CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

Power Engineering Department

Battery Energy Storage System in the Distribution Network

Bateriové systémy skladování energie v distribuční soustavě

Master's Thesis

Study program: Elektrotechnika, energetika a management

Specialization: Applied Electrical Engineering

Supervisor: Ing. František Vybíralík, CSc.

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2. Description of the EV Charging Technologies and Power Control within the Network
3. Case study

Bibliography / sources:

[1] S. Dhameja, Electric Vehicle Battery Systems-Newnes (2001)
[2] T. B. Reddy, Linden's Handbook of Batteries, 4th Edition-McGraw-Hill Professional (2010)
[3] F. Díaz-González, et al., Energy storage in power systems, John Wiley & Sons (2016)
[4] J. Jiang, et al., Fundamentals and Application of Lithium-ion Batteries in Electric Drive Vehicles, Wiley (2015)

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Acknowledgement

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Abstract

This thesis is about the basics of battery energy storage system (BESS) connected to distribution network (DN), such as its advantages, basic technical design (components and topologies), applications, benefits such as peak shaving, load leveling, basics of cell balancing such as SoC, brief explanation of power converter systems, EV charging station/load and its impact on DN, and also how BESS may support DN balance with DP generation.

Keywords

Battery energy storage system, cells, batteries, distribution system, charging, discharging, control, peak shaving, peak shifting, power conversion system, distributed power generation.

Abstrakt

Tato práce pojednává o základech systému akumulace energie do bateriových úložišť (BESS) připojených k distribuční síti (DN), také popisuje jaké jsou výhody, základní technické řešení (komponenty a topologie), aplikace jako je peak shaving, vyrovnání zátěže, základy vyvažování baterií jako SoC, stručné vysvětlení systémů měniče, EV nabíjecí stanice/zátěž a její dopad na distribuční síť, jak může BESS podporovat vyvážení distribuční síti (DN) s obnovitelnými zdroji.

Klíčová slova

bateriové úložiště, články, baterie, distribuční soustava, nabíjení, vybíjení, řízení, peak shaving, peak shifting, systém přeměny energie, distribuovaná výroba energie.

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Abbreviations

AC	Alternating current
BESS	Battery energy storage system
BEV	Battery electric vehicle
BMS	Battery management system
CCM	Continuous conduction mode
CHP	Combined heat and power
DC	Direct current
DCM	Discontinuous conduction mode
DNO	Distribution network operator
EV	Electric vehicle
EU	European union
EN	European standards
ESS	Energy storage system
GSC	Grid-side converter
HVDC	High-voltage direct current
IEC	International electrotechnical commission
JIT	Just in time
LV	Low voltage
LCC	Line-commutated converter
MV	Medium voltage
MG	Microgrid
OLTC	On-load tap changing transformer
TSO	Transmission system operator
PV	Photovoltaic
PQ	Power quality
PEV	Plug-in hybrid electric vehicle
VR	Voltage regulation
VSC	Voltage source converter
PWM	Pulse width modulation

PCS	Power conversion system
RES	Renewable energy source
SAE	Society of automotive engineers
SVR	Step voltage regulator
SSC	Storage side converter

1 Introduction

1.1 Brief overview of power system structure

Power systems are complex structures composed of many various installations, economic factors, and in smaller quantities system operators. Electric power systems are real-time energy supply systems. Real-time indicates that power is generated, transmitted, and delivered the moment the light switch is turned on or any other appliances. This also implies that the electric power systems are not storage systems like battery energy storage systems (BESS), hydro systems and others. But instead, the power is generated and operated on demand. In power systems, various forms of energy are converted into electrical energy (shown in *Figure 1.1*). The process of conversion is called electric power generation. There are the following forms of energy that may be involved in process of the electric power generation: nuclear, chemical, mechanical, heat, hydraulic and other energy sources are used for the electrical energy generation.

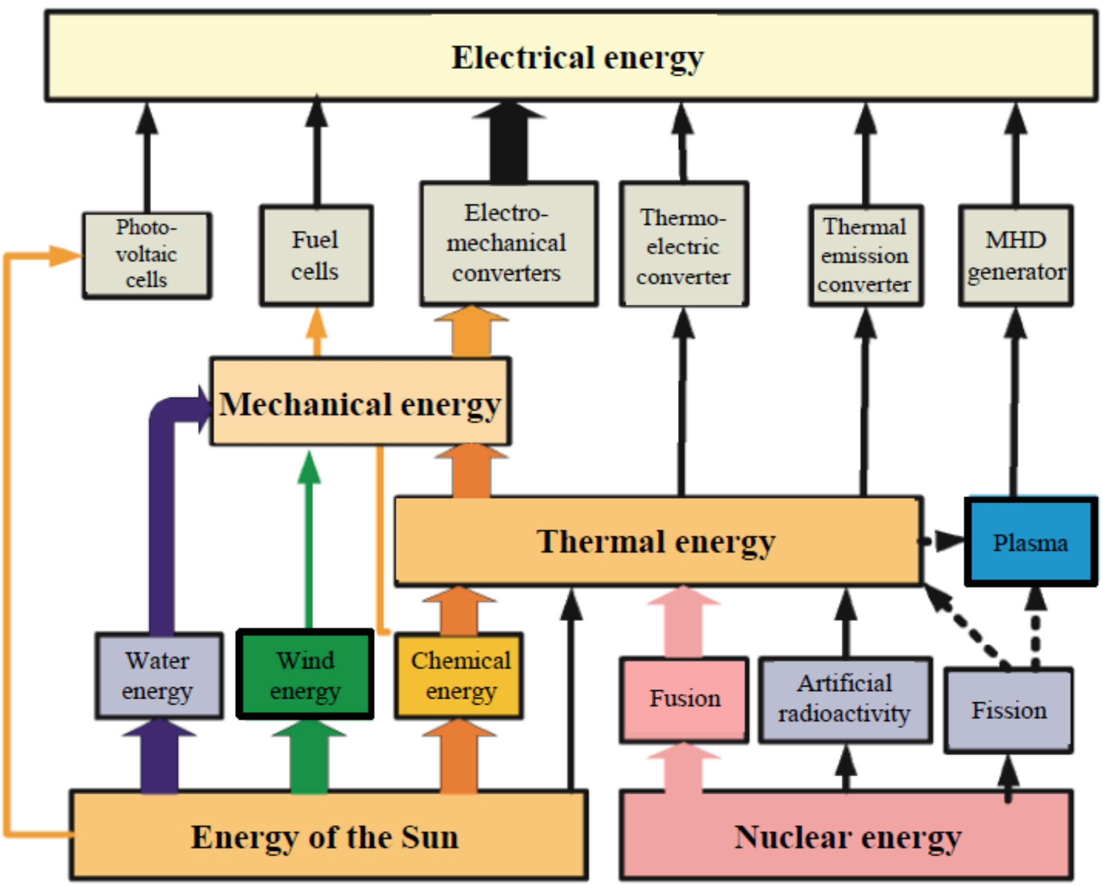

Figure 1.1 *– Intermediate steps of different types of energy conversions*

In *Figure 1.2* is represented a simple schematic of a radial electric power system. The power flow, which is foremost unidirectional that means from generators to customers, who are connected to medium or low voltage side. It is clear from *Figure 1.2* that the process begins with generation, where the electricity is generated in a power plant over several stages of energy conversion. Usually, the last stage is the conversion of mechanical energy into electrical energy. As soon as this conversion is carried out using a synchronous generator the electric energy is produced as a three-phase AC power. Synchronous generators have the output voltages, which are typically between 12 kV and 25 kV. This power is transmitted and further distributed over of four or three wires. The electric power transmission over long distances in general means that the voltage is stepped up by using a transformer due to more suitable and efficient long-distance transmission. The voltage of such lines in the Czech Republic may vary from one line to another and it is commonly between 110 kV, 220 kV, and 400 kV. In the last step, the transmitted electric energy can be delivered to the demand, and also its voltage shall be stepped down. The remote substations are responsible for transforming this HV electrical energy for delivering on lower high voltage power lines so called "feeders", which are more appropriate for the distribution of the electrical energy. Power distribution in the Czech Republic occurs at different voltage levels with the highest level being 22 kV and/or 35 kV. Usually, there are several stages for voltage step down, which are accomplished by transformers at power substations or by pole mounted transformers. This power is supplied to residential customers with the voltage equal to 400/230 V. Now it is clear from the presented discussion that electric power systems have three main elements such as generation, transmission, and distribution.

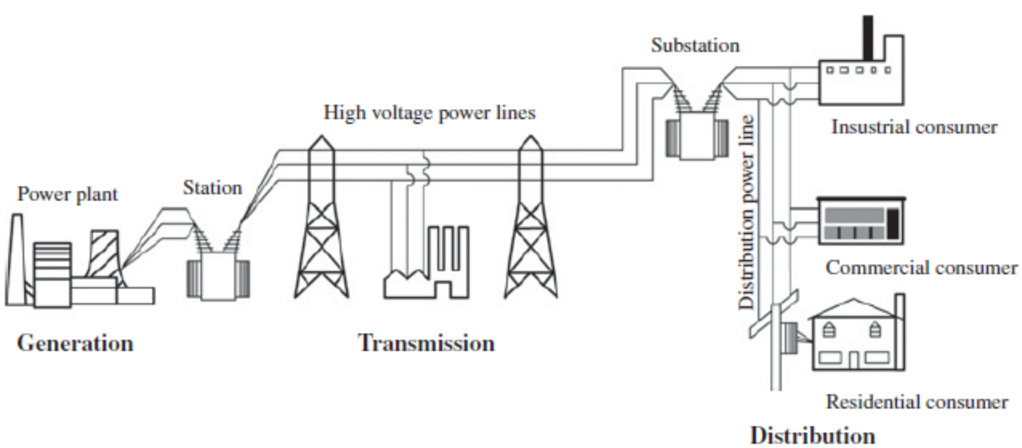

Figure 1.2 *– Electric Power System Overview*

1.2 Distributed power (DP) generation [1]

"In our generation, electricity is one of the most important necessities in everyday life. Nowadays the grid structure is implemented by novel approaches such as distributed power (DP) generation. Basically, DP refers to the process and concepts in which low to medium (a few kW up to 10 MW or more) power generation facilities, energy storage facilities (thermal, flywheel, hydro, flow, and regular batteries) need to be integrated. DP technologies installed near customers' loads operate as grid-connected or islanded resources at the distribution or sub-transmission level and are geographically scattered throughout the service area. DP generation harnesses renewable and nonrenewable energy sources, such as solar irradiance, wind, biomass, tides, hydro, waves, geothermal, biogas, natural gas, hydrogen, and diesel, in a distributed manner. DP also includes several nonutility sources of electricity, including facilities for self-generation, energy storage, and combined heat and power (CHP) or cogeneration systems. DP is ideally suited to power sensitive loads, small remote loads located far from the grid, and integrated renewable energy sources into the grid. Regarding the integration of renewable energy generators at different levels in the power grid, there are two approaches. Although there is the massive connection of small-scale renewable generators at the distribution level (low and medium voltage), mainly photovoltaic (PV) installations in households or small-scale generation in light–industrial or commercial facilities. Alternatively, utilities and big investors are increasing their portfolio with renewable generation assets. These plants are at the scale of several kilowatts up to decades of megawatts. They are considered to operate like traditional power plants and therefore TSOs ask for compliance with grid codes. In order to integrate remotely located renewables (in the most common case, offshore wind) in the system, high-voltage direct current (HVDC) technology is employed to connect such plants to the transmission grid. One of the first technologies HVDC has been employed in the past to perform long-distance transmission is thyristor based line commutated converter (LCC)."

1.3 Challenges of the integration of renewable sources (RES)

Today's distributed power generation mainly consists of renewable energy sources (RESs) such as PV systems, wind turbines, biomass, etc., whose intermittent nature generates heavy power imbalances in the microgrids (MG). For a better understanding of why large RESs penetration leads to problems in the grid, let's consider an example of PV power generation.

- **Change of load**

The PV generation is only obtainable within the daylight and therefore the PV generation of peak hours is not matched with the peak load hours. Typically, a zone substation peak demand happens in the evening when PV power is not possible to get. A usual demand curve in some city is represented in *Figure 1.3* with and without PVs. By taking a look at the graph it is possible to see that a high PV output decreases the daytime load. Hence, the reformed curve of the load consists of a down opening parabola around the afternoon and a peak in the evening.

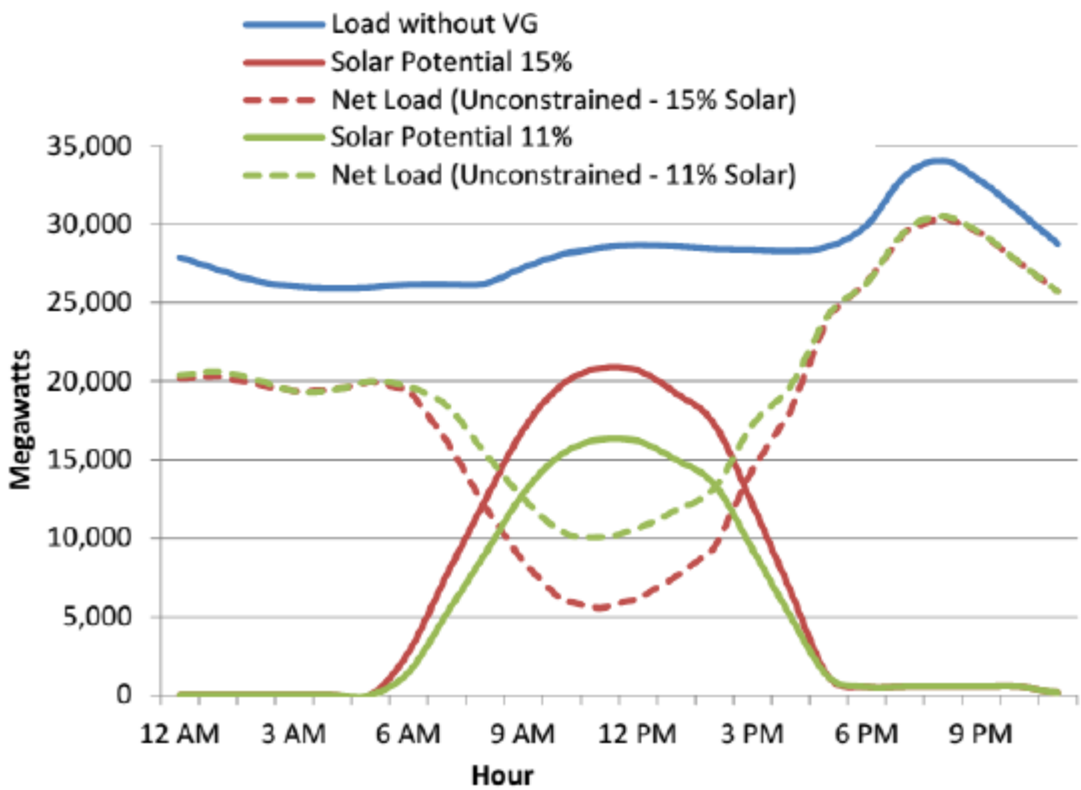

***Figure 1.3** – A typical load and variable generation profiles with 11% and 15% annual solar irradiation*

With increasing PV penetration, the difference between the lower and upper peaks of the net load curve increases. Load reduction in the afternoon produces the uneconomic operation of several base power plants under a wholesale market. In addition, the necessity of fast generation resources is obvious in order to meet the evening peak due to the increase in the load curves. Thus, dispatchable generation sources are required to adapt more PVs in power systems.

- **Voltage rise, reverse power flow and fluctuations**

Several technical challenges have arisen in the planning and operation of distribution systems due to high PV integration. The key issues include voltage rise, fluctuations, and reverse power flow. Distribution network operators (DNOs) aim to deliver power to the customers at specified voltage levels (e.g. 400/230 V). The service voltage has to be maintained within allowable ranges under changing load conditions depending on the relevant system standards, which is known as Voltage Regulation (VR). Usually, distribution voltage regulation is carried out by an on-load tap changing transformer (OLTC) at a substation, a fixed tap changer through a feeder, step voltage regulators (SVRs) and fixed capacitors.

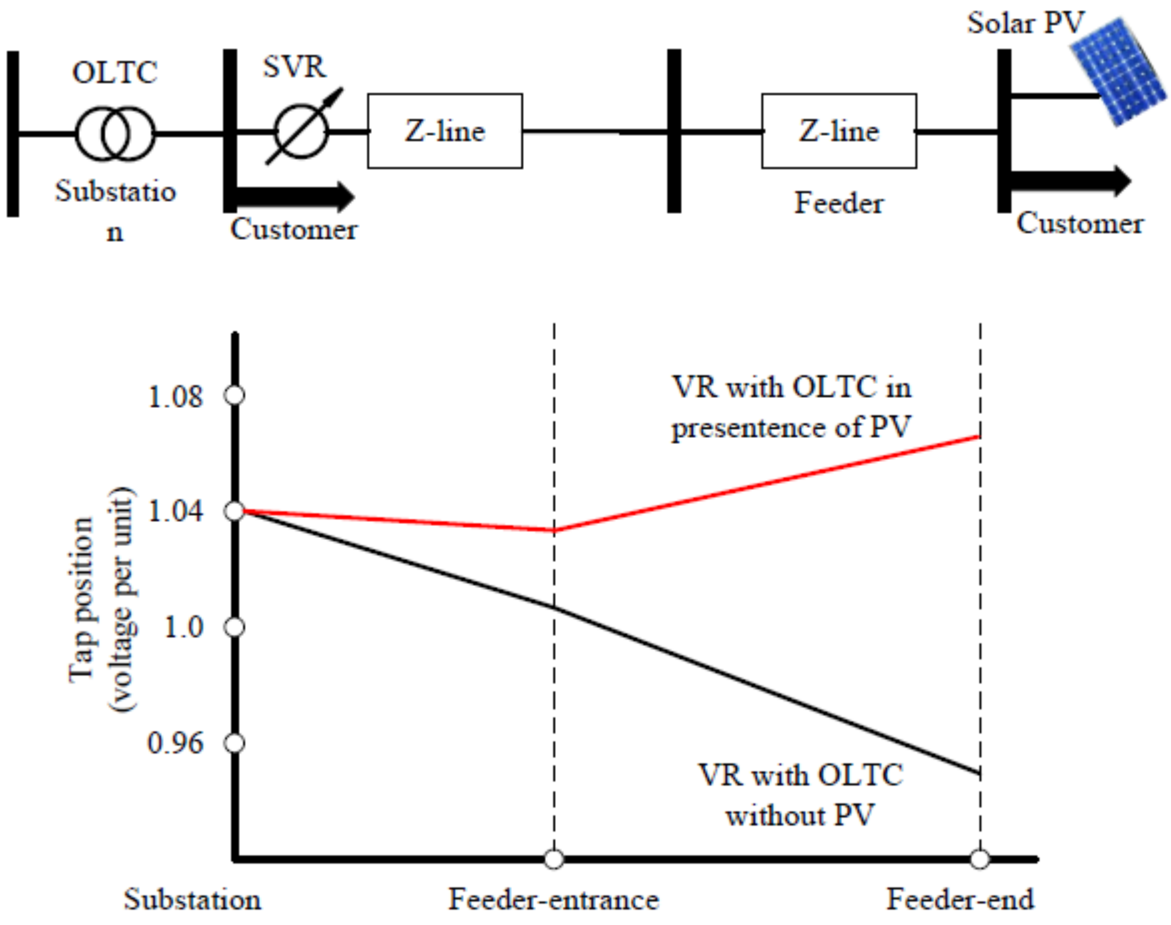

***Figure 1.4** – Radial distribution network with voltage regulation devices*

Figure 1.4 presents the schematic diagram of a typical radial distribution feeder with voltage regulation equipment. If there is no solar PV at the customer end, current flows from a distribution substation to loads/customers causing a consistent voltage drop on the feeder side. When solar PV is connected and if the output of PV exceeds local demand, the surplus PV power is sent into the network. Hence, the current flow direction is reversed, which in turn causes voltage rise at the customer's point. *Figure 1.4* represents voltages of the distribution feeder with and without solar PV.

Unlike transmission systems, line transposition is rarely executed in distribution networks. Therefore, three phase distribution lines have unbalanced coupling and distinct voltage characteristics. Since the cross-sectional area of transmission lines is much bigger than those of distribution conductors, relatively higher resistance to reactance (R/X) ratios are observed in distribution systems. Thus, voltage rise caused by reverse power flow from PV might propagate to upstream locations due to the mutual reaction of high R/X ratios of the lines and PV penetration levels in the corresponding feeders.

1.4 Impacts of electric vehicle (EV) charging station load on distribution network (DN) [2]

Nowadays, there are not many numbers of EVs across Europe, therefore it does not yet make significant problems in DNs. However, as their number will be increasing in the future, the impact of EV charging will primarily affect the low-voltage DNs, as drivers will mostly depend on domestic or semi-public charging environments for charging their cars. Given that these networks were designed without predicting the arrival of the new EV loads, DSOs most probably will need to invest in conventional grid reinforcements if no load management is considered. This implies increasing the existing hosting capacity of transformers, LV lines, and feeders to meet the growth in peak demand. Cost calculations include complex economic factors for LV grid investments they may be different and depending on the local situation. Traditional grid reinforcements can be between three and ten times more expensive than smartening the grid. However, conventional grid investments can remain a viable alternative for some LV networks that may anyways need reinforcements even without considering the penetration of electric vehicles (e.g. municipal networks in the oldest areas of cities or weak countryside, which were electrified first). *Figure 1.5* below represents the total EU increase by 2030 but the increase at already existing peak periods in local areas.

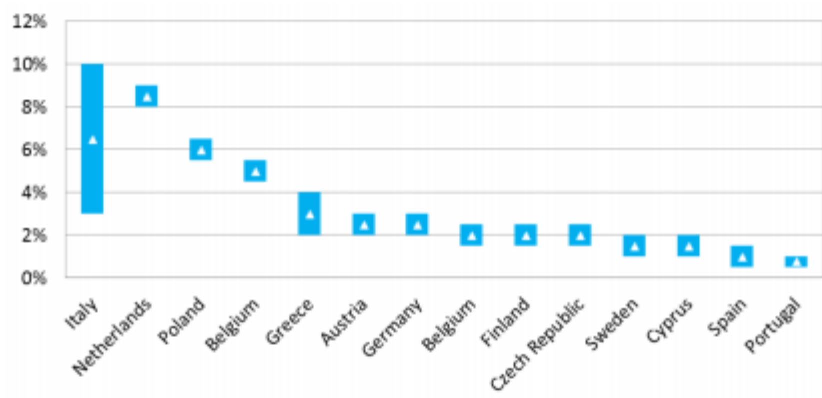

Figure 1.5 *– Approximate EV range consumption as a function of total electricity consumption in 2030 (%)*

Higher peak loads cause (usually for relatively short time) overloads on distribution grids, disadvantageously affecting on network capacity and voltage. The network equipment overloads can reduce the lifetime of grid components. These can also lead to voltage fluctuations beyond their designated margins causing to stop working consumers' devices. Moreover, it can also be a problem in networks where gas stations on the roads and highways are connected to low powered transformers (up to 220 kVA). In such cases, DSOs will have to modernize transformers or even the whole MV feeder in order to be capable of handling the additional power.

Along with other electronic devices, EVs can bring power quality (PQ) challenges for DNs. In order to minimize PQ issues, the right standards and advanced technologies must be used. Some of these issues are harmonics distortion and voltages deviations that can overload components of distribution system if not properly designed to eliminate these problems. When the disturbance in the current is high sufficiently, it may affect the voltage in the grid. That is why network operators are currently testing the PQ effects of EVs to explore future impacts. EV charging must comply with harmonics and voltage levels as defined by the following standards EN 50160 and IEC 61000-3-2. [3], [4]

1.5 General features. Motivation

The electricity supply grid has been described as the largest just in time (JIT) production and supply system in the world. JIT means that electricity generated at power stations is instantly used by loads connected to it. At the present time, there is very little capacity to store the energy generated on the electric grid. Without the possibility to store surplus energy grid operators are permanently balancing the energy needs of consumers with the generation resources they control. Hence, the generation of electricity must equal the demand for electricity at any given time. The ability of storing considerable amounts of electricity would change the JIT mode of network operation and provide great benefits that could improve not only the reliability of the network, but also significantly reduce its carbon footprint by decreasing fuel consumption.

Variations between generation and demand lead to changes in frequency and/or voltage. According to the practical and theoretical knowledge, frequency and voltage fluctuations must be maintained within strict limits, otherwise PQ will deteriorate. That is, the system can become unstable, equipment can be damaged, and blackouts/outages may occur. Energy storage systems (ESSs) can supply this energy and power and act as a buffer between the ever-changing demand for electricity and the capacity to generate this electricity. Allocation of an ESS near a load centers will enable the demand load leveling and allow systems with lower peak capacity to be installed initially or may allow postponement of upgrades by the utility as the demand load increases. An energy storage for network operations consists of several orders of magnitude both in timescale, in power and energy requirements. The fast response necessities for the fast acting energy storage can only be obtained by batteries, electrochemical capacitors, or flywheels. In order to meet the potentially large storage requirements for some energy applications, several battery energy storage systems (BESS) can be distributed across the network. In *Figure 1.6* an overview of power system with various BESSs connected in different locations. If energy storage is located near load centers, the storage can be charged during off peak times and discharged during on peak times. By doing so the system upgrade can be delayed and/or prevented from upgrading of the system as demand increases. Distributed storages in power system can also increase power quality, buffer variable, distributed solar or wind generators, and add further flexibility to network operators.

RESs are rapidly being added to power grids all around the world. Both wind generation and PV generation varies as the wind rises and falls, or when clouds pass above the PV field. These variations may be substantial and occur over short time scales. The output of wind farms may be increased or decreased up to 90% within ten minutes, as regards PV systems output varies in a matter of seconds. The affected utility should adjust these changes to maintain grid stability. One of the options that can be used to absorb and restrain these fluctuations is BESS. Furthermore, renewable generation does not always coincide with peak demand. Hence, BESS would allow the excess generated power to be stored and later used on the peak when demand is the highest.

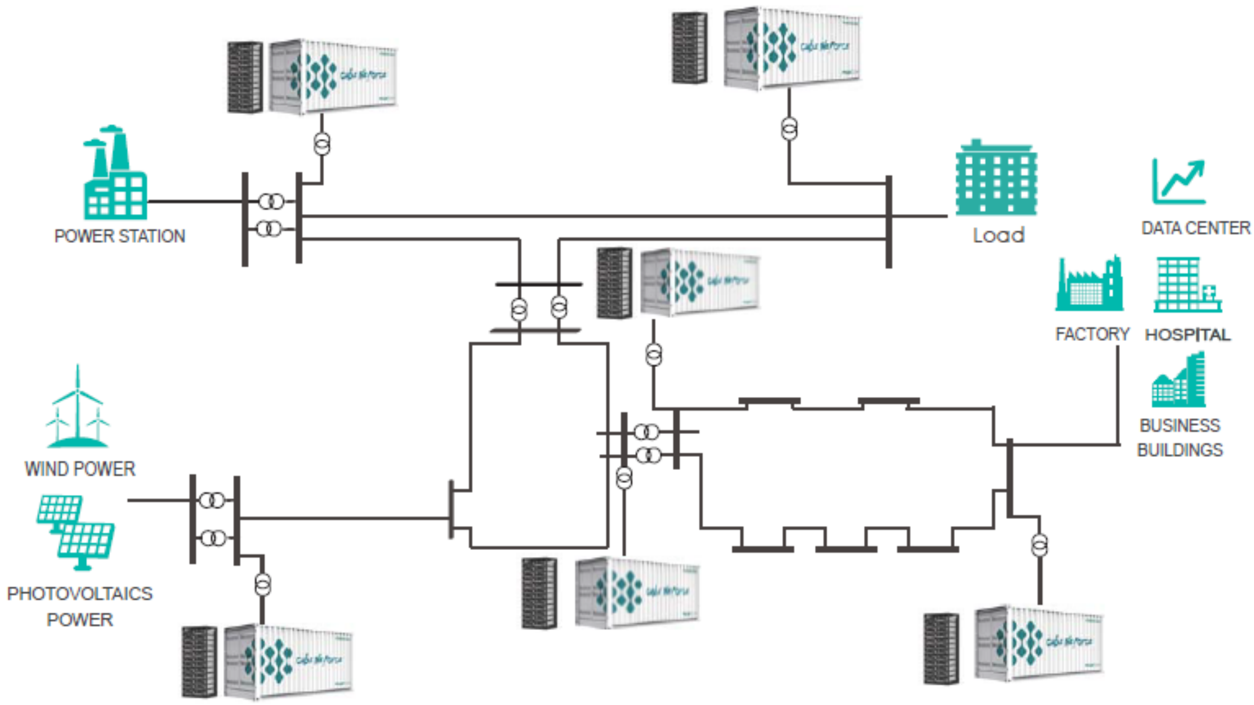

***Figure 1.6** – Schematic diagram of BESSs in Power System*

2 Battery Concept

2.1 Basic principles and operation

2.1.1 Components of a battery

Batteries are devices that convert the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction (typically, called redox reactions). In the case of a rechargeable system, the battery is recharged by a reversal of the process. This type of reaction involves the transfer of electrons from one material to another through an electric circuit. While the term battery is often used, the basic electrochemical unit being referred to is the cell. A battery consists of one or more of these cells, connected in series or parallel, or both, depending on the desired output voltage and capacity.

The cell consists of the following major components:

- The anode or negative electrode - the reducing or fuel electrode—which gives up electrons to the external circuit and is oxidized during the electrochemical reaction.
- The cathode or positive electrode (the oxidizing electrode) that accepts electrons from the external circuit and is reduced during the electrochemical reaction.

- The electrolyte is the ionic conductor, which provides the medium for transfer of charge, as ions, inside the cell between the anode and cathode. The electrolyte is typically a liquid, such as water or other solvents, with dissolved salts, acids, or alkalis to impart ionic conductivity. Some batteries use solid electrolytes or gel-type polymer electrolytes, which are ionic conductors at the operating temperature of the cell.

The most advantageous combinations of anode and cathode materials are those that will be lightest and give a high cell voltage and capacity. Such combinations may not always be practical, however, due to reactivity with other cell components, polarization, difficulty in handling, high cost, and other deficiencies. Physically, the anode and cathode electrodes are electronically isolated in the cell to prevent internal short-circuiting, but they are surrounded by the electrolyte. In practical cell designs, a separator material is used to separate the anode and cathode electrodes mechanically. The separator, however, is permeable to the electrolyte in order to maintain the desired ionic conductivity. Electrically conducting grid structures or materials may also be added to the electrodes to reduce internal resistance.

The cell itself can be built in many shapes and configurations like cylindrical, button, flat, and prismatic - and the cell components are designed to accommodate the particular cell shape. The cells are sealed in a variety of ways to prevent leakage and dry-out. Some cells are provided with venting devices or other means to allow accumulated gases to escape. Suitable cases or containers, means for terminal connection and labeling are added to complete the fabrication of the cell and battery.

2.1.2 Operation of a cell [5]

Having presented the main components of a battery cell, now it is much easier to understand the operating principle. The operation of a cell during discharge is graphically supported by *Figure 2.1*. When the cell is connected to an external load, electrons flow from the anode, which is oxidized, through the external load to the cathode, where the electrons are accepted, and the cathode material is reduced. The electric circuit is completed in the electrolyte by the flow of negative ions (anions) and positive ions (cations) to the anode and cathode, respectively.

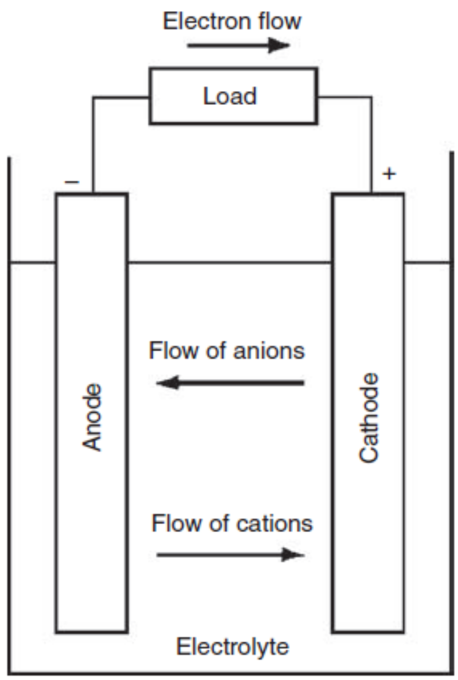

Figure 2.1 *– Operating principle of a cell (discharging state)*

The discharge reaction in the lithium ion (Li-ion) cell can be summarized as follows:

Negative electrode: Oxidation, loss of electrons (anode)

$$\mathrm{Li(C)} \Leftrightarrow \mathrm{Li^+} + \mathrm{e^-}$$

Positive electrode: Reduction, gain of electrons (cathode)

$$\mathrm{Li^+} + \mathrm{e^-} + \mathrm{CoO_2} \Leftrightarrow \mathrm{LiCoO_2}$$

Total reaction: Discharge

$$\mathrm{Li(C)} + \mathrm{CoO_2} \Leftrightarrow \mathrm{LiCoO_2}$$

During the charging of a storage cell, the current flow is reversed, and oxidation takes place at the positive electrode and reduction at the negative electrode, as shown in *Figure 2.2*. As the anode is, by definition, the electrode at which oxidation occurs and the cathode the one where reduction takes place, the positive electrode is now the anode and the negative the cathode.

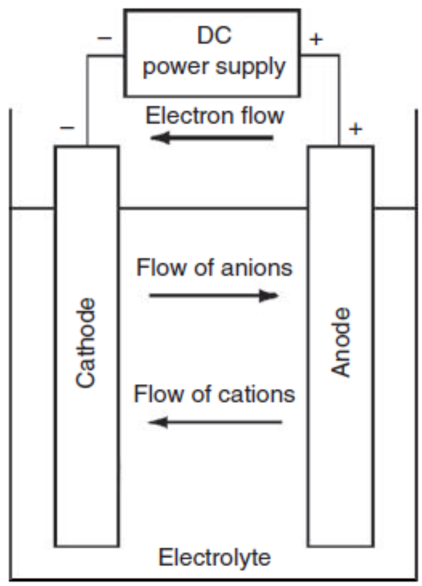

Figure 2.2 *– Operating principle of a cell (charging state)*

2.1.3 Cell voltage, capacity and energy [6]

The standard and/or theoretical potential of the cell is determined from the chemical reactions by the type of electrochemical materials contained in the cell, when disconnected from any circuit, and it is called the open-circuit voltage V_0. It can be calculated from free-energy data using free energy equation (2.1) also known as the Gibbs free energy or can be obtained experimentally, based on evaluating several voltage curves during the charging process using a decreasing sequence of currents. It is important to differentiate concept of the open-circuit voltage from the voltage measured in the cell during the discharging process. *Figure 2.3* shows the voltage curve during discharge at several different current rates. A listing of electrode potentials (reduction potentials) under standard conditions is given in *Table 2.1* (cathode materials) and *Table 2.2* (anode materials).

$$\Delta G^0 = -nFE^0$$

(2.1)

Where: **F** – the constant known as the Faraday ($\approx$ 96,500 C or 26.8 Ah)

N – number of electrons involved on in reaction

$\mathbf{E^0}$ – potential (standard) [V] obtained from free energy data or experimentally

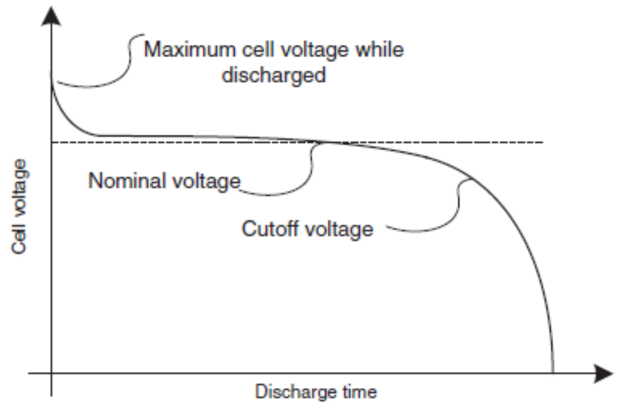

Figure 2.3 *– Typical voltage discharge curve of a cell*

Material	Atomic/molecular weight, [g]	Standard Potential at 25°C, [V]	Valence change	Density, [g/cm^3]	Electrochemical equivalents		
					Ah/g	g/Ah	Ah/cm^3
Cathode materials							
MnO_2	86.9	1.28	1	5	0.308	3.24	1.54
NiOOH	91.7	0.49	1	7.4	0.292	3.42	2.16
CuCl	99	0.14	1	3.5	0.270	3.69	0.95
AgO	123.8	0.57	2	7.4	0.432	2.31	3.20
HgO	2.16.6	0.10	2	11.1	0.247	4.05	2.74
PbO_2	239.2	1.69	2	9.4	0.224	4.45	2.11
$LiFePO_4$	163.8	0.42	1	3.44	0.160	6.25	0.554
$LiMn_2O_4$	148.8	1.20	1	4.1	0.120	8.33	0.492
Li_xCoO_2	98	1.25	0.5	5.05	0.155	6.45	0.782
I_2	253.8	0.54	2	4.94	0.211	4.73	1.04

Table 2.1 – *Typical electrode material characteristics for cathode*

Material	Atomic/molecular weight, [g]	Standard Potential at 25°C, [V]	Valence change	Density, [g/cm^3]	Electrochemical equivalents		
					Ah/g	g/Ah	Ah/cm^3
Anode materials							
Li	6.94	-3.01	1	0.54	3.86	0.259	2.06
Na	23	-2.71	1	0.97	1.16	0.858	1.14
Mg	24.3	-2.38	2	1.74	2.20	0.454	3.8
Al	26.9	-1.66	3	2.69	2.98	0.335	8.1
Ca	40.1	-2.84	2	1.54	1.34	0.748	2.06
Fe	55.8	-0.44	2	7.85	0.96	1.04	7.5
Zn	65.4	-0.76	2	7.14	0.82	1.22	5.8
Cd	112.4	-0.4	2	8.65	0.48	2.10	4.1
CH_3OH	32.04	-	6	-	5.02	0.20	-
Pb	207.2	-0.13	2	11.34	0.26	3.87	2.9

Table 2.2 *– Typical electrode material characteristics for anode*

The capacity of a cell is determined by the amount of active materials in the cell. This term is usually expressed as the total quantity of electricity involved in the electrochemical reaction and is defined in terms of coulombs or ampere per hour (Ah). The ampere-hour capacity of a battery is directly associated with the quantity of electricity obtained from the active materials. The electrochemical equivalence of typical materials is listed in *Tables 2.1 and 2.2*. Let' consider a real-life example, we can read in datasheets that a battery is rated 20 Ah at 2C and/or 20Ah at C/4. In the first case, the battery will provide 20 Ah/0.5 h = 40 A for half an hour. Similarly, in the second case, the battery will deliver 20 Ah/4 h = 5 A for four hours. In general, the calculation of discharging and charging current of a cell is given by the equation (2.2).

C -Rate: $$I = M \times C_n \qquad (2.2)$$

Where:

I – the discharge current [A]

C – value of rated capacity of a cell [Ah]

n – time in hours, for which the rated capacity is stated

M – multiplier

Battery type	Anode	Cathode	V	Theoretical values		
				g/Ah	Ah/kg	Specific energy Wh/kg
Secondary batteries						
Lead-acid	Pb	PbO_2	2.1	8.32	120	252
Nickel-cadmium	Cd	Ni oxide	1.35	5.52	181	244
Nickel-zinc	Zn	Ni oxide	1.73	4.64	215	372
Silver-zinc	Zn	AgO	1.85	3.53	283	524
Silver-cadmium	Cd	AgO	1.4	4.41	227	318
Zinc-chlorine	Zn	Cl_2	2.12	2.54	394	835
Lithium-ion	Li_xC_6	$Li_{(i-x)}CoO_2$	4.1	9.14	109	448
Lithium-iron	Li (Al)	FeS_2	1.73	3.50	285	493
Sodium-sulfur	Na	S	2.1	2.65	377	792
Sodium-nickel chloride	Na	$NiCl_2$	2.58	3.28	305	787

Table 2.3 – *Theoretical values of voltage, capacity and specific energy*

The capacity of a cell can also be considered on an energy (watthour) basis by taking both the voltage and the quantity of electricity into consideration. The theoretical voltages and capacities of several major electrochemical systems are given in *Table 2.3* (above). This theoretical energy value is the maximum value that can be delivered by a specific electrochemical system and it is given by equation (2.3):

$$\text{Watthour (Wh)} = \text{voltage (V)} \times \text{ampere-hour (Ah)} \tag{2.3}$$

In the $\mathrm{Li_xC_6/Li_{(i-x)}CoO_2}$ (lithium-ion) cell example, if the standard potential is taken as 4.1 V, the theoretical watthour capacity per gram of active material is as follows:

Specific energy (watthours/gram) = 4.1 V × 394/1000 Ah/g = 0.448 Wh/g or 448 Wh/kg

2.1.4 Factors and properties affecting battery performance

Many factors affect a battery performance, the operational characteristics, capacity, and output power of a battery. The factors that influence by its effects the battery performance are discussed in this section. The maximum electric energy, which can be supplied by the chemicals that are stored internally or delivered to the electrodes in the cell depending on the change in Gibbs energy ΔG^0 of the electrochemical couple, as shown in the formula (2.1).

If during the discharging process all the energy could be transferred to the useful electric energy It would be very much desirable. Though, polarization losses take place when the load current i(t) flows via the electrodes, accompanying the electrochemical reactions. The losses comprise:

- activation polarization, which drives the electrochemical reaction at the electrode surface, and
- concentration polarization, which rises from the concentration differences of the reactants and products at the electrode surface and in the bulk as a result of mass transfer.

These polarization effects take part of the energy, which is dissipated as heat, and therefore not all of the available energy stored in electrodes is entirely converted into useful electrical energy. Likewise, the capacity losses at low temperatures (compared with normal temperature discharges) will be greater at heavy than at light discharging loads.

There is also another significant factor that highly affects the performance or rate capability of a cell it is the internal impedance of the cell. It induces a voltage drop within an operation, which also wastes some part of the useful energy as dissipated heat. The voltage drop due to internal impedance is usually referred to as "ohmic polarization" or *IR* drop and is proportional to the current drawn from the system. The total internal impedance of a cell is the sum of the ionic resistance of the electrolyte (within the separator and the porous electrodes), the electronic resistances of the active mass, the current collectors and electrical tabs of both electrodes, and the contact resistance between the active mass and the current collector. These resistances are ohmic in nature, and follow Ohm's law, with a linear relationship between current and voltage drop.

When connected to an external load *R,* the cell voltage *E* can be expressed as follows:

$$E = E_0 - [(\eta_{ct})_a + (\eta_c)_a] - [(\eta_{ct})_c + (\eta_c)_c] - iR_i = iR$$
(2.4)

Where:

$\mathbf{E_0}$ – electromotive force or open-circuit voltage of cell

$(\boldsymbol{\eta}_{\mathbf{ct}})_{\mathbf{a}}$, $(\boldsymbol{\eta}_{\mathbf{ct}})_{\mathbf{c}}$ – activation polarization or charge-transfer overvoltage at anode and cathode

$(\boldsymbol{\eta}_{\mathbf{c}})_{\mathbf{a}}$, $(\boldsymbol{\eta}_{\mathbf{ct}})_{\mathbf{c}}$ – concentration polarization at anode and cathode

i – operating current of cell on load

$\mathbf{R_i}$ – internal resistance of cell

As shown in equation (2.4), the useful voltage delivered by the cell is reduced by polarization and the internal IR drop. It is only at very low operating currents, where polarization and the IR drop are small, that the cell may operate close to the open-circuit voltage and deliver most of the theoretically available energy. *Figure 2.4* shows the relation between cell polarization, internal resistance and discharge current. [6]

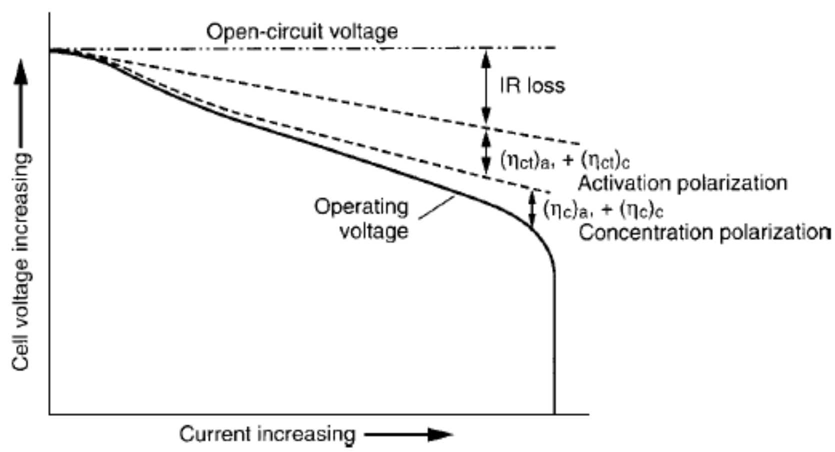

Figure 2.4 *– Cell polarization as a function of operating current*

In the idealized case, the discharge of the battery proceeds at the theoretical voltage until the active materials are consumed and the capacity is fully utilized. Under actual conditions, the discharge curve is similar to the other curves in *Figure 2.5*. The initial voltage of the cell under a discharge load is lower than the theoretical value due to the internal cell resistance and the resultant *IR* drop as well as polarization effects at both electrodes. The voltage also drops during discharge as the cell resistance increases due to the accumulation of discharge products, activation and concentration, polarization, and related factors. Curve two is similar to curve one but represents a cell with a higher internal resistance or a higher discharge rate, or both, compared to the cell represented by curve 1. As the cell resistance or the discharge current is increased, the discharge voltage decreases, and the discharge shows a more sloping profile.

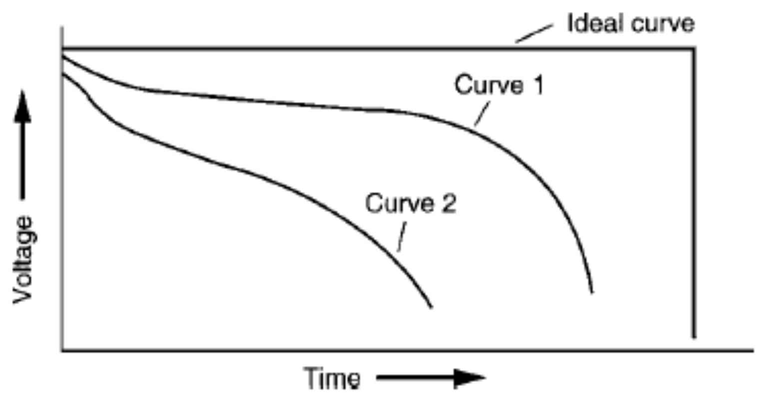

Figure 2.5 *– Discharge curve of a cell with changing internal resistance*

3 Battery energy storage system (BESS) in DN

3.1 Introduction to BESS

Distribution network (DN) connected to storage systems such as BESS are able to deliver a diversity of services, such as storing excess energy at a time, in order to provide it different time and more in *Table 3.1* as follows:

Services provided by a BESS connected to DN	
From customer perspectives	***From the DN point of view***
Peak shaving is for reducing peak demand costs, especially if they are based on electricity tariffs.	Peak shaving is for decreasing demand within the peak hours. Reducing investments on distribution lines, transmission lines, and substations.
Utilization of PV excess power for solar asset optimization.	Grid buffer instability for helping to stabilize the grid providing more discontinuous power to the grid.
Increasing the value of solar power in smoothing PV fluctuations.	Using BESSs as a spinning backup for frequency control in DN. Avoiding investments in spinning backup and/or more peak plants.
Decreasing operational risks such as power outages using UPS, also known as a backup solution.	Providing other supporting network services for improving the network quality, such as voltage maintenance.
Price arbitrage in peaks shifting to reduce power changes when buying inexpensive energy from off peak hours.	Arbitrage or peak shifting to decrease demand within peak hours. Lowering of investments into the power lines, DN and substations.

Table 3.1 *– Services provided by a BESS connected to DN*

More detailed information of these services is provided in chapter 3.2.

A number of applications focus on the storage system as an independent and reliable power source. One of the first BESSs commercial applications is uninterruptible power supply. Therefore, today it is one of the largest markets for stationary battery systems. Recently, the emerging market, which focuses on power supply of electricity is frequency management, i.e. balancing production and demand, which is broken down into immediate, primary, secondary and tertiary management reserves. Onwards load shifting and peak shaving are power delivery oriented applications. The added value for these applications is to avoid peak loads that would need rarely used network capacity.

Requirements regarding the technical specifications of BESSs may vary from one application to another. The typical characteristics of an application are as follows: required capacity of energy, number of cycles over time, required power, state of charge (SoC) characteristics, and the ratio of energy to power. These characteristics lead to different selections of storage technologies, operating strategies, system configuration, as well as determining the cost-effectiveness of an application.

One of the common features that many storage applications have is the thing that they can be supplied by other components of the system or by a conjunction of reduction and additional production. Whether an application is a storage system market or not it depends on the storage system economics and competing solutions. Nevertheless, in recent years, battery energy storage systems have become much more economical, and further development is expected to be even broader, especially for systems based on lithium-ion battery. Hence, many applications have already become more economical for BESSs, and it is expected that the market volumes will grow significantly over the next, for instance, 15 years.

3.2 Main services of BESS connected to DN

3.2.1 Peak shaving and peak shifting

The peak shaving or peak shifting concepts are about using batteries or BESS during of peak demand times. There are multiple advantages of such concepts that have already been partially described and will continue in the following chapters. In order to avoid overloads in the grid, energy stored during lower demand periods can be used. In addition to that this stored energy can reduce charges of demand since less energy is demanded within the usual peak hours.

In opposition to their similarities, a slight difference can be seen between the two. Both of them (peak shaving and shifting) are utilized during peak hours. Nevertheless, peak shaving is characterized in reducing peaks and shaving them but the energy is supposed to be used at the same time. Basically, a peak is decreased to a lower power level but applies to a longer period, while peak shifting reduces a peak at the predefined time in order to consume this energy sometime later. It decreases the shifted peak energy but does not have much interest for reducing the new peak energy. Throughout of this thesis, the term like peak shifting is going to be used with the arbitrage concept in order to shift power peaks and to use cheaper electricity later, while the term peak shaving is used with the peak shaving concept to only decrease demand costs.

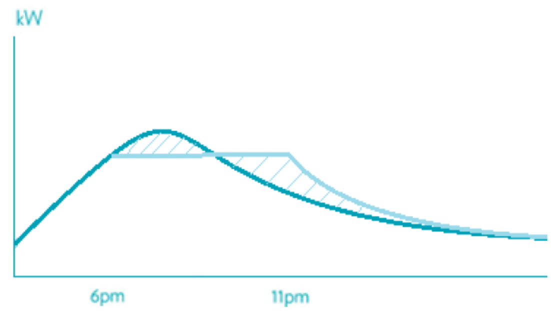

Figure 3.1 *– Representing peak-shaving concept*

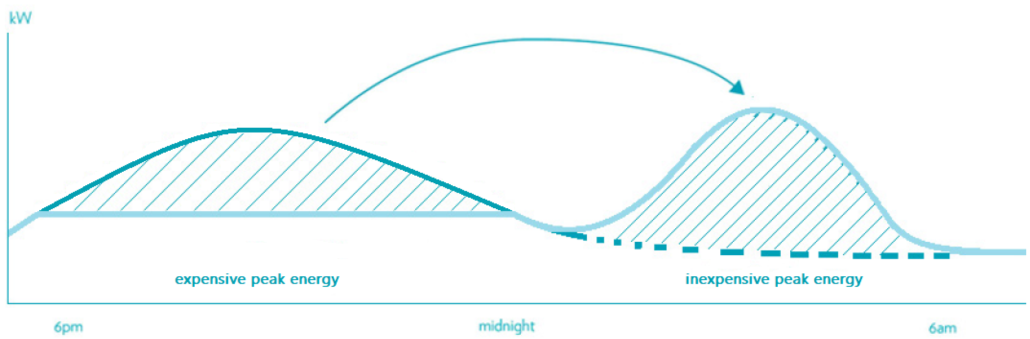

Figure 3.2 *– Representing peak-shifting concept*

In the most countries peak hours are different during different seasons and the user types. Typically during the winter especially in the nights and mornings consumption is much higher for residential users. However, in industrial and commercial centers, offices, and etc., all of them can have different peak hours and that is why it shall be distinguished apart in order to be able to ensure appropriate services.

Using BESSs, in addition to removing some of the restrictions in the grid, end users are able to save some money by reducing their peak demand costs. In reality, consumers usually must pay either monthly or annually payment fees depending on the place of usage and depending on the maximum peak demand within predefined periods.

Therefore, on of the main benefits concerning peak reduction is the opportunity for consumers to save money on their payment fees by decreasing peak demand. An advantage for utilities is that it decreases the need for peak units, and so lowering power generation operational costs within the peak periods. In the end network operators also earn on saving investment costs for the network infrastructure, which is in turn less stressful due to flatter loads with lower peaks.

3.2.2 Management of PV power surplus

Photovoltaic systems or simply PVs create some noticeable problems for grid operators and end users due to their fast variations on the output terminals, generation discontinuity and regular imbalance between the PV generation and the peak demand. A BESS connected to the power grid ensures the means to solve these problems and renew PV power to a sustained renewable energy source. The BESS can assist in optimizing local PV generation. As the time goes by more and more consumers are seeing the potential of PV generation for sustainability development or in terms of money. It is less attention for industrial and commercial buildings in terms of shifting the power generated by PV plant/panels to peak hours that usually is different in comparison to PV generation, whereas it is reverse in the case of residential sector.

BESSs may also let in the near future to increase the generation of PV power in order to save the excess of energy for many other different services such as EV charging, frequency regulation in DN, and as it was already mentioned the need to satisfy the load within peak hours. Thus, PV with BESS can decrease the power taken from the power grid and consequently decrease costs and increase their life expectancy.

Figure 3.3 represents a surplus management concept of photovoltaic energy excess used when the power generated during the day is used later in order to meet load requirements:

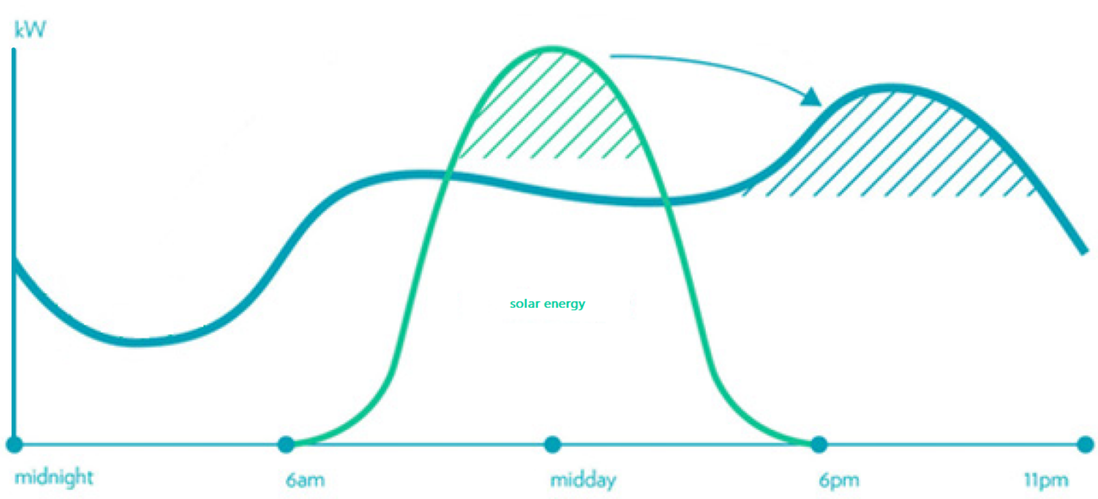

***Figure 3.3** – Representing PV surplus management concept*

3.2.3 Price electricity arbitrage

Since, it will be discussed about a battery management system in chapter 3.3.2, and from there it can be assumed that arbitrage of price electricity corresponds to certain type of BMS. When the price for the electricity is low a battery pack/rack gets charged, whereas when the price of electricity is high, that is, during peak hours batteries are discharged. In the case when peak price hours correspond to peak demand, price electricity arbitrage would be the same as in the case of peak shaving. In other words, since the energy utilized within the peak hours is charged as for within low price hours, it can be considered as low demand. As a rule, the peak demand for residential loads happens during the peak price hours, that is, when both price for electricity and the consumption are the highest levels. Therefore, it can be said that having price arbitrage is a great strategy to save money by decreasing peak load while peak power hours correspond to peak price hours. Nevertheless, these hours for other consumers such as commercial buildings can be different; consequently it is of interest for further studies.

The price arbitrage principle can be summarized by the following *Figure 3.4*:

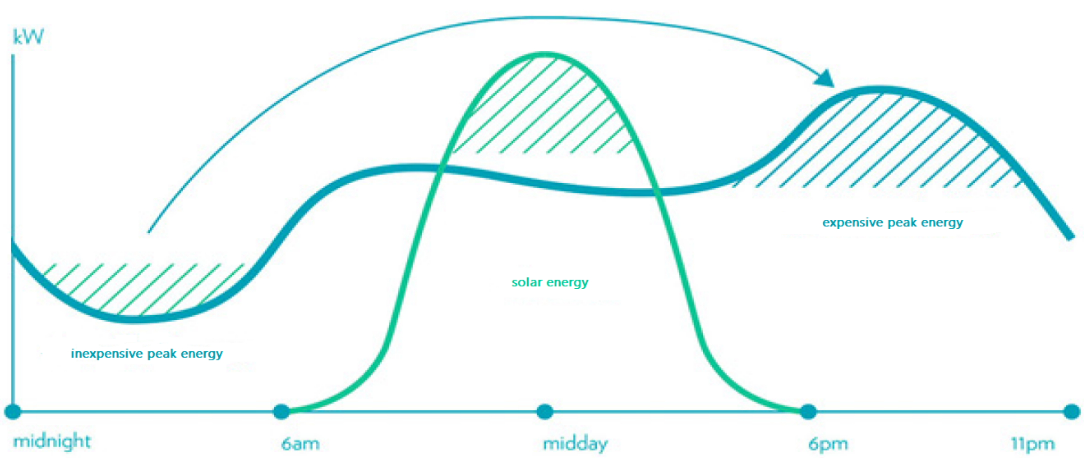

Figure 3.4 *– Representing price arbitrage concept*

So the price arbitrage for the consumers is a good benefit, which can decrease electricity price at the end of the month payment. The benefit itself represents the delta in prices between high peak and low peak hours. Many other complex aspects has not been considered here but consumers should be aware of the fact they should decrease this delta income by subtracting the energy loss costs that occur during the charging and discharging cycles and maintenance.

But electricity suppliers such as power distribution companies, retailers and electricity regulatory office may not appreciate the fast tendency of implementation of such concept. Generally, it is known that prices are calculated according to estimations and predictions. And it is also known that If the consumption/consumer declared less amount of power to be delivered then it is needed now, and at the last moment changes the expected value to be higher, regulatory office and retailers would need to make some changes in their energy supply which would lead to much higher prices and even to penalties. Thereby, such program shall be developed in close contact with authorized offices such as regulatory offices, retailers, and etc., in order to entirely enter to the electricity market.

3.3 BESS structure [7]

3.3.1 Major components of BESS

BESS systems have been utilized in the power systems all around the world and for different purposes. This chapter gives an explanation about the BESS structure, its major components and topologies of power conversion systems (PCSs) such as basic operational principles of a DC-DC converter, and fundamental principles of voltage source converter (VSC)/inverter operation. As it can be noted in *Figure 3.5*, a common part of PCSs for different storage systems is consisting of a coupling transformer, switchgear, filters and VSC or also known as a gird side converter (GSC). The objective of having PCSs in storage systems is because of unsynchronized conditions within the distribution networks, which in turn can be managed using power electronic devices.

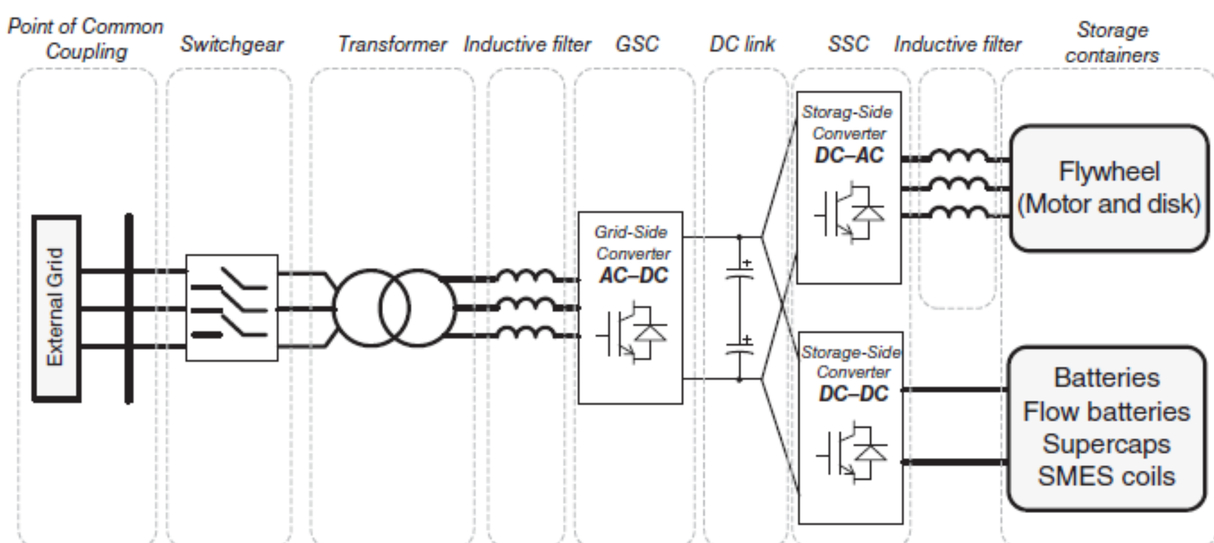

Figure 3.5 *– PCs topology for different storage systems within DN*

In addition to the mentioned components above in the BESS there are also components such as battery packs/banks, battery management systems (BMSs), current, voltage, power measurement tools, control systems, and communication.

3.3.2 Battery pack and battery management system (BMS)

A battery pack composes of separate battery cells in series and/or in parallel. In order to form a battery pack a series of battery cells are connected among each other using DC contactors. In the cases when over or under voltage or over current take place in a cell these DC contactors are utilized to disconnect a battery pack from the rest of the cells. For protection purposes such as when temperature goes too high or over current occurs in the system different types of fuses and cooling systems are used in a battery pack. *Figure 3.6* shows the individual cells connection in series and in *Figure 3.7* is represented the parallel connection of cell strings, which eventually make up a battery pack.

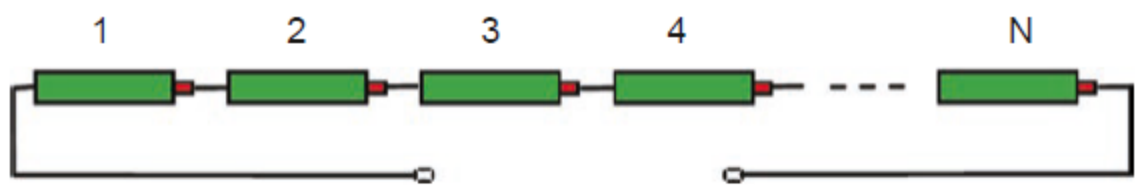

***Figure 3.6** – Serial connection of individual cells in a battery with high overall voltage*

$$U_{total} = N \times U_{single\ cell}$$

(3.1)

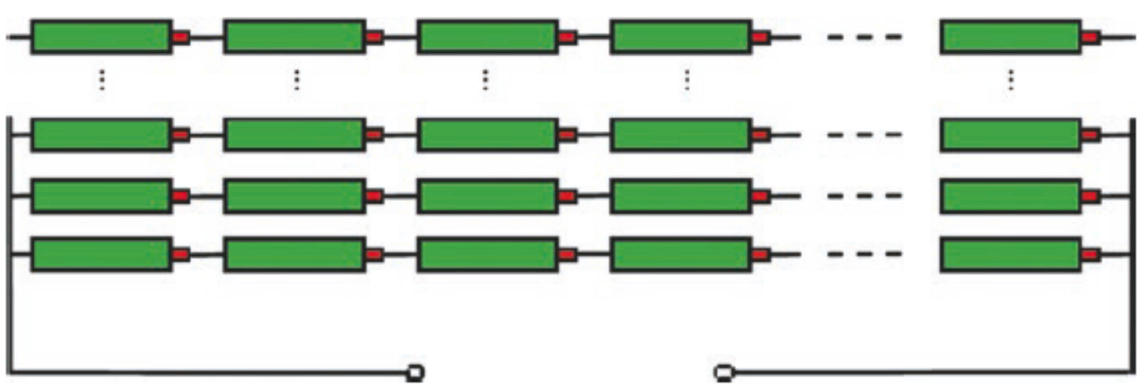

***Figure 3.7** – Parallel connection of cell strings in a battery with high overall voltage and high capacity and/or high energy content*

$$U_{total} = N \times U_{single\ cell}$$

(3.2)

Battery tracking and control systems, referred to as the battery management system (BMS), ensures that the battery cells functioning in a proper way and safe operation throughout the whole lifetime of the cells. The BMSs are electronic boards consisting of several analogue and digital inputs and outputs, central processing units (CPU), as well as communication modules for evaluating and reading external signals like voltage and temperature signals. The main goal for the most BMSs with respect to the individual cells is preventing them from any over/under voltage or temperature rise in the system, and the state of charge (SoC) calculations in a battery cell. Another significant feature of BMS is the cell balancing function, specifically for Li-ion batteries. In order to supply desired voltages, battery cells shall have series connection. Throughout charging and/or discharging states, each cell in a string will be exposed to the identical current but they will have different SOCs due to the following factors. Firstly, cells in the battery pack have different capacities because even if a manufacturer tries its best to produce cells and to match capacities due to non-uniform operating conditions that contribute different electrical and thermal stress on cells, induce changes in batteries' capacities. Though Li-ion cells do not have a tendency for big self-discharges, some small differences may pile up after some time, which in turn causes different state of charges (SoCs) for cells with almost the same capacities. Moreover, changes in the internal impedances and also aging of the materials bring to non-uniform cell properties and/or characteristics respectively. The protection of cells from overcharging, overheating, and over discharging, the string operation is in principle limited by the weakest cell, the one reaches SoC upper and lower boundaries first. This imbalance in the system prevents cells to be supplied by their full capacities, and hence, restricts the run time/life of the battery, and life cycles respectively. As it was already mentioned before on of the goals of the BMS is to perform cell balancing in order to reduce SoC imbalances in a string the BMS controls the SoCs of the cells so they become nearly the same level. For achieving this goal the energy from cells with higher SoC should be dissipated through the shunt resistor shown in *Figure 3.8*. Another way to accomplish the balance is shifting energy from the cell with the highest SoC to the cell with the lowest SoC, it is represented by *Figure 3.9*. And the last method is by incremental cell balancing through paired cells. The simplest structure of cell balancing is the shunt resistor circuit shown in *Figure 3.8*. When the SoC of a cell is estimated to be higher than others, there is a bypass circuit that gets turned on and the cell starts its discharging in order to decrease the SoC. During the balancing the energy gets dissipated as heat through a shunt resistor. As a consequence, this cell balancing decreases efficiency of the battery. On the contrary, the energy shifting circuit shown in

Figure 3.9 will be connected to a cell with the highest SoC and to its balancing capacitor in the given string and charge/fill the capacitor. After these steps the energy that was stored in the capacitor is shifted to one of the cells in the pack.

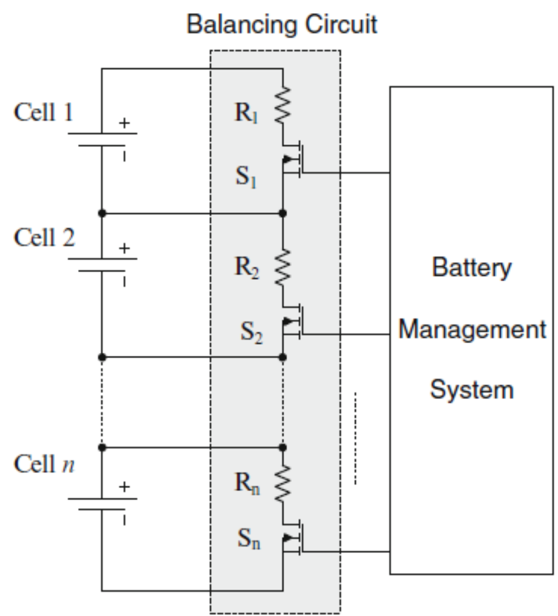

***Figure 3.8** – Cell balancing through bypass resistors*

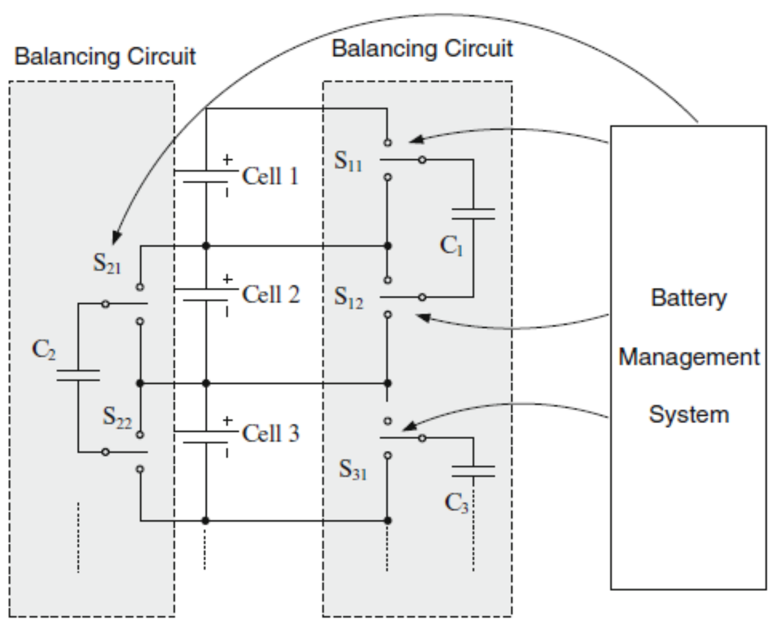

***Figure 3.9** – Cell balancing through energy shifting via capacitors*

This process gets repeated through the string little by little to distribute the power from one cell that contains the highest SoC to the other cells in the string with lower energy levels. This balancing technique improves efficiency of batteries but required higher costs and it takes longer time to complete the balancing procedure.

3.3.3 Power conversion systems (PCSs) [8]

3.3.3.1 DC-DC converters

The DC-DC converters or storage-side converter (SSC) are widely used in ESSs and renewable energy applications. To keep the output voltage at a specific level is the main purpose of the converter. Some basics of the DC-DC converters are discussed in this chapter.

Buck Converter:

The buck converter or step-down converter takes a higher input voltage (supply) and outputs required output voltage, so it is bucking or stepping down the voltage. A basic topology of the buck converter is shown in *Figure 3.10.* Typically the converter consists of input voltage, inductor, capacitor at the output to maintain the voltage, and the load resistor. Notice that there are two switches, where commonly one of them is a MOSFET that is called active switch. The active switch is for control purposes such as to turn on and off a signal, and also there is a passive switch that is a diode. *Figure 3.11* represents two states of the circuit, between on and off states. During the first state when the active switch is on the diode is reversed-biased meaning that it will not conduct current. When the active switch is off, it is required to consider in which mode it runs at that instant (depending on the current through the inductor). In the continuous conduction mode (CCM) current must flow through the inductor (can be thought of constant current source) that means the flowing current must have a path to flow. Hence, if the active switch is in off state the only path for current to flow is through the diode. If it happens to be in discontinuous conduction mode (DCM) and over the region where current stops flowing through the inductor, then both switches are in off states and the circuit is completely open. The relationship between input and output voltage is determined by controlling the duty cycle. That is, ratio between on state and total period. This relationship can be given as follows:

$$\mathrm{D} = \frac{\mathrm{V_o}}{\mathrm{V_S}} \tag{3.3}$$

Where:

D – duty cycle (control variable)

$\mathbf{V_o}$ – output voltage

$\mathbf{V_S}$ – supply voltage

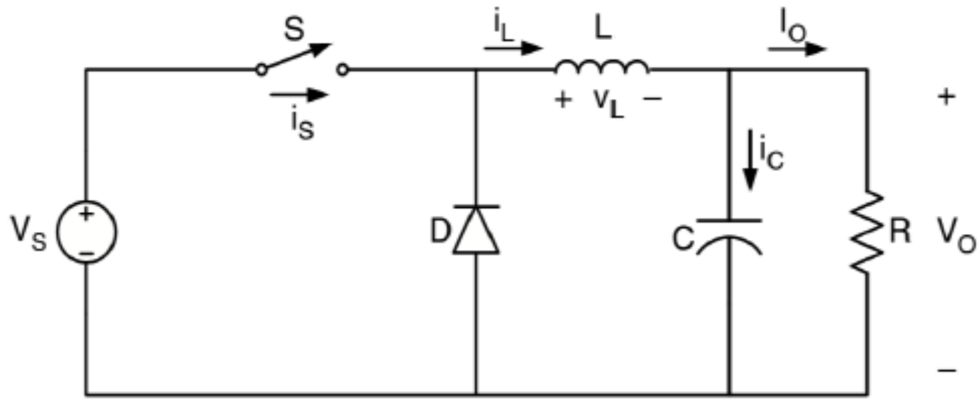

Figure 3.10 *– Buck converter topology*

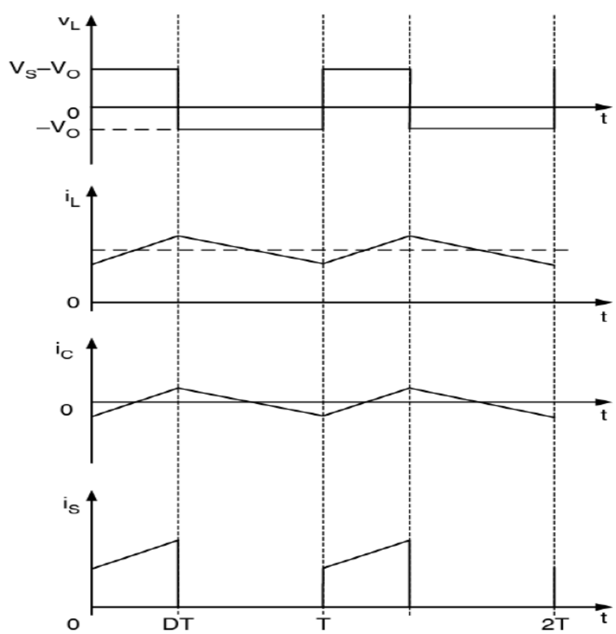

Figure 3.11 *– Output waveforms of the buck converter*

Boost converter:

The boost converter or step-up is a converter that takes an input voltage and increases the voltage or boosting it up to get desired output voltage. The basic topology of a boost converter is given in *Figure 3.12*. This converter consists of the same components, but configuration is slightly different than in the buck converter (shown above) and due to this rearrangement in the circuit we get a different function. The two different switching phases again can be broken down as follows: when the active switch is in on state assuming the circuit is in CCM, meaning the current on the inductor never falls to zero point during a commutation cycle, the circuit is shorted and so the diode or passive switch is reversed-biased therefore no current flows through the diode into the right hand side of the circuit. In the next switching phase, when the active switch is in off state the inductor current flows through the diode and to the load respectively. Basically, what is happening in the inductor is that during the active switch being on, the inductor's energy is increasing in the form of the magnetic field and once the active state is changed to the off state the inductor releases this energy. In order to define the relationship between the input voltage and the output it is needed to look at the inductor's current (current in the inductor and in the input are the same). The waveforms of current and voltage are shown in *Figure 3.13*. The relationship between input and output voltages is given by the following transfer function:

$$\frac{1}{1-\mathrm{D}} = \frac{\mathrm{V_o}}{\mathrm{V_S}}$$

(3.4)

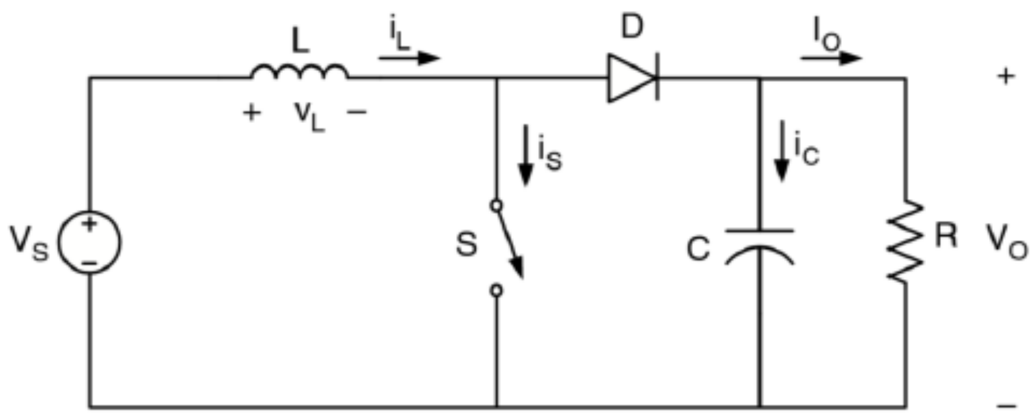

Figure 3.12 *– Boost converter topology*

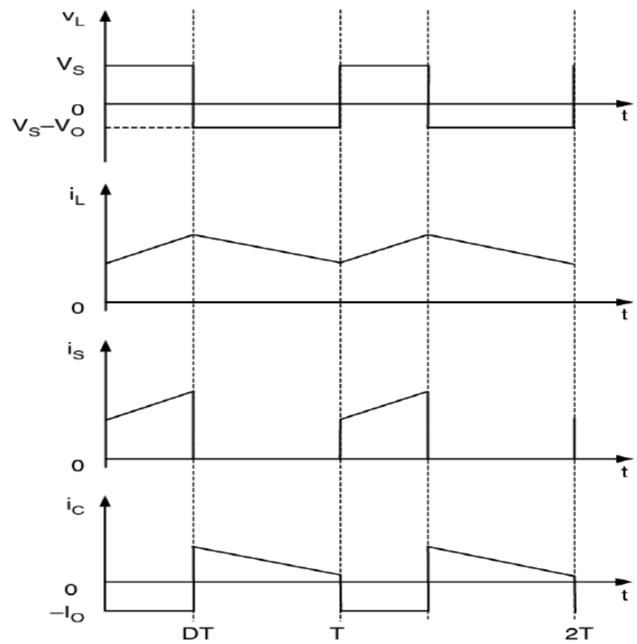

Figure 3.13 *– Output waveforms of the boost converter*

Buck-Boost converter:

The buck-boost converter is the integration of DC-DC buck and boost converters. The circuit diagram is shown in *Figure 3.14.* It enables to combine two functions such as stepping up and stepping down the ouptut voltage. In addition to that It incorporates the inverting functionality of the voltage at the output. In this way, polarity of the obtained voltage at the output will be flipped over and thus opposite to the input voltage.

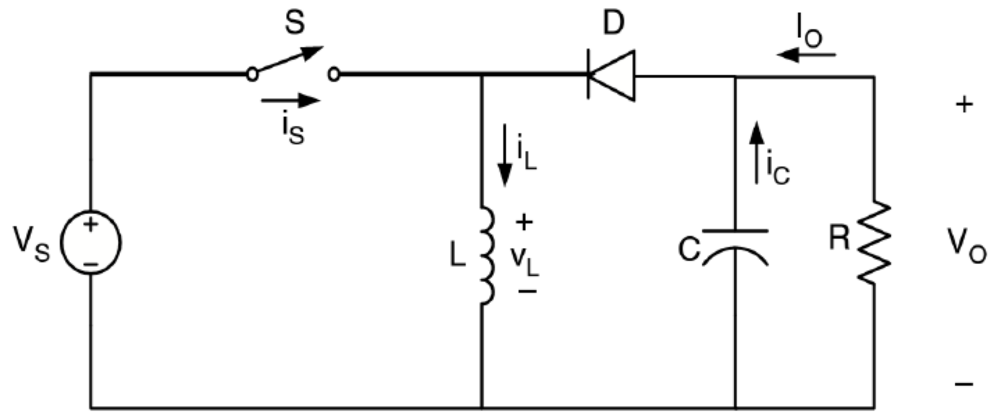

Figure 3.14 *– Back-Boost converter topology*

Assuming the circuit in the CCM, so when the active switch is in on state the diode acts as reverse-biased and inductor stores the energy from the input power. The load at the output is powered by the already charged capacitor. In the case when the switch is off the inductor releases its stored energy and it acts as a power source. It supplies the energy to the capacitor and the load. In this state the diode operates in forward-biased mode. The current and voltage waveforms in the converter can be seen in *Figure 3.15*. Finally, the relationship between input and output voltages can be written as:

$$\frac{-D}{1-D} = \frac{V_o}{V_S}$$

(3.5)

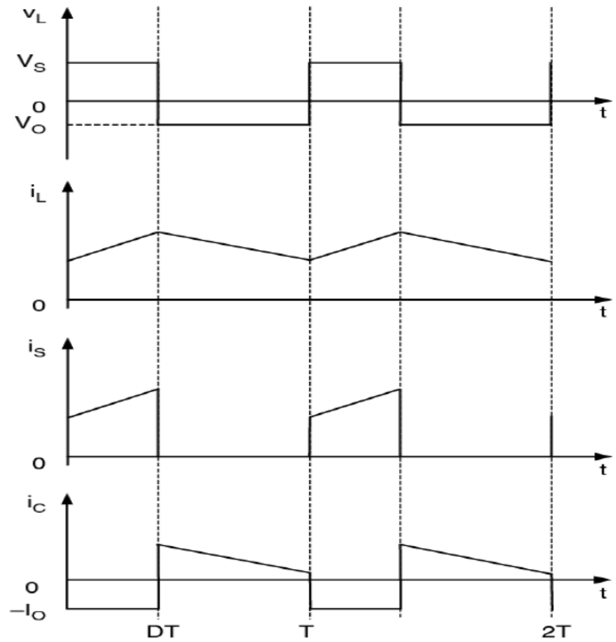

Figure 3.15 *– Output waveforms of the Back-Boost converter*

3.3.3.2 DC-AC converters

In such applications like BESSs and RESs connected to the DN, DC-AC converters or so called VSCs are required to convert DC power into AC, which in turn can be directly connected to a DN. The DC-AC converters interface the AC grid voltages within the DC link. The purpose of this converter is to provide a constant and stable voltage to the DC link, in order to ensure that the SSC control algorithm working correctly. In *Figure 3.16* a simplified schematic diagram of a one-phase full-bridge VSC is presented. At the moment when a control pulse turns off the first pair of switches, there is a finite period of time within which its current drops, and turning on the second pair of power switches during this interval leads to short circuit of the source over the two switches in the series. Consequently, the operation of the second pair shall be delayed for some time, ensuring the complete current decrease in the first pair of power switches to zero (also known as the dead time). In cases when the dead time is not greater than 0.01 – 0.02 of the interval between the power switches commutations, processes in the dead time offer little effect on the inverter's output voltage.

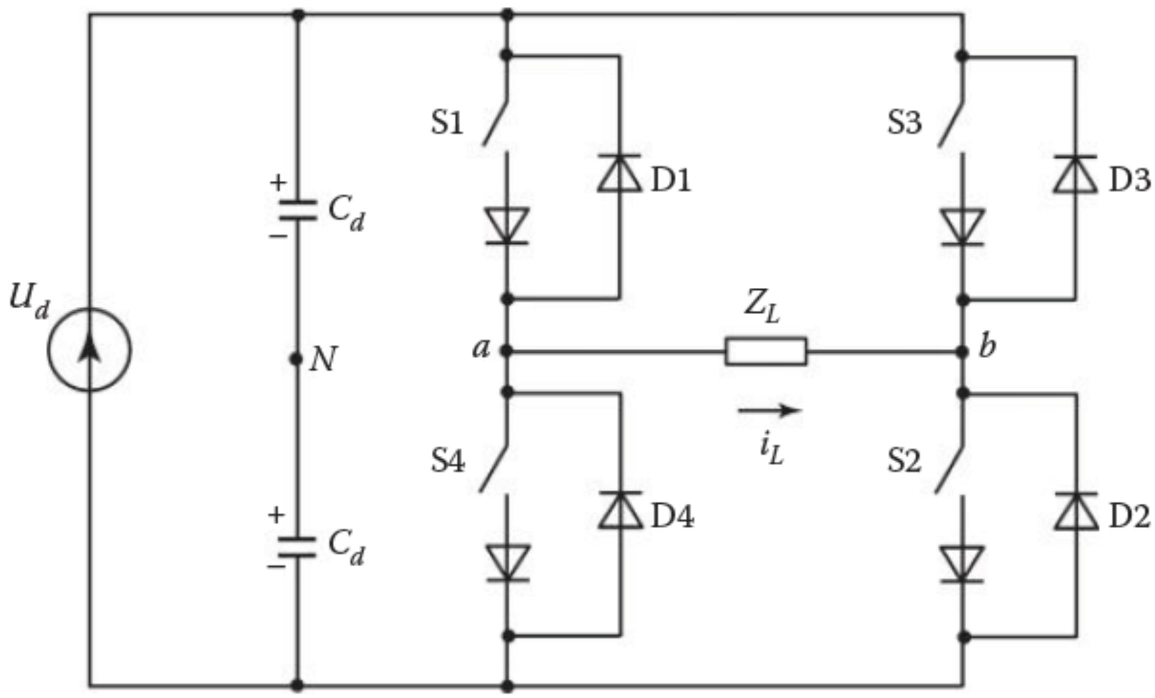

Figure 3.16 *– A single-phase full-bridge VSC*

Neglecting the dead time, it can be concluded that the power switches run alternately. There is a method for controlling these pulses, so called “Pulse Width Modulation” (PWM). According to the definition in IEC 551-16-30, PWM is a pulse control in which the pulse width or frequency or both are modulated during each fundamental period to produce a specific output waveform. In most cases, PWM technique is used to provide a sinusoidal voltage and/or current, that is, to reduce the magnitude of the higher harmonics relative to the fundamental (the first harmonic). The standard method of sinusoidal PWM involves alternating the width of the pulses that form the output voltage (current), by comparing a given (the reference) voltage signal with a triangular (the carrier) voltage signal that has higher frequency. The reference signal or the given is the modulating signal and it defines the desired output voltage (current) waveform.

In the present case, this signal is sinusoidal and it has the same frequency as the fundamental component of the voltage or the current. There are many versions of this method, with particular no sinusoidal shapes of modulating signals. Thereby, the level of specific harmonics can be noticeably reduced.

A control based on PWM allows us to produce current or voltage of the fundamental component, which has the required amplitude, frequency, and phase. Since, in many cases including this case of AC–DC converters force commutated switches are used, this implies that it enables operation in the four quadrants of the complex plane. Otherwise stated, it can be operated in two modes. That is, inverter and rectifier modes are possible, despite any value of $\cos\varphi$ (power factor) within the following diapason −1 to +1. Furthermore, with a growth of the modulation frequency, the capability to regenerate the given voltages/currents on the inverter output is improved. Respectively, active power filters might be realized on the basis of converters with force commutation characteristics in order to exclude unwanted harmonics.

Switches S1, S2, S3, S4 are considered as force commutated switches and as it can be seen they are connected in series and parallel to diodes. The diodes that are connected in series allow current to flow only one way and they are considered as the unidirectional switches (for instance thyristors or transistors), while the diodes that are in parallel also known as freewheeling diodes provide the negative currents conduction. The reference modulating signal $u_m(\vartheta)$ and the carrier signal $u_c(\vartheta)$ are graphically supported by *Figure 3.17*. According to the following method the control pulses for switches S1, S2, S3, and S4 are generated. Apparently, the pulse width depends on the ratio of the amplitudes of the signals $u_m(\vartheta)$ and $u_c(\vartheta)$. The following parameter describes this ratio, known as the modulation index and it is defined as:

$$M_a = \frac{U_m}{U_c}$$

(3.6)

Where: $\mathbf{M_a}$ – modulation index

$\mathbf{U_m}$ and $\mathbf{U_c}$ – the amplitudes of the $u_m(\vartheta)$

$\mathbf{u_m(\vartheta)}$ – modulating signal

$\mathbf{u_c(\vartheta)}$ – carrier signal

A full-bridge inverter has four combinations of switching as it is represented in *Table 3.2*, where on state is designated by and off state by 0. The corresponding voltages for these states are presented in *Table 3.3* as follows u_{aN}, u_{bN}, and u_{ab}= u_{aN} – u_{bN}. Various combinations of switching states can be used depending on the modulation type.

For modulation type of unipolar, two modulating signals are used simultaneously as follows $u_m(\vartheta)$ and $-u_m(\vartheta)$ (*Figure 3.17*). In such a case, there are two sequences of switch control pulses. The first sequence controls switches of leg one, which is S1 and S4, while the second one controls the second leg, thus the rest of the switches S2 and S3. By comparing the reference $u_m(\vartheta)$ and the triangular signals a pulse sequence is generated that is $u_c(\vartheta)$ which in its turn determines the voltage u_{aN}. For instance, just as the negative modulating signal $-u_m(\vartheta)$ is compared with the carrier signal $u_c(\vartheta)$, the pulse sequence for u_{bN} is generated. As a result it leads in simultaneous modulation of the node potential *a* with respect to *N* (S1 and S4 switches are used) and the node potential *b* modulation (S2 and S3 switches are utilized). In which case, when switch S1 is on or 1 that is, in states I and III, the node potential *a* with respect to the node *N* is $U_d/2$, and it is $-U_d/2$ during switch S4 is on that is, in states II and IV. The potential difference of node *b* with reference to node *N* will be $U_d/2$ while switch S3 is on in states II and III and $-U_d/2$ when S2 is on in states IV and I. The commutation states of switches are as follows:

Switch States	**S1**	**S2**	**S3**	**S4**
I	1	1	0	0
II	0	0	1	1
III	1	0	1	0
IV	0	1	0	1

Table 3.2 *– Combinations of switch states for a single-phase full-bridge VSC*

Conducting Switches and Diodes			**Voltage**		
States	$i_L > 0$	$i_L < 0$	u_{aN}	u_{bN}	u_{ab}
I	S1, S2	D1, D2	$U_d/2$	$-U_d/2$	U_d
II	D3, D4	S3, S4	$-U_d/2$	$U_d/2$	$-U_d$
III	S1, D3	D1, S3	$U_d/2$	$U_d/2$	0
IV	S2, D4	S4, D2	$-U_d/2$	$-U_d/2$	0

Table 3.3 *– Conducting Components and Voltage Values for the Switch States*

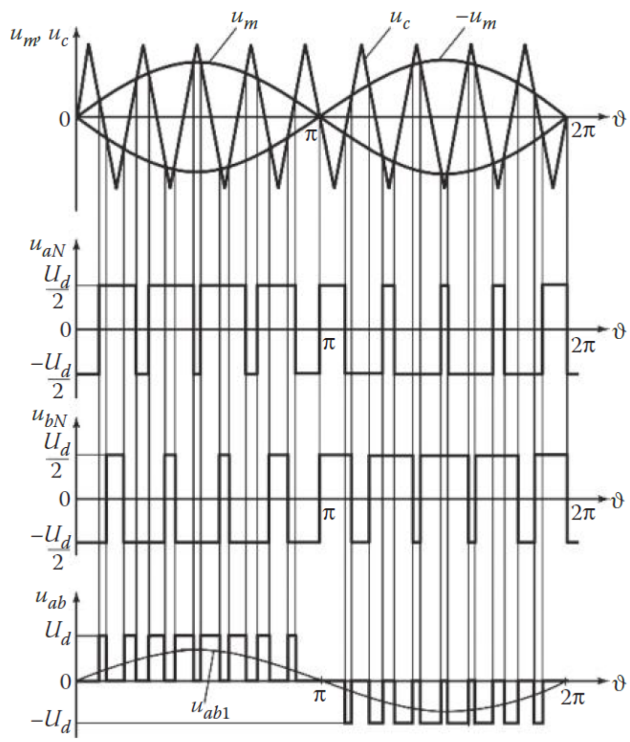

Figure 3.17 *– Output voltage waveforms and modulating and carrier signals for the unipolar sinusoidal PWM in a single-phase full-bridge inverter.*

$u_m(\vartheta) > u_c(\vartheta)$ – S1 is on and S4 is off

$u_m(\vartheta) < u_c(\vartheta)$ – S4 is on and S1 is off

$-u_m(\vartheta) > u_c(\vartheta)$ – S3 is and S2 is off

$-u_m(\vartheta) < u_c(\vartheta)$ – S2 is on and S3 is off

Resulting in a waveform of the output voltage $u_{ab}(\vartheta)$ of the inverter is a sequence of pulses (unipolar) in each half-period of the sine wave given by the modulation signal $u_m(\vartheta)$, as shown in *Figure 3.17*.

4 Field of electromobility

4.1 Introduction

In these latter days, the transportation system has become one of the primary areas of energy consumption. Plug-in hybrid electric vehicles (PEVs) and purely electric vehicles (EVs) offer the potential to lower the CO2 emissions and the dependency on mineral oil. The purposes behind this are the higher efficiency of electric power trains and the possibility of utilizing power generated by renewable energy sources for transportation. In addition to the environmental reasons, economic reasons will contribute the introduction of EVs. Rising mineral oil prices and lower battery prices are very important drivers for this. Combination of all of these factors is likely to increase the share of EVs in the transportation sector in the near future. As it was already mentioned in chapter 1.4, EVs bring a high influence on the sectors of electrical power sources, such as additional methods for coordinating the absorption of the EV charging loads, lines loading, transformers' capacity, etc. EVs connected in a radial distribution system are graphically supported by *Figure 4.1.* Given this fact and the typical use of private electric vehicles with their long downtime and the installed battery capacity, it seems appropriate to make them suitable also for use as a part of distribution network, via the so-called vehicle-to-grid (V2G) concept. Besides that, in order to minimize these effects in bigger fractions BESSs become needful. In this scope V2G concept means a bidirectional power flow from the batteries to the DN and vice versa.

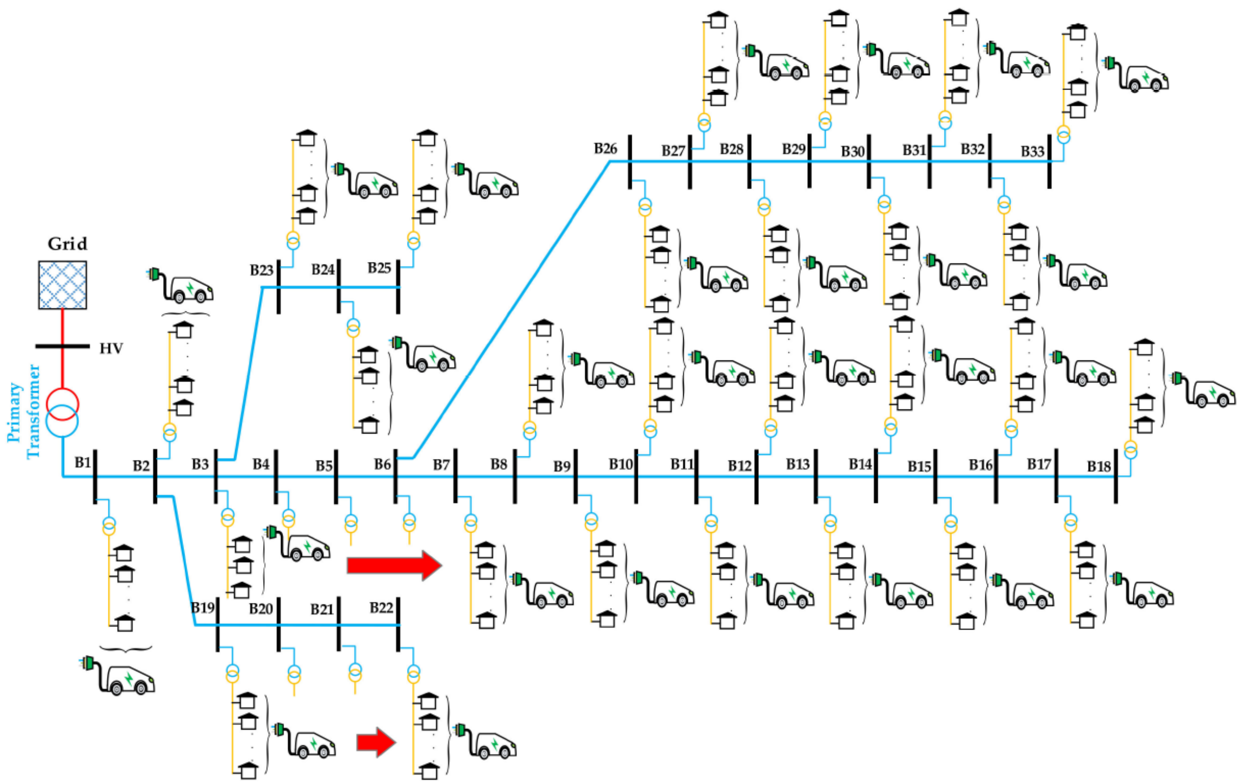

***Figure 4.1** – PEVs and EVs connected in a radial distribution system*

4.2 Charging stations

Throughout EV charging, a charger transforms power provided by the nearby utility into power compatible with voltage requirements of a battery pack in a vehicle. As stated by the Society of

Automotive Engineers (SAE), the full EV charging structure shall consist of the equipment needed to condition and transfer energy from a constant frequency, voltage source or distribution network (DN) to DC. The DC is required for the goal of charging batteries and/or operating electrical systems/electronic control units or subsystems in the EVs (e.g., interior conditioning, lightning, power and thermal management of the batteries, vehicle computer). The communication between an EV charger and an EV is carried out by the battery management system (BMS). The BMS performs calculations in order to obtain required values for voltage and current that is needed to charge the batteries in the EV. The charging is performed by a current flowing through the batteries in order to convert its dynamic substances into a state of their high energy charge state. So the reverse procedure of the charging is basically the discharging process. An electric current is forced to pass back to the traction battery pack, and consequently the chemical reaction is carried in the opposite direction. Due the fact that there are many different types of batteries the logic by which this can be accomplished is different and it depends upon the types of batteries and in their chemical compounds. An EV is connected to an EV supply facility (EV charger), which in turn is connected to a nearby utility. As shown in *Figures 4.2 and 4.3,* there are two possibilities that can be determined as for station architecture. In the first one the secondary side winding of the step down transformer is used as an AC bus, and where each load is getting connected to the bus through an AC-DC converter independently. While in the second architecture there is only single AC-DC converter for providing a common DC bus for all loads in the network.

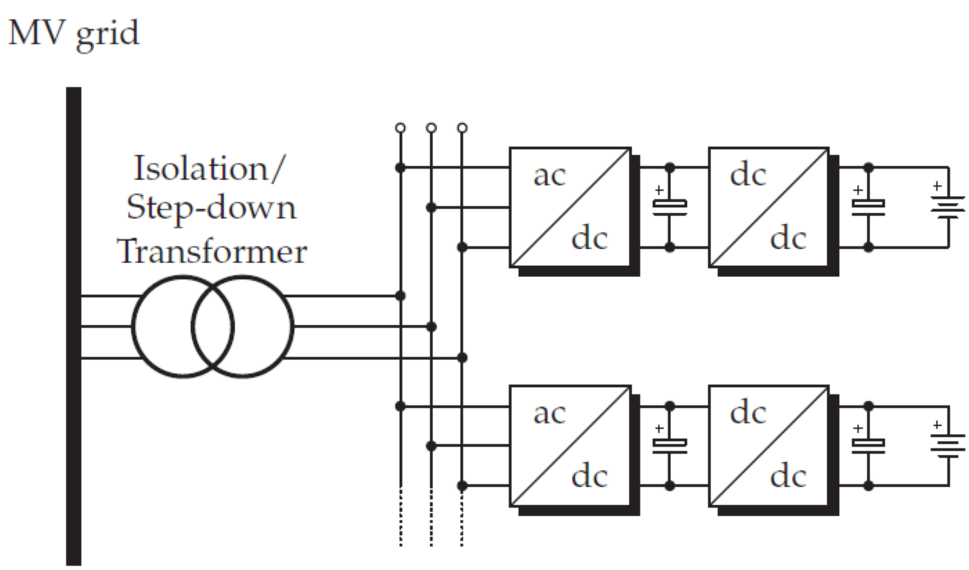

Figure 4.2 *– Schematic diagram of a charging station with common AC bus*

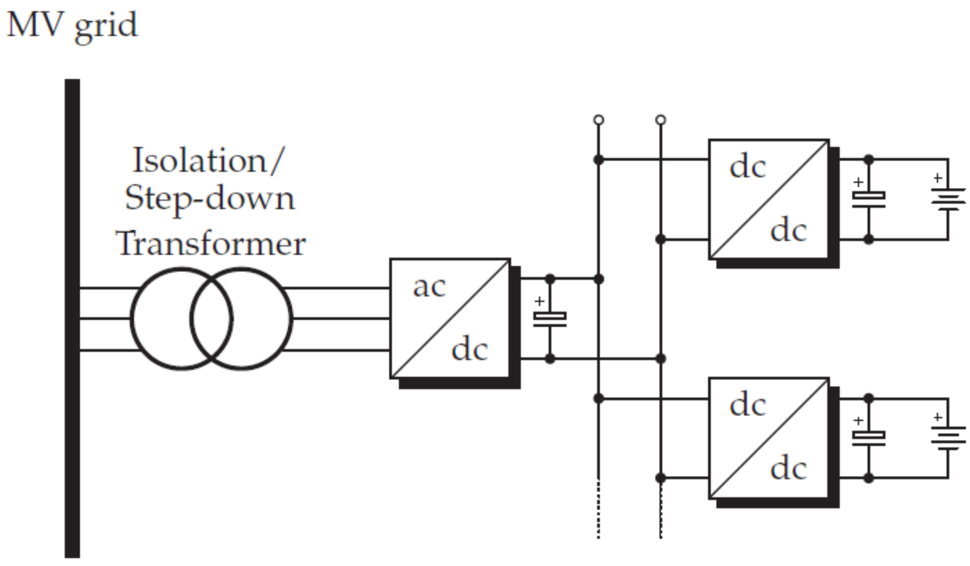

Figure 4.3 *– Schematic diagram of a charging station with common DC bus*

In the International Electrotechnical Commission Standard (IEC 61851-1) and Society of Automotive Engineers standard (SAE J1772) a charging scheme and arrangement of some EVs are depicted and characterized. The charging regime is determined in connection regime of AC and DC powers in accordance with a battery charger and the charging position like for example normal charging regime that is utilized in residential distribution networks. Thus, the reference levels of power charging of the IEC 61851-1 and SAE J1772 standards were used for household environments, private sectors or public areas shown in *Tables 4.1 and 4.2.*

There are two power levels for the majority prevalent private or residential and most public charging places as follows: level 1 and level 2 are for AC charging type. Level 1 or in other words convenience charging, lets to charge the battery pack traction whereas the EV is connected to a 120 V, 12-16 A circuit. One full charging cycle takes somewhere from 9 to 15 hours to be accomplished. For this charging type a system uses the common grounded electrical outlets and it is used while charging level 2 cannot be used or simply is not at disposal. The level 2 charging occurs when an EV is connected to a 240V, < 80 A branch circuit, dedicated exclusively to charge the EV battery only. A complete charging cycle for the level 2 happens from 2.5 to 9 hours, depending on voltage and current levels and on a battery type. For the maintaining power requirements of the level 2, EV supply equipment shall be wired to premises wiring. In the third power level, that is, level 3 EV supply equipment shall be with a power ratings greater than in level 2. In most cases charging stations that are related to level 3 charging systems are located near vehicle platforms. Nowadays, charging stations that are rated to be at level 3 are defined as an EV equivalent of a commercial petrol station. In the case when it comes to charging station of the level 3 also known as fast charger, one full charging cycle can be successfully obtained in a matter of minutes. In order to perform charging of level 3, power-rating levels of the equipment shall be rated from 75 to 150 kW. As regards the supply circuit for the level 3 it is required to have ratings for equipment at 600 V, three-phase and current between 90 to 400 A. Nevertheless, the supply circuit for charging equipment of the level 3 can be even bigger in capacity.

Type of Charge	Grid Connection	Voltage	Current	Charging type
Mode 1 (AC)	1 phase 3 phase	230 V 400 V	16 A 16 A	Slow Slow
Mode 2 (AC)	1 phase 3 phase	230 V 400 V	32 A 32 A	Slow Slow
Mode 3 (AC)	1 phase 3 phase	230 V 690 V	32 A 250 A	Slow Medium
Mode 4 (AC)	3 phase	600 V	400 A	Fast

Table 4.1 *– Power levels of charging given by IEC 6185-1 standard*

Type of Charge	Grid Connection	Voltage	Current	Charging type
AC level 1	1 phase	120 V	12 – 16 A	Slow
AC level 2	1 phase	240 V	< 80 A	Slow
AC level 3	1, 3 phase	240 V	> 80 A	Slow
DC level 1	–	200 – 450 V	80 A	Slow
DC level 2	–	200 – 450 V	200 A	Medium
DC level 3	–	200 – 600 V	400 A	Fast

Table 4.2 *– Power levels of charging given by the SAE J1772 standard*

4.3 Charging methods

There are three essential techniques/methods of charging EV batteries:

1) Constant voltage;

2) Constant current; and

3) Combination of the two.

Majority of EV charging systems utilize a steady voltage for the initial stage of the charging process, that follows by a constant current for the final. Most of the battery capacity is restored within the steady voltage part of the charging cycle. The steady current part of the charge cycle, generally known as a trickle charge, serves to gradually fill a battery at a rate slow enough to prevent the release of either hydrogen gas or oxygen gas from electrolyte.

5 A case study for integrated BESS in a medium voltage distribution system

BESSs are used for many applications and most of them were described in the previous chapters. To date, BESSs more frequently are used for peak shaving, load shifting and leveling applications. The following model, which is shown *in Figure 5.1* demonstrates how peak shaving function interacts with both DN and load.

Figure 5.1 *– A Simulink diagram of the model*

A changeable load profile (presented by *Table 5.1*) is loaded into the simulation model, and the goal of the BESS is to calculate usage of the BESS and DN and to output to the model's workspace.

	1	2
1	0	250
2	1	227
3	2	206
4	3	220
5	4	197
6	5	203
7	6	210
8	7	191
9	8	353
10	9	464
11	10	518
12	11	544
13	12	588
14	13	565
15	14	562
16	15	606
17	16	576
18	17	494
19	18	409
20	19	322
21	20	301
22	21	288
23	22	268
24	23	228

Table 5.1 *– Load profile (kW) during a day*

The BESS block receives the input shown in *Table 5.1*, where the first column represents time in hours that stars from zero hour of a day and in the second column is the power consumption of the load during the day. The purpose of the BESS is to compensate the variability of the load so that the load can be visible from the DN is constant. Therefore, the BESS will provide support when the load is high (peak shaving) and draw power from the DN when the load is low. In the model configuration parameters in the solver options, fixed step type was chosen, and the fundamental sample time or fixed-step size was chosen to be one.

A complete diagram of the simulated model is represented by *Figure 5.2* below:

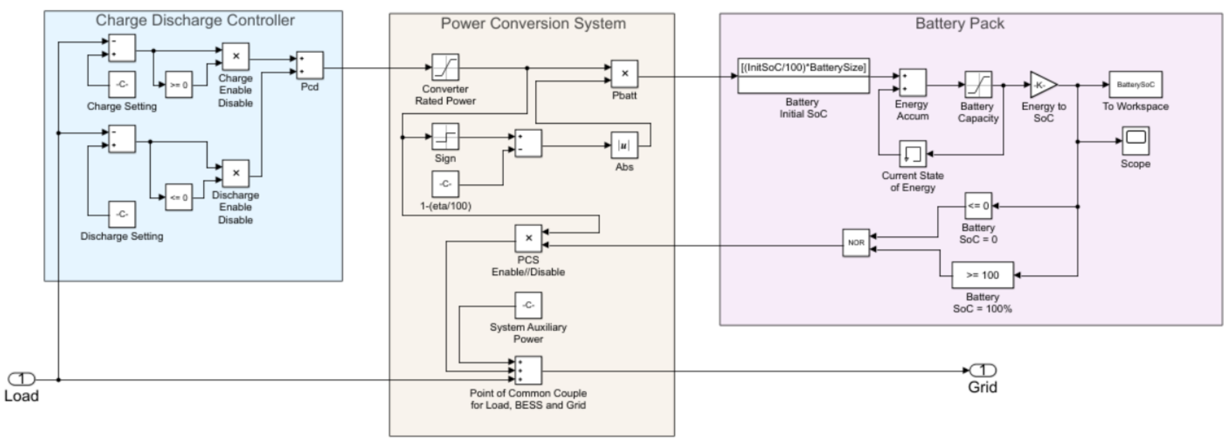

Figure 5.2 *– A Simulink block diagram of the model*

The complete diagram consists of the following sections – the load, the charge discharge controller, the PCS, the BESS, and the DN. The DN is the model is not simulated directly. Nevertheless, the required power provided by the DN is simulated by determining the needful battery charging/discharging power. The DN power P_{DN} is computed as the sum of the load power P_L and the battery charging/discharging power P_{bat} (also represented in the Simulink block diagram as a point of common couple):

$$P_{DN} = P_L + P_{bat}$$

(5.1)

The logic uses three input parameters (shown in *Figure 5.2*) to decide whenever the battery will be charging or discharging:

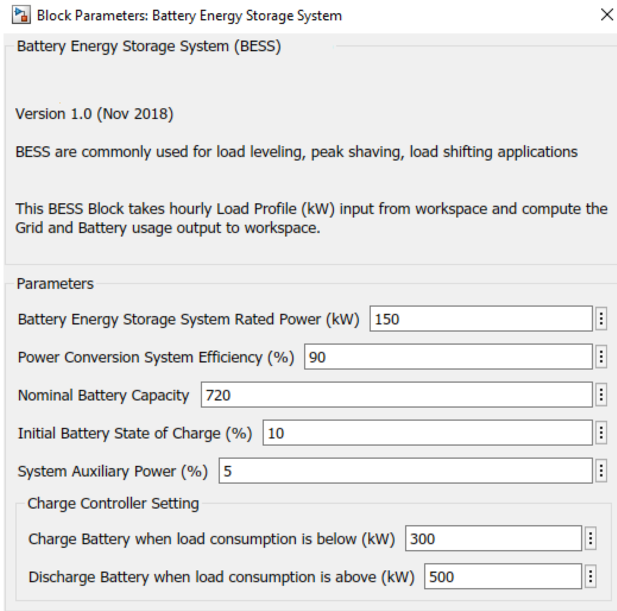

Figure 5.3 *– Parameters used for the model*

The obtained results for charging and discharging of the battery and peak shaving from the simulation are given below in *Figures 5.3 and 5.4*:

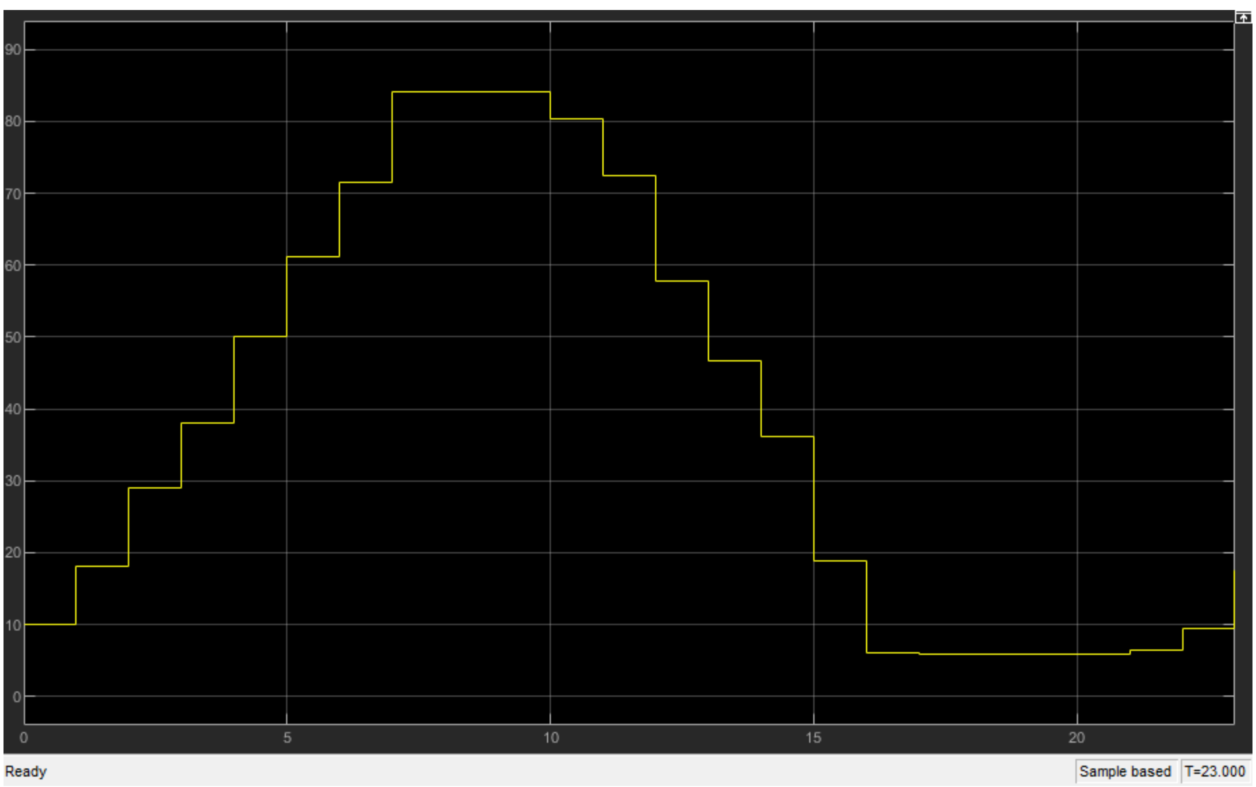

Figure 5.4 *– Battery charge and discharge responses*

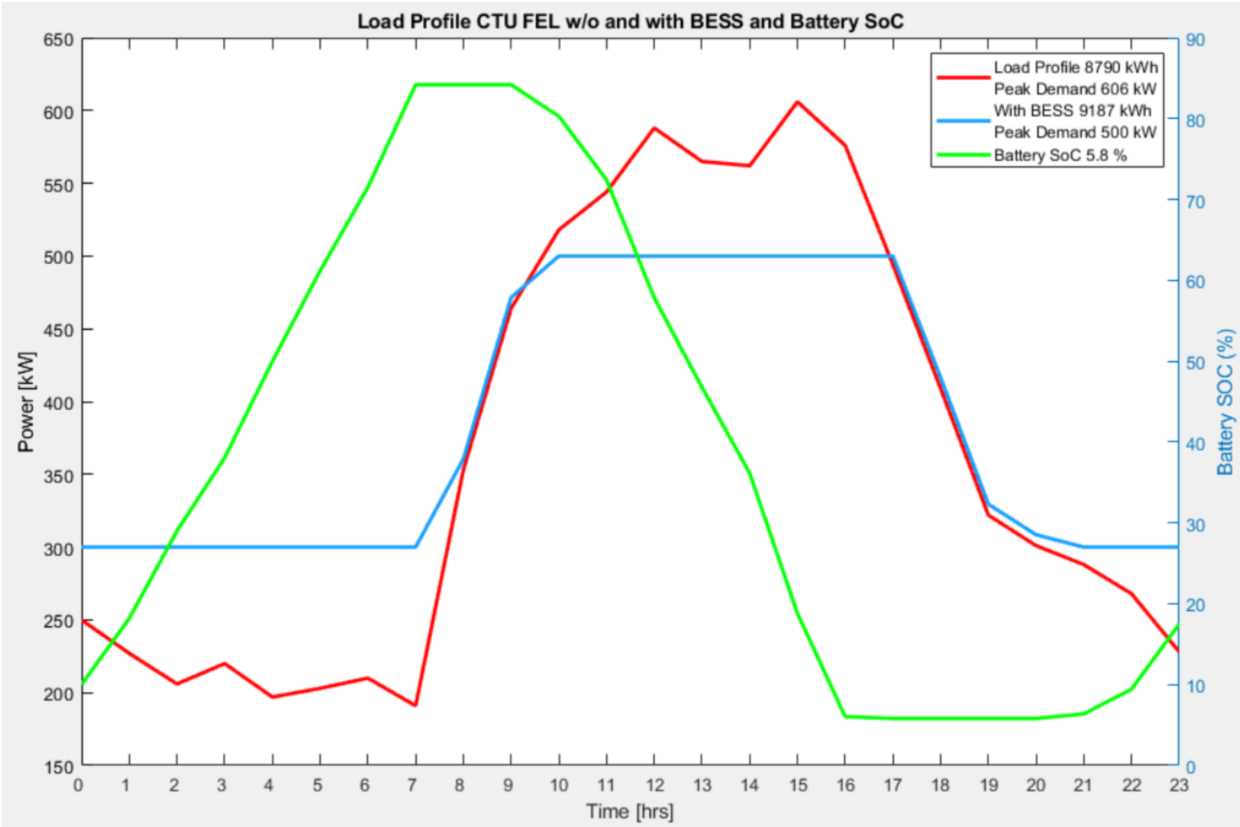

***Figure 5.5** – Load profile w/o and with BESS and battery SoC*

5.1 Conclusion

The aim of the thesis and the case study was to show and demonstrate how the placement of BESS into DN positively influences many factors of the DN. Due to ever-growing peak demand such as DP generation, EV loads etc., distribution network operators require periodic reinforcement of their networks involving significant investments. If energy storage will be used near load locations, the storage can be charged during off peak times and discharged during on peak times. Hence, the system upgrade can be delayed or prevented from upgrading it as demand increases. Distributed storages in power system can also increase power quality, buffer variable, distributed solar or wind generators, and add further flexibility to network operators.

In the case study the MATLAB Simulink environment was used to carry out and show charging and discharging techniques of BESS connected to DN and load. Moreover, the advantages of peak shaving were demonstrated by using energy stored during periods of lower demand, it avoided congestion in the grid and at the same time reduced demand charges, as less power was demanded during the peak hours. BESS technology has a big potential and indeed can help to lower consumers' electricity bills, increase grid flexibility and foster the integration of renewable sources.

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