform to implement ANM schemes, where the DGs are interconnected and inter-communicable in real time to work in tandem to supply energy demands.

In this chapter, an overview of distributed generation, i.e. their classification and role in ANM of smart grid operations and adjoining control methodologies will be addressed in detail. Energy storage systems plays crucial role as flexible energy resources for ANM in smart grids. Their technology types and various applications they tend to be used will be explained. Battery energy storage systems (BESSs), especially Lithium-ion batteries with their current technology and economic maturity are considered as a viable option for stationary grid applications. Design and control of Li-ion battery integration by means of power electronic converters for ANM in medium voltage distribution system, along with managing other flexibility services of DGs are in the scope of this chapter.

2. Distributed Generation Sources

DGs have made a significant contribution to producing energy in the last decade. Most energy players and utilities have found that utilizing DGs can decrease their net-costs, as the marginal costs of producing electricity by renewable-based DGs are very low, near to zero [1]. System operators including transmission system operators (TSOs) and distribution system operators (DSOs) can also benefit from the large installation of DGs since they offer benefits for the power systems. The DGs' advantages from the operators' viewpoints can be supporting network voltage and frequency, reducing network losses, reducing transformers loading stress, promoting system reliability, as well as providing the environmental benefits [2]. In addition, end-users who are equipped with DGs are also able to take advantage of the economic benefits of installing DGs. In this way, not only they can be self-sufficient, but they can also sell their production surplus and make profits. DGs mainly assist in satisfying distribution network located demand and they are located in distribution networks (low voltage (LV) and medium voltage (MV) levels). Photovoltaic (PV) panels and wind turbines are currently the most popular renewable-based distributed energy resources that are located in distribution networks. Micro-CHP and fuel cells are the other common DGs which can be adopted in distribution networks. The following sections give more information about these DGs.

2.1 PV Panel

There exist various methods estimating the active power produced by a PV module. In one of the first research, the power output of a PV module was proposed to be estimated based on the cell temperature as well as solar irradiance. The cell temperature is in turn dependent on the ambient temperature as stated in (1) [3][4].

$$\theta^{cell} = \theta^{ambient} + G(\frac{\theta^{NOCT}-20}{800}) \qquad (1)$$

The output power captured by a PV cell is estimated accordingly, utilizing (2).

$$P^{pv} = P^{STC}G(1 + c(\theta^{cell} - 25)) \qquad (2)$$

Where, in the above equations, *c* indicates the power-temperature coefficient. θ^{cell} is the PV cell temperature, $\theta^{ambient}$ denotes ambient temperature while θ^{NOCT} refers to the temperature associated with the nominal operation of the cell all in [°C]. In addition, P^{pv} and P^{STC} are the output power of the PV cell and the power produced under the standard test condition, respectively. Finally, the solar irradiance is shown by G [3].

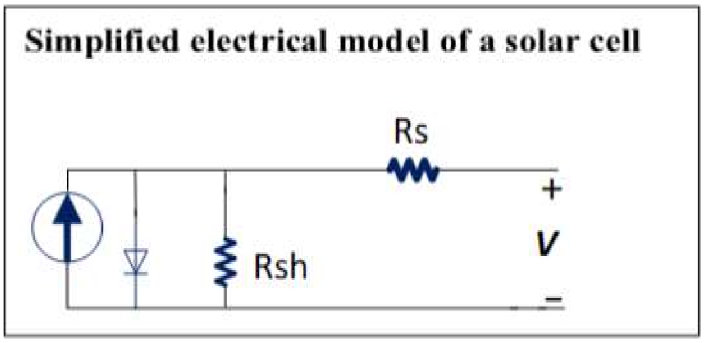


Figure 2. An electrical single diode model for a PV cell

The output power of PV can be also calculated according to its simplified equivalent circuit illustrated in Fig. 2 [5]. Thus, the following equations are adopted in order to calculate the produced PV power equipped with the boost converter [5]:

$$I^{pv} = I^{ph} - I^{sa}\left(e^{\frac{q(V+IR^{S})}{nkT}} - 1\right) - \frac{V+IR^{S}}{R^{sh}} \quad (3)$$

$$P^{pv} = \eta^{boost} I^{pv} V^{pv} \qquad (4)$$

Where in (3), I^{ph} denotes the photocurrent and I^{sa} refers to the saturation current of the diode. Moreover, the series and shunt resistances are represented by R^{s} and R^{sh}, respectively while n indicates the factor related to the diode ideality, k is Boltzmann's constant, q refers to the electron charge, and T is a parameter expressing the absolute temperature in Kelvin. In (4), P^{pv} is obtained utilizing $I^{ph},$ the open circuit voltage, $V^{pv},$ and the efficiency of the boost converter, η^{boost}.

It is worth mentioning that the power produced by a single PV cell is so small. However, PV modules can be connected in parallel and series in various topologies in order to generate more power.

In general, a PV system that is connected to the grid may consist of a boost DC-DC converter, a Maximum Power Point Tracking (MPPT) controller, a voltage source inverter, and some other equipment. The main responsibility of the boost converter is to balance the system while the inverters convert the output DC power of the PV system to the AC power. In order to ensure the efficient operation of the PV panel, the point in which the output power of the PV panels reaches its maximum value should be found. In this regard, an MPPT controller is deployed so as to track the MPP of the panel [6] [7].

2.2 Wind Turbine

The active power produced by a wind turbine is dependent on some factors such as the area and location where the wind turbine's rotor blades are spinning (swept area), the wind speed as well as the air mass density. In addition, the output power of the wind turbine is restricted by a coefficient of power denoted by c_p. If the coefficient of power equals its optimal value, the maximum wind turbine output is obtained. This value can be calculated by (5) [8].

$$P^{WT} = 0.5{c_p}^{opt}(\gamma,\beta)A^{s}\rho^{air}(WS)^3 \qquad (5)$$

Where , P^{WT} is the maximum output of wind power, ${c_p}^{opt}(\gamma,\beta)$ is the coefficient of wind power which is a function of speed ration (γ) and blade pitch angle (β). the parameter A^{s} indicates the swept area in which the rotor spins, ρ^{air} is the air mass density, and finally WS is the wind speed.

In the following model, wind power is considered a non-linear function of the wind speed. There also exists another model aiming to explain the linearized relationship between wind power output and the wind power speed. The linear model can be adopted especially for scheduling several energy resources. This model is expressed by (6) [9].

$$P^{WT} = \begin{cases} 0 & WS < WS^{cut-in} \\ \frac{P^r}{WS^r - WS^{cut-in}} WS + P^r\left(1 - \frac{WS^r}{WS^r - WS^{cut-in}}\right) & WS^{cut-in} \leq WS < WS^r \\ P^r & WS^r \leq WS < WS^{cut-off} \\ 0 & WS \geq WS^{cut-off} \end{cases} \quad (6)$$

Where, WS, WS^r, WS^{cut-in}, $WS^{cut-off}$ are wind speed, rated wind speed, cut-in wind speed, and cut-off wind speed, respectively. Additionally, P^r denotes the rated power of the wind turbine.

2.3 Micro-CHP

A combined heat and power (CHP) is utilized in order to combine the heat with electricity production. A micro-CHP is regarded as a decentralized small-scale CHP located at the customer-level of the electrical network. The micro-CHP is able to simultaneously produce heat and power which increases the efficiency of the system. The maximum capacity of the micro-CHP is usually below 15 kW. The energy efficiency of the CHP unit can be assumed to be constant. However, in practice, the CHP unit's efficiency varies with dynamic operation due to the variation of the output power of the micro-CHP [10]. Moreover, ramping constraints need to be applied in energy scheduling problems since the CHP requires some time to reach the steady-state after its set-point changes [10].

2.4 Fuel Cells

A fuel cell can produce electricity by converting the chemical energy originating from hydrogen and oxygen into electricity. Fuel cells can be also located at customer levels and utilized as DGs. In the solid-oxide fuel cell, anode supplies Hydrogen and catalytically split it into a number of protons and electrons. The electrons are then flowing towards the positive side i.e. the cathode by flowing through the external circuit. The oxygen then reacts with the protons and also the electrons flowing in the circuit, forming water formula [11]. The solid-oxide fuel cell can operate in parallel with PV panels, meaning that it can be integrated with solar power. In the night time, when PV panels cannot produce electricity, the fuel cell can be deployed to supply the demand.

3. Challenges in DG implementation

The challenges associated with DGs can be different according to the type of DG, the amount of intermittent power injected from renewable-based DGs, the type of distribution network as well as the location of DGs. However, DGs give birth to some new technical challenges in the power system. DGs are mainly installed in the vicinity of residential loads. It results in the bidirectional flow of power in distribution networks.

The connection of DGs to the distribution network exerts significant impacts on voltage profiles and also on the network power flow. These effects can be positive or negative. The positive effects include improving the reliability of supply and reducing losses of power system by bringing the generation closer to consumption. The negative impact is increasing the voltage magnitude at nodes with DGs which may violate the maximum permissible value in the moments with high generation. Accordingly, the voltage control is the most serious challenge and voltage regulation of the distribution network needs more advanced strategy [12]. Moreover, the connection of DGs to the distribution networks exacerbate the challenges related to the traditional Volt-Var control equipment. Traditional and expensive Volt-Var control actions are significantly delayed in order to react to the fast fluctuations resulted from the output power of renewable-based DGs [13]. Besides, the voltage regulation and control devices in the traditional distribution networks are mostly designed to operate without DGs. In this light, the network voltage magnitudes are assumed to decrease along the distribution feeder starting from the substation to the customers. However, with the presence of DGs, the mentioned assumption is no longer valid [14].

In addition to regulation problems, a large standalone DG (like wind turbine) can result in power quality issues, especially in a weak and rural distribution network during the time in which the DG is switched on and off [12]. According to [15], integration of DGs can affect power quality. Voltage dips are a significant event that can occur due to failures of the DG.

In terms of protection, the connection of large number of DGs on the distribution network’s feeders has significant influence on the applicable protection practices. DGs can have a major contribution to the short-circuit currents. This issue may, for example, result in unexpected operation of fault indicators which are deployed to locate fault position. Besides, some additional factors should be considered when installing a number of DGs in distribution networks [16]. These factors include the protection of the installed DGs from internal faults, the protection issues associated with the faulted distribution network from the fault currents produced by a DG, and the issues related to islanding detection (anti-islanding / loss-of-mains) as the high DG installation may increase islanding in distribution networks. Also, management of these DGs in the distribution systems needs to be efficiently controlled. Hence, integrating vast amounts of DGs raises multiple challenges related to the distribution system’s control, operation and protection. Such challenges are mitigated by innovative distribution grid management architectures reinforcing the need for rapidly controllable flexible energy sources. Following section shall introduce such control architectures in detail.

4. Management-related Solutions

There are several studies implying that active management of distribution networks and also active management of DGs can help to increase the hosting capacity and accommodate higher number of DGs connected to the current networks [17]. Fig. 3 presents an overview of the management-related solutions.

Future active network management methods can enable active control and facilitate the deployment of DGs' available flexibilities during both operation modes including grid-connected and islanded [18]. However, previous studies state that the benefits brought by utilizing DGs are expected to exceed the cost of the active management implementation [16], there exist some uncertainties related to the cost of active management in distribution networks.

From the economic side, the appropriate price control mechanism is needed in order to recover the expenses of applying active network management. Additionally, developing active distribution networks requires new commercial arrangements. In this way, different incentive schemes and market mechanism should be employed to effectively integrate DGs and motivate the owners of these resources to actively participate in different programs. On the other hand, the lack of policies and well-defined regulatory frameworks in the traditional design of distribution networks limits the high utilization of DGs. Hence, supporting DG integration requires appropriate policies applied to the distribution networks.

As previously stated, the growing number of DGs in distribution networks can have both negative and positive impacts on the power system. The active management of DGs, not only is able to decrease the negative impacts but can also enhance the flexibility of the network. In light of this, the following subsections deal with the

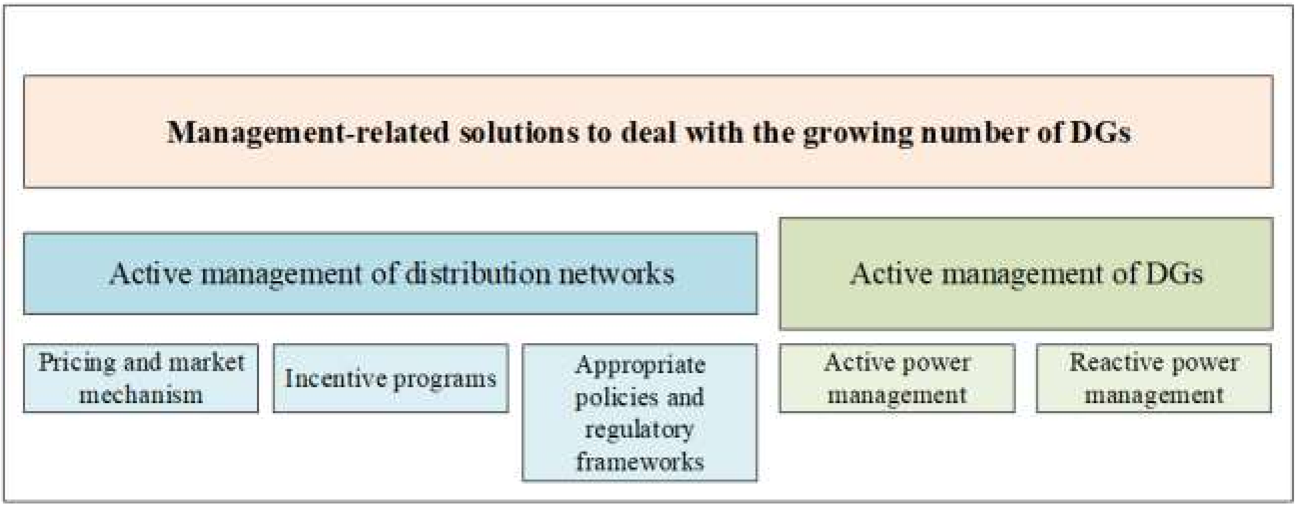


Figure 3. An overview on the management-related solutions of the growing number of DGs in distribution networks

management of active power and reactive power of DGs seeking to help the system operators and enhance the flexibility of the networks.

4.1 DG Inverters' Reactive Power Management

Inverter-based DGs can be regarded as excellent alternatives to resolve the issue related to the rapid response and control of the voltage variation resulted from DGs. Power flowing in feeders is restricted by the line branch's thermal capacity and also by bus voltages along the feeder. When the flow of one of the branches reaches its maximum thermal capacity or one of the bus voltages of the feeder approaches the upper or lower limits, no further power is able to flow the feeder. In this way, DG inverters can assist in increasing the feeder transfer capability by absorbing/injecting the specified amount of reactive power [19].

Inverter-based DGs are equipped with power electronic devices so as to procure the required reactive power in less than 50 milliseconds. This will avoid fast voltage fluctuations stemming from the transient cloud passing [20]. With the help of this feature, inverter-based DGs can be independent on the control actions of traditional distribution system such as deploying capacitor banks, static Var compensators as well as on-load tap changers. Furthermore, DG inverters produce a fast response and also provide more flexible reactive power support. Note that unlike shunt capacitors, the inverters are able to both absorb and inject reactive power to assist in controlling voltage.

In order to highly exploit the flexible capacities of DGs for operating the distribution networks, the reactive power capacity of the DG inverter should be highly utilized. For example, PV inverter can operate to its full capacity during daytime when there exists active power injection. However, both reactive power absorption and injection can be used during evening time when there exists no PV power.

The reactive power of DG's inverters is generally limited by the nominal value of the active power output of the DGs. However, the capacity of inverters may be over-sized to provide surplus reactive power support as well as maintaining the fully active power capability. The maximum reactive power should satisfy the following constraint [21].

$$|Q^{DG}| \leq \sqrt{((1+OF)S^{DG,r})^2 - (P^{DG,r})^2} \tag{7}$$

In (7), *OF* is the over-sizing factor of DG inverter (per unit) in comparison with the normal values of DG units [22].

4.2 DGs Active Power Management

The appropriate management of DGs' active power can be seen as potent DSO-level flexible resources, reducing the need for DSO operational actions which include grid reinforcement and reconfiguration [23]. DGs may be curtailed in a dynamic or static way [24]. The curtailment of DGs is performed in order to increase system flexibility and provide the system with downward flexibility. When the system needs downward flexibility, it has surplus production which violates the balance constraint of the power system. Hence, it should curtail

In the static curtailment, the system operator imposes a predefined threshold related to the injection of active power produced by renewable-based DGs whereas, in dynamic curtailment, the injection of active power is under the full control and may be curtailed due to the network constraints.

Curtailment resulted from network constraints can be performed either voluntary or involuntary [25]. In voluntary cases, an ex-ante agreement was reached between the DG owner and the network operator which specifies the amount of curtailment as well as the possible compensation. It should be noted that the DG owners require to sign the contract voluntarily. The DG owners may also participate in flexibility markets. However, the existing flexibility markets for balancing purposes are designed for large-scale flexibility products. Hence, the DG owners should firstly be aggregated and then participate in selling downward flexibility services. Involuntary curtailment due to network constraints is resulted from an obligation for the network operators including DSOs and TSOs. However, this kind of curtailment may decrease future investment in renewable-based energy resources.

The interactions between DG owners and the DSO have been covered by some research such as IMPROGRES project [25]. This project states that the location of DGs highly depends on regulation and policies designed by the DSO. In order to find the optimal location of DGs, the appropriate cost mechanism should be determined for the DSO. For example, the DG owners may be encountered several curtailments providing that they invest in the locations with high network reinforcement costs. However, curtailment with appropriate compensation can avoid overinvestment in the grid and also motivate renewable DG investors to find the best location in which the reinforcement costs of the grid are the lowest. This may lead to increasing the capability of the grid to host a large amount of renewable-based DG capacities.

4.3 Distribution Network Management with DGs

The increasing number of DGs in distribution networks leads to power systems restructuring the existing management and control architectures. Power systems have been traditionally managed in a centralized way. They consist of generation, transmission, and distribution levels. In a generation level, generators are centrally dispatched through the centralized pool-based markets. The transmission system is then responsible for transmitting the electrical high-voltage (HV) level power to lower-level systems. Transmission networks are also centrally managed by transmission system operators (TSOs). The distribution system delivers electrical power to final customers and end-users. These networks are controlled and operated by DSOs. However, the dramatic growth of DG in distribution networks creates considerable challenges [26]. The traditional centralized architecture fails to exploit potent flexibility capacities of new distribution network located resources such as DGs since in the centralized paradigm, these resources are not able to actively participate in energy and flexibility provision. Accordingly, the power system needs to adopt new control and management methods in order to adapt to the changes associated with the growing number of DGs in distribution networks.

4.3.1 Hierarchical Architecture for Distribution Network

The deployment of hierarchical management aims to facilitate the integration of DGs at different levels of the power system. This architecture contains different levels of management. In each level, the related elements are controlled and managed through the external signals receiving from the upstream layers. In other words, the controller in each layer has a certain degree of autonomy which should set its functionalities in accordance with the upstream layers.

Regarding the LV level of distribution networks, at the first hierarchical level, the microgrid is managed and controlled by its control center named a microgrid control center (MGCC). The center is located on the LV side of the MV/LV secondary substation and has some operational functionalities associated with the management and control of the DGs in the MG. The MGCC acts as an interface between the DSO and the MG. At a second hierarchical level, each DG unit is managed and controlled locally through a micro source controller (MC). Loads can be also controlled locally through a load controller (LC) [26]. Fig. 4 describes this kind of control and management structure.

At MV levels of the system, the MGs, the DG units located at MV levels, and MV loads are taken as active cells. The cells are given a certain degree of autonomy. In this regard, the decision making of each cell follows a hierarchical structure. In other words, a central controller is in charge of collecting data from different control units as well as establishing rules for the downstream control units [26].

With regard to the hierarchical structure, consider an aggregator who is responsible for aggregating DGs in the distribution system. In this way, the aggregator negotiates a contract with the owner in order to control their DGs. The aggregator directly controls DGs by sending its control signal to the DGs. The aggregator, itself, receives the control signals from the upper entity, which can be the DSO. This management method can be regarded as a hierarchical management and control method.

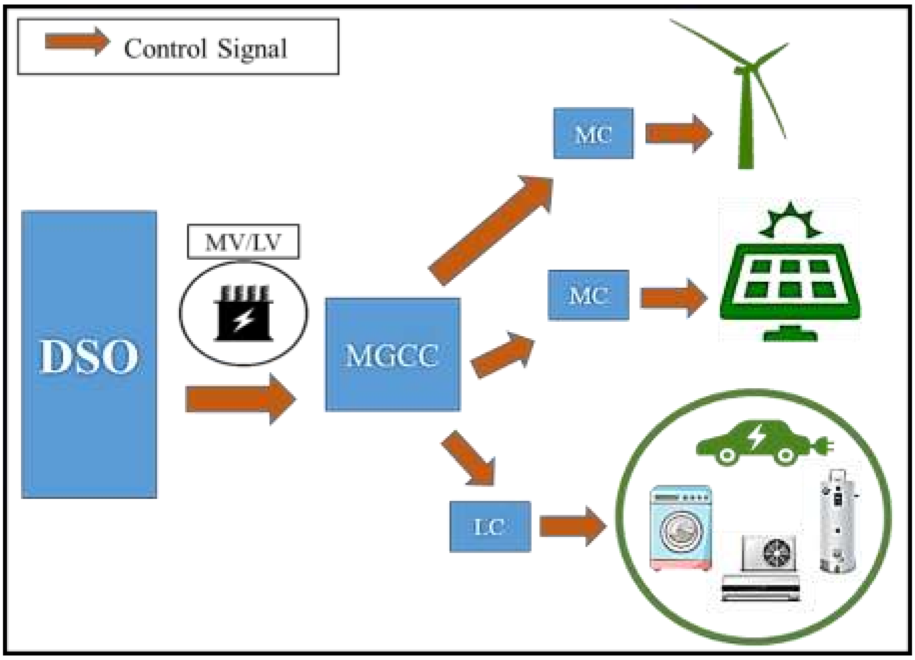


Figure 4. Hierarchical control of DGs located in a microgrid

4.3.2 Decentralized Architecture for Distribution Network

Unlike a hierarchical approach, each controller in a decentralized management method has full control over its elements. The recent advances in artificial intelligence enable each controller to act as an independent agent and form the multi-agent system. In this regard, various agents in the distribution grid can communicate with each other aiming to optimize the global objective function. However, each agent has its own objective function. In the decentralized approach, different grid components can be counted as independent agents. For example, flexible loads, electric vehicles, switchers, on-load tap changing, and DGs can have their own objective and autonomous management [26].

For example, consider a DG owner acting as an autonomous agent. It decides for controlling the DG autonomously with the target to maximize its profits by participating in the local market. It controls its resources using an energy management system (EMS). On the other hand, the local market operator (LMO), which can be the DSO or receives signals from the DSO, is responsible for finding the optimal operating points for players based on their offers and bids.

The aim of the local market operator can be maximizing the social welfare of all of the players with respect to the network constraints imposed by the DSO. Therefore, the DG owners have their own autonomous objectives while they follow a community-based objective by participating in the local market. Fig. 5 illustrates the decentralized management method of DGs in the local market environment. The DGs may also participate in flexibility local markets by providing active power and reactive power support for the grid.

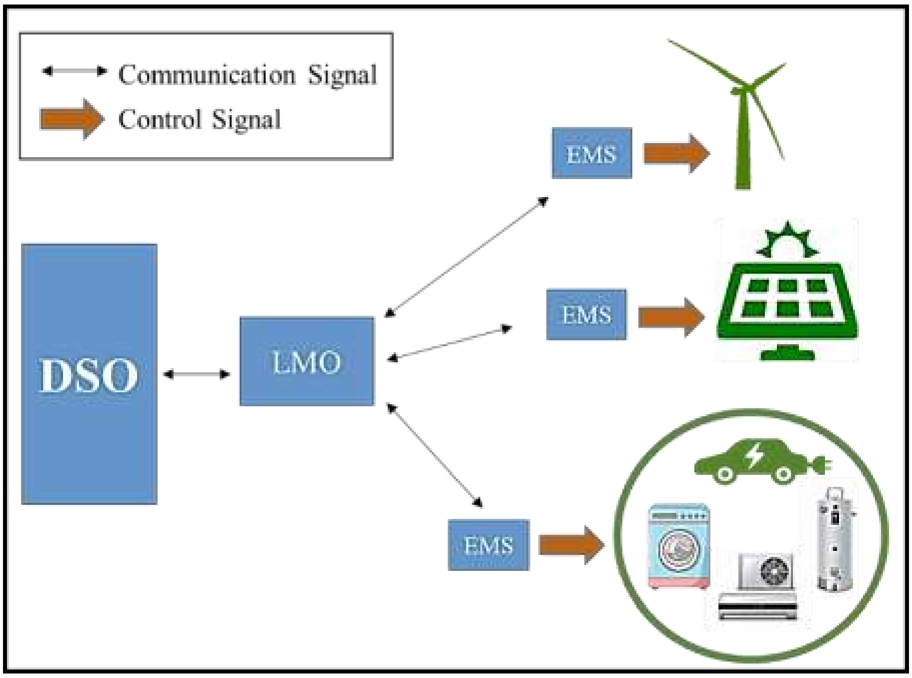


Figure 5. Decentralized control and management of DGs in a local market

An overview of various control architectures provides a clear view on utilization of FESs to mitigate various challenges posed by the integration of DGs in the distribution system. Following section provides a detailed account on utilizing ESSs as FESs in the distribution system, with focus on their classification and range of applications they are capable of tending in smart grid applications.

4.3.3 Future Distribution Network Management Architecture - Potential General Approach

In the future distribution grid zones with flexibilities (Fig. 6) i.e. FlexZones could be seen as building-blocks of a smart, flexible and resilient distribution grid as described in Fig. 6. FlexZone could be also called as an active cell, zone with DER or local energy community. Also, for example, one utility grid connected MV or LV microgrid could create one FlexZone (Fig. 6a)). FlexZone approach could also create basis to implement new business and market models for flexibilities (flexibility service markets). As illustrated in Fig. 6 there can be different level of FlexZones and higher level FlexZone can consist of multiple lower level FlexZones like grid-connected nested microgrids (i.e. for example one/multiple smaller LV microgrids inside larger MV microgrid).

In the future different local (DSO) active network management (ANM) functionalities could be realized by (de)centralized, hierarchical and coordinated management solutions at HV/MV, MV/LV substations with dedicated management units i.e. FlexZone Units (FZUs), because it is more feasible to distribute also the needed processing and calculation capacity closer to the actual measurement points and controlled flexibilities. With this kind of distributed data processing approach it is possible to avoid too extensive 'raw data' transfer and reduce the risk related to loss of one central management unit or communication. However, still fast, secure and reliable communication between different devices will play essential role in future smart grids with flexibilities to enable the needed management and protection functionalities. HV/MV and MV/LV FZUs could include, in addition to different ANM functionalities, also other functionalities like protection/fault indication & fault location, islanding detection & logic, status monitoring, predictive protection, available flexibilities, flexibility forecasts and historian from flexibilities control/use (Fig. 6b).

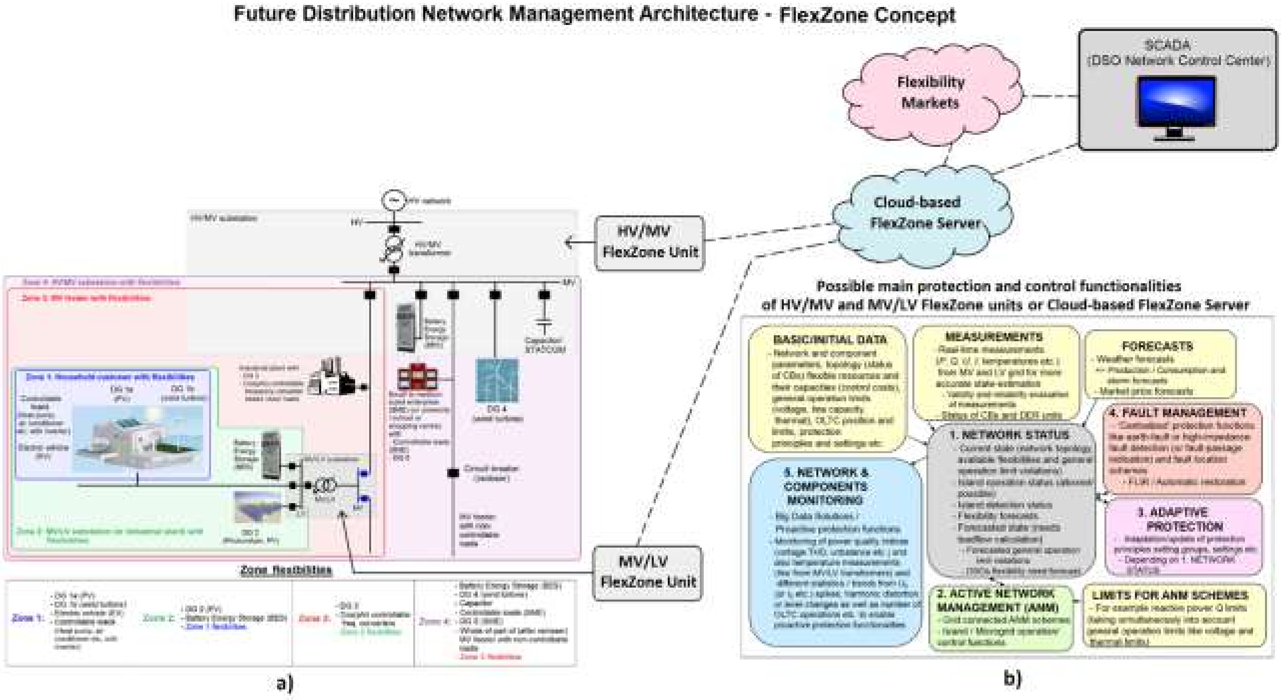


Figure 6. Potential future distribution network management architecture (FlexZone Concept) and a) Different level of FlexZones with possible flexibilities, b) Possible main protection and control functionalities of HV/MV and MV/LV management units

Active network management may simultaneously have an effect on protection settings if, for example, the network topology is changed. On the other hand, active management of flexibilities could be used to enable correct and reliable operation of certain islanding detection methods or, for example, due to earth-fault the grid topology may be changed and it may have an effect on active network management functionalities such as voltage control or losses minimization. Therefore, dependencies between active network management and protection functionalities require careful planning and development to enable creation of future-proof solutions for the Smart Grids.

In the future, one alternative could also be that some of the less critical / high-speed communication dependent DSO FZU functionalities (Fig. 6) like, for example, monitoring or predictive protection related big data solutions, flexibility forecasts, some ANM schemes etc. would be alternatively located in cloud servers. This approach could enable more flexible and scalable solutions when only most communication and time-critical protection and islanding detection applications would remain at actual HV/MV or MV/LV FZUs. Communication reliability and cyber security will play more and more important role in the future grid protection and management solutions and, for example, potential short data packet loss should not cause false operation of FZU functionalities (Fig. 6). In possible cloud server based applications role of redundant back-up schemes, like hot-standby or hot-hot schemes, becomes also significant.

5. Energy Storage Systems (ESSs)

Integration of RES has been progressing at a faster pace at all the voltage levels in the power systems, particularly in the low and medium voltage distribution grids. RESs are typically intermittent and low inertia generation sources leading to large voltage and frequency instabilities in the distribution systems compared to traditional centralized power systems. Flexible energy sources are capable of providing stability in the modern power grids with higher RES penetration. ESSs play key roles with their ability to provide multiple flexibility services in smart grids spread over different time ranges. In this section, various ESS technologies capable of acting as flexible energy sources will explained along with their application ranges for smart grid applications.

5.1 ESS Technologies for stationary grid applications

Energy storage technologies for stationary grid applications are primarily classified based on the nature of energy conversion. From the literature [27]–[29] , a brief outline of the classification of energy storage types are defined as below. Also, Fig. 7 provides details on the technologies applicable for grid scale applications.

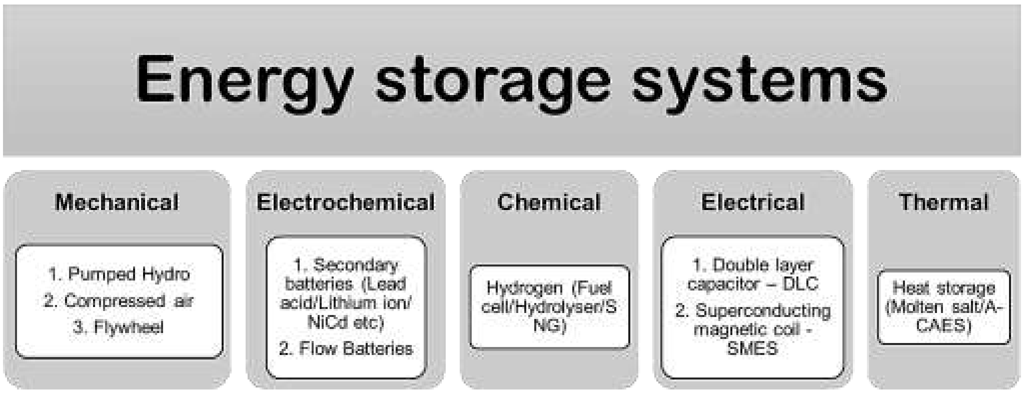


Figure 7. Classification of electrical energy storage systems

1. Mechanical energy storage systems: Stores and convert electrical energy in various forms of kinetic and/or potential energy
2. Electrical energy storage systems: Stores the electrical energy by transforming electrical or magnetic fields with the aid of capacitors and superconducting magnets
3. Electrochemical energy storage systems: Chemical energy of active materials are converted into electrical energy during the discharge phases and vice versa while charging. Simultaneous Redox reactions are responsible for the energy conversion
4. Chemical Energy Storage systems: These systems store energy in the chemical bonds of atoms and molecules and released by electron transfer to generate electrical energy
5. Thermal energy Storage systems: Stores energy in the form of heat or ice, and converted to electrical energy when required

5.2 Application of ESSs Smart Grids

Energy storage systems plays a key role in smart grids by bridging gaps in power generation and demand, especially in the modern power grids where higher amount of renewable energy sources are integrated in the MV and LV distribution systems. ESSs are capable of tending multiple applications and services in the distribution systems and are mainly classified based on the duration of their usage. Based on the available literature [30]–[33], three major categories of applications are observed based their local and system wide requirements. Table I provides details on their classification based on their points of usage, i.e. generation, transmission & distribution and end users.

Based on the duration of energy dispatch, they are classified into three major categories [34],

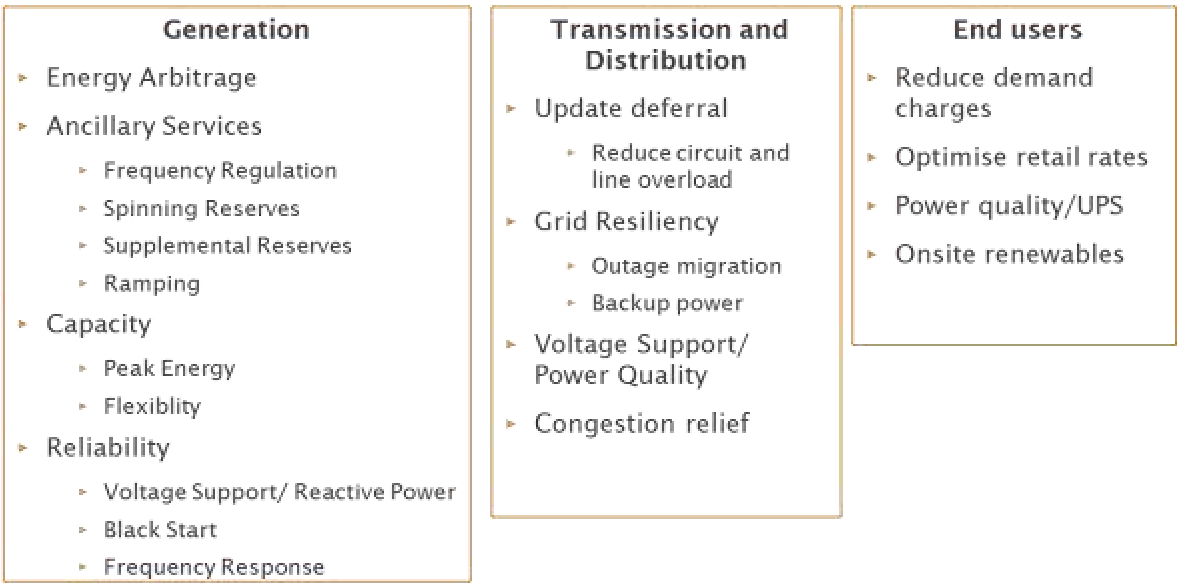
1. Reserve and response ancillary services: Power quality services where dispatch varies between micro-seconds to minutes
    a. Supply interruptions
    b. Voltage sags or dips

    c. Voltage swell
    d. Harmonic distortion
2. Transmission and distribution grid support: Dispatch time typically varies between few seconds to hours supporting ancillary services in T & D grids to operate as specified by grid codes.
    a. Grid frequency support
    b. Voltage control
    c. Spinning reserve
    d. Congestion relief
3. Energy management: Application where duration of dispatch varies between several hours to days
    a. Energy arbitrage
    b. Load levelling
    c. Peak shaving
    d. Black start
    e. Non-spinning reserve

Fig. 8 provides a pictorial representation of the power ratings and the overall discharge duration required from energy storage technologies for various applications. It defines the requirements or specifications to select various energy storage technologies for particular applications in the smart grid. Based on the requirements defined in Fig. 8, suitable ESS technologies that can be utilized for various grid applications are depicted in Fig. 9. The power/energy requirements for a particular application must match with the characteristics of the ESS technology to be deployed. It is also important to have the detailed load curves while conduction feasibility analysis of ESS technologies considering the fact that the energy & power densities, cost and life-cycle characteristics vary from each ESSs. Based on mix and match of various technologies, it is possible to develop hybrid ESS solutions to cater particular load requirements in the smart grid applications.

From Fig. 9 it is evident that the Lithium ion (Li-ion) based BESSs are capable of tending applications in all the time ranges, i.e. reserve and response applications, T & D grid support and energy management. Also, their superior energy and power densities, shelf and cycle life and low self-discharge makes them an ideal candidate for flexibility applications in smart grids. Hence, Li-ion batteries are modelled to cater various power system applications by the authors of this chapter. Based on [35], integration of lithium ion batteries in the MV distribution system by means of power converters shall be explained. Followed by a case study to verify the operations of the developed converter controls for battery integration.

Table I. Classification of ESS applications.



Generation

- Energy Arbitrage
- Ancillary Services
  - Frequency Regulation
  - Spinning Reserves
  - Supplemental Reserves
  - Ramping
- Capacity
  - Peak Energy
  - Flexiblity
- Reliability
  - Voltage Support/ Reactive Power
  - Black Start
  - Frequency Response

Transmission and Distribution

- Update deferral
  - Reduce circuit and line overload
- Grid Resiliency
  - Outage migration
  - Backup power
- Voltage Support/ Power Quality
- Congestion relief

End users

- Reduce demand charges
- Optimise retail rates
- Power quality/UPS
- Onsite renewables

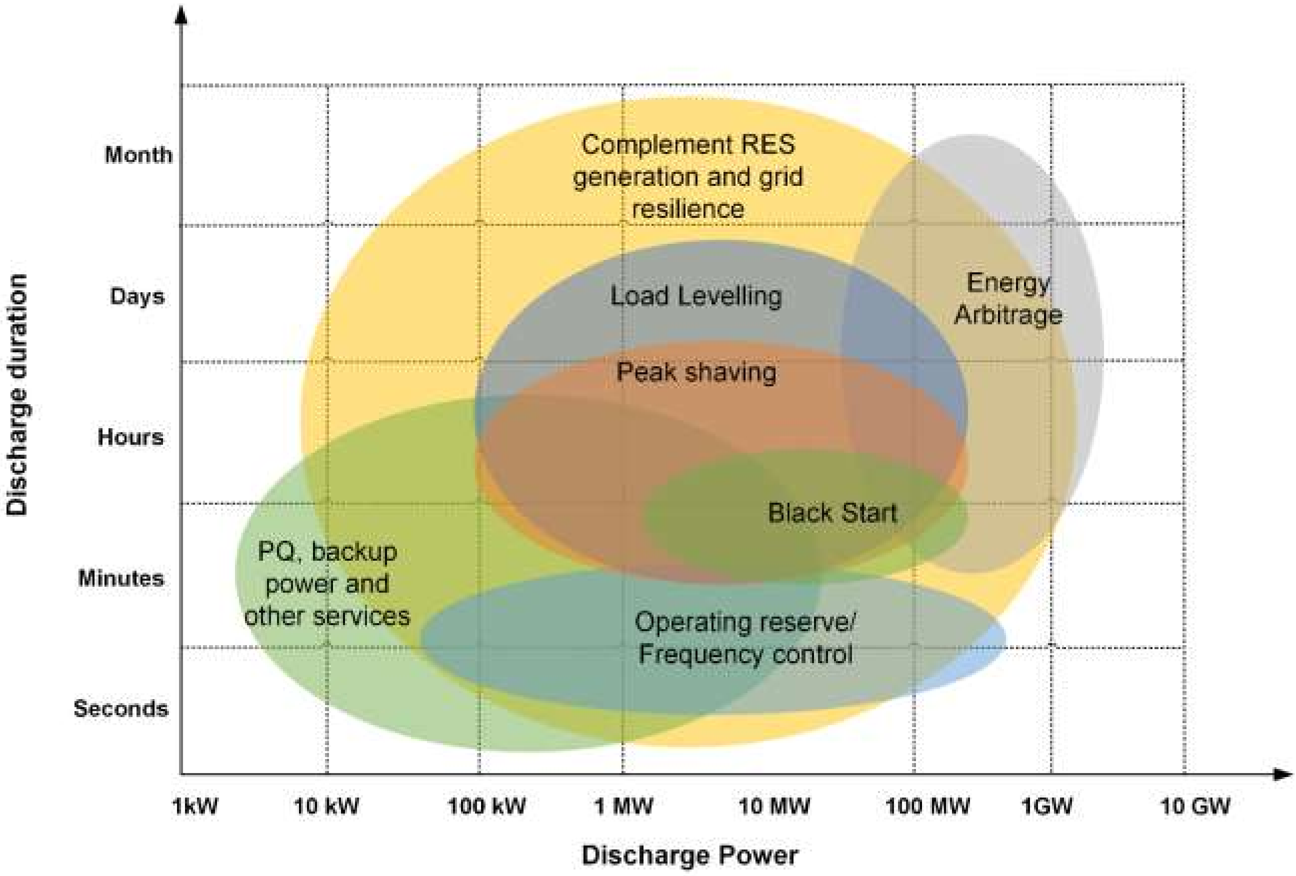


Figure 8. ESS requirements for grid applications

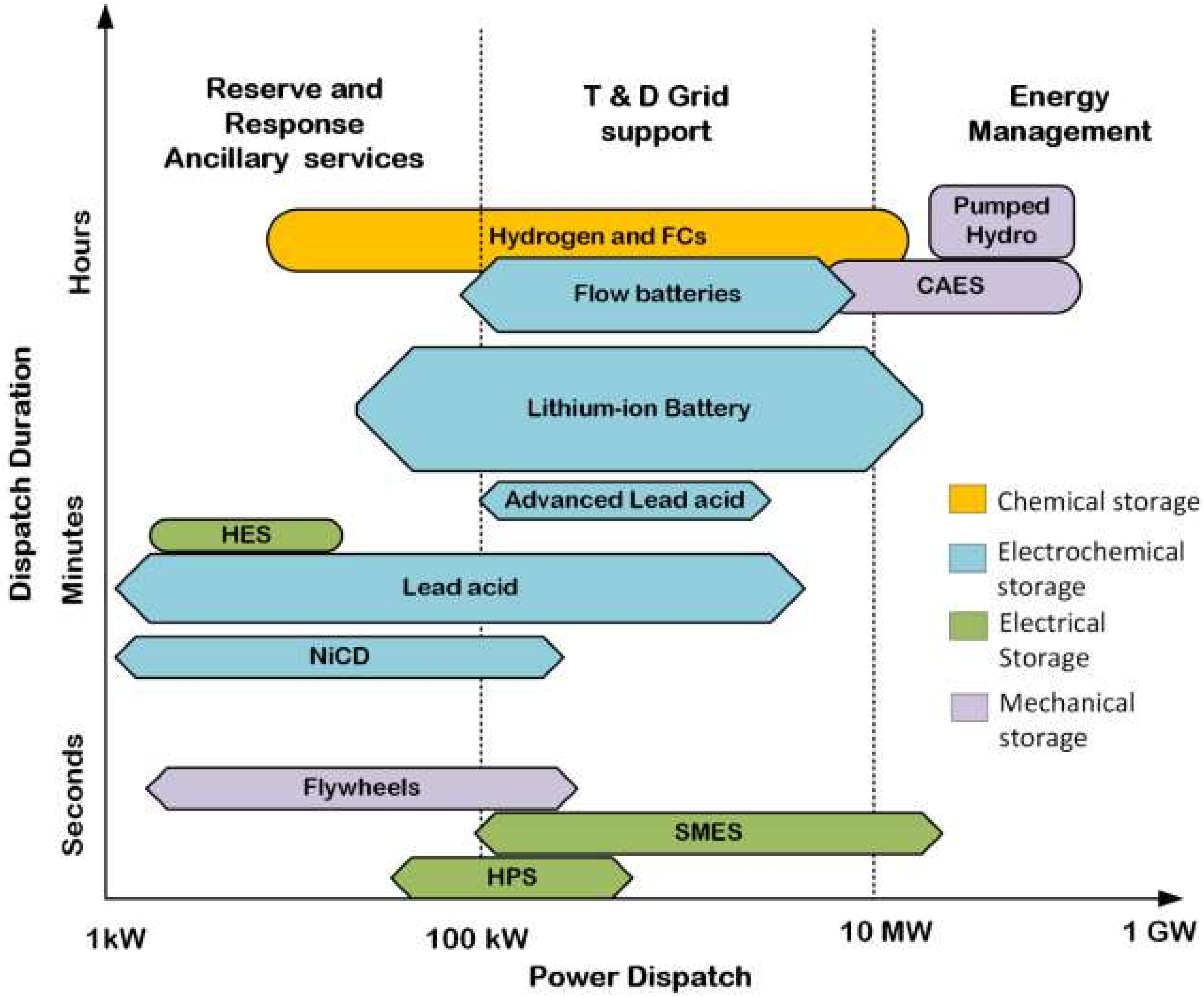


Figure 9. ESS capability for land based applications

6. Integration of Battery Energy Storage Systems

Battery energy storage systems (BESSs) are typically inverter based FESs capable of providing both active and reactive power management. Integration of these BESSs follows the same methodology despite being used in centralized or decentralized control architectures. Hence, in this section design and integration methodology of Lithium-ion BESSs to the medium voltage distribution system.

6.1 Power Electronic converters

Power electronic (PE) converters provide the vital technology for integration of BESS to the power grids. Maintaining various grid code requirements in the modern distribution systems are satisfied by the PE converters, as most the RESs are connected to the grid through PE. Simultaneously PE interface controls BESS in active (P) and reactive (Q) power flow modes, keeping in view of the current and voltage variations across the battery pack which affects BESS health, performance and lifetime [36]. This section briefly reviews the available and widely used PE topologies for large scale

BESSs discussing main parts of the system in detail. The used configuration and its modelling aspects to integrate BESS to the studied real-life smart grid pilot will be addressed in next section.

Fig. 10 shows the elements of PE units for a typical BESS grid integration which including three main parts;

- DC-DC converter
- DC-AC inverter
- Coupling transformer

In order to design an optimized BESS system, selection and design of each part needs to be investigated in detail. Different parameters affect selection and design of PE units such as power ratio, energy density, response time (speed of system) and grid interconnection requirements.

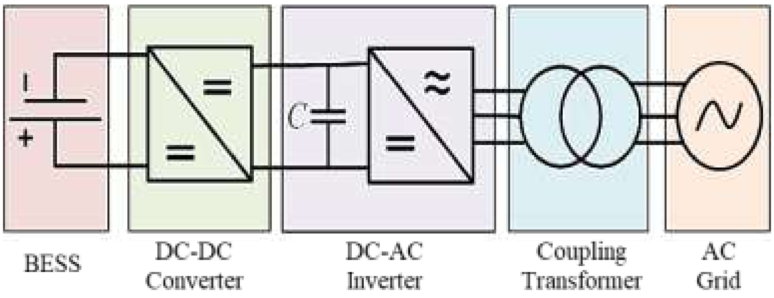


Figure 10. Typical PE units for BESS grid integration

6.1.1 DC-DC Converter

Presence of DC-DC converter increases system performance and flexibility, but it also adds losses and costs. Therefore, it is worth considering to connect BESS directly to DC-AC inverter DC bus. BESSs with and without DC-DC converter have been used in recent applications.

6.1.1.1 BESS without DC-DC Converter

PE system design without DC-DC conversion stage could be a cost effective solution in one sense, but it can add complexity to the DC-AC inverter system. Some issues can be linked to this solution. The BESS voltage varies depending on SoC and this introduces DC bus voltage variation which will affect the DC-AC inverter operation performance. Also, safety problems can be associated with this solution since over-voltages or over-currents can happen at BESS side and their management is not easy by only grid side DC-AC inverter. Another possible drawback could be low-order harmonic injection to the battery and this also can affect BESS health and lifetime [37].

6.1.1.2 BESS with DC-DC Converter

Adding a DC-DC conversion stage eliminates above mentioned low-order current harmonics flowing in the battery since the DC-DC converter isolates the BESS from inverter DC bus. With DC-DC converter, BESS can be designed to lower voltage level (less cells in series). Moreover, it can be used as protective and current limiting device which will increase the safety and controllability of the system.

Simple bidirectional Buck-Boost DC-DC converter is widely used due to its simplicity when a lower voltage level is used for BESS side and higher voltage level at the DC bus of the grid side DC-AC inverter. However, Buck-Boost converters have their own intrinsic limits for levelling up/down the voltage [38]. This issue can be dealt with using a full-bridge bidirectional DC-DC converter which also increases the costs and losses (due to increased number of the switching modules).

For high power applications, advanced solutions such as isolated DC-DC converters [39] and isolated dual active bridge (DAB) converters have been proposed [40] which include high frequency isolation transformer (20kHz). This transformer can eliminate need for coupling transformer and since it is working in high frequency, it can decrease the size and weight of the system considerably. These are interesting solutions, but the technology is in research stage and at the moment there are not any commercial solutions available.

6.1.2 DC-AC Inverter

DC-AC inverter is a necessary part of the PE system in the BESS grid integration applications. Main task of it is to convert the DC voltage to the AC voltage and guarantee fulfilment of grid code requirements [41]. Two level inverters are widely used in different applications, including also BESS integration (with centralized BESS at DC bus), due to the maturity of the technology and availability of the commercial solutions. Recently three-level, five-level and more general, multi-level inverters have also been developed and used in wide range of applications.

More specifically, cascaded H-bridge (CHB) converters are used for BESS integration where the BESS can be equally distributed among sub-modules (SMs) in the form of smaller battery packs. However, advanced control algorithms are required in order to ensure balanced SoC for all battery packs.

Modular Multilevel Converter (MMC) is another developing solution in which both centralized BESS at DC bus and distributed BESSs among SMs have been proposed [42]. However, distributed approach can be preferred where the benefits of cascaded structure can be better utilized. With centralized BESS at DC bus, some positive features of MMC structure will be lost [43], [44].

Apart from technology readiness, using CHC and MMC solutions are linked with few issues [36],

- Need for an extra battery management system (BMS) to ensure balanced SoC among the battery modules
- One of the main advantages using CHB or MMC solutions is to eliminate the need for coupling transformer (otherwise these solutions cannot be economically justified), but in BESS application unbalanced SoC can cause DC current injection to the grid (this should be limited to 0.5% according to [41])
- Complexity of the control and system cost.

6.1.3 Coupling Transformer

Conventional grid connected PE for BESS system consists of a coupling transformer. Transformer based solution is favoured so far [36] and for large-scale BESS system it could be the preferred solution providing galvanic isolation between grid and energy storage system. However, several transformer-less solutions have been investigated as well. The advantages of using a coupling transformer are,

- DC-AC inverter can work in lower voltage and the transformer can match the voltage level up to kV level
- Inverter AC side passive filter size can be decreased
- It can protect PE devices against grid side faults till certain level
- Losses of the device can be compromised with high efficiency transformers

However, transformers are bulky and heavy units and coupling transformer can increase the weight and size of final installation unit. In medium voltage (MV) level and working with few MWs, the size and weight of coupling transformer itself (in 50 Hz) can be comparatively close or even higher than the rest of system. Isolated DAB converters with high frequency transformers could also be an attractive solution but as mentioned earlier, still DAB commercial solutions does not exist and are in research stage. In addition, it is worth mentioning that correct transformer energization principles should be considered in order to ensure safe and feasible operation conditions.

6.2 Grid Code Requirements

IEEE standard considering BESS systems for stationary applications is still in drafting stage, but IEEE standard 1547-2018 [41] and ENTSO-E RfG requirements [45] can be used as a good reference for BESS system PE design from grid code requirements point of view. The standard defines general requirements for power quality (harmonics, reactive power, voltage levels and sag/swells) and DER response to power systems disturbances (such as faults, open phase conditions, voltages and frequency deviation and also islanding situations) i.e. fault-ride-through (FRT) requirements. It can be used as reference to design PE unit but it's focus is mostly on grid side and talks about general requirements and in most cases it leaves the details to the transmission and/or distribution systems operators (TSOs and DSOs) [41].

6.3 BESS Integration Design

This section provides an overview on the design and development of power electronics converters for BESS integration to the MV distribution system. Control design and development of voltage source converter (VSC) and DC/DC bidirectional buck-boost converter are explored in detail.

6.3.1 BESS Integration Methodology

Li-ion BESSs are best suited for multiple energy storage applications in smart grids, which is evident from their characteristics explained earlier. Hence, they were modelled as flexible energy sources to meet short/medium time energy storage demands in smart grids. Fig. 11 explains to complete BESS integration methodology in the MV distribution system. Li-ion BESSs are integrated to the MV bus by means of power electronics interfaces, i.e. through DC/DC bidirectional buck-boost converter whose low voltage side is connected to the BESS and the high voltage side is connected to the 600V DC bus. DC/AC VSC converts $600V_{DC}$ to 3-phase, 400 V_{RMS}. Coupling transformer converts VSC output to the MV bus voltage which is 21 kV in this case. Equivalent circuit model of Li-ion BESS [35] is utilized in the method. Power electronics converters controller design are explained in the following section.

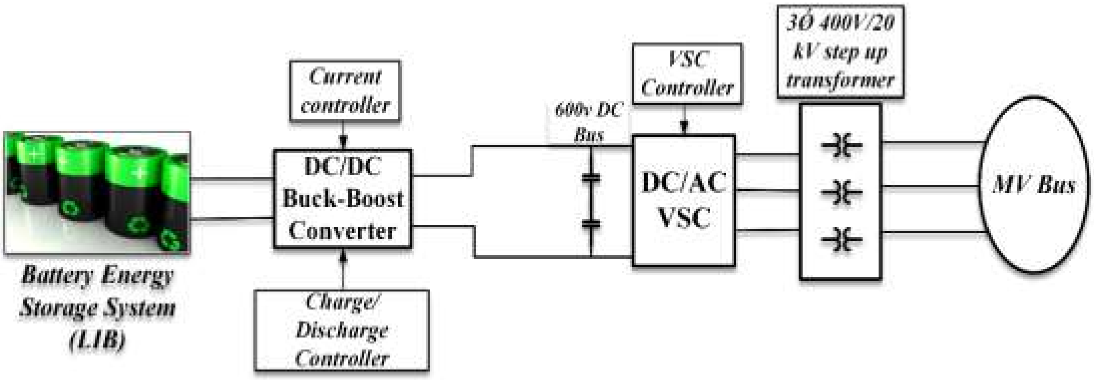


Figure 11. BESS grid integration methodology

6.3.2 VSC Controller

VSC controller design is based on voltage oriented control (VOC) technique [46] which is shown in Fig. 12. Primary advantage of the VOC techniques lies in its and high static performance and fast transient response through its current control loop. Three phase voltages and currents (i.e. *I,abc* and *Vabc*) are transformed into *dq0* frames by means of Park's transformation [47] to *I,dq* and *V,dq* frames. *Id,ref* is provided by the PI- controller for V_{dc} management and the Iq,ref is dictated by the reactive power demand for the MV grid application. *Iq,ref* and *Id,ref* controls the active power (*P*) and reactive power (*Q*) outputs respectively. However, the controller's dynamic performance shall be affected by cross coupling between d- and q- axes components. Hence, V_d feedforward signal is provided to the d-component control loop. Similar Feedforward signal shall be added to the q-component control loop, however, it is not needed in this application. VSC was designed to provide 1.5 times the nominal power to accommodate transient requirements from the grid.

6.3.3 Battery Charge and Discharge Controller

Bidirectional Buck-Boost converter acts as the battery charger (buck mode) while charging the batteries and the DC supply converter (boost mode) during discharging scenarios. In this case, it is developed as an average model system with single IGBT and its accompanying anti-parallel diode with a switching inductance [48]. Current control through the converter is provided by a simple PI-controller as shown in Fig. 13. DC bus voltage is regulated and controlled by the VSC's d-component control loop, so the positive or negative sign carried by the PI- controller output defines the *P* -flow direction. Hence, an additional DC bus voltage control loop is not necessary in this case in the battery discharging scenarios. During both control modes, i.e. charging or discharging modes, the PI-controller output delivers the duty cycle to the Buck or Boost converter.

To keep the Li-ion BESS in the safe operational threshold, BESS Discharge mode is set in the range between 20 to 90% of the battery State of Charge (SoC). While, charging the batteries the maximum SoC is set at 90% which is provided by the constant current charging technique alone, thereby eliminating constant voltage charging sequence. Adding SoC of the BESS control loops, the battery charging and discharging currents are always maintained within the specifications provided by the manufacturers.

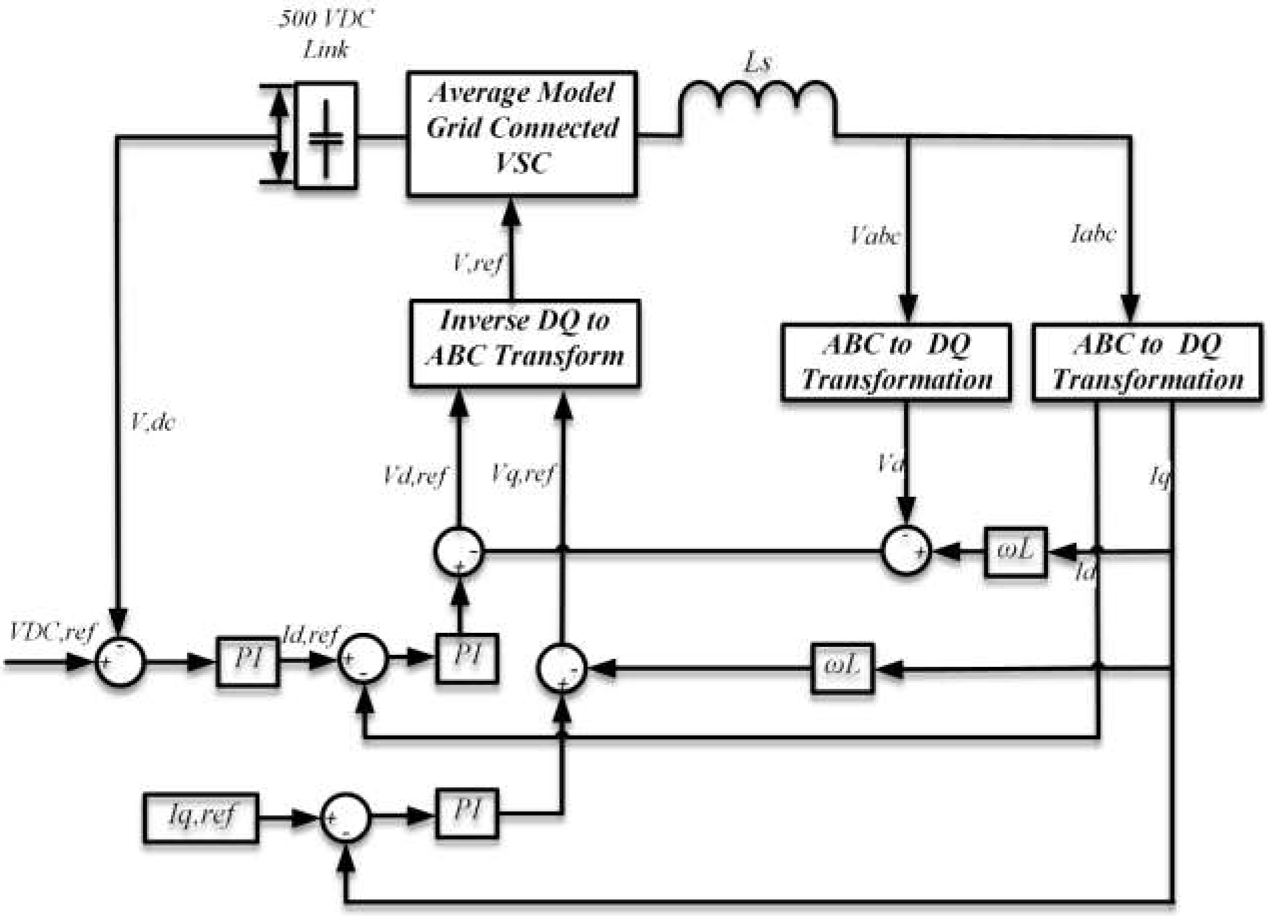


Figure 12. VSC Controller

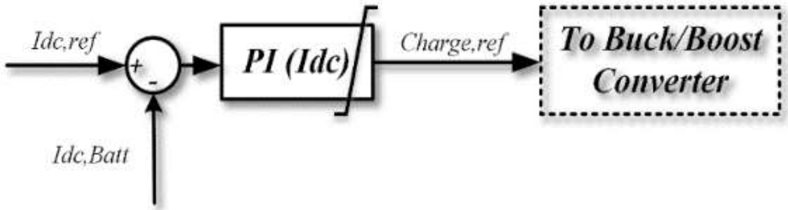


Figure 23. Battery Charge Discharge controller

6.4 Case Study and Simulation Results

Integration of Li-ion BESSs to the MV distribution system is validated by means of simulation based on a case study. Grid side controllers provided the P_{REF} reference to the DC/DC converter stage which is associated with the battery operations. Nature of the designed use case was to validate the stability of VSC and the DC/DC- bidirectional buck boost converter during transient and steady state system behaviour.

Table II presents the characteristics of the Li-ion BESS used in the study. It is sized for a nominal discharge (1C) of 0.335 MW and a peak power discharge (3C) of 1 MW. The DC/DC converter was rated for 3C battery discharge and the VSC is sized at 1.5 MVA. Battery's initial SoC is maintained at 50% which can accommodate both charge and discharge operations as commanded by the grid services.

Table II. Li-ion BESS Specifications

Nominal voltage	312 V
Maximum Voltage	354 V
Minimum Voltage	236 V
Discharge Energy(1C)	335 kWh
Discharge current (1C)	945 A

Table III. Simulation case details

Simulation Time (Secs)	***Active Power ref* (kW)**	**Status**
T1	670	Discharge
T2	330	Discharge
T3	168	Discharge
T4	-168	Charge

Total simulation time span was considered at 80 seconds. The P_{REF} given to the BESS is shown in Table III. It corresponds to the various C-rates of battery discharge and changes every 20 seconds during the simulation time period, there by inducing transient instability conditions. In the final time period of simulation, BESS charges at a rate of 0.5C. Such loads are not usually existent upon the BESSs, however, the simulation cases were developed considering extreme events or changes while supporting RESs such as PV/Wind power generation.

Performance of the Li-ion BESS integration through its PE converters are shown in Fig. 14. Battery load current characteristics are as shown in 14(a), where its magnitude changes as set by P_{REF}. 14(b) shows Li-ion BESS voltage. Voltage fluctuations in the Li-ion BESS are evident. Such accurate voltage characteristics provides set-points for V_{dc} control in the DC bus. DC power output of the BESS is shown if Fig 14(c), whose characteristics are defined based on the C-rates from Table II. Such large step changes were chosen to observe the DC bus stability and the controller interactions during transient stability conditions. Li-ion BESS SoC changes are as shown in 14(d). The DC bus voltage is presented in 14(e) where it is constantly maintained at 600V, despite changes in Li-ion BESS voltage and current dispatch characteristics. VSC is designed to provide both P & Q control capabilities, which is demonstrated after 40 seconds into simulation, where the converter starts to absorb reactive power as shown in 14(f). Therefore, overall design objectives of the Li-ion BESS integration to the MV distribution system is achieved by controlling active and reactive power flows in the power system, maintaining the safe operations of Li-ion batteries.

Summary and Conclusion

Integration of Distributed generators, i.e. including the renewable energy sources has been ever increasing in the LV and MV distribution systems. Higher penetration of DGs in the power grids comes with its own set of challenges and multiple innovative ways are needed to mitigate those issues. Active network management of the distribution system, by effective management and control of the available flexibilities plays a crucial role in managing network challenges caused by higher DG penetration. Energy storage systems form a key component in executing ANM schemes by providing both active and reactive power control related flexibilities. Overall, this book chapter provides an overview on DG types, ANM control methodologies, energy storage system (fundamentals, classification and applications) and integration design and methodology for battery energy storage systems in the MV distribution grids.

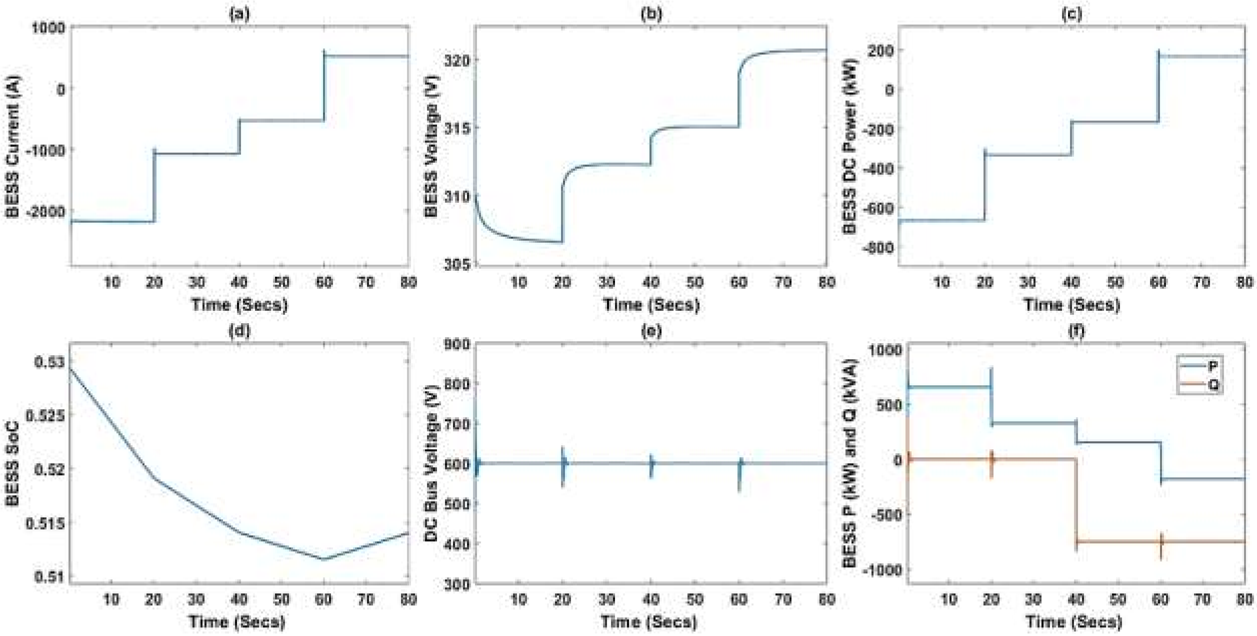


Figure 34. a) Battery Load current (b) Battery Voltage (c) Battery DC Power (d) Battery SoC (e) Battery DC Bus voltage (f) Battery *P* and *Q* characteristics

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