POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science in Electrical Engineering

Use of storage systems for primary frequency control in the presence of large wind farms

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Thesis of Master of Science of:

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Academic Year: 2019-20

Acknowledgement

I would like to express gratitude to my thesis supervisor Prof. Morris Brenna for his useful comments, remarks, and engagement throughout the learning process of this master thesis. I also thank Polytechnic University of Milan teaching staff for their precious time. I also like to thank my loved ones for their precious support throughout my life. I will be grateful for their support throughout my life.

Muhammad Umer Farooq

Dedicated to my Parents

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Abstract

With rising concern and awareness about environmental pollution and global warming, the existing trend is towards meeting energy demand by shifting primary energy sources from fossil fuels to electrical energy from renewable sources. Distributed generation systems that are based on renewable energy sources result in a decrease of overall inertia of the system and because of which there are oscillations in the system during disturbance conditions. Therefore, penetration with distributed generation has a significant impact on system reliability and stability. This thesis discusses the impact of battery energy storage systems in providing primary frequency control for supporting increased wind penetration levels. A battery energy storage system is modeled like a storage energy system with DC/AC converter and other power electronics interfaces. In this thesis, the results of the simulated model whose objective is replacing the current synchronous generator in proportion with increasing wind penetration while maintaining the reliability and stability of the power system are analyzed. The battery energy storage system model is studied, and the system is compared with and without a battery energy storage system by considering load demand increment with various penetration of distributed generation. The results show that the battery storage system could reduce system oscillations following disturbances and it supports distributed generation penetration increment in the existing power system.

Keywords: BESS, CASE, Inertia, VRLA, MMC, PCR, SCR, TCR

Sommario

Con la preoccupazione crescente e la consapevolezza dell'inquinamento ambientale e del riscaldamento globale, la tendenza recente è quella di soddisfare la domanda di energia spostando le fonti di energia primaria dai combustibili fossili all'energia elettrica da fonti rinnovabili. I sistemi di generazione distribuita basati su fonti di energia rinnovabile determinano una riduzione dell'inerzia complessiva del sistema e a causa della quale vi sono oscillazioni nel sistema durante le condizioni di disturbo. Pertanto, la penetrazione con generazione distribuita ha un impatto significativo sull'affidabilità e stabilità del sistema. Questa tesi discute l'impatto del sistema di accumulo di energia della batteria nel fornire il controllo di frequenza primario per supportare un maggiore livello di penetrazione del vento. Il sistema di accumulo dell'energia della batteria è modellato come un sistema di archiviazione con convertitore DC / AC e altre interfacce di elettronica di potenza. In questa tesi, vengono analizzati i risultati del modello simulato il cui obiettivo è la sostituzione del generatore sincrono esistente in proporzione all'aumento della penetrazione del vento mantenendo l'affidabilità e la stabilità del sistema di alimentazione. Il modello del sistema di accumulo di energia della batteria è studiato e il sistema viene confrontato con e senza il sistema di accumulo di energia della batteria considerando l'incremento della domanda di carico con varie penetrazioni di generazione distribuita. I risultati mostrano che il sistema di accumulo di batterie ha la capacità di ridurre le oscillazioni del sistema in seguito a disturbi e supporta l'incremento della penetrazione della generazione distribuita nel sistema di alimentazione esistente.

Parole chiave: BESS, CASE, Inertia, VRLA, MMC, PCR, SCR, TCR

Chapter 1

1. Introduction

1.1 Electric Power Systems Reforms

For the past some years, there is a steadfast change in power systems towards integration of large number of renewable energy sources. This is gaining momentum because of rising concern and awareness of future of planets climate and detrimental effects of energy conversion from fossil fuels.

This optimization is encouraged by governments across the world for reducing carbon emissions, which is the main reason for global warming. The EU is committed to reducing the greenhouse gas emissions up to 80-95% below the 1990 levels by 2050 in context of the necessary reductions by developed countries. [1] In this way, renewable energy is to play an increasing role in both today and future energy supply.

According to IEA's forecasted installed power generation capacity by type in a sustainable development scenario, solar and wind power generation globally are estimated to be the largest contributors by the mid of this century. [2]. This is shown in figure 1.1.

Renewable energy sources are generally located far from cities due to a lot of natural resources such as offshore wind and solar energy in deserts. In addition, renewable energy sources can generate energy in other instants and in other places than is optimal for the energy supply system. The TuNur project and the European super-grid proposal are examples.

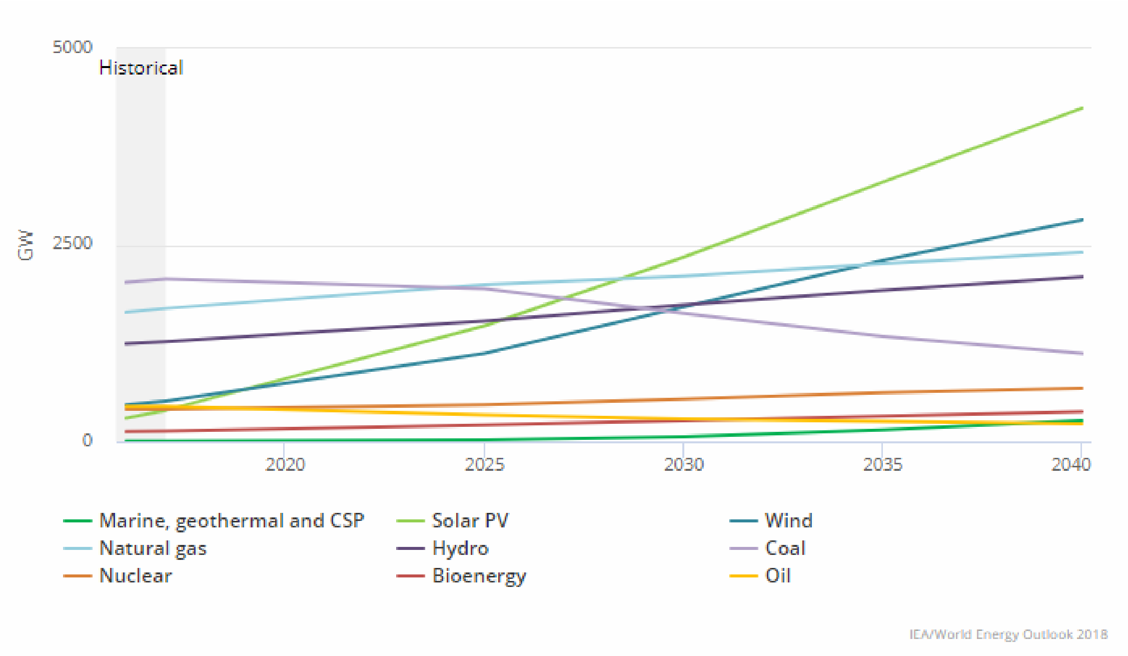


FIgure 1. 1 Installed power generation future shares by type

Due to limitations in power based on frequency, HVAC transmission is not feasible for long distances since there are very high transmission losses. However, the majority of power transmission networks are AC grids. The conventional model of power system has to be restructured to make it capable of incorporating some amount of distributed energy generation.

1.2 Reduced Inertia

Inertia of the AC system allows it to resist changes in the operating frequency due to disturbances. Conventional power plants that use huge turbines rotating at very high speed have very high inertia. The growing share of energy sources which do not provide output power at nominal frequency of AC systems tends to decrease the inertia of AC power grid. This problem can be solved by introducing more rotating masses or introducing energy storage elements connected to power system by means of power electronic converters designed to supply or absorb aggregate power for maintaining frequency during transients.

Power electronics converters do not contribute towards system inertia in a significant way and so system inertia declines which threatens frequency stability. For maintaining or enhancing system wide frequency stability the control systems of converters must be modified for contributing to system inertia.

Energy storage available for this purpose are of several types, each one with its own advantages and limitations. Figure 1.2 shows the performance of various electrical energy storage technologies. [3]

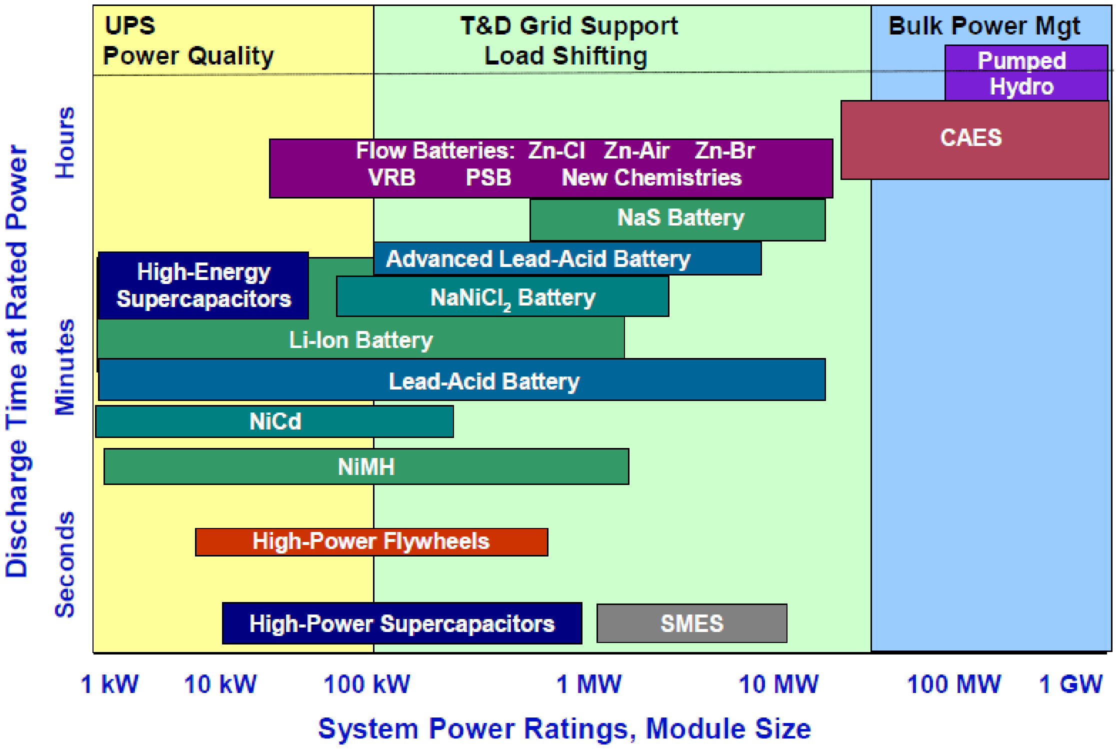


FIgure 1. 2 Comparison of power rating and discharge time for various electrical energy storage technologies.

All these technologies need new devices in power system to emulate inertia. Some techniques for providing inertia with power electronic converters are:

- Event based inertia emulation schemes.
- Virtual Synchronous Machines (VSM).
- Frequency based inertia.

1.3 Rotational and Synthetic Inertia

Inertia is defined as the ability of power system for opposing changes in frequency. Tripping of large power generation units cause large deviations in frequency which result in imbalances in generated and consumed active power. Synchronous generators which are connected to the power system help resist changes in frequency of system. The inertia of a power system is Instantaneous Power Reserve.

Due to the high presence of nonsynchronous and renewable energy resources in the modern electrical system, the ratio of production of power from traditional synchronous generators decreases, thus reducing the instantaneous power reserve. The solution to this problem is to introduce the energy storage system which is interfaced with power system with a controlled converter for sustaining frequency during transients. HVDC systems and most of renewable energy sources are connected to AC grid with a power electronic converter.[4]

1.4 Synchronous Generator Inertia Response

When a sudden load change occurs on a synchronous generator there are various factors determine the behavior. Its response can be delineated based on time periods following the real power demand variation event as follows

------

Time	Factor	Effect	Description
0 - 3 s	Size (Inertia) of the Machine	Frequency Decline with Power Compensation from Inertia.	Instantaneous Power Reserve. The larger the Generator , the more it will compensate in system Real Power demand. This is the Time Period during which the Synthetic Inertia has to be emulated using other energy storage in the network.
3 - 30 s	Primary Speed Control (Governor)	Generation Increases with frequency stabilizng to a lower value, with a new power setpoint.	Primary Power Reserve. This reserve is generally controlled by a droop control. It has to be activated within few seconds after the disturbance took place and has to last until the secondary reserve has restored the frequency near to the nominal value
1 - 10 min	Supplementary Control	Conrol Centre reallocates new setpoint for each generator to return frequency to nominal.	Secondary Power Reserve. Restores the rated frequency of the system, releasing primary reserves and to restore active power interchanges between power system areas to their set point values. This reserve is activated by TSOs changing generators power set points.

Table 1 Real Power Demand Behavoiur of a Synchronous Generator[4]

Now analyze the inertia response of synchronous generator, before the primary control kicks in. In power system during steady state operation there is perfect balance between power consumption and generation, including losses. All generators are rotating with synchronous electrical speed. If balance is lost due to load change or some other causes, power generated will be lower or higher than power consumption.

$$\Delta P_{Mechanical} - \Delta P_{Electrical} = 0 \tag{1.1}$$

When there is an increase in electrical load without changing mechanical input to generator, the generator slow down trying compensating power mismatch. This is done by extracting kinetic energy from inertial storage of system which cause electric frequency to fall because generator is slowing. Now we analyze behavior using swing equation.

Swing equation is the basic equation that drives the motion of the rotor of a synchronous generator.

$$J \frac{d^2 \delta_m}{dt^2} = T_{Mech} - T_{Elect.} = T_{Acceleration} \tag{1.2}$$

where:

- T: Torque (Mechanical Shaft, Electrical, Accelerating) [Joules]
- δ: Rotational Angle [mechanical radians]
- J: Moment of Inertia [kg-m^2]

When the generation is higher than consumption, the synchronous generator will accelerate, in other case it will slow down. The first derivative of δ will give the Angular Speed of rotor **Ω_m**, and the second derivative will give Angular Acceleration α.

The swing equation can be expressed in terms of Power by multiplying with Ω_m:

$$J\, \Omega_m \frac{d^2 \delta_m}{dt^2} = \Omega_m\, T_M - \Omega_m\, T_{E.} = \Omega_m\, T_A \tag{1.4}$$

$$M\,\frac{d^2\delta_m}{dt^2} = P_M - P_E = \Delta P \tag{1.3}$$

Where M is Angular Momentum [J rad/s], it is constant for machine because it is defined at synchronous mechanical speed.

$$J\,\Omega_m\,\frac{d\,\Omega_m}{dt} = P_M - P_E = \Delta P$$

$$\Delta P = P_M - P_E = \frac{d}{dt}\left(\frac{1}{2}\,J\,{\Omega_m}^2\right)$$

$$\Delta P = P_M - P_E = \frac{d}{dt}\,K.E. \tag{1.4}$$

K.E. is Kinetic Energy stored in moving parts of synchronous generator (including Turbine, Rotor,Shaft).

Usually, H (Inertia constant) is defined as ratio between stored kinetic energy in MJ at synchronous speed Ω_{sm} and S (the rating of machine in MVA).

$$H \triangleq \frac{K.E.}{S} = \frac{\frac{1}{2}\,J\,{\Omega_{sm}}^2}{S} = \frac{\frac{1}{2}\,M\,\Omega_{sm}}{S} \tag{1.5}$$

$$M = \frac{2\,H}{\Omega_{sm}}\,S$$

Now equation 2.3 can be re written as:

$$\frac{2\,H}{\Omega_{sm}}\,S\,\frac{d^2\delta_m}{dt^2} = P_M - P_E = \Delta P \tag{1.6}$$

The relationship is in absolute values; by dividing by S we have per unit power and speed and angles are in mechanical radians per second and mechanical radians, respectively.

$$\frac{2\,H}{\Omega_{sm}}\,\frac{d^2\delta_m}{dt^2} = \dot{P}_M - \dot{P}_E \tag{1.7}$$

Another important factor is Starting or Acceleration Time constant T_{ST}. It is time needed to speed up a rotating system from zero to nominal speed Ω_{sm}, with nominal moment of inertia J. From equation 1.2:

$$T_A = T_M - T_E = J\,\frac{d^2\delta_m}{dt^2}$$

$$T_A = J\,\frac{d\Omega_m}{dt}$$

we divide by base torque T$_0$ to bring equation in p.u. and perform some changes on RHS by considering Ω_{sm} ≈ base speed

$$\dot{T}_A = \frac{J}{T_0}\,\frac{\Omega_{sm}}{\Omega_{sm}}\,\frac{d}{dt}\left(\frac{\Omega_m\,.\,\Omega_{sm}}{\Omega_{sm}}\right)$$

$$\dot{T}_A = \frac{2\,.\left(\frac{1}{2}\,J\,\Omega^2{}_{sm}\right)}{S}\,\frac{d}{dt}\left(\dot{\Omega}_m\right)$$

$$\dot{T}_A = 2\,\frac{K.E.}{S}\,\frac{d}{dt}\left(\dot{\Omega}_m\right) \tag{1.8}$$

Here, angular speed is converted to per unit. And Rated Power of machine is multiple of its rated torque and rated angular speed.

The starting time constant is defined as:

$$T_{ST} = 2\,\frac{K.E.}{S} = 2\,H \tag{1.9}$$

And half of T$_{ST}$ is the constant of inertia as seen in equation 1.5. Then equation 2.8 can be written as:

$$T_{ST} = 2\,\frac{\frac{1}{2}\,J\,\Omega^2{}_{sm}}{T_0\,\Omega_{sm}} = \frac{J\,\Omega_{sm}}{T_0}$$

$$H = \frac{T_{ST}}{2} = \frac{J\,\Omega_{sm}}{2\,T_0}$$

We now recognize that T$_{ST}$ is starting time which is time necessary for machine to reach rated speed starting from standstill, without load and with a constant accelerating torque equal to nominal one. H or Ta is an important parameter for a generating group, because it synthesizes how the angular speed will vary after power disturbance. From equation 1.7:

$$\dot{P}_M - \dot{P}_E = \Delta\dot{P} = \frac{T_{ST}}{\Omega_{sm}}\,\frac{d\Omega_m}{dt}$$

If we consider $\Omega_m \approx \Omega_{sm} \approx$ base speed, then from equation 1.8

$$\dot{T_A} = \dot{T_M} - \dot{T_E} = 2\,\frac{K.E.}{S}\,\frac{d}{dt}\left(\dot{\Omega_m}\right)$$

$$\frac{T_M\,.\,\Omega_m}{T_0\,.\,\Omega_{sm}} - \frac{T_E\,.\,\Omega_m}{T_0\,.\,\Omega_{sm}} = T_{ST}\,\frac{d}{dt}\left(\dot{\Omega_m}\right)$$

$$\frac{\mathrm{P}_M}{S} - \frac{\mathrm{P}_E}{S} = T_{ST}\,\frac{d}{dt}\left(\dot{\Omega_m}\right)$$

$$\dot{P_M} - \dot{P_E} = \Delta\dot{P} = T_{ST}\,\frac{d}{dt}\left(\dot{\Omega_m}\right)$$

Now by comparing $\Omega = \frac{2\pi}{60}\,N_{rpm}$ and $N_{rpm} = \frac{120\,f}{p}$ we obtain $\Omega = \frac{4\pi}{p}\,f$, so previous equation can be written as.

$$\dot{P_M} - \dot{P_E} = \Delta\dot{P} = T_{ST}\,.\,\frac{4\pi}{p}\,.\,\frac{d\dot{f}}{dt}$$

Generally, this equation is written like below:

$$\Delta\dot{P} = T_{ST}\,.\,\frac{d\dot{f}}{dt} \tag{1.10}$$

Therefore, we see from the analysis above that sudden increase in demand of real power in electrical grid prompts an abrupt frequency drop.

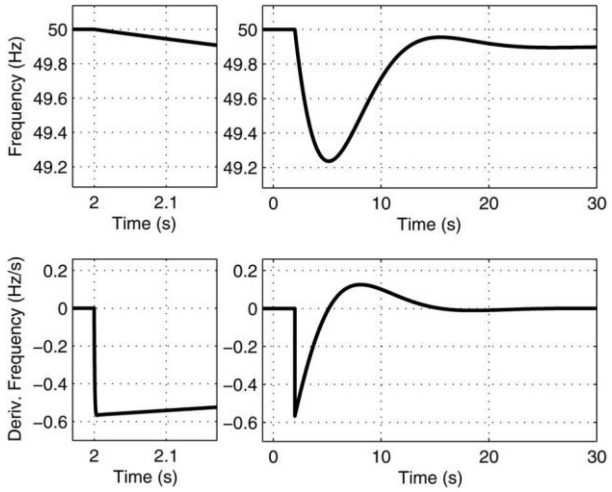


FIgure 1. 3 Variation of frequency of grid and df/dt to a sudden demand[4]

The inertia constants and rated apparent powers of individual generators can be used for calculating inertia of power system:

$$H_{sys} = \frac{\sum_{i=1}^{N} S_i H_i}{S_{sys}}$$

Where S_i is the rated power of each generator connected to power system and $S_{sys} = \sum_{i=1}^{N} S_i$. All the generators connected to power system compensate for change in the power demand as:

$$\Delta P_i = \left(\frac{H_i}{H_{sys}}\right) \Delta P_{sys}$$

The settling time and maximum overshoot are proportional to values of inertia constant (within certain range). The higher the values of inertia constant the higher settling time and the maximum frequency overshoot. Taking a very large inertia constant can make waveform completely sinusoidal. If very small value of inertia constant is considered, frequency waveform will be completely exponentially decaying function.

The minimum frequency value reached by grid after frequency drop is known as Dynamic Frequency Deviation Δf_{dyn}. The value of time of the Frequency Nadir t_{nadir} is time that occurs between frequency event and the minimum frequency.[4]

Chapter 2

2. Services and Benefits of Electric Storage

2.1 Energy Storage

Energy storage system mediates between variable energy production sources and variable nature loads. Without the storage, energy generation must be equal to energy consumption. Energy storage system works by displacing energy through time. Energy generated at a moment can be used at another moment through storage. Electricity storage is one form of energy storage. Other forms of energy storage comprise oil in the Strategic Petroleum Reserve and in storage reservoirs, natural gas in underground storage reservoirs and pipelines, thermal energy in ice, and thermal mass/adobe.

Electricity storage is not new. In the 1780s, Galvani demonstrated “animal electricity” and in 1799 Volta invented the modern battery. In 1836, batteries were accepted in telegraph networks. In the 1880s, lead-acid batteries were the original solution for night-time load in the remote New York City area direct current (dc) systems. The batteries were served to supply the electricity to the load throughout high-demand period and to store surplus electricity from generators during low-demand periods for sale later. The first U.S. large-scale electricity storage system was 31 megawatts (MW) of pumped storage system in 1929 at the Connecticut Light & Power Rocky River Plant. As of 2011, 2.2% [5] of electricity was stored worldwide, mostly in pumped storage.

In this study, a comprehensive complete electricity storage system (that can be connected to electric grid or operated in the stand-alone mode) comprises two major sub-components: storage and the power conversion semiconductor electronics. These sub-systems are supplemented by other balance-of-plant components that are included monitoring and control systems that are important to maintain the health and safety of the complete system. These balance-of-plant components include the building or other physical enclosure, miscellaneous switchgear, and hardware to connect to the grid or the customer load. A schematic illustration of a complete ESS is shown in Figure 1 with a generic storage device showing a dc storage source, such as a battery. [6]

In battery storage systems, power conversion system (PCS) is a bidirectional device that allows the dc to flow to the load after it is converted to alternating current (ac) and allows ac to flow in the reverse direction after conversion to dc to charge the battery or flywheel. The monitoring and control sub-components might not be a discrete box, as shown in Figure 1, but could be combined within the PCS itself.

The Compressed air energy storage (CAES). systems involve high-pressure air stored in underground caverns or above-ground storage. containers (for example, high-pressure pipes or tanks). In pumped hydroelectric energy storage (PHES), energy is stored by pumping. water to an upper reservoir at a higher elevation than the system’s lower elevation reservoir.

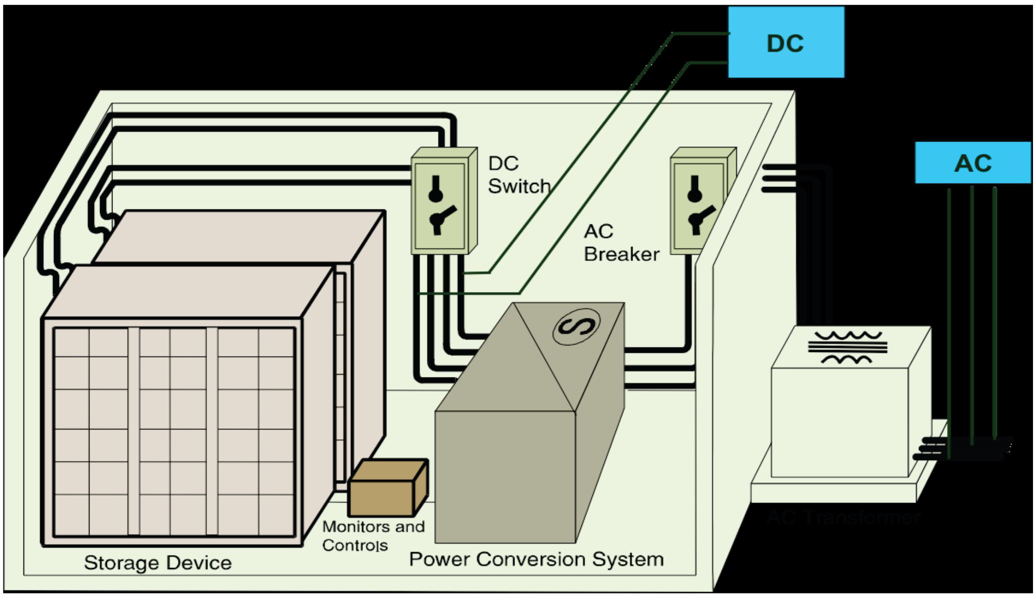
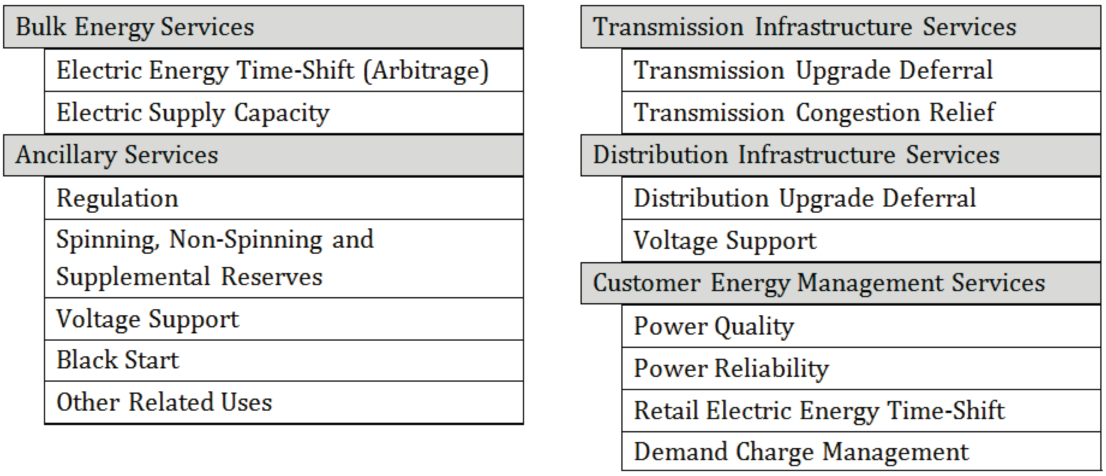


Figure 2. 1 Future shares of installed power generation by type[3]

Approach

Two SNL report [7],[8] in the early 1990s identified and described 13 of the services that these emerging energy storage technologies could provide. A recent report [9] extended the range of the grid services and provided significantly additional detail on 17 services and guidance on estimating the advantages accrued by these services. Other works have also documented. use cases and services that storage provides to the grid. Most notably, EPRI's Smart Grid Resource Center Use Case Repository comprises over 130 documents that discuss numerous features of storage systems [10] We will discuss 18 services together with the description and technical particulars in five groups. We have dedicated a separate chapter for ancillary services which will be discussed in the next chapter in detail.



Bulk Energy Services	
	Electric Energy Time-Shift (Arbitrage)
	Electric Supply Capacity
Ancillary Services	
	Regulation
	Spinning, Non-Spinning and Supplemental Reserves
	Voltage Support
	Black Start
	Other Related Uses
Transmission Infrastructure Services	
	Transmission Upgrade Deferral
	Transmission Congestion Relief
Distribution Infrastructure Services	
	Distribution Upgrade Deferral
	Voltage Support
Customer Energy Management Services	
	Power Quality
	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management

Table 2 Electric Grid Energy Storage Services[3]

2.2 Data Bulk Energy Services

2.2.1 Electric Energy Time-Shift (Arbitrage)

Electric energy time-shift includes purchasing low-cost electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the energy can be used. or sold later when the price or costs are higher. Alternatively, storage can deliver similar. time-shift duty by storing excess energy production, which would otherwise. must be curtailed, from renewable sources such as wind or photovoltaic (PV). [11]

The functional operation of the storage system is similar in both cases, and they are treated interchangeably in this discussion.

Technical Considerations

Storage System Size Range: 1 – 500 MW
Target Discharge Duration Range: <1 hour
Minimum Cycles/Year: 250 +

Storage used for time-shifting energy from PV. or smaller wind farms would be in the lower end of the system storage magnitude.and period ranges shown above, whereas storage for arbitrage in large utility applications.or in conjunction with bigger wind farms or groups of wind and/or PV plants would fall in the upper end of these ranges.

Both storage variable operating cost. (non-energy-related) and storage efficiency are especially important for this service. Electric energy time-shift involves many possible transactions with economic merit based on the difference between the cost to purchase, store, and discharge energy (discharge cost) and the profit derived once the energy is discharged.

Any increase in variable operating cost or reduction of efficiency decreases the number of transactions for which the benefit exceeds the cost. That number of transactions is quite sensitive to the discharge cost, so a modest increase may reduce the- number of viable transactions considerably. Two performance characteristics that have a. significant influence on storage. variable operating cost are round-trip efficiency of the storage system and the. rate at which storage performance decays as it is used.

In addition, seasonal and diurnal electricity. storage can be considered as a bulk service. It can be very useful for wind or PV if there are significant seasonal and diurnal differences.

2.2.2 Electric Supply Capacity

Depending on the conditions in a given electric supply system network, energy storage could be used to defer and/or to reduce the requirement to purchase new central station generation capacity and/or purchasing capacity in the wholesale electricity marketplace. [12]

The marketplace for electric supply capacity is evolving. In some cases, generation capacity cost is included in wholesale energy prices (as an allocated cost per unit of energy). In other situations, market mechanisms may allow for capacity-related payments.

Technical Considerations

Storage System Size Range: 1 – 500 MW
Target Discharge Duration Range: 2 – 6 hours
Minimum Cycles/Year: 5 – 100

The operating profile for storage system used as supply capacity (characterized by annual hours. of operation, frequency of operation, and duration. of operation for each use) is location specific. Therefore, it is challenging to generalize about storage discharge period for this service. There is another key standard affecting discharge period for this service is the way in which that generation capacity is priced. For example, if energy is priced per hour, then storage plant duration is flexible. If prices require that the energy resource be available for a specified duration for each occurrence (for example, 5 hours), or need operation during a whole time period (for example, 12:00 p.m. to 5:00 p.m.), then storage plant discharge duration should accommodate those needs. The two plots in Figure 2 demonstrate the capacity constraint and how storage acts to compensate the shortfall. The upper plot demonstrations the three weekdays once there is need for peaking the capacity. The lower plot shows storage discharge to compensate load during those three durations and also shows that the storage is charged starting just before midnight and ending late-night during all the times when system load is lower.

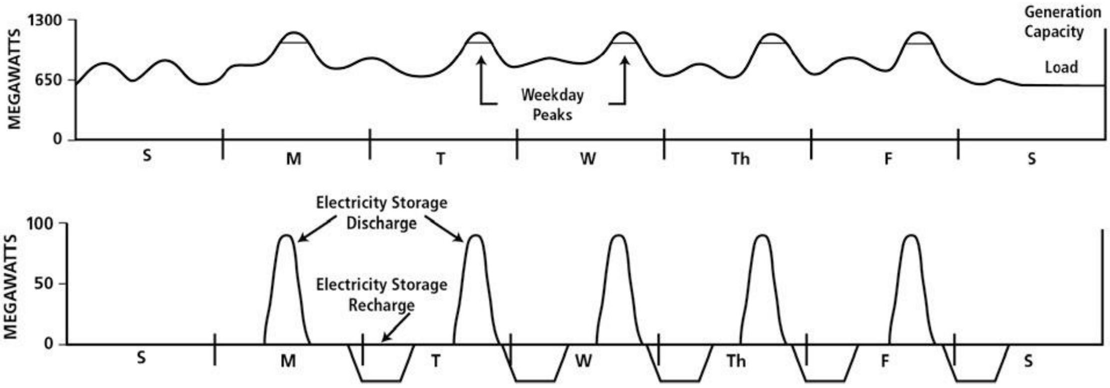


Figure 2. 2 Storage for Electric Supply Capacity

2.3 Transmission Infrastructure Services

2.3.1 Transmission Upgrade Deferral

Transmission upgrade deferral includes postponing – and in some cases avoiding completely – utility investments in transmission system upgrades investments, by using relatively small amounts of storage.

Let’s Consider a transmission system with the peak electric loading that is approaching the system’s load- carrying capacity (design rating). In some situations, installing a small quantity of energy storage downstream from the approximately overloaded transmission node could avoid the necessity for the upgrade for a few years.

The important consideration is that a little amount of energy storage can be served to deliver sufficient incremental capacity to defer the requirement for a large lump investment in transmission equipment infrastructure. While Doing so reduces overall price to ratepayers, it improves overall utility asset utilization, allows to save and make use of the capital for other projects, and decreases the financial risk related to lump investments.

Notably, for most nodes inside a transmission system, the highest loads occur on just a few days per year, for just a few hours per year. Often, the highest annual load occurs on one specific day with a peak somewhat higher than any other day. One important implication is that the storage used for this application can deliver significant benefits with limited or no need to discharge. Given that the most modular storage has a high variable operating cost, this may be especially attractive in such instances.

Although the emphasis for this application is on the transmission line upgrade deferral, a similar rationale applies to transmission equipment life extension. That is, if storage energy use reduces loading on existing equipment that is nearing its expected life, the result could be to extend the life of the existing equipment. This may be especially compelling for transmission equipment that includes aging transformers and underground power cables.

Technical Considerations

Storage System Size Range: 10 – 100 MW
Target Discharge Duration Range: 2 – 8 hours
Minimum Cycles/Year: 10 – 50

Energy storage system must serve enough load, for as long as desired, to keep loading on the transmission line equipment below a specified maximum level.

Figure 2.3 illustrates the use of energy storage for transmission deferral. The lower plot shows storage being discharged on Wednesday afternoon to compensate for the high load on the substation transformer, as shown in the upper plot. The storage is recharged when the feeder load reduces in the late evening. Alternatively, the storage can be recharged during the late night as long as it is available to serve the peak load that the transformer is likely to see the following day(s).

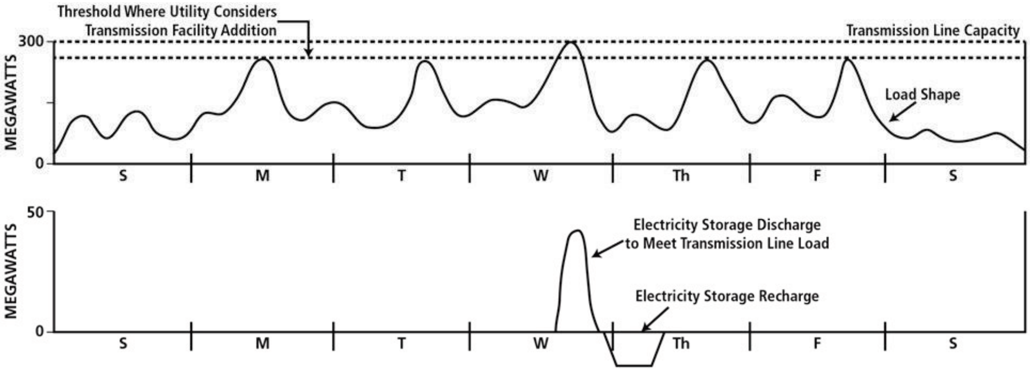


Figure 2. 3 Storage for Transmission and Distribution Deferral

2.3.2 Transmission Congestion Relief

The Transmission congestion happens when available, least-cost energy cannot be supplied to all or some loads because transmission facilities are not sufficient enough to deliver that energy to the loads. When transmission additions do not keep pace with the growing peak electric demand on particular day, the transmission systems become congested. Thus, during periods of peak demand, the need and cost for more transmission capacity increases along with transmission access charges. Transmission congestion may also lead to increased congestion costs or locational marginal pricing (LMP) for wholesale electricity at certain transmission nodes.

Electric energy storage can be served to avoid the congestion-related costs and charges, especially if the costs become onerous due to significant transmission system congestion. In this service, storage systems would be connected at locations that are electrically downstream from the congested part of the transmission system. Energy would be stored when there is no transmission congestion, and it would be discharged (during peak demand periods) to reduce peak transmission capacity requirements.

Technical Considerations

Storage System Size Range: 1 – 100 MW
Target Discharge Duration Range: 1 – 4 hours
Minimum Cycles/Year: 50 – 100

The discharge period required for transmission congestion relief cannot be generalized straightforwardly, given all the possible options. As with the transmission upgrade deferral service, it may require only a few hours of support during the year when congestion relief is required. Generally, congestion charges apply for just a few occurrences during a year when there are several consecutive hours of transmission congestion.

Figure 2.4 illustrates the energy storage response during transmission congestion relief service. The upper plot demonstrations four examples in which the load during day surpasses the capacity of the transmission line.

The lower plot demonstrations storage discharge during those four periods and a recharge during the late night once the system load is lower, and the transmission line is lightly loaded.

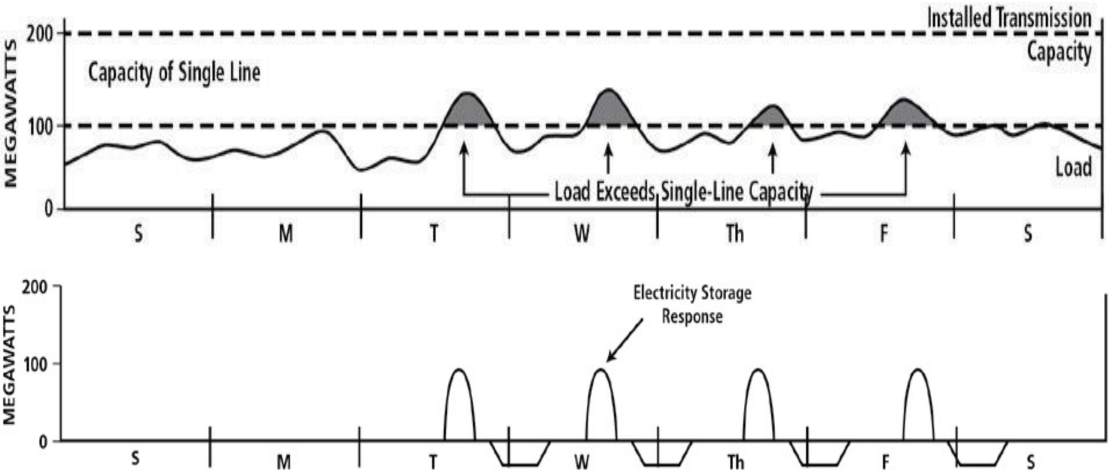


Figure 2. 4 Storage for Transmission Congestion Relief

2.4 Distribution Infrastructure Services

2.4.1 Distribution Upgrade Deferral and Voltage Support

The Distribution system upgrade deferral includes using storage system to delay or to avoid investments that could otherwise be essential to maintain satisfactory distribution capacity to supply all load requirements. The upgrade delay could be replacing an old or over-loaded existing distribution transformer at a substation or re-conductoring distribution lines with heavier wire.

Once a transformer is replaced with a newer, larger transformer, its power capacity is selected to accommodate future load growth over the next 15- to 20-year of plan. Thus, a major part of this investment is underutilized for most of the new equipment’s life. The upgrade of the transformer can be deferred by using a storage system to off-load it during peak times of the day, thus expanding its operational life by number of years. If the storage system is containerized, then it can be physically transported to other substations where it can remain to defer similar upgrade decision points and further maximize the return on its investment. [13]

A result to this strategy is that it also minimizes the ever-present risk that planned load growth does not occur, which would strand the investment made in upgrading the transformer or re-conductoring the line. This could be the case when a bulky load, such as a shopping mall or a residential development, did not construct because the developer delayed or cancelled the project after the utility had achieved the upgrade in anticipation of the new load. A storage system allows not only deferring the upgrade decision point, but also permits time to assess the certainty that planned load growth will materialize, which could be a 2- to 3-year window.

considerably, for maximum number of nodes in a distribution system, the highest loads arise on just a few days per year, for just a few hours per year. Frequently, the peak annual load occurs on one day with a peak somewhat higher than any other day. One significant implication is that energy storage used for this application can deliver significant benefits with limited or no requirement to discharge.

A storage system that is served for upgrade deferral could simultaneously offer voltage support on the distribution lines. Utilities regulate voltage within definite limits by tap changing regulators on transformers at the distribution substation and by switching capacitors to follow load changes. This is especially significant on long, radial lines where a bulky load such as an arc welder or a residential PV system may be producing unacceptable voltage excursions on neighboring customers. These voltage variations can be efficiently damped with negligible draw of real power from the storage system.

Technical Considerations

Storage System Size Range: 500 kilowatts (kW) – 10 MW
Target Discharge Duration Range: 1 – 4 hours
Minimum Cycles/Year: 50 – 100

Figure 2.5 illustrates the use of storage for T&D deferral. The lower plot demonstrations storage being discharged on Wednesday after-noon to compensate for the high load on the substation transformer, as illustrated in the upper plot. The storage energy is recharged when the feeder load decreases in the late evening hours. Otherwise, the storage can be recharged throughout the late night, as long as it is available to supply the peak load that the transformer is likely to see the following day(s).

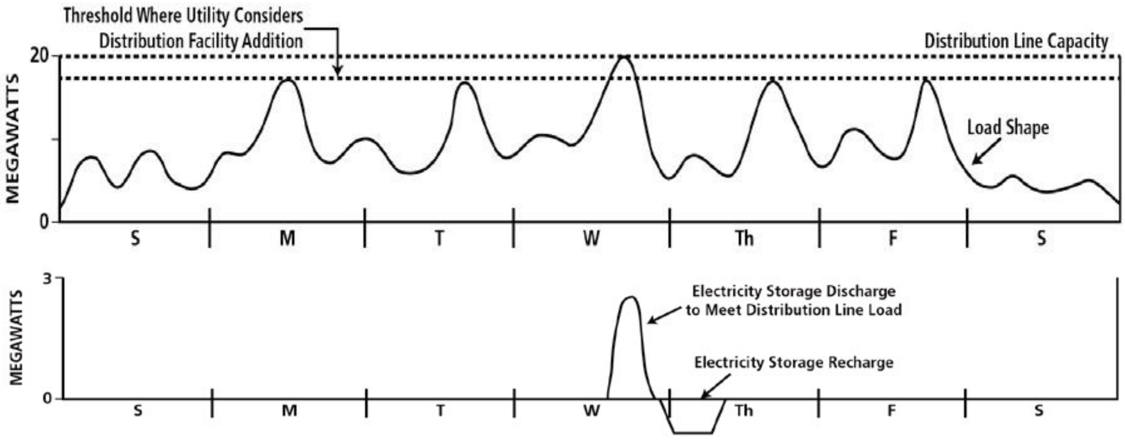


Figure 2. 5 Storage for Distribution Upgrade Deferral

2.5 Customer Energy Management Services

2.5.1 Power Quality

The electric power quality service includes using storage to protect the customer on-site loads downstream (from storage) against short-duration events that can affect the quality of power delivered to the customer's loads. Some indicators of poor power quality include the following:

- Voltage magnitude Fluctuations (short-term spikes or dips, longer term surges, or sags).
- Primary 50-hertz (Hz) frequency variations.
- Low power factor (voltage and current out of phase).
- Harmonics (the presence of currents or voltages at frequencies higher than fundamental frequency).
- Interruptions in service, of any duration, ranging from a fraction of a second to minutes,

Technical Considerations

Storage System Size Range: 100 kW – 10 MW
Target Discharge Duration Range: 10 seconds – 15 minutes
Minimum Cycles/Year: 10 – 200

Typically, the discharge duration mandatory for the power quality use ranges from a few seconds to minutes. The on-site storage system monitors the utility power quality and discharges to smooth out the disturbance so that it is constant to the load.

The upper plot in Figure 15 demonstrates a voltage spike of 50 volts (V) and the lower plot demonstrates storage absorbing the 50V-spike to maintain a constant 480V to the load. These anomalies in the electric supply to the customer, which can happen several times in quick succession due to events in the T&D network that supplies the customer, required to be corrected to protect sensitive processes and loads at the customer site.

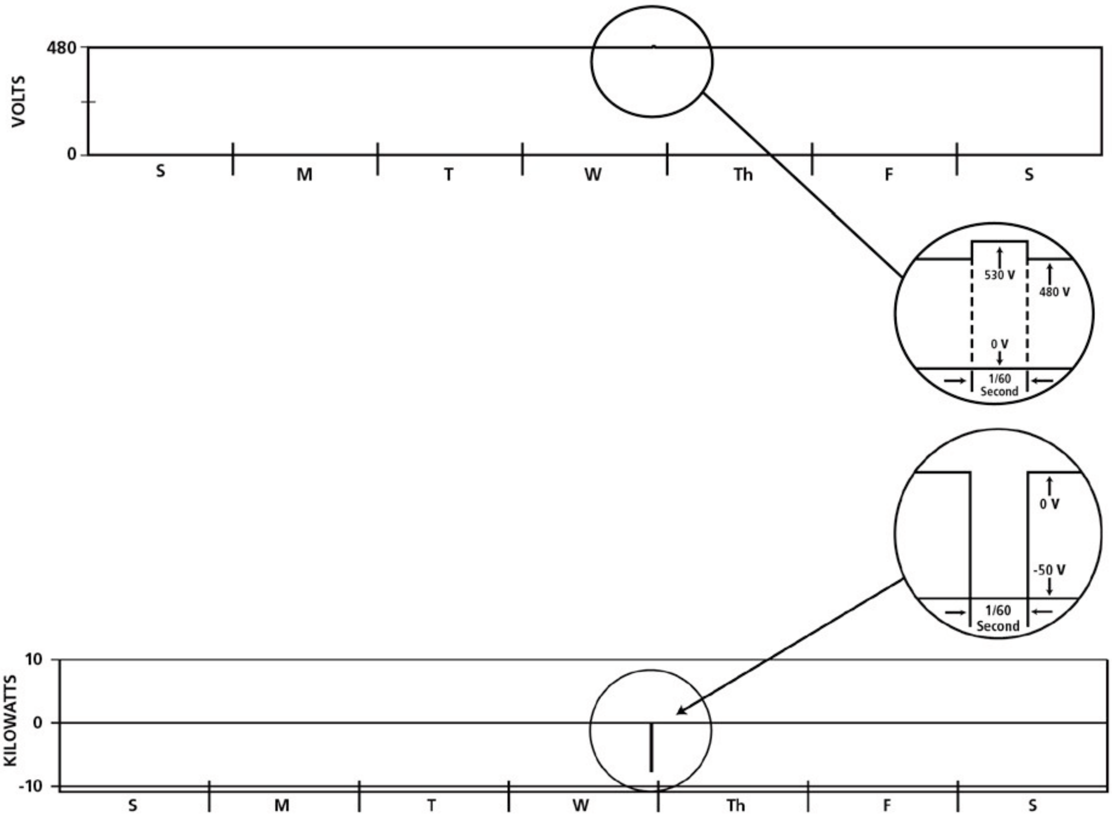


Figure 2. 6 Storage for Customer-side Power Quality

2.5.2 Power Reliability

A storage system could efficiently support the customer loads once there is a total loss of power from the source. This support involves the storage system and customer loads to island during the utility grid outage and resynchronize with the utility grid once power is restored. The energy capacity of the storage system related to the size of the load it is protecting determines the time period the storage can serve that load. This time can be prolonged by supplementing the storage system with on-site diesel generators that can continue supply the load for long outages that are beyond the capacity of the storage system.

The storage system can be possessed by the customer and is always under customer control. An alternate ownership scenario can be that the storage system is owned by the utility and is treated as a demand-side, dispatchable resource that serves the customer requirements and is available to the utility as a demand reduction resource.

2.5.3 Retail Energy Time-Shift

Retail electric energy time-shift involves storage used by energy end users (utility customers) to minimize their overall costs of electricity. Customers charge the storage during off-peak times when the retail electric energy cost is low, then discharge the energy during times when on-peak time of use (TOU) energy prices apply. This application is like electric energy time-shift, although electric energy prices are dependent on the customer’s retail tariff, whereas at any given time period the price for electric energy time-shift is the prevailing wholesale price.

For example, a hypothetical TOU tariff is demonstrated in Figure 2.7. It applies to Commercial and Industrial electricity end users from May to October, Monday through Friday, whose peak power requirements are less than or equal to 500 kW.

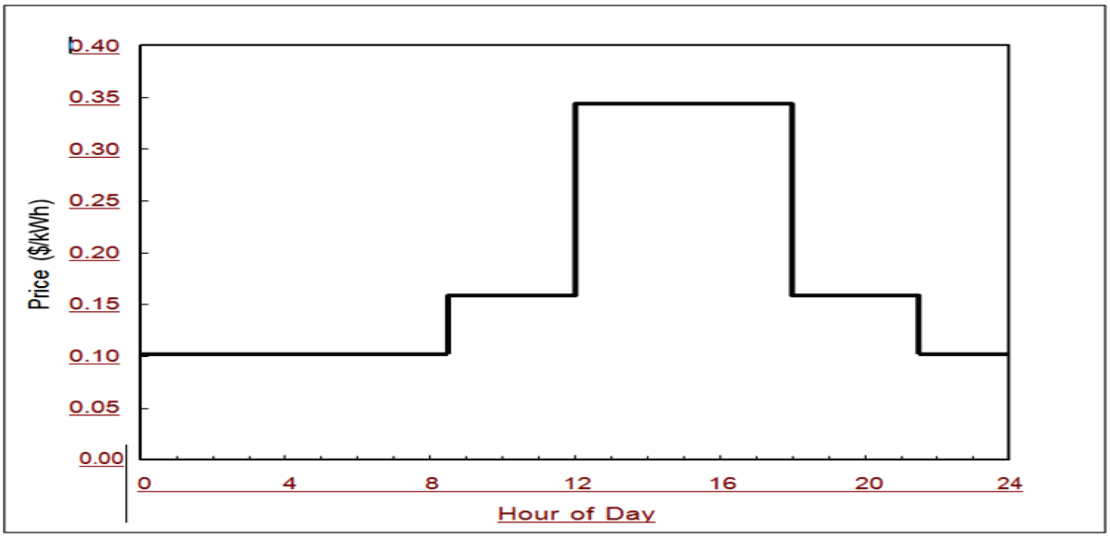


Figure 2. 7 Time of Use Summer Energy Prices for Small Commercial / Industrial Users

As shown in Figure 2.7, energy prices are about 32¢/kilowatt hour (kWh) on-peak (12:00 p.m. to 6:00 p.m.). Cost during partial-peak (8:30 a.m. to 12:00 p.m. and 6:00 p.m. to 9:30 p.m.) are about 15¢/kWh, and during off-peak (9:30 p.m. to 8:30 a.m.), prices are about 10¢/kWh.

Technical Considerations

Storage System Size Range: 1 kW – 1 MW
Target Discharge Duration Range: 1 – 6 hours
Minimum Cycles/Year: 50 – 250

The maximum discharge duration in this case is calculated based on the relevant tariff. For example, for the assumed hypothetical tariff, there are six on-peak hours (12:00 p.m. to 6:00 p.m.). The standard value presumed for this case is 5 hours of discharge period.

Chapter 3

3. Ancillary Services

3.1 Frequency Control

Frequency response is very similar to regulation, described below, except it responds to system requirements in even brief time periods of seconds to less than a minute when there is a sudden loss of a generation unit or a transmission line. As shown in Figure 3.1. It is very important to note that the rate at which the frequency decays after the triggering event – loss of generator or transmission – is directly proportional to the aggregate inertia within the grid at that instant. The rotating mass of large generators and/or the aggregate mass of many smaller generators collectively determines this inertia. Different types of generator response actions are required to counteract this unexpected imbalance between load and generation to maintain the system frequency and stability of the grid. The first response within the initial seconds is the primary frequency control response of the governor action on the generation units to increase their power output as shown in the lower portion of the figure. This is followed by the longer-duration secondary frequency control response by the AGC that expands the half a minute to several minutes shown by the dotted line in the lower portion of figure 3.1.

The combined effect of inertia and the governor actions determines the rate of frequency decay and recovery shown in the arresting and rebound periods in the upper portion of Figure 3.1. This is also the window of time in which the fast-acting response of flywheel and battery storage systems excels in stabilizing the frequency. The presence of fast-acting storage assures a smoother transition from the upset period to normal operation if the grid frequency is within its normal range. The effectiveness of fast-acting storage in this application has been successfully utilized by utilities [16] and described in other reports and papers.[17]

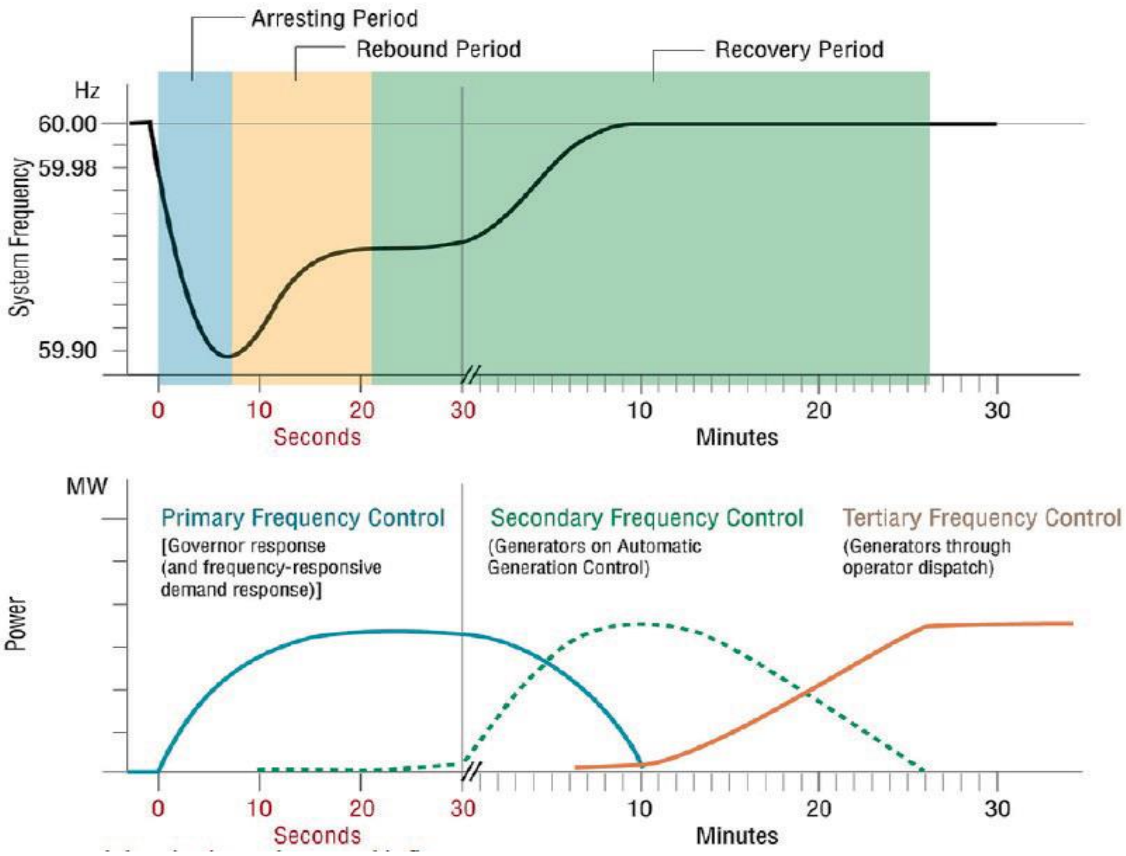


Figure 3. 1 The Sequential Actions of Primary, Secondary, and Tertiary Frequency Controls Following the Sudden Loss of Generation and Their Impacts on System Frequency

The size of storage systems to be used in frequency response mode is proportional to the grid or balancing area in which they are needed. Generally, storage systems in the 20 MW and greater size can provide effective frequency response due to their fast action; some studies [18] have shown that the response is twice as effective as a conventional fossil-fuelled generator, including combustion turbines (CTs) and coal units. However, location of the storage system within the grid with respect to other generation, transmission corridors, and loads plays a crucial role in the effectiveness as a frequency response resource.

3.2 Frequency Containment Reserve:

3.2.1 Primary Control Regulation (PCR)

This reserve is the fastest one. It acts quickly whenever Δf exceeds a dead band (usually ±20 mHz). The scope of this regulation is to contain the frequency variation within the maximum thresholds (±200 mHz). The ceasing in action of this reserve happens when frequency gets to a steady-state. To perform its action, PCR act as follows:

1. In case of under frequency, positive reserve injects power in the grid;
2. In case of over frequency, negative reserve withdraw power from grid. All relevant units inject less power than programmed in grid.

In any case, after PCR balance is restore in grid:

$$\Sigma Pproducers = \Sigma Pconsumers$$

This means frequency reaches a steady value.

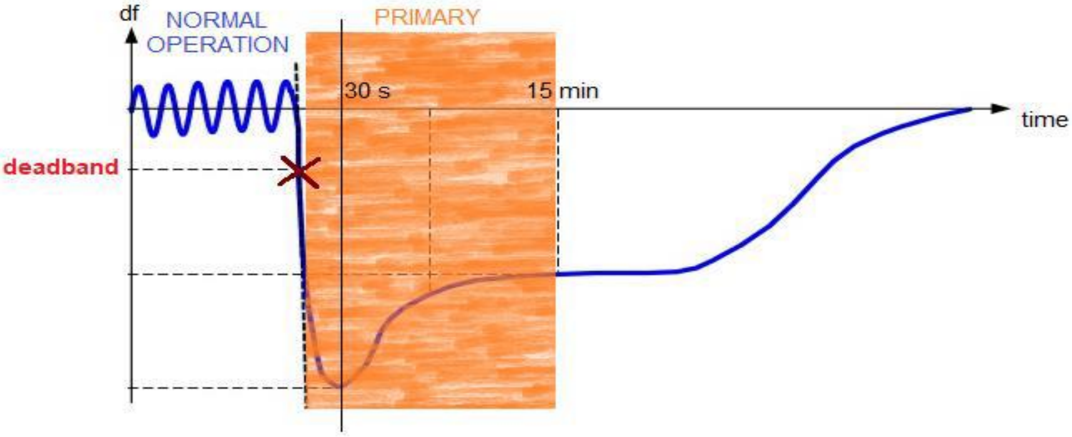


Figure 3. 2 Primary regulation diagram

In Italy, PCR is a mandatory service provided by every relevant unit (Unità Rilevanti: > 10 MVA, programmable). It is not subject to ASM, but it has a remuneration that is function of zonal price of electricity. To characterize and bind operation of units participating in PCR, a law of functioning called droop control law is implemented. This law links the variation in frequency with respect to nominal value to the variation in power output requested by generators. Droop means the ratio of a steady-state change of frequency to the resulting steady-state change in active power output, expressed in percentage terms with respect to regulating band offered (maximum power offered for reserve by each unit). The change in frequency is expressed as a ratio to nominal frequency and the change in active power is expressed as a ratio to maximum power offered for reserve by the unit. So, a single value in percentage chosen by TSO allow every unit to know the power output required in each moment of regulation. Usually a droop control curve features (see Figure 3-3):

1. A lower flat part, called dead band (power output = 0), where frequency variation is low and does not request any power regulation.
2. A part lead by droop law, in which power output requested increases (decreases) while frequency decreases (increases).

3. An upper flat part (power output = 100% of regulating band), in which power output is steady at maximum (minimum) since frequency is far from nominal value.

The equation for droop is:

$$droop\ [\%] = 100 * \frac{\frac{\Delta f}{f_{nom}}}{\frac{\Delta P}{P_{reg}}}$$

Where fnom is nominal frequency and Preg is regulating band offered for service.

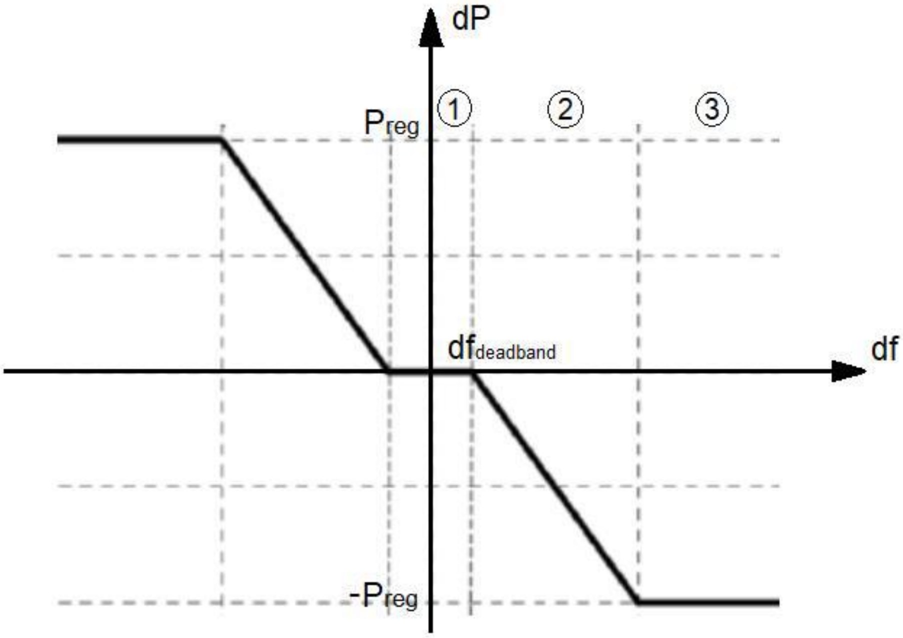


Figure 3. 3 Droop control curve

The service specifications in Italy are:

1. 20 mHz dead band.

2. Fixed droop varying among 2-5% depending by type of unit.

3. Regulating band of ±1.5% of nominal power of plant (Symmetric Reserves).

4. Fully activation maximum delay is 30 seconds after dead band is overpassed.

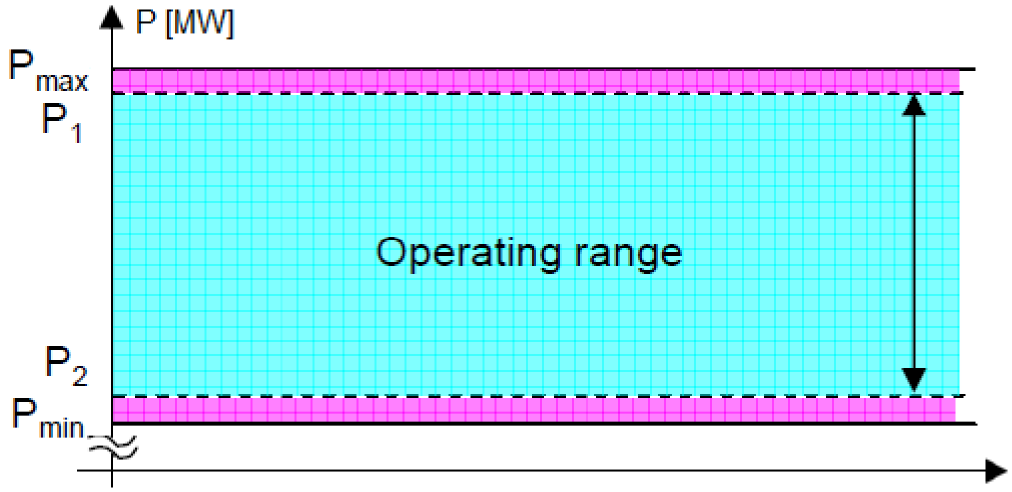


Figure 3. 4 Scheme of maximum and operating range of a unit relevant for PCR. Pink bands are PCR regulating bands, limiting maximum and minimum power output

3.2.2 Secondary Control Regulation (SCR)

Primary regulation does not restore frequency to nominal value. It just interrupts deviation and gets to a steady value that could be higher or lower than nominal value (50 Hz in Europe). SCR start working after PCR to reset nominal frequency. It acts causing an unbalance in grid for a certain period, injecting power if frequency is below nominal value and withdrawing it in case frequency is above nominal value.

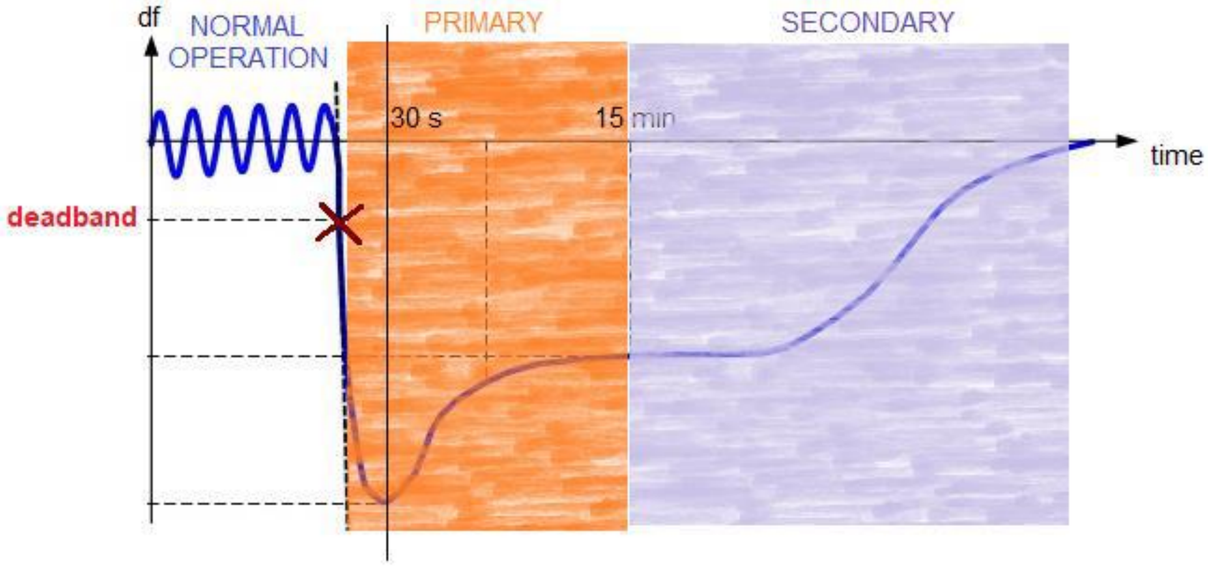


Figure 3. 5 Primary and secondary regulation diagram

With respect to PCR, this service is less standardized and has more constraints. There are less actors, so larger power flows requested to each actor. Therefore, there can be topology constraints. Given the quantity of reserve available, output required to restore frequency must be computed by TSO and shared among generators. The result, for Italian case, is a common signal in percentage corresponding to power output requested to every generator selected in market with respect to its total capacity offered (regulating band). In Italy, Secondary Reserve is a paid service on MSD. Specifications of service on Italian market are:

I. Every unit willing to enter market must bid same power bands (Semi Bande: SB, in MW) in positive and negative reserve: symmetric service.

II. Selected units automatically follow set points given by Segnale di Livello for the whole period in which they are selected. Segnale di Livello is a value [0,100] given each minute by TSO and valid simultaneously for all plants selected for SCR, defining how much power output of unit must differ from its DAM program:

$$\begin{cases} \Delta P = +SB \ if \ Segnale \ di \ livello = 100 \\ \Delta P = 0 \ if \ Segnale \ di \ livello = 50 \\ \Delta P = -SB \ if \ Segnale \ di \ livello = 0 \end{cases}$$

And all partial regulations are expressed by intermediate values.
Fully activation maximum delay is 15 minutes.

At the end of SCR, frequency is back to steady nominal value.

3.2.3 Tertiary Control Regulation (TCR)

Since units providing SCR are plants with strong programmability and high ramp rate (ΔP/time), it is of interest to have them ready for new events. That is why Replacement Reserve enters the field after SCR to restore the Secondary Reserve. For instance, in case positive reserve of a plant providing SCR has been exploited, TCR provides positive power to grid allowing the plant enrolled in SCR to reduce its power output and get back to setpoint it was following before SCR. So, that power plant can be ready to give once more positive reserve. In Italy, Replacement Reserve is a service traded on MSD. it is not automatic, but manually activated by TSO if needed. It requires slower but longer action: therefore, slow ramp and large energy output. On Italian market, this requirement is translated in a rule asking that energy can be delivered by the unit in 24 hours must be at least four times the power offered on market [19].

3.3 Regulation

Regulation is among one of the ancillary services for which storage is especially well suited. Regulation involves in management of interchange flows with other control areas to match closely the scheduled interchange flows and momentary variations in demand within the control area. The primary motives for including regulation in the power system are to keep balance the grid frequency and to comply with the Real Power Balancing Control Performance (BAL001) and Disturbance Control Performance (BAL002) Standards.

Regulation is used to reconcile the momentary differences that are caused by little fluctuations in generation and loads. Regulation is used for damping for that difference in load and generation. Consider the example shown in Figure 3.6 The load demand line in Figure 3.6 shows numerous fluctuations that are depicting the imbalance between generation and load without the regulation. The thicker line in the plot shows a smoother system response after damping of those fluctuations with regulation.

In power plants, generating units that are online and ready to increase or decrease power as needed are used for regulation and their output is increased when there is a momentary shortfall of generation to provide up regulation. Conversely, regulation resources’ output is reduced to provide down regulation when there is a momentary excess of generation.

An important consideration in this case is that large thermal base-load generation units in regulation incur significant wear and tear when they provide variable power needed for regulation duty.

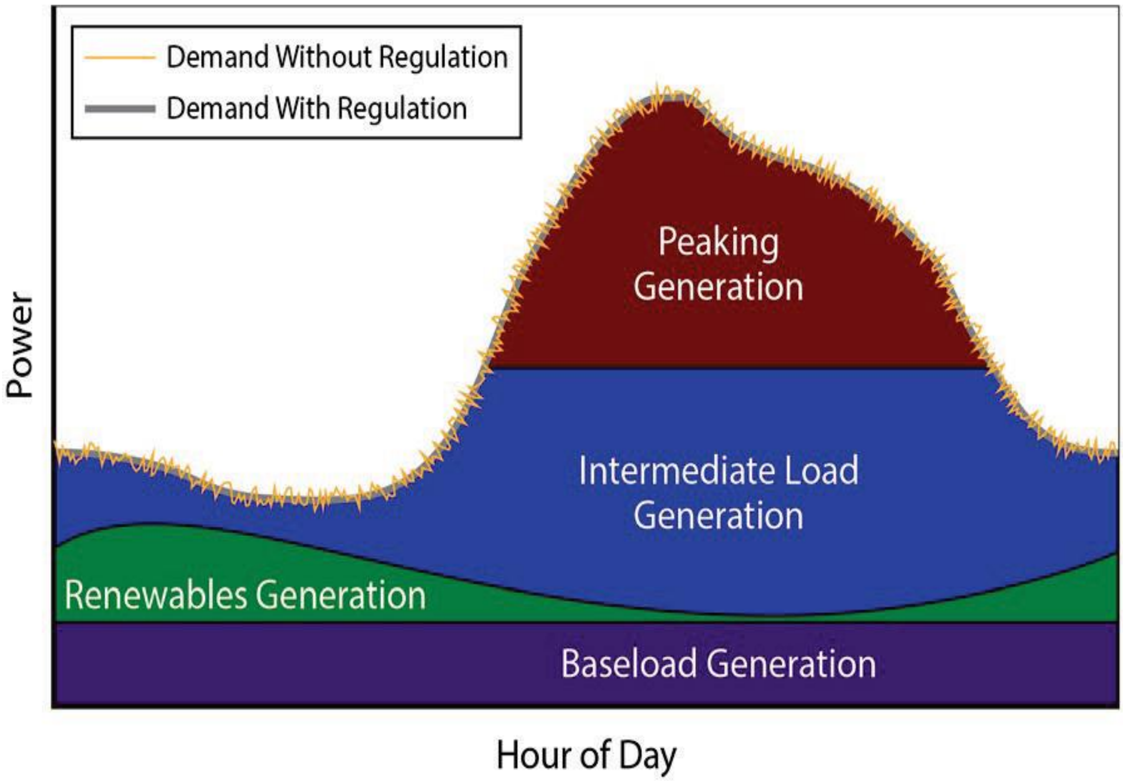


Figure 3. 6 System Load Without and With Regulation

There are two possible modes of operation for 1 MW of storage used for regulation and three possible operational modes for generation used for regulation are shown in Figure 3.7. The leftmost plot shows how less-efficient storage could be used for regulation. In that case, increased storage discharge is used to provide up regulation and reduced discharge is used to provide down regulation.

For up regulation one-half of the storage's capacity is used, and the other half of the storage capacity is used for down regulation (like the rightmost plot, which shows how 1 MW of generation is often used for regulation service). Now, consider the second plot, which shows how 1 MW of efficient storage can be used to provide 2 MW of regulation – 1 MW up and 1 MW down – using discharging and charging, respectively.

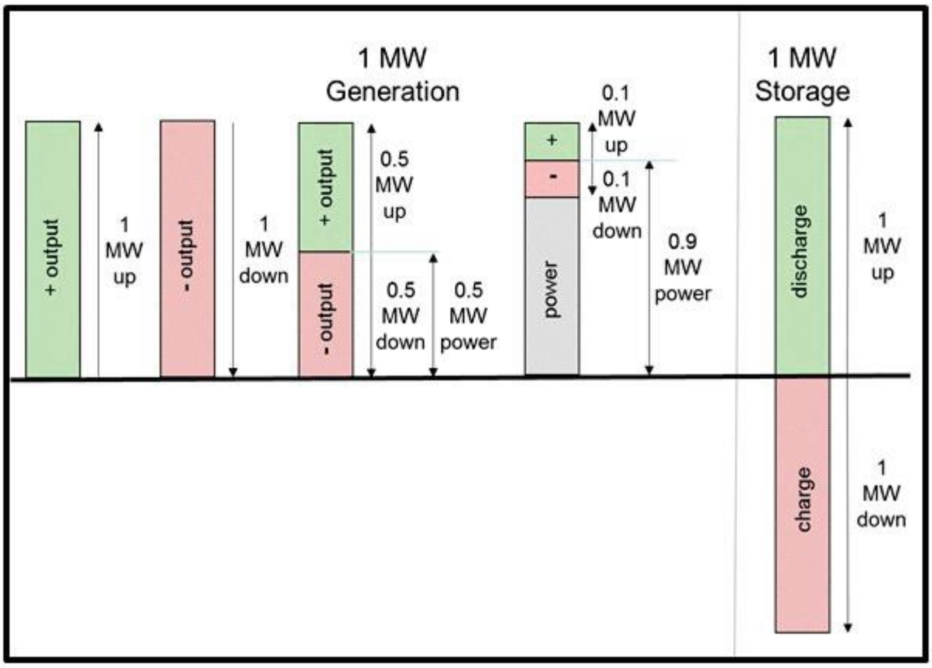


Figure 3. 7 Storage and Generation Operation for Regulation

Technical Considerations

Storage System Size Range: 10 – 40 MW
Target Discharge Duration Range: 15 minutes to 60 minutes
Minimum Cycles/Year: 250 – 10,000

Most of the storage systems have the rapid-response characteristic (that is, fast ramp rate) makes it valuable as a regulation resource. The Storage system used for regulation should have access to and be able to respond to the area control error (ACE) signal or an automatic generation control (AGC) signal if one is available from the Balancing Authority in which the storage system is located, as opposed to conventional plants, which generally follow an AGC signal. The equivalent benefit of regulation from storage with a fast ramp rate (for example, flywheels, capacitors, and battery storage types) is on the order of two times that of regulation provided by the conventional generation [14] because it can follow the signal more accurately and thus reduce the total wear and tear on other generation.

Figure 3.8 shows two plots to illustrate the storage response for a regulation requirement. The upper plot is an exaggerated illustration of the generation variance in response to fluctuating loads. The lower plot shows storage either discharging or charging to inject or absorb the generation as needed to eliminate the need for cycling of the generation units.

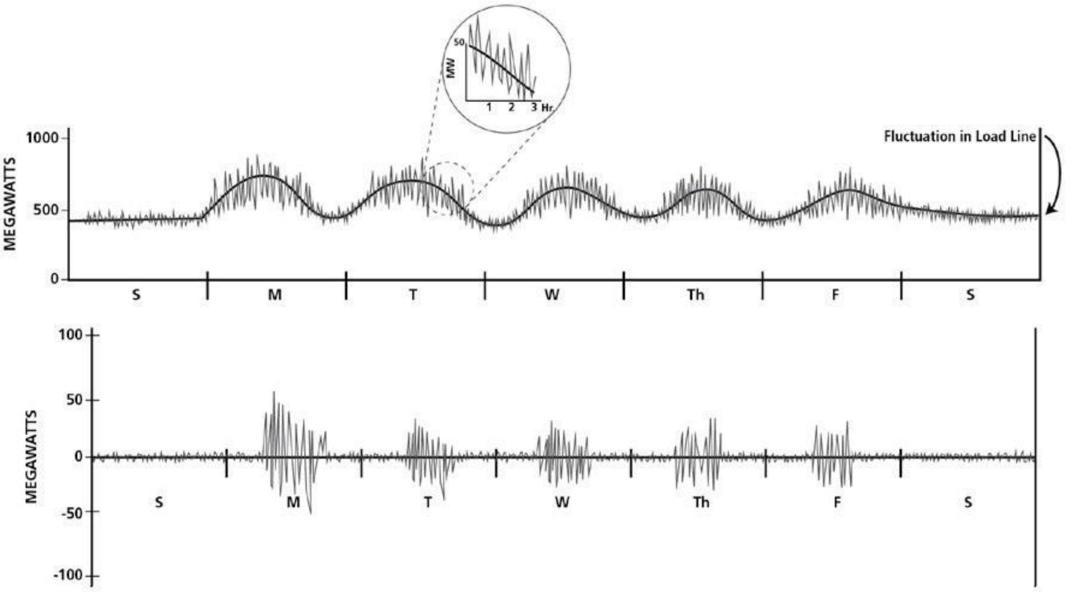


Figure 3. 8 Storage for Regulation

3.4 Spinning, Non-Spinning, and Supplemental Reserves

Operation of an electric grid requires reserve capacity that can be called upon when some portion of the normal electric supply resources becomes unavailable unexpectedly.
Generally
reserves are at least as large as the single largest resource (for example, the single largest generation unit) serving the system and reserve capacity is equivalent to 15% to 20% of the normal electric supply capacity. NERC and FERC define reserves differently based on different operating conditions. For simplicity, this study discusses three generic types of reserve to illustrate the role of storage in this service:

a. **Spinning Reserve (Synchronized)** – Generating unit that is online but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. "Frequency-responsive" spinning reserve responds within 10 seconds to maintain system frequency. Spinning reserves are the first type on the list used when a shortfall occurs. [15]

b. **Non-Spinning Reserve (Non-synchronized)** – Generating unit that may be offline or that comprises a block of curtailable and/or interruptible loads and that can be available within 10 minutes.

c. **Supplemental Reserve** – Generating unit that can pick up load within 1 hour. Its main purpose is, fundamentally, to be a backup for spinning and non-spinning reserves. Backup supply may also be used as backup for commercial energy sales. Unlike spinning reserve capacity, supplemental reserve capacity is not synchronized with grid frequency. Supplemental reserves are used after all other spinning reserves are online and supply power.

Importantly for storage, generation plants served as reserve capacity must be online and operational (that is, at part load). Unlike generation, in almost all circumstances, storage used for reserve capacity does not discharge at all; it just must be ready and available to discharge when needed.

Technical Considerations

Storage System Size Range: 10 – 100 MW
Target Discharge Duration Range: 15 minutes – 1 hour
Minimum Cycles/Year: 20 – 50

Reserve capacity resources should receive and respond to suitable control signals. Figure 3.9 shows that how storage plant responds to spinning reserve requirements. The upper plot shows a loss of generation and the lower plot shows the instantaneous response with a 30-minute discharge to deliver the reserve capacity until other generation sources is brought online.

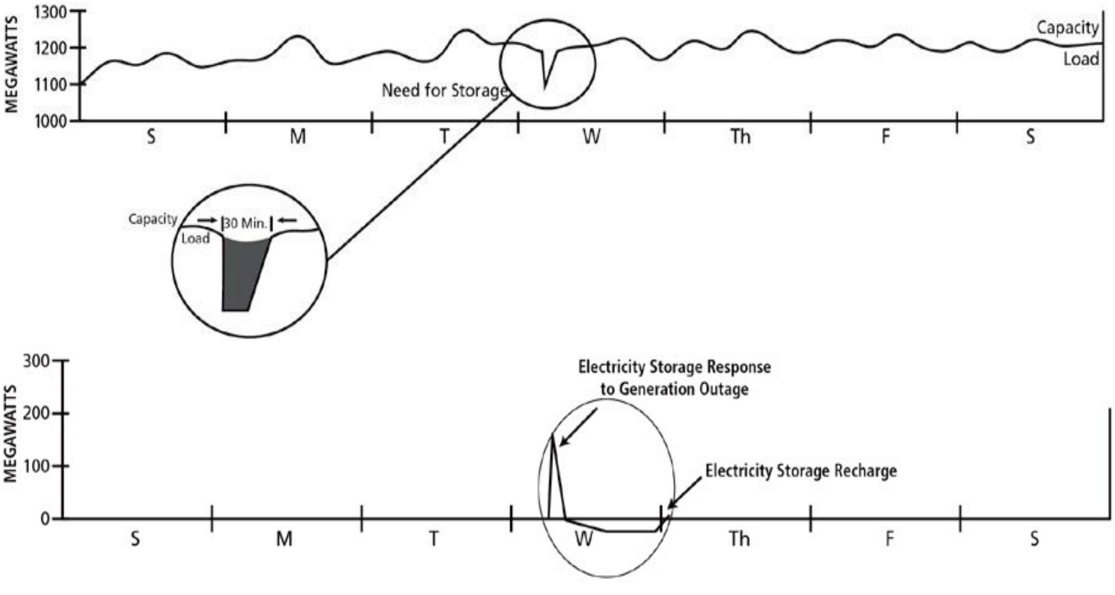


Figure 3. 9 Storage for Reserve Capacity

3.5 Voltage Support

A requirement for electric grid operators is to keep voltage within specified limits. In most of the cases, this requires the management of reactance, which is caused by grid-connected equipment that generates, transmits, or uses electricity and frequently has or displays characteristics like those of inductors and capacitors in an electric circuit. In order to manage reactance at the grid level, system operators need voltage support resources to offset reactive effects so that the transmission system can be operated in a stable way.

Typically, designated power plants are used to generate reactive power (VAR) to offset reactance in the grid. These power plants could be displaced by strategically placed energy storage within the grid at central positions or taking the distributed approach and employing multiple VAR-support storage systems near bulky loads.

Technical Considerations

Storage System Size Range: 1 – 10 mega volt-ampere reactive (MVAR)
Target Discharge Duration Range: Not Applicable
Minimum Cycles/Year: Not Applicable

The PCS of the storage systems used for voltage support should be proficient of operating at a non- unity power factor, to source and sink reactive power or volt-ampere reactive (VARs). The very same capability is available in all PCSs used in today's storage systems. Real power is not required from the battery in this mode of operation and thus discharge duration and minimum cycles per year are not relevant in this case.

The nominal time needed for voltage support is presumed to be 30 minutes time for the grid system to stabilize itself and, if essential, to begin orderly load shedding to match available generation. Figure 3.10 shows three discharges of storage: with active injection of real power and VARs, with absorbing power to balance voltage while providing VARs, and providing VARs only without real power injection or absorption as needed by the grid.

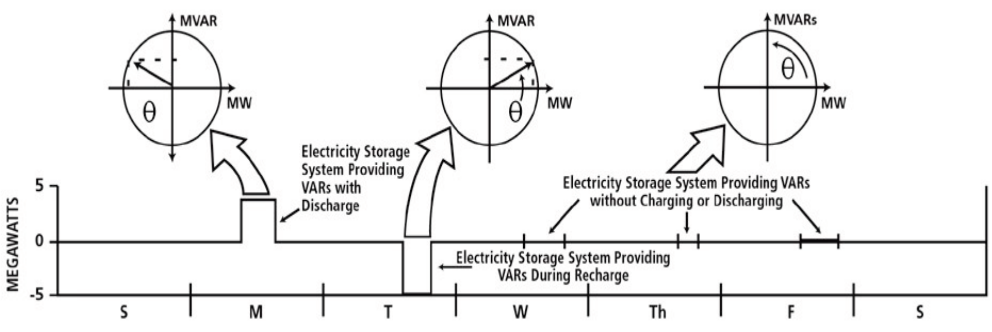


Figure 3. 10 Storage for Voltage Support Service

3.6 Black Start

Storage systems deliver an active reserve of power and energy within the grid and can be served to energize transmission and distribution lines and provide station power to bring the power plants on-line after a catastrophic failure of the grid. Golden Valley Electric Association uses the battery system in Fairbanks for this service once there is an outage of the transmission intertie with Anchorage. The operation of the battery is illustrated in Figure 3.11, which shows its discharge to provide charging current to two transmission paths as needed, and startup power to two diesel power plants that serve Fairbanks until the intertie is restored.

Storage can provide similar startup power to larger power plants, if the storage system is suitably sited and there is a clear transmission path to the power plant from the storage system's location.

Technical Considerations

Storage System Size Range: 5 – 50 MW
Target Discharge Duration Range: 15 minutes
1 hour Minimum Cycles/Year: 10 – 20

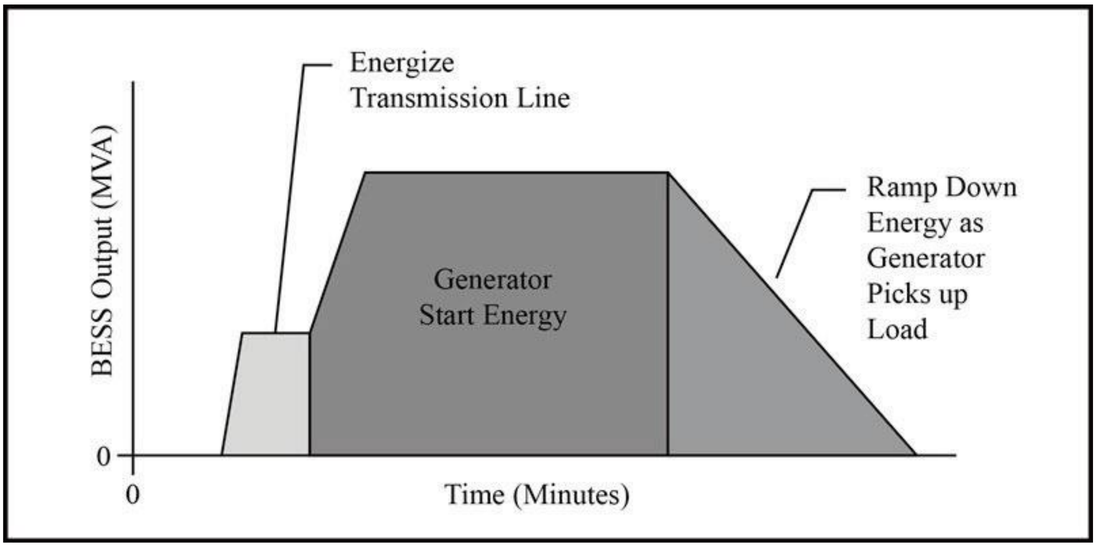


Figure 3. 11 Black Start Service by Storage

3.7 Other Related Uses

Load Following/Ramping Support for Renewables

Electricity storage is extremely appropriate for damping the inconsistency of wind and PV systems and is being extensively used in this application.

Technically, the operating requirements for a storage system in this application are the identical as those required for a storage system to respond to a swiftly or arbitrarily fluctuating load profile. Most renewable applications with a requirement for storage will setup a maximum expected up- and down-ramp rate in MW/minute and the time duration of the ramp. The design guidance for the storage system is applicable for load following and renewable ramp support; this study therefore considers them as the identical applications.

Load following is specified by power output that generally changes as frequently as every several minutes. The output changes in response to the changing balance between the electric supply and the load within a particularly specified region or area. The Output difference is a response to changes in system frequency and timeline loading, or the relation of these to each other that happens as needed to maintain the scheduled system frequency and/or established interchange with other areas within predetermined parameters.

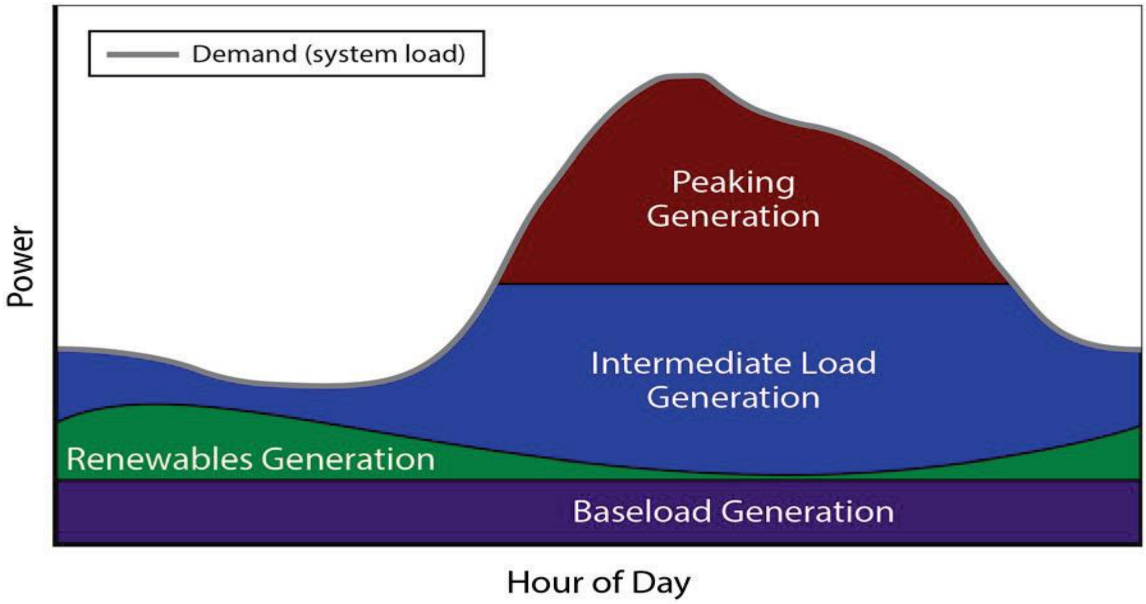


Figure 3. 12 Electric Supply Resource Stack

The output of conventional generation-based load following power plants increases to follow demand up as system load increases continuously. Conversely, the output of load following power plants *decreases* to follow demand down as a whole system load starts to decrease. Typically, the amount of load following desirable in the up direction (load following up) increases each day as load increases during the morning hours. In the evening hours, the amount of load following desirable in the down direction (load following down) increases as aggregate load on the grid drops. A simple depiction of load following is shown in Figure 3.12.

Generally, generation is used for load following. For load following up, generation is operated in a way such that its output is less than its design or rated output (also referred to as “part load operation”). Consequently, the plant heat rates, fuel cost, and emission are increased. This allows operators to increase the generator’s output, as required, to provide load following up to meet the increasing load. For load following down, generation jump starts at a high output level, maybe even at design output, and the output is decreased as load decreases.

These operating scenarios are prominent because operating generation at part load needs more fuel per megawatt hour (MWh) and consequences in increased air emissions per MWh relative to generation operated at its design output level. Fluctuating the output of generators (rather than operating at a constant output) will also increase fuel use and air emissions, as well as the need for generator maintenance and thus variable operations and maintenance (O&M) expenses. In addition, if a fossil fuel plant must shut down throughout off-peak periods, there will be a significant increase in fuel use, O&M, and emissions. Power Plant reliability will also deteriorate, resulting in the need for significant purchases of replacement energy.

The Storage is well suited to load following for several reasons. First, most categories of storage can operate at partial output levels with comparatively modest performance penalties. Second, most kinds of storage can respond rapidly (compared to other most types of generation plants) as soon as output is needed for load following. Consider also that storage can be used effectively for both load following up (as load increases) and for load following down (as load decreases), either by discharging or by charging.

In market platforms, once charging storage for load following, the energy stored must be purchased at the wholesale price. This is an important consideration, particularly for storage with relatively lower working efficiency and/or if the energy used for charging is relatively expensive, because the cost of energy used to charge storage (to provide load following) might exceed the value of the load following service.

Conversely, the worth of energy discharged from the storage to deliver load following is calculated by the prevailing price for wholesale energy. Dependent on circumstances (that is, if the actual price for the load following service does not include the value of the wholesale energy involved), when discharging for load following, two advantages accrue – one for the load following service and another for the energy.

Technical Considerations

Storage System Size Range: 1 – 100 MW
Target Discharge Duration Range: 15 minutes
1 hour Minimum Cycles/Year: Not Applicable

Electricity Energy Storage used for load following should be reliable or it cannot be used to meet contractual obligations that are associated with bidding in the load following market structure. The Storage used for load following will probably require access to AGC from the respective independent system operator (ISO).

Typically, an ISO requires an output from an AGC resource to change every minute.

Other considerations comprise synergies with other services. Large or central electricity storage used for load following may be particularly complementary to other service area if the charging and discharging for the other services can be synchronised. For example, the storage used to deliver generation capacity midday could be charged in the evening, thus following diminished system demand down during evening hours.

Load following could have good synergies with considerations of renewables capacity firming, electric energy time-shift, and possibly electric supply reserve capacity applications. If storage is distributed, then that same storage could also be used for most of the distributed applications and for voltage support.

Chapter 4

4. Battery Storage Systems in Electric Power Systems

Energy storage is most complex and challenging issue of industry whether its for industrial applications or for electric utilities. The new applications are seen in areas of electric utility storage, portable electronics, electric hybrid vehicles and storage of electric energy generated by renewables like wind or solar. The need for efficient storage of energy has seen new technologies which promise productivity, reliability and use of renewables.

Energy storage can balance fluctuations in supply and meet growing demand of electricity For short time requirements they can bring about frequency control and stability and for long time requirements it can bring about management of energy or reserves. Another use of storage is that it can be used to complement primary generation as it can be used to produce energy during off peak periods and the energy produced can be stored as reserved power as shown in graph below [20]

.

- Energy storage can bring about a reduction in capital expenditures or operating costs when used as generation resource in utility sector.
- When used with renewable resources energy storage can increase their usability of wind generated electricity and photovoltaic by making this generation coincident with peak load demand. Energy storage may facilitate inclusion of solar and wind energy into the electric grid.
- Energy storage can increase existing transmission and distribution equipment and eliminate need for expensive T& D additions. Energy storage can be used for reducing load on peaking transmission lines. Therefore some of the T & D benefits are (a) deferral of construction of new transmission lines, transformers, capacitor banks, substations etc (b) stability of transmission line preventing possible system collapse (c) increasing quality of power of the service which would result in protection of equipment of customer.

- Energy storage has been used in stand-alone application for a long time, where it serves as an uninterruptible power supply (UPS) unit. UPS units are basically used for back-up power while energy storage systems today can serve number of online applications.

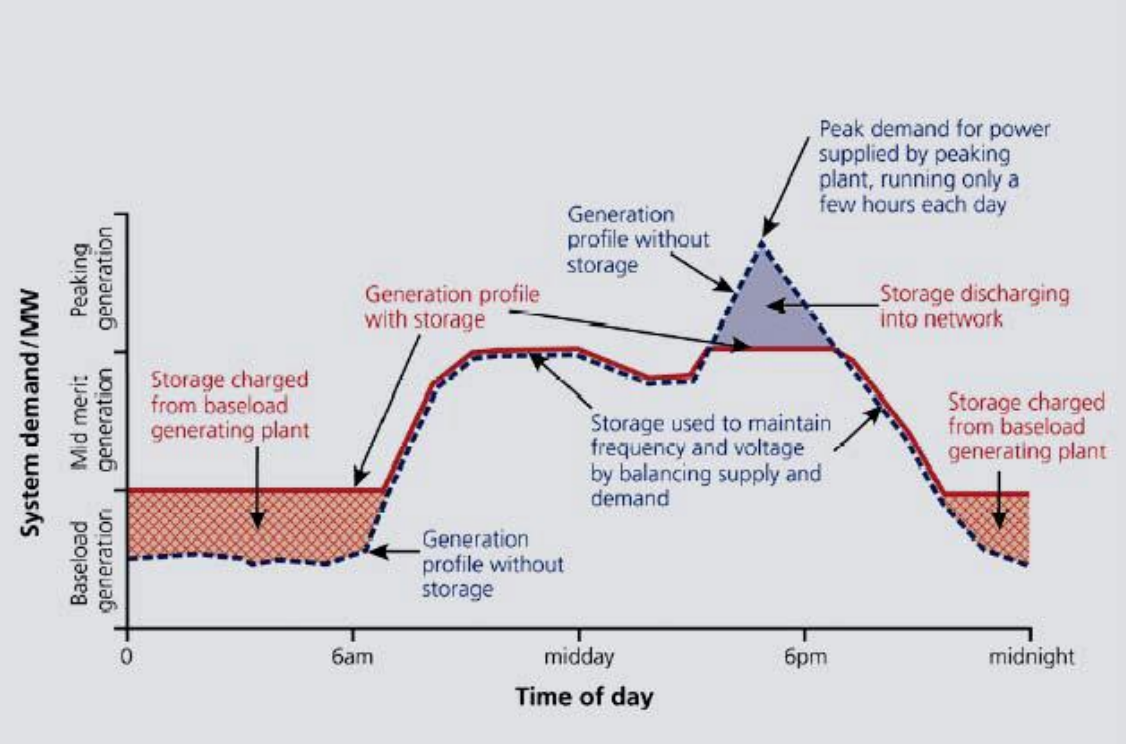


Figure 4. 1 Showing demand of a system can be handled efficiently if storage is integrated into electrical network

The graph explains that demand of system can be handled efficiently if storage is integrated into the electrical network. As shown in fig 4.1 storage is charged from base load generating plant during early hours of day when demand is low. And then as demand rises during day generating plants belonging to mid merit category account for the demand. And during peak demand time if storage is taken into account then demand can be supplied by peaking plant which runs only for few hours of the day decreasing total cost of operating such a storage incorporated system. Thus we can see that when generation profile with storage is taken there is much controlled demand graph as storage takes care of levelling of load and then it is again charged at the days end from base load generating plant.[20]

4.1 ELECTRIC STORAGE TECHNOLOGIES

A number of electric storage technologies have been developed which serve numerous electric applications, including:

- Pumped Hydropower
- Compressed air energy storage (CAES)
- Batteries
- Flywheels
- Superconducting magnetic energy storage (SMES)
- Super capacitors
- Hydrogen Storage

4.1.1 Pumped Hydropower:

Pumped hydro has been around as an electric storage technology since 1929, making it the oldest used technology.

Operation:

Conventional pumped hydroelectric plants consist of two reservoirs, each one is built on two different levels. A body of water at the highest elevation represents stored or potential energy. Electric energy is produced when water is released from the higher reservoir to lower reservoir which cause water to flow through hydraulic turbines that generate electricity of up to 1,000 MW. In the last ten years advanced pumped storage technology has been introduced for increasing efficiency, speed and reliability.

Example:
A seawater pumped hydro plant was first built in Japan in 1999 (Yanbaru, 30 MW). There is over 90 GW of pumped storage in operation world wide, which is about 3 % of global generation capacity.

4.1.2 Compressed Air Energy Storage (CAES):

Compressed air energy storage sysetms is an attractive energy storage technology for large, bulk storage.

Operation:

Compressed air energy storage systems store energy by compressing air within air reservoir using compressor powered by less cost electric energy. During charging plant’s generator operates in reverse as motor for sending compressed air into the reservoir. When plant discharges, it uses compressed air for operating the combustion turbine generator. An important performance parameter for a c system is charging ratio, which is defined as ratio of electrical energy required to charge the system versus electrical energy generated during discharging.

Example:
In 1991, the first U.S. Compressed air energy storage facility was built in McIntosh Alabamaby the Alabama Electric Cooperative and EPRI and has a capacity of 110 MW.

4.1.3 Flywheels:

Operation:

The flywheel storage device consists of a wheel which rotates at very high speed and an integrated electric appliance that can either act as a motor to turn flywheel and store energy, or as a generator for producing on demand electric power using energy stored in fly wheel. The use of magnetic bearings and a vacuum chamber contributes to reducing energy losses. Flywheel are proposed for improving the range, performance and energy efficiency of electric vehicles. The development of utility flyers has been focused on energy quality applications.

Example:
While high-power flywheels are developed and deployed for aerospace and UPS applications there is an effort pioneered by Beacon Power, for optimizing low cost commercial flywheel designs for long duration operation (up to several hours) 2kW / 6kWh systems are in telecom service today.

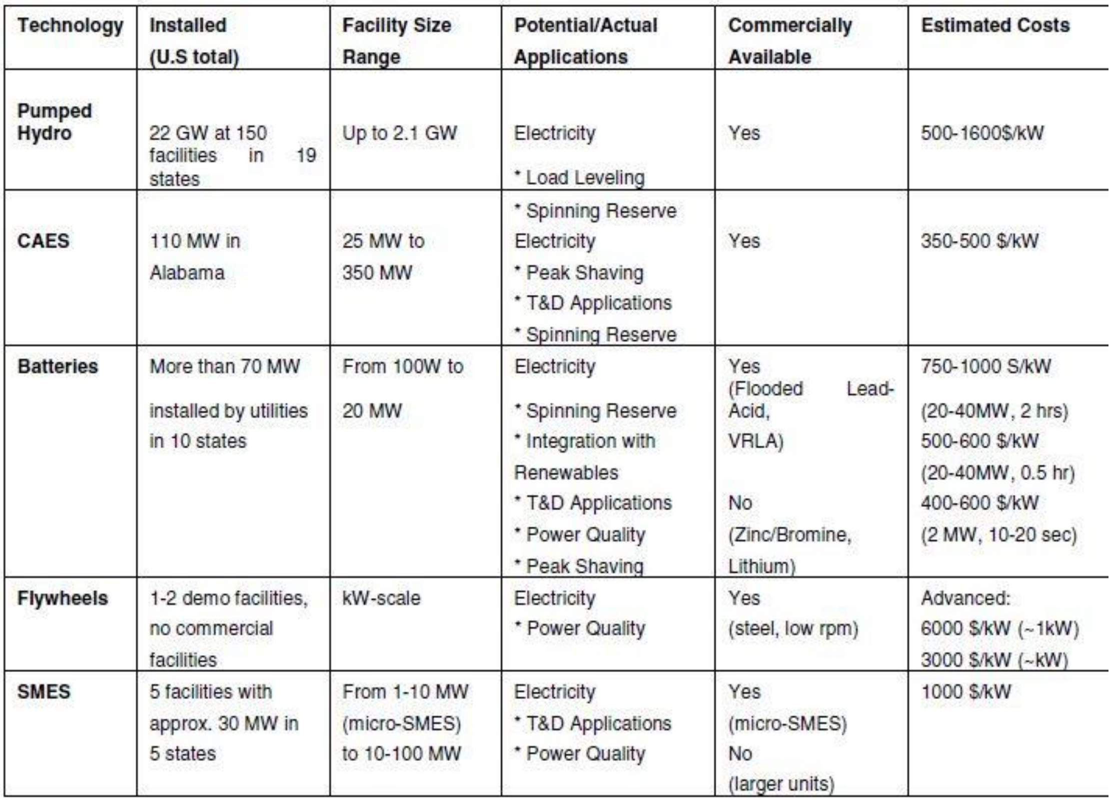
4.1.4 Advanced Electrochemical Capacitors:

Operation:

An electrochemical capacitor has components related to both battery and capacitor. Consequently, cell voltage is limited to few volts. Specifically charge is stored by ions as in a battery. But as in a conventional capacitor there is no chemical reaction takes place in energy delivery. An electrochemical capacitor consists of two oppositely charged electrodes, a separator, electrolyte and current collectors.

Example:

Presently, very small super capacitors in the range of seven to ten watts are widely available commercially for consumer power quality applications and are commonly found in household electrical devices. Development of larger scale capacitors has been focused on electric vehicles. Currently small-scale power quality (<250 kW) is considered to be most promising utility use for advanced capacitors[20]



Technology	Installed (U.S total)	Facility Size Range	Potential/Actual Applications	Commercially Available	Estimated Costs
Pumped Hydro	22 GW at 150 facilities in 19 states	Up to 2.1 GW	Electricity * Load Leveling	Yes	500-1600$/kW
CAES	110 MW in Alabama	25 MW to 350 MW	* Spinning Reserve Electricity * Peak Shaving * T&D Applications * Spinning Reserve	Yes	350-500 $/kW
Batteries	More than 70 MW installed by utilities in 10 states	From 100W to 20 MW	Electricity * Spinning Reserve * Integration with Renewables * T&D Applications * Power Quality * Peak Shaving	Yes (Flooded Lead-Acid, VRLA) No (Zinc/Bromine, Lithium)	750-1000 S/kW (20-40MW, 2 hrs) 500-600 $/kW (20-40MW, 0.5 hr) 400-600 $/kW (2 MW, 10-20 sec)
Flywheels	1-2 demo facilities, no commercial facilities	kW-scale	Electricity * Power Quality	Yes (steel, low rpm)	Advanced: 6000 $/kW (~1kW) 3000 $/kW (~kW)
SMES	5 facilities with approx. 30 MW in 5 states	From 1-10 MW (micro-SMES) to 10-100 MW	Electricity * T&D Applications * Power Quality	Yes (micro-SMES) No (larger units)	1000 $/kW

Table 3 Comparison of various storage technologies

Having discussed all the different types of energy storage we compare the different technologies in the table below

4.2 BATTERY ENERGY STORAGE SYSTEMS

In recent years considerable focus is on the development of electric storage technology which is battery storage which is the main emphasis of this topic.

In a chemical battery, charging causes reactions in electrochemical compounds for storing energy from a generator in a chemical form. Upon demand reverse chemical reactions cause electricity to flow out of battery and back to grid. The first commercially available battery was flooded lead acid battery which was used for fixed, centralized applications. The valve regulated lead acid battery is latest commercially available option. The valve regulated lead acid battery is low maintenance, spill and leak proof, and relatively compact. Zinc/bromine is a newer battery storage technology that has not reached commercial market. Some other lithium based batteries are under development. Batteries are manufactured in a wide variety of capacities which range from less than 100 watts to modular configurations of several megawatts. As a result, batteries can be used for various utility applications in areas of generation, transmission and distribution, and customer service. Batteries currently have widest range of applications as compared to other storage technologies. The type and the number of battery storage applications are constantly expanding mainly in areas of electric and electric hybrid vehicles, electric utility energy storage and storage of electric energy produced by renewable resources such as wind and solar generators.

They are also used for a variety of applications such as power quality assurance, transmission and distribution (T&D) facility deferral, spinning reserve, load leveling, peak shaving, and integration with renewable energy generation plants. Battery systems appear to offer most benefits for utilities when they provide power management support and when responding to instant voltage spikes or sags and outages[20]

Operation

Electric batteries are devices which store electric energy in electrochemical form and deliver direct electricity. Electrode plates typically consisting of chemically reactive materials are placed in electrolyte which makes easy transfer of ions within the battery. The negative electrode , gives up electrons during discharge via the oxidation part of the oxidation reduction electrochemical process. Those electrons flow through electric load connected to battery, giving up energy. Electrons are then transported to the positive electrode for electrochemical reduction. The process is turned around during charging. Battery systems consist of cells which have characteristic operating voltage and maximum current capability, configured in various series/parallel arrays to create desired voltage and current. Typically a battery energy storage system consists of a power conditioning system which process electricity from battery and makes it suitable for alternating current (ac) loads. This includes (a) adjusting current and voltage for maximising power output (b) converting DC power to AC power, (c) matching the converted AC electricity to a utility's AC electrical network, and (d) halting current flow from system into the grid during utility outages for safeguarding utility personnel. The conversion from DC to AC power in the power conditioning system is achieved by inverter, which is a set of electronic switches which change DC voltage from battery to AC voltage in order for serving an AC load.[20]

4.3 Available Types of Battery Storage

Until recently the only battery technology that was economically beneficial is the lead acid battery. Improved valve regulated lead-acid (VRLA) batteries are now emerging in utility systems. Advanced batteries (such as lithium ion and zinc/bromide) are being developed and are at different levels of size and readiness for utility operation. Following are the different kinds of battery available in the market today[20]

4.3.1 Lead-Acid Battery

Lead acid batteries are kind of economic but they have substantial space and maintenance requirements. They also have shorter life, which decreases rapidly if battery is discharged below 30%. This results in reduction of energy density which amounts to increased capital costs. They are commonly installed in uninterruptible power supply systems as well as in distributed power systems and renewables. The largest one installed is a 40 MWh system in Chino California. They have several key limitations: (a) they require relatively frequent maintenance to replace water lost in operation, (b) they are relatively expensive in comparison to conventional options with limited reduction in cost expected, and (c) because they use lead, they are heavy, reducing portability and increasing construction costs. The strengths of flooded lead acid batteries center around their relatively long life span and durability.

4.3.2 Valve Regulated Lead Acid Battery (VRLA)

Valve regulated lead acid batteries use same basic electrochemical technology as flooded lead acid batteries but these batteries are closed with pressure regulating valve so that they are essentially sealed. Furthermore, the acid electrolyte is immobilized. This eliminates the need to add water to the cells for keeping the electrolyte functioning properly or mixing the electrolyte for preventing stratification. The oxygen recombination and the valves of valve regulated lead acid batteries prevent the venting of hydrogen and oxygen gases and the ingress of air into the cells. The battery subsystem may need to be replaced more frequently than with the flooded lead-acid battery increasing levelized cost of system. The major advantages of VRLAs over flooded lead-acid cells are given below a) the dramatic reduction in maintenance that is necessary for keeping the battery in operation, and b) battery cells can be packaged more tightly because of sealed construction and immobilized electrolyte reducing the footprint and weight of the battery. The disadvantages of VRLAs are that they are less robust than flooded lead-acid batteries and are more costly and shorter-lived. VRLAs are recognized as being maintenance free and safe and have become popular for standby power supplies in telecommunications applications and for uninterruptible power supplies in situations where special rooms cannot be set aside for the batteries[20]

A. Lithium ion Battery (Li-Ion)

The main advantages of Li-ion batteries, compared to other advanced batteries are High energy density, high efficiency which is near 100% ,Long cycle life (3,000 cycles @ 80% depth of discharge). The cathode in these batteries is a lithiated metal oxide ($LiCoO2$, $LiMO2$, etc.) and anode is made of graphitic carbon with layer structure. The electrolyte is made up of lithium salts such as $LiPF6$ which is dissolved in organic carbonates. When the battery is charging the Lithium atoms in the cathode become ions and migrate through the electrolyte toward carbon anode where they combine with the external electrons and deposited between carbon layers as lithium atoms. This process is reversed during discharging. While Li ion batteries took over 50% of small portable market in few years , there are still some challenges for making large-scale Li-ion batteries. The main complication is high cost (above $600/kWh due to special packaging and internal overcharge protection circuits. Several companies are working for reducing manufacturing cost of Li-ion batteries for conquering large markets of energy.

B. Vanadium Redox Flow Battery (VRB)

VRB stores energy by employing vanadium redox couples (V2+/V3+ in the negative and V4+/V5+ in the positive halfcells). These are stored in mild sulfuric acid solutions. During the charge/ discharge cycles, H+ ions are exchanged between two electrolyte tanks through hydrogen-ion permeable polymer membrane. The cell voltage is 1.4-1.6 volts. The net efficiency of this battery can be as high as 85%. Like other flow batteries the power and energy ratings of VRB are independent of each other. VRB was pioneered in the Australian University of New South Wales in early 1980's. VRB storages up to 500kW, 10 hrs (5MWh) are installed in Japan by SEI. VRBs have also been applied for power quality applications (3MW, 1.5 sec,SEI).

C. Zinc Bromine Flow Battery (ZnBr)

In each cell of ZnBr battery, two different electrolytes flow past carbon-plastic composite electrodes in two compartments separated by a micro porous polyolefin membrane. During discharge, Zn and Br combine into zinc bromide, generating 1.8 volts across each cell. This will increase the Zn2+ and Brion density in both electrolyte tanks. During charging metallic zinc will be deposited as a thin film on one side of carbon plastic composite electrode. Meanwhile, bromine evolves as a dilute solution on the other side of the membrane, reacting with other agents (organic amines) to make bulky bromine oil that sinks down to the bottom of the electrolytic tank. It is allowed to mix with the rest of the electrolyte during discharging. The net efficiency of this battery is about 75%. The ZnBr battery was developed by Exxon in the early 1970's. Over the years, many multi-kWh ZnBr batteries have been built and tested.

D. Sodium Sulfur Battery (NaS)

A NaS battery consists of liquid (molten) sulfur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. During discharge, as positive Na+ ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2 volts. This process is reversible as charging causes sodium polysulfides to release the positive sodium ions back through the electrolyte to recombine as elemental sodium. The battery is kept at about 300 degrees C to allow this process. NaS battery cells are efficient (about 89%) and have a pulse power capability over six times their continuous rating (for 30 seconds). This attribute enables the NaS battery to be economically used in combined power quality and peak shaving applications. NaS battery technology has been demonstrated at over 30 sites in Japan totaling more than 20 MW with stored energy suitable for 8 hours daily peak shaving. The largest NaS installation is a 6MW, 8h unit for Tokyo Electric Power company.

E. Metal-Air Battery

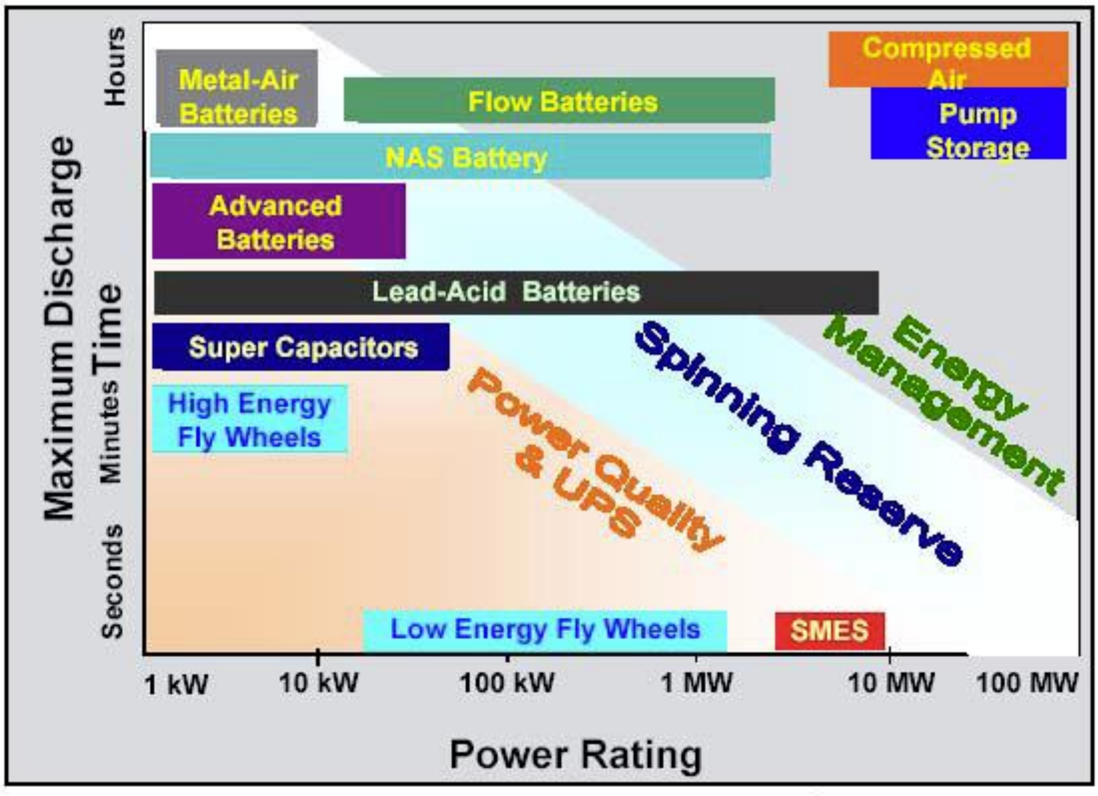
Metal-air batteries are the most compact and potentially least expensive batteries available. They are also environmentally benign. The main drawback however is that electrical recharging of these batteries is very challenging and inefficient. Although many manufacturers offer refuelable units where the consumed metal is mechanically replaced and processed separately not many developers offer an electrically rechargeable battery. Rechargeable metal air batteries that are under development have life of only a few hundred cycles and efficiency of about 50%. The anodes in these batteries are commonly available metals with high energy density like aluminum or zinc that release electrons when oxidized. The cathodes or air electrodes are often made of a porous carbon structure or a metal mesh covered with proper catalysts. The electrolytes are often a good OH- ion conductor such as KOH. The electrolyte may be in liquid form or solid polymer membrane saturated with KOH. While the high energy density and low cost of metal air batteries may make them ideal for many primary battery applications the electrical rechargeability feature of these batteries have to be developed more before they can compete with other rechargeable battery technologies.

F. Polysulfide Bromide Flow Battery (PSB)

Polysulfide Bromide battery (PSB) is regenerative fuel cell technology that provides a reversible electrochemical reaction between two salt solution electrolytes (sodium bromide and sodium polysulfide). PSB electrolytes are brought close together in battery cells where they are separated by polymer membrane that only permits positive sodium ions to go through, producing about 1.5 volts across the membrane. Cells are electrically connected in series and parallel for obtaining the desired voltage and current levels. Net efficiency of this battery is around 75%. This battery works at room temperature. It has been verified in the laboratory and demonstrated at multikW scale in UK. Regenesys Technologies is building a 120 MWh, 15 MW energy storage plant at Innogy's Little Barford Power Station in the UK.

Having talked about different battery storage technologies now we will compare them. From the above graph shown, we have come to the conclusions below:

- For energy storage involving greater capacity systems generally pumped storage and CAES storage systems are used whereas for lower storage applications, High Energy Fly Wheels, Super capacitors and batteries are used.
- For mid capacity applications generally flow batteries, lead-acid batteries and NaS batteries are used.
- CAES and Pumped Hydro are more costly as compared to other technologies but they are serving larger load applications.



Electricity Storage Association

Figure 4. 2 Comparison of different battery storage technologies

4.4 CONSTRUCTION OF POWER PLANT

A battery energy storage system facility is much smaller than Compressed air energy storage or pumped hydro storage facility largely because there are lesser geological requirements, economy of scale factors, and battery energy storage system facilities can be placed near to the load. Site buildings are dependent on type of battery, lead-acid batteries are being housed in an enclosed structure, while flow batteries may use separate external storage tanks, depending on the application. The Power Conditioning System consists of rectifiers and DC-AC inverters needs cooling under high load conditions. The presence of potentially dangerous liquid electrolytes may restrict siting and require additional monitoring and containment equipment. Figure below shows the basic features of large 15 MW, 120 MWh flow battery system, including external electrolyte tanks, and enclosed structure which contains the stack and PCS system. Another project has been set up in Metlakatia, Alaska having a capacity of 1.0 MW 1.4MWh using GNB Absolyte II VRLA using G.E Power Conditioning System. It had a system cost of $2.2M US in 1997 with an expected payoff in 3 years. [20]

Figure 4. 3 Storage Plant

4.5 Capital Equipment

A complete battery energy storage system consists of PCS, battery stacks, electrolyte tanks, pumps and electrolyte materials. The battery components vary widely depending on type, but the PCS and balance of plant are similar, and will be assessed equally for both types. For assessing the facilities equally, a unit lifetime of 15 years is assumed. During this time lead-acid batteries will be requiring replacement. Virgin materials are assumed for the manufacture of all components, except the second set of lead-acid batteries, where 99% secondary lead source is assumed, representing closed loop recycling process.

A substantial advantage of battery energy storage system is the ability to place the unit at or near the point of use. There are no geologic requirements, and since there are no operation-related emissions, batteries can be placed near or in occupied buildings. Battery energy storage system units may be placed at substations for local voltage support, and may also provide additional economic benefits such as transmission and delivery deferral and increased system reliability. This geographical benefit translates to substantially reduced transmissions losses associated with battery energy storage system use as compared with pumped hydro storage or compressed air energy storage. Placement at substations lessens incremental battery energy storage system transmission distance to near zero. While the round trip electrical conversion efficiency for a battery cell can be substantially higher than pumped hydro storage system (in excess of 90% for vanadium) additional loads substantially reduces net efficiency of battery energy storage systems. Flow batteries require fluid pumps, which will decrease overall efficiency by approximately 3%, and active cooling requirements results in additional losses. Unlike pumped hydro storage or compressed air energy storage batteries store and produce direct current, which will require AC-DC converters. These solid state devices have improved in both cost and efficiency but are still more expensive and less efficient than transformers of equivalent power. Typical losses associated with roundtrip AC-AC conversion are at least 4%, and can be significantly more depending on loading conditions. [20]

4.6 CONCLUSIONS

Critical environmental aspects have been identified and quantified for established and emerging battery systems. The environmental impact of a battery system is mainly influenced by application and conditions of use and choice of battery technology should be assessed for each specific application. In applications where batteries are arduous to collect at the end of their life, dissipative losses and material flows of toxic metals are of main concern. Energy requirements during production and usage are important for battery systems where material losses throughout the battery life cycle are less. For portable batteries dissipative losses of toxic metals from landfills and incineration are of environmental concern. Significant parameters affecting energy flows in battery systems are the battery charge discharge efficiency, the type of cycling regime, the battery service life and energy requirements for battery production.

- In cases where focus is on the efficient use of fossil fuels, and electricity generated by solar energy can be thought of as a free energy source, a high energy return factor is important.
- Sensitivity analysis showed that the charge discharge efficiency is the battery parameter with highest influence on the energy return factor and is important for lithium-ion, sodium-sulphur, polysulphide-bromide, zinc bromine and vanadium-redox batteries.

Chapter 5

5. Battery Parameters and BESS Structure

Electrochemical energy storage systems which are also known as batteries, are rechargeable systems used for storing energy and delivering in the form of electricity. These reactions take place inside a basic cell, between two electrodes which is anode and cathode plunged into an electrolyte, when a load is connected to the cell terminals. The reaction involves transfer of electrons from one electrode to other through an external electric circuit. The anode provides electrons to load and it is oxidized during reaction, while cathode accepts electrons and it is reduced in reaction process. The electrolyte provides medium for transferring of electrons between anode and cathode, which are electrically insulated by a separator. Because the voltage of a cell is limited to 1 - 2 V, it is generally necessary to connect in series more cells so that a module is created, and higher voltages can be obtained. As shown in Fig. 5.1, generally a battery is composed by more modules connected in series between them. The parallel connection between modules is not frequently used because it is not possible to know how current is shared between different cells. As shown in Fig. 5.2, a battery can be seen as device with two terminals that operates with DC current. When current enters in positive terminal energy is stored, whereas when current exits from same terminal energy is transferred to external circuit. Generally negative and

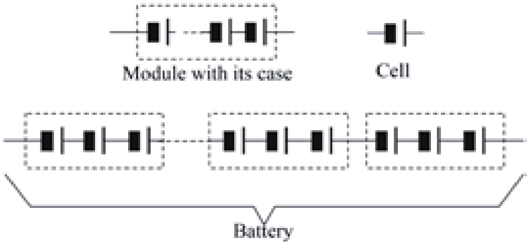


Figure 5. 1 Structure of a module and of a battery

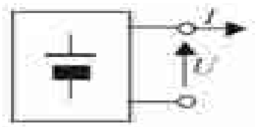


Figure 5. 2 Simplified representation of a battery

positive terminals are respectively anode and cathode, even if theoretically the cathode should be electrode from which current exits. With these assumptions it is possible to state that during battery discharging current exits from cathode, while during charging it exits from anode.[21]

5.1 Battery Types and Principals

Batteries are electrochemical devices that convert chemical energy into electrical energy. Batteries are classified as primary and secondary batteries**.**

Primary batteries

- Convert chemical energy to electrical energy and can’t be recharged.
- Examples include zinc carbon batteries and alkaline batteries.

Secondary batteries

- AKA rechargeable batteries which convert chemical energy to electrical energy and are rechargeable when chemical reaction is reversed using forced electrical energy.
- Examples are lead acid batteries and lithium-ion batteries.

There are several kinds of available secondary battery technologies that can be used for different applications like lead-acid and lithium-ion batteries. Lead-acid batteries use most aged and most mature battery technology available, although lithium-ion batteries are being heavily researched, but their costs are till now not competitive.

Figure 5.3 illustrates the comparison between various battery technologies in terms of volumetric energy density and gravimetric energy density. If we compare battery technologies based on both energy per volume and energy per weight, we can see that lead-acid batteries have less energy density than Li Ion batteries.[22]

Volumetric energy density is amount of energy stored per unit volume of battery. The unit of measurement is Wh/l. We can observe that higher volumetric energy density the smaller the battery size.

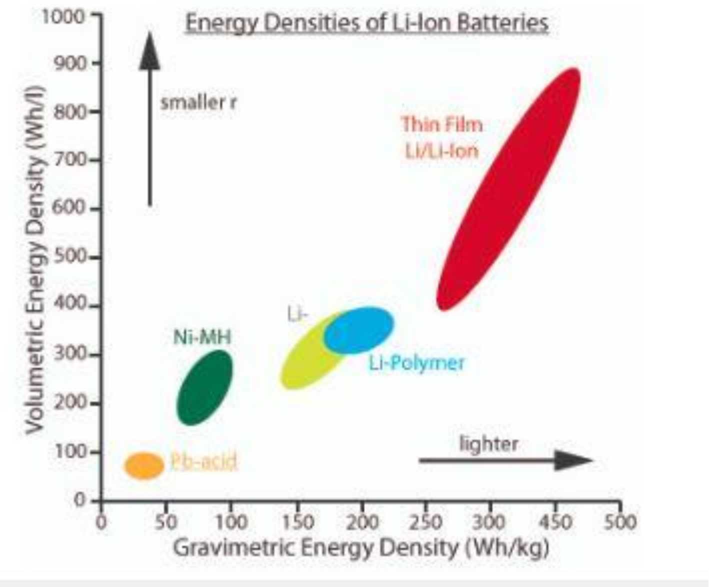


Figure 5. 3 Ragone plot showing the Volumetric energy vs Gravimetric energy of different battery types

Gravimetric energy density is the amount of energy stored per unit mass of battery. The typical unit of measurement is Wh/kg. We can also observe that higher the gravimetric energy density, the lighter the battery. As shown in Figure 5.3, lead acid shows lowest volumetric and gravimetric energy densities among batteries while Li-ion exhibits best combination.

Similar to most batteries lead-acid battery consists of several individual cells, each of which has nominal voltage of around 2 V. Lead acid batteries could have different types of assembly. For example, common lead-acid battery pack voltage is 12 V which means 6 cells are connected in series.

When battery is recharged, flow of electrons is reversed, as external circuit does not have a load, but a source that has higher voltage than battery can enable reverse reaction. In a PV system this source is nothing but PV module or array providing solar power and can charge battery when sun is available. In other words, loads are at mercy of availability of sun. In that case, energy storage option such as batteries can be very useful. As an example, a typical daily solar irradiance profile is shown in Figure 5.4. If we observe the orange curve that represents daily solar irradiance, we see that a significant amount of energy generated during daytime while no energy generated during nighttime. Daily energy demand represented in blue curve shows that energy is needed all day long with higher demands at certain time periods. When we put daily load demand curve on same figure, we can see that a significant energy demand exists when there is no sun.

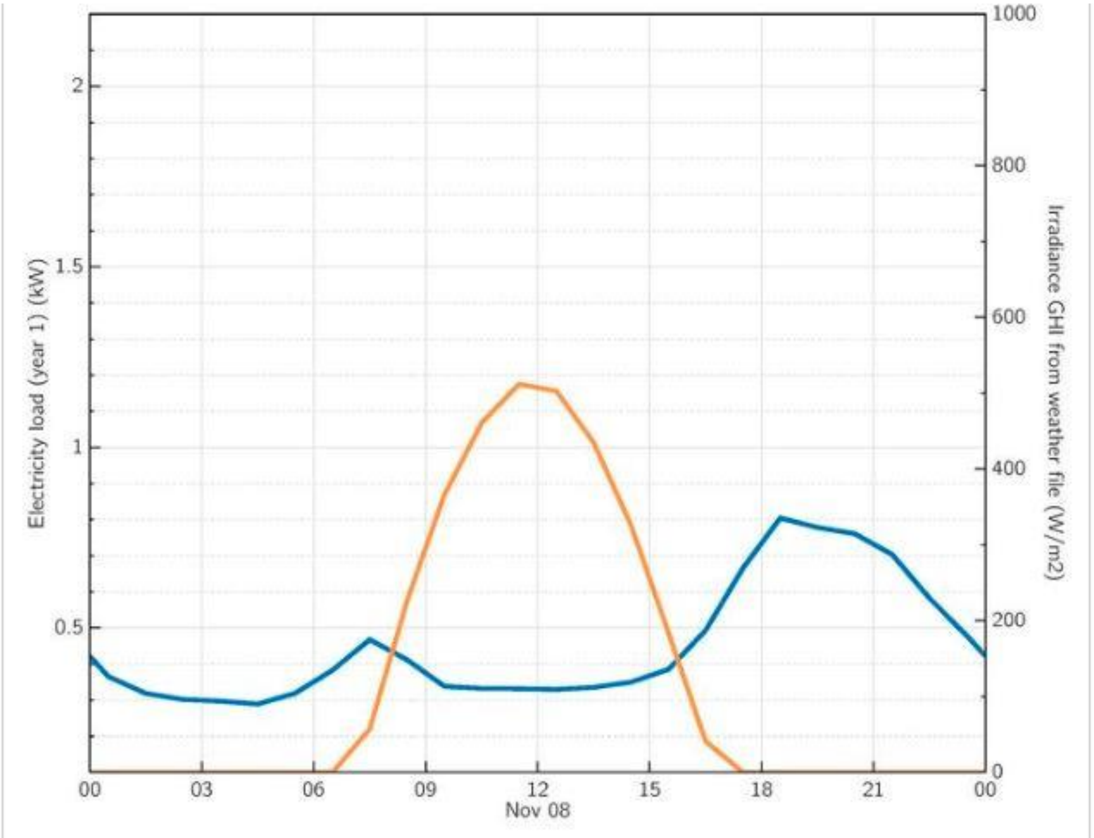


Figure 5. 4 Daily solar irradiance (Orange) and daily load profile (Blue) for State College, PA.[22]

As for a standalone system without storage, even though sun has more than enough power during day, system fails to utilize this excess energy to power loads when sun is not available. With introduction of battery storage, excess energy from sun during day can be stored in battery and then used later to meet load demand when sun is not available. This is represented in highlighted areas A1 and A2 in Figure 3.5, below, for excess solar power and evening load demand, respectively. The perfect match occurs when area A1 equals to area A2 and that can be accomplished by perfectly sizing solar PV system for meeting average daily load energy demand. Furthermore, excess solar energy can be stored using Battery systems.[22]

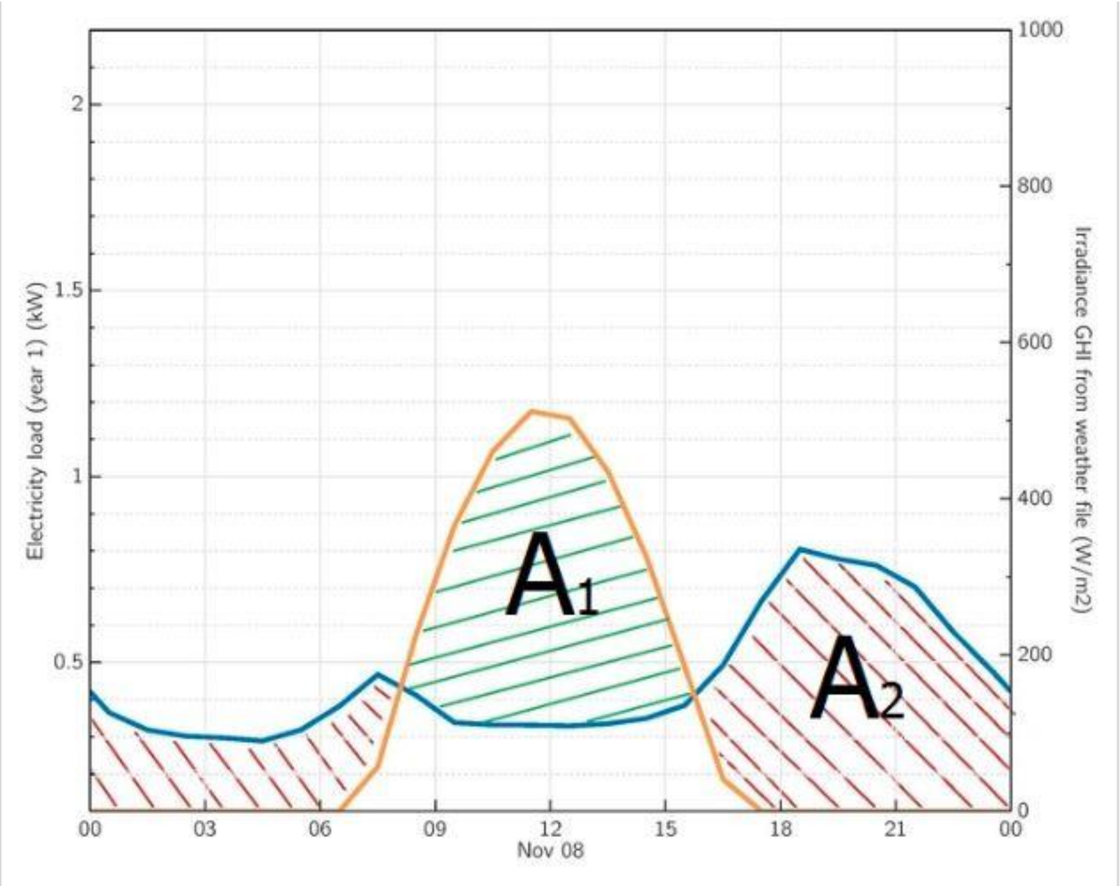


Figure 5. 5 Excess solar energy highlighted (green) and daily load highlighted (red) for State College, PA[22].

5.2 Interpreting Battery Parameters and Specification Sheets

Batteries are final commercial product that is delivered to customers and which requires some data provided from manufacturers for allowing customers to evaluate performance of different battery types in terms of allowable DOD, capacity ratings, and temperature operating ranges

The first important parameters are voltage and capacity ratings of battery. Every battery comes with a certain voltage and capacity rating. As briefly discussed earlier, there are cells inside each battery that form the voltage level, and that battery rated voltage is nominal voltage at which battery is supposed to operate. The capacity refers to amount of charge that battery can deliver at rated voltage, which is directly proportional to amount of electrode material in battery. The unit for measuring battery capacity is ampere hour, denoted as (Ah). The capacity can also be expressed in terms of energy capacity of battery. The energy capacity is rated battery voltage in volts multiplied by battery capacity in amp hours, giving total battery energy capacity in watt hours, In general, it is total amount of energy that device can store[23]

C-rate

Let's move to another important battery parameter, called C-rate. C-rate is **discharge rate** of battery relative to its capacity. The C-rate number is nothing but discharge current, at which battery is being discharged, over nominal battery capacity. It is calculated as following

$$C|=\frac{I_{dis}}{C_{nom}}$$

Where

I_{dis} is discharge current
C_{non} is nominal battery capacity
The discharge rate is sometimes referred to as C/"number" and that number is number of hours it takes battery to be fully discharged. In other words, it is inverse of previous notation and it is calculated as following

$$C/\text{"number"}=\frac{C_{nom}}{C_{dis}}$$

Efficiency

Since there is no energy conversion system that is 100% efficient, the term efficiency represents system capability to transfer energy from input of system to output. Each battery type comes with different efficiency rating as and usually we talk about efficiencies of both charge and discharge combined. Battery efficiency is ratio of total storage system input to total storage system output. For example if 10 kWh is pumped into battery while charging, and you can effectively retrieve only 8 kWh while discharging, then round trip efficiency of storage system is 80%.
Let's discuss another important battery parameter, state of charge or SOC. It is defined as percentage of battery capacity available for discharge, so thus, a 100 Ah rated battery that has been drained by 20 Ah had an SOC of 80%. Another parameter that complements SOC is depth of discharge or DOD, which is percentage of battery capacity that has been discharged. Thus, a 100 Ah battery that has been drained by 20 Ah has a DOD of 20%. In other words, DOD and SOC are complementary to one another.
Now we come to a very important parameter, cycle lifetime of battery. Cycle lifetime is defined as number of charging and discharging cycles after which

battery capacity drops below 80% of nominal value. Usually cycle life is specified as an absolute number. However, to be more precise, cycle life and other battery parameters are affected by changing ambient condition such (temperature in this case). So what is relationship between battery parameters? The cycle life depends heavily on depth of discharge. This can be seen in Figure 5.6 for a typical flooded lead-acid battery. If we look at effective capacity at different depth of discharge (DOD) rates for a lead-acid battery, we see that cycle number diminishes as DOD increases.[23]

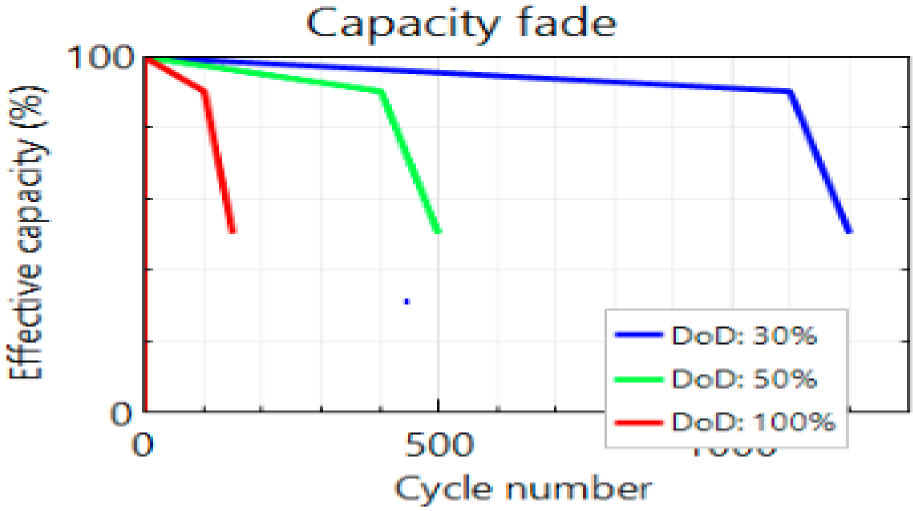


Figure 5. 6 The effective capacity (%) vs cycle number at different DOD rates for a flooded lead-acid battery.

Cycle lifetime also depends on temperature. The battery lasts longer under colder temperatures of operation. Furthermore, we can observe from Figure 5.6 that for a particular temperature, cycle lifetime depends nonlinearly on depth of discharge. The smaller the DOD, higher is the cycle lifetime. However, such a higher cycle life would also mean that those additional cycles you gain can only help you for a smaller depth of discharge. Thus, it could be said that battery will last longer if average DOD could be reduced over its normal operation. Battery overheating should be strictly controlled. Overheating could occur due to overcharging and subsequent overvoltage of lead acid battery.

While battery life is increased at lower temperatures, then there is one more effect that must be considered. The temperature affects battery capacity during regular use too. As seen in Figure 5.7, the lower the temperature, the lower is battery capacity and higher the temperature, the higher is battery capacity.[23]

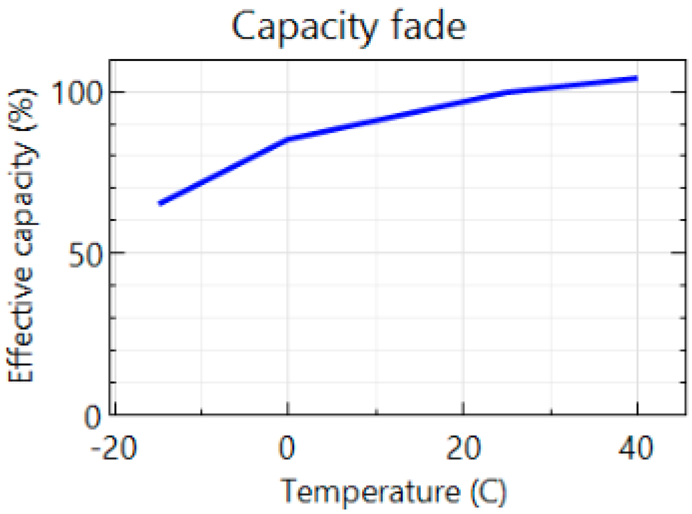


Figure 5. 7 the effective capacity (%) vs temperature for a flooded lead-acid battery

5.3 Battery Aging Factors

It might not seem scientific, but it is even possible to reach an above rated capacity of battery at higher temperatures. However, such high temperatures are severely detrimental for battery health. There are several factors that contributes to aging of any battery. Sulphation is one of major causes of aging and if battery is not fully recharged after being heavily discharged, that causes sulphate crystals to grow, which cannot be completely transformed back into lead or lead oxide. As a result, battery slowly loses mass of active material and therefore discharge capacity will be lower. Corrosion of lead grid at electrode is another common aging factor. This leads to increased grid resistance due to high positive potentials. Moving further, when battery loses moisture, it causes electrolyte to dry out, which occurs at high charging voltages and this results in loss of water. It is referred to as gassing effect and it may battery lifetime of battery. This thing should be taken care of with routine maintenance by addition of distilled water to battery. Researchers have developed maintenance free lead acid batteries for solar systems that exhibit very high lifetimes. However, these are also high-end products which can be more expensive [23]

5.4 Battery Parameters

Battery Basics [24]

• Cell, modules, and packs

Hybrid and electric vehicles have high voltage battery pack that consists of individual modules and cells which are organized in series and parallel. A module consists of several cells generally connected in either series or parallel. A battery pack is then assembled by connecting modules together again either in series or parallel.

• Battery Classifications

Not all batteries are created equal even batteries which are of same Chemistry. The main tradeoff in battery development is between energy and power. Batteries can be either high energy or high power, but they cannot be both. Often manufacturers will classify batteries using these categories. Other common groupings are high durability which means that chemistry has been modified for providing higher battery life at the expense of power and energy.

• C and E rates

In describing batteries, discharge current is often expressed as C-rate for normalizing against battery capacity, which is often very different between batteries. A Crate is a measure of rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that discharge current will discharge entire battery in 1 hour. For a battery with capacity of 100 Amp-hrs, this will equate to discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a C/2 rate would be 50 Amps. Similarly, an E-rate will describe discharging power. A 1E rate is discharge power to discharge the entire battery in 1 hour.

• Secondary and Primary Cells

Batteries for hybrid, plug-in, and electric vehicles are all secondary batteries. A primary battery is one which cannot be recharged. A secondary battery is one which is rechargeable.

- **Battery Condition**

This section describes some of the variables used to describe the present condition of a battery.

- **State of Charge (SOC)**

An expression of present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine change in battery capacity over time.

- **Depth of Discharge (DOD) (%)**

The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD is referred to as a deep discharge.

- **Terminal Voltage (V)**

The voltage between battery terminals with load applied. Terminal voltage varies with SOC and charge/discharge current.

- **Open-circuit voltage (V)**

The voltage between battery terminals with no load applied. The open-circuit voltage depends on battery state of charge which will increase with state of charge.

- **Internal Resistance**

The resistance within battery, generally different for charging and discharging, also dependent on battery state of charge. As internal resistance increases, the efficiency of battery decreases, and thermal stability is also reduced as more of energy of charging is converted into heat.

- **Battery Technical Specifications**

This section explains the specifications you may see on battery technical specification sheets used to describe battery cells, modules, and packs.

- **Nominal Voltage (V)**

The reported or reference voltage of battery, also sometimes thought of as normal voltage of battery.

- **Cut-off Voltage**

The minimum allowable voltage. It is this voltage that generally defines empty state of battery.

- **Capacity or Nominal Capacity (Ah for a specific C-rate)**

The coulometric capacity, total Amp-hours available when battery is discharged at a certain discharge current from 100 percent state of charge to cut-off voltage. Capacity is calculated by multiplying discharge current by discharge time (in hours) and decreases with increasing C-rate.

- **Energy or Nominal Energy (Wh (for a specific C-rate))**

The energy capacity of battery the total Watt hours available when battery is discharging at certain discharge current (specified as a C-rate) from 100 percent state of charge to cut off voltage. Energy is calculated by multiplying discharge power by discharge time. Like capacity, energy decreases with increasing C rate.

- **Cycle Life (number for a specific DOD)**

The number of discharge charge cycles battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of battery is affected by rate and depth of cycles and by other conditions such as temperature and humidity. The higher DOD lower the cycle life.

- **Specific Energy (Wh/kg)**

The nominal battery energy per unit mass, sometimes referred to as gravimetric energy density. Specific energy is a characteristic of battery chemistry and packaging. Along with energy consumption of vehicle, it determines battery weight required to achieve a given electric range.

- **Specific Power (W/kg)**

The maximum available power per unit mass. Specific power is a characteristic of battery chemistry and packaging. It determines battery weight required to achieve a given performance target.

- **Energy Density (Wh/L)**

The nominal battery energy per unit volume, sometimes referred to as volumetric energy density. Specific energy is a characteristic of battery chemistry and packaging. Along with energy consumption of vehicle, it determines battery size required to achieve a given electric range.

- **Power Density (W/L)**

The maximum available power per unit volume. Specific power is a characteristic of battery chemistry and packaging. It determines battery size required to achieve a given performance target.

- **Maximum Continuous Discharge Current**

The maximum current at which battery can be discharged continuously. This limit is usually defined by battery manufacturer in order to prevent excessive discharge rates that would damage battery or reduce its capacity. Along with maximum continuous power of motor, this defines acceleration of vehicle and top sustainable speed.

- **Maximum 30-sec Discharge Pulse Current**

The maximum current at which battery can be discharged for pulses of up to 30 seconds. This limit is usually defined by battery manufacturer to prevent excessive discharge rates that would damage battery or reduce its capacity. Along with peak power of electric motor, this defines acceleration performance (0-60 mph time) of vehicle.

- **Charge Voltage**

The voltage that battery is charged to when charged to full capacity. Charging schemes are generally consisting of a constant current charging until battery voltage reaching charge voltage, then constant voltage charging, allowing charge current to taper until it is very small.

- **Float Voltage**

The voltage at which battery is maintained after being charged to 100 percent SOC to maintaining that capacity by compensating for self-discharge of battery.

- **Charge Current**

The ideal current at which the battery is initially charged (to roughly 70 percent SOC) under constant charging scheme before transitioning into constant voltage charging.

- **Internal Resistance**

The resistance within battery, generally different for charging and discharging.[24]

5.5 Battery Energy Storage Systems and Battery Management Systems

Because of limits related to areas of installation, capacity, response times and costs, storage technologies such as PHS, CAES, SMES and flywheels are not suitable for all grid applications. On the contrary, electrochemical energy storage devices offer flexibility in capacity, response and location required for satisfying a wider range of functions than many other types of storage. While battery energy storage systems currently account for only a small portion of energy storage within grid, they are expected to grow thanks to their versatility, efficiency and increasing performances.[21]

Battery energy storage applications in power systems can be classified into following types

- Instantaneous, as rapid spinning reserves, primary frequency regulation and power quality. These applications will require batteries with high power densities and battery energy storages which can instantly deliver large power for short times

- Short term, as secondary and tertiary frequency regulation, smoothing of power output from wind and solar plants, black start capability and voltage regulation. These applications will require batteries with modest power and energy densities and battery energy storage system must be able to store energy for a longer time

- Midterm, as load balancing and peak shaving. These applications will require high energy density batteries for long term, which will avoid new generation and transmission construction costs. These applications will require very high energy density batteries.

- Instantaneous, short and midterm applications seem to be very economically feasible, differently from long term one which will require a detailed analysis.

5.6 STRUCTURE OF BESS

A typical battery energy storage system structure for grid applications consist of DC system, a Power Conversion System (PCS), a Battery Management System, a System Supervisory Control and grid connection.

In DC system, individual cells are assembled into batteries which in turn are put together for creating systems of sufficient capacity for supporting application requirements. Batteries are connected in series and parallel configuration for obtaining a high voltage bus which is connected to PCS. The PCS is four-quadrant DC/AC converter (inverter) which connects the DC system to grid through a circuit breaker and a transformer (only in MV networks). It allows to have a bidirectional power flow between the network and batteries during charging and discharging phases. The transformer is needed to decrease network voltage to suitable values for power converter. The battery management system is necessary to monitor and guarantee safety and optimal operation of each battery pack, while SSC is needed for controlling full system. As shown in fig. 6.1, a battery energy storage system can consist of several independent DC subsystems, PCSs, and transformers which together constitute many power blocks. DC systems can be identical, or they can include hybrid battery units of different sizes or types. The operation of individual power blocks is coordinated by a battery management system, while management of all power blocks is controlled by the SSC.[21]

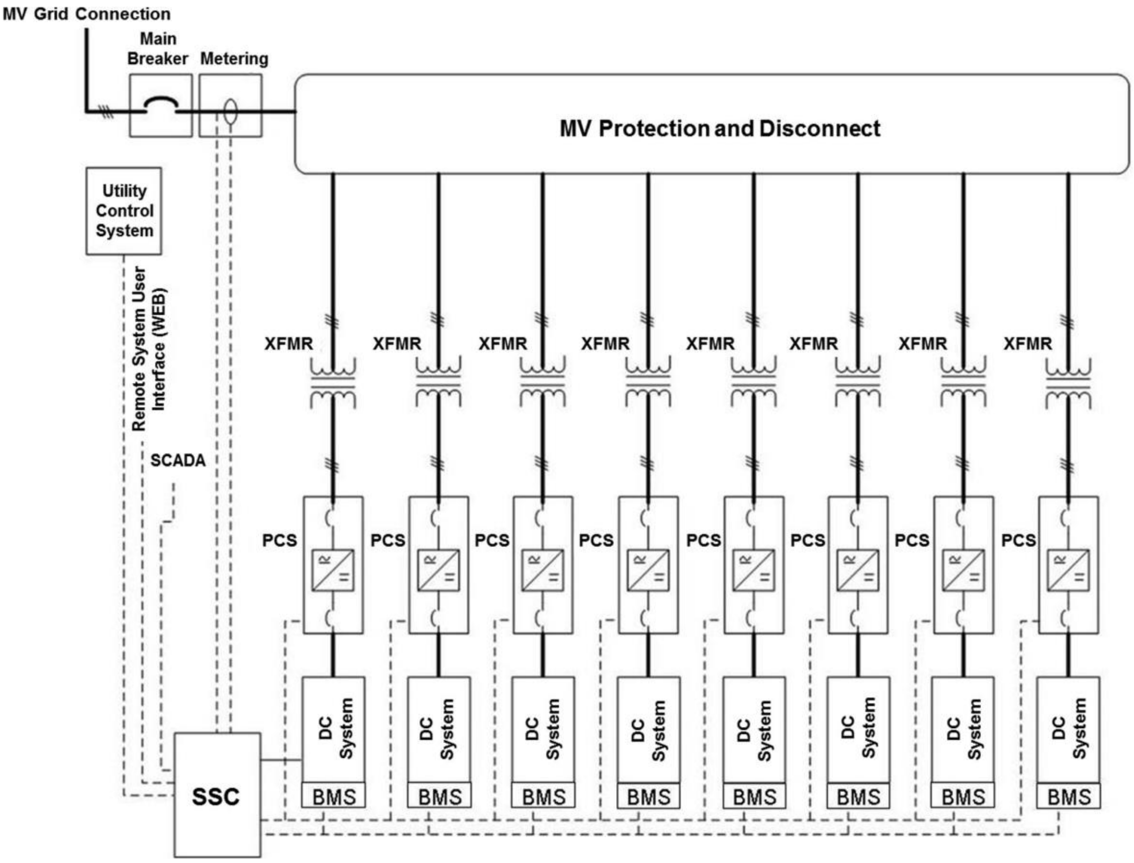


Figure 5. 8 Structure of BESS

5.7 Battery Management and Diagnostic System

The fault resilience structure of smart grid, in cooperation with renewable energy, depend on storage facilities to provide customers with an uninterrupted service [35]. The deployment of battery-arrays increases consistently as they can restore system voltage and frequency after a power failure [36] - [37] [38]. Furthermore, the promotion of the smart grid concept with the deployment of the distributed renewable energy generation in modern-day grid architectures will facilitate the deployment of the new (ESS) energy storage systems [39]. Lead-acid based batteries are currently extensively served for the storage of grid electric energy due to their”resourcefulness and cost effectiveness but are subject to several factors that result in poor performance without an adequate management system. They are. As lead acid ages, resistance in series begins to get increase as it becomes more vulnerable to many other factors those affects its durability

[40]. The number of charge and discharge cycles, the effect of temperature and the type or level of discharge current exposed are the most notable [41]. These factors cause electrochemical changes within the battery, reducing usable capacity and making charging inefficient. Many studies on (BMS) battery management system architectures have been published in the literature, but most of the time we have only considered case studies with smaller configurations.

[42] The study presents the management system that stresses the significance of introducing battery's (SOH) state of health in the measurement of network applications. Focusing on the discharge rate range and (DOD) depth of discharge of two lead-acid batteries configured in parallel, the life consumption rate is modelled separately for each of the two batteries. Battery stack configurations are optimized to produce a total (SOC) state of charge using current integration methods or simplified voltage measurements [43] in some cases. In [44], an advanced method to represent a Li-ion SOC Utility Array is assessed in grid connection mode and on microgrid island mode. There are three types of operation have been recommended to measure battery SOC arrays indirectly. The system could validate the effectiveness of its control strategy but could not access individual battery modules [44].

Although it was difficult to access individual modules in a serial configuration, the search was done with SOC balancing for parallel connections. In [45], the supervisory power management algorithm was designed to regulate the charge flow to a three-battery bank. It uses constant current to charge each battery individually for the load. Profile. and of the individual. SOC. measurements. The balancing of the array was easily performed by switching and the charge current cannot be adjusted. Various methods of cell equalization in lithium-ion batteries include flying capacitor charging methods and methods for sharing single transformer and multi-transformer schemes are described in [46]. The BMS proposed in [47] uses a charge equalization -technique like transformer based techniques. The technology makes use of a topology developed exclusively for lithium-ion cells. In this topology, the charge voltage is pulsed through the control signal and passes through the transformer. The current from the cell stack induces a current in each winding of the secondary coil and the secondary coil with the smallest reactor (connected to each battery) has the largest current induced. This guarantees a charge current proportionate to the SOC of each cell.

[48] provides a complete overhaul of existing Battery Management system BMS for network level applications. A national model of the implementation of BMS on battery powered ESS is presented. The under-study model identifies many objectives, such as peak source power demand, cell balancing and thermal control, but does not yet can extract from parallel configuration or individual cells from a stack. In this case, SoH and SoC methods are identified only for lithium-ion and Redox flow batteries. Lead acid has been identified as a means of technical maturity and low cost but has not been used in this study. [49] and [50] show two simplified battery management schemes. The latter stressed the importance of not ignoring differences in internal battery resistance during charging.

In [51] an energy management system was developed to extend efficiency and the lifetime of ESS. The Peukert Lifetime Energy Throughput model improves the efficiency of ESS. The optimization algorithm is presented in [52] and a discrete time model of an electrochemical storage device was developed to implement the ESS system but was limited to a combination of wind turbine and nickel-nickel chloride battery system.

The Pulse charging introduces innovative control over the battery-charging behaviour, increase the charge rate, and providing the battery's charge balance [53]. [54] proposes a battery equalization method that uses positive/negative pulse charging to balance the cells of an electric vehicle. To regulate the charging current the Pulse charging method is not the only method. If the battery is damaged, a charge current pulse can be used to identify or improve the battery's SoH by neutralizing the electrolyte inside [55] - [56]- [57]. Introducing this function into each stacked battery provides not only a controlled current charge, but also a tool to recover the battery in case of failure.

An advanced BMS is developed to monitor individual battery in a series configuration and identify the independent voltage of each battery, current contribution and SoC level. Proven methods to balance SoC and diagnose SoH. BMS can apply the battery to the charging and diagnostic bus while completely disconnecting the battery from the system and maintaining the load connection. The system bypasses the decoupled battery to ensure continuous power supply to the entire stack and normal operation. The proposed system offers the ability to charge multiple batteries simultaneously at different charge levels after applying pulsed charge current at different duty cycles and frequencies. Voltage fluctuations due to battery coupling / decoupling are mitigated by the DC-DC step-up converter to maintain bus voltage and prevent the BMS from propagating to grid side problems.

This document is motivated by the need to control each unit individually and independently in the battery bank for operation efficiently. There is another aim is to prevent the failure of a single battery from affecting the operation of the entire battery bank. The system can be made suitable for applications ranging from microgrid to scales, tested to heavy pulse loads and suitable for on-board power systems. The proposed topology has several features that can be summarized below.

You can control individual units in a series or parallel battery array. That each unit can be controlled, monitored, and processed separately from the other units. Some units can be charged in a battery array while remaining units continue to handle the load. Using the pulse charging profile with varying frequency and duty cycle, BMS can alter the charge energy for each unit. Therefore, SoC balancing can be achieved without the requirement of power electronics converters. The unit can be electrically disconnected, and the operator can perform any maintenance necessary or replacement without affecting the performance of the entire array. With proper designing, choice of relays, and other components, the system can be extended to control range of Battery energy storage.This system is a low-cost to design and implement.

5.7.1 Background and Theory

The system comprises of battery bank array connections divided into a scalable number of stacks, each stack containing Nbatt batteries.There is a common misunderstanding is that each battery in the array will be introducing the same aging and power supply distribution if they have the same working days. Without measuring the current and voltage profile of each battery, there is no such guaranteed way to determine SoC.

Let us consider 4-12 V battery connected to achieve [48 VDC (VDC)] with a capacity of 110 Ah. It turns out that when you charge the bank, only a single battery reaches a true full charge level and the rest of the batteries are prematurely cut to about 90% of the SoC level. Equation (1) represents the average function to get the SoC for the entire array.

$$SoC_{tot} = \frac{1}{N_{batt}} \sum_{i=1}^{N_{batt}} SoC_i \tag{5.1}$$

Here, SoC_i of batteries connected in series. A true SoC_i in this configuration can show a 5% reduction in individual battery charge levels until corrected. The 5% calculation error on SoC seems minimal, except when comparing 5.5 Ah of power to the array capacity that was left unused. Also, if batteries 2 to 4 are charged continuously to maintain 90% SoC, the battery cannot be fully charged at the end [58].

This change in performance is caused by the difference in SoH for each battery. Impurities in different materials, small offsets in the production process and thermal stresses can lead to different results. These metrics are further complicated by the introduction of pulse loads or charge currents. To model the displacement mathematically, we illustrate the operation of a lead-acid battery. The lead and lead dioxide electrodes are inserted into the sulfuric acid and an aqueous solution of electrolyte to facilitate the storage and removal of electrons. The chemical equation is described in eq (2),

$$Pb + PbO_2 + 2H_2SO_4 + 2e^- \leftrightarrow 2PbSO_4 + 2H_2O + 2e^- \tag{5.2}$$

A fully charged battery comprises of an electrolyte, which consists of about 60% sulphuric acid, and a discharged battery consists mainly of water. The discharge accelerates the removal of electrons from the sulphuric acid and forms the solid sulphate used in the plate. The charging process removes solid sulphates in the electrolyte but is not 100% efficient and some sulphates remains. In number of cycles the sulphate mass increases. This phenomenon, called sulphating, is one of the most important factors for the degradation of SoH and the loss of capacity.

Several articles have been written in research to find an electrochemical method that significantly degrades sulphate recovery on battery plates [55] [56] [57]. When the solid sulphate decomposes, it can be returned to the electrolyte. The pulse of the current is like the repeated pushing of the sulphate layer with the pulse frequency. The resulting stress on the material can lead to decomposition of the sulphate layer.

The investigation of cell performance with a variable SoH relative to a current pulse requires a continuation of a typically corresponding cell equivalent circuit for impedance variations at the electrode-electrolyte interface. Electrochemical impedance spectroscopy (EIS) presents a kinetics for solving three new factors that regulate the performance of lead acid cells [59]. In Figure 5.9 a new modified RC circuit is connected in series with the electrolyte resistance (Re), (Cs) and (Rs) illustrate resistive elements and Faradic capacitive in parallel with non-faradic capacitance values (Cnf) and explain the decreased absorption and extracting of electrons from the electrode in the electrolyte. The transfer function of the impedance, is

$$\mathrm{Z(s)} = \frac{R_S C_S + 1}{R_S C_{nf} C_S s^2 + \left(C_{nf} + C_S\right) s} + R_e \qquad (5.3)$$

The voltage response V(t) on the battery cell Vc,

$$V(t) = V_c - \left[\frac{C_S e^{-\frac{t\left(C_S + C_{nf}\right)}{C_S C_{nf} R_S}}}{C_{nf}\left(C_S + C_{nf}\right)} + \frac{1}{C_S + C_{nf}} + \right] i(t) \qquad (5.4)$$

Whereas Cs and Cnf is called the model capacitive response on the battery during and after a pulse, the voltage drop following a pulse train is controlled by Rs, and Re controls the steepness of the voltage drop ΔV in each pulse.

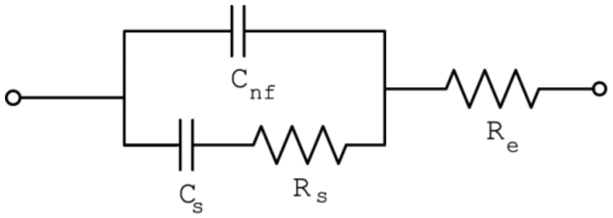


Figure 5. 9 Equivalent circuit of a lead acid cell derived from EIS.

The comparison can be seen in Figure 10. The solid continuous and dashed lines show the impulse load response for normal healthy and damaged batteries. Small modifications have been made to Cs and Cnf to show the post-impulse response and reduced recovery time in a damaged battery, with Ds and Rs showing the most important features. The voltage drops ΔVeh after pulsing a typical battery. Increases. Significantly. as the. battery ages, where the voltage drop of the damaged battery is much more acute ΔVed. In addition, the effect of the pulse train on a healthy Vsh' battery has a much more delicate voltage gradient than a damaged Vsd' battery. The strong descending trend is direct related to the impact of the SoC. Without the accurate measuring of each battery, these properties cannot be determined.

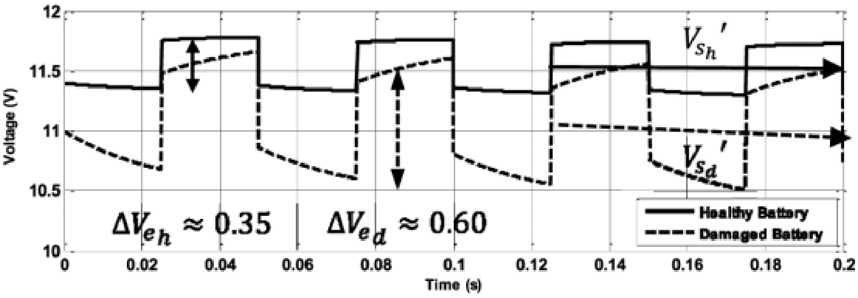


Figure 5. 10 Pulsed load response on healthy and damaged battery.

5.8 BMS Design and Implementation

This section describes the BMS design philosophy and how it works. It is worth remembering that this design. is generic and that the BMS developed. can be connected to individual batteries or an entire battery pack in large power applications. In this context, the design process and implementation are described for a 12 V battery, but it is necessary to consider that the system can be adapted to a utility-scale with due consideration of current and voltage values.

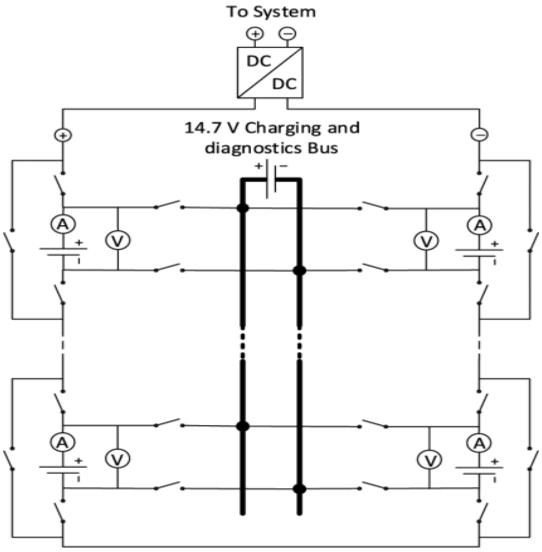


Figure 5. 11 Battery management unit array for Nbatt .

Figure 11 shows the overall topology for connecting the BMS unit to the Nbatt battery. The 14.7V battery charge and diagnostic bus are connected.

in parallel to all BMS connections. The battery bank terminals are connected to a DC-DC step-up converter used to stabilize the DC side voltage. In the setup considered the converter is configured unidirectional as the separate bus is used for battery charging.

A. <u>BMS Design</u>

A diagram of a single BMS unit is shown in Figure 12. A battery is positioned between the relay network to provide complete coupling and decoupling.

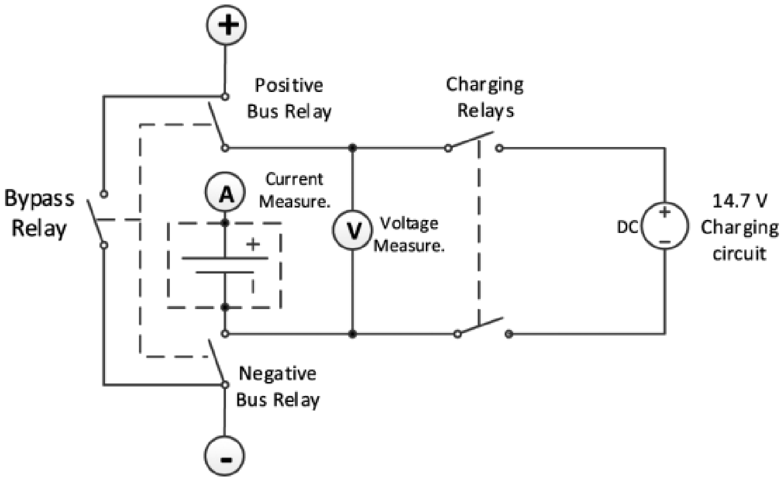


Figure 5. 12 Individual BMS unit schematic.

1. DC-bus connection:

To realize complete isolation, connect the positive and negative terminals of the battery to the DC bus by two normally closed relays. The relay normally open (NO) connects the positive terminal of the BMS to the negative side to provide an alternate path to maintain battery continuity while the battery bypass circuit decouples from the array. An interlock between the three relays is provided to prevent simultaneous connections. This ensures that the battery is completely isolated during maintenance or connection of the charging circuit.

2. Current measurement:

Current measurements are taken directly at the battery terminals. The LA 25-NP current transducer is mounted in series in the current path from the positive terminal [60]. The LA 25-NP can measure currents up to 36 A. The battery used for the test has a nominal capacity of 110 Ah, so the nominal current C20 is rated at 5.5 A. Up to 7 times the constant current (C3 rate) can be passed through this transducer for an accurate measurement.

3. Voltage measurement:

The data acquisition equipment, the voltage range of ± 10 V DC must be observed due to the limitations. This had to be decreased with the LV25-P voltage transducer as the stack voltage would be between 10.5 and 14.7 V DC. A simple voltage divider circuit cannot be used because it does not have the required isolation. Compared to maintaining the universal BMS for use with other battery chemicals and cell configurations, we decided to set a maximum voltage to handle lithium-ion series battery configurations of up to 8 cells (≤29.6 VDC).

4. Charging bus connection and diagnostics:

To connect / disconnect the DC bus The BMS is installed to the bus with two switches. Figure 11 shows the voltage of the bus at a charging voltage of a lead-acid battery (14.7VDC), but with the versatility to operate over a very wide range of voltages to accommodate different types of batteries. This is one of the major flexibilities added by the proposed system. Two NO relays provide complete connection or isolation from this bus, depending on the operating scenario. This bus can provide charging current to multiple batteries in parallel or can isolate a single battery capable of diagnostics. A battery diagnostic signal can be sent directly to the battery to evaluate battery performance or individual SoH. This handy feature allows the operator to initiate a test procedure and identify batteries that are constantly discharging while the system is running. These relays work together with other relays to prevent simultaneous charging or discharging of the battery.

B. The Operation

There are three modes of operation.

1. **Ideal Operation:** In this operation, all relays are open except the bypass relays. In this case, the battery terminals have no voltage. The entire energy storage can continue to operate. This mode is useful for maintenance.

2. **Charging Operation:** The negative and positive bus relays are open, and the charging and bypass relays are closed. The battery is connected to the charging and diagnostic bus and to be charged. The operator can use constant charging or pulse charging.

3. **Load connection Operation:** In this mode, the positive and negative bus relays are closed and the bypass and charging relays are open. The battery is connected to the Stack and supply power to the load.

5.9 BMS and SSC

Each battery energy storage system must be controlled properly for ensuring efficient and safe functioning while it is meeting requirements of different grid applications. Even under normal operation battery packs of Battery energy storage system can have degradation that can be accelerated during cycling by extreme charging/discharging patterns, high temperatures (both ambient and operating), overcharging, or undercharging. A basic BMS controls battery packs only for meeting power demand, while smarter BMS can reduce causes of degradation and improve performances of system.

The SSC of the battery energy storage system is the interface between the grid and the battery management systems. The information about battery packs are conveyed from battery management system to the SSC. When the grid require power to be supplied from batteries, SSC chooses optimal protocol for release of charge considering both current state of batteries and grid request. This SSC protocol asks power from individual packs for meeting final power demand. During certain periods, required power profiles of batteries are more flexible and battery energy storage systems can have more control over charging pattern. For example, in a peak shaving application, discharge power is imposed but charge power can be chosen by BMS for optimizing charging profiles. These are communicated to SSC which can control power input from grid.

The monitoring action of battery management system is performed by a hierarchical hardware structure in which data processors are situated at multiple levels of dc system. At lowest level, a processor is assigned for monitoring and balancing individual cells in a single battery module. Another processor is assigned to monitor and manage data and activities of lower level processors. The top-level processor of battery management system communicates with SSC which handles demands from both DC system and grid. By distributing intelligence to lower level monitoring systems only necessary information are sent to main controller lowering information traffic [21]

The combination of BMS and SSC is necessary to help the battery energy storage system in:

- maintaining good safety level reducing temperature gradients and keeping voltage and current within limits.
- protecting cells from internal degradation and ageing
- providing optimal charging patterns
- performing charge balance between cells
- controlling the electrolyte flow rate in accordance with power demand (for flow batteries).

All these aspects can be controlled by acting on currents, ambient temperature, and electrolyte flow (only for flow batteries). Because internal states of cells are not accessible to control systems, battery management system must be able to accurately estimate state of health, state of charge and consequently time remaining in function of load. A battery management system can improve battery performance and prolong its life only if it has access to reliable information about these values.

One method for determining SOC consists in tracking flow of charge into and out of battery (Coulomb counting). Because of inaccuracies of current measures, variable losses inside battery and undesired reactions that occurs in system, estimation of SOC based on this algorithm is not reliable if it does not consider all physical realities of battery. Another method to estimate SOC consists in measure of open circuit voltage at terminals of battery. As battery SOC decreases, terminal voltage also reduces, indicating how much charge remains. This method is more accurate for some chemistries than for others, but in all cases, complex non-linear models need to be created. Some batteries, as A123 nano phosphate, have very flat voltage characteristic in function of SOC and for this reason it is not possible to estimate remaining charge through this method.

The most common method for estimating SOH is measuring cell internal equivalent dc resistance, which generally rises with capacity loss. However, some battery chemistries as A123 nano phosphate do not exhibit trends in resistance that reliably indicate state of health. Alternatively, battery management system can determine battery state of health by doing complete charging and discharging cycle under controlled conditions and measuring of effective capacity. This method provides accurate estimation of state of health for any battery type. However, removing a system from service to test its capacity reduces its overall availability to perform functions on grid. When full charges and discharges are not allowed, the need for detailed and accurate models becomes very important for providing an estimation of existing capacity [21]

5.10 Switch-mode DC/AC converters

The switch mode DC/AC converters are devices used for controlling exchange of power between storage system and grid. Considering simplified equivalent circuit in Fig 5.9 and its AC output waveforms in Fig 5.10, it is observed that power flow, which is product between voltage and current, is reversible. When instantaneous power is positive, it goes from DC to AC side and converter works as an inverter when instantaneous power is negative, it goes from AC to DC side and device works as rectifier. This shows that switch mode DC/AC converters can operate in all four quadrants in a period (positive and negative currents and voltages). However, most of the time power flow is from DC to AC side and for this reason converter is generally called inverter. Inverters can be classified as Voltage Source Inverter, when the DC source is a voltage, and Current Source Inverter, when DC source is a current. Because Current Source Inverter have limited applications, these will not be discussed.[21]

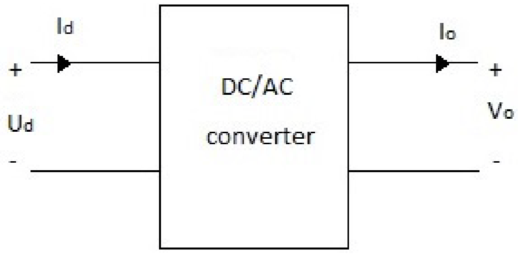


Figure 5. 13 Basic model of the converter

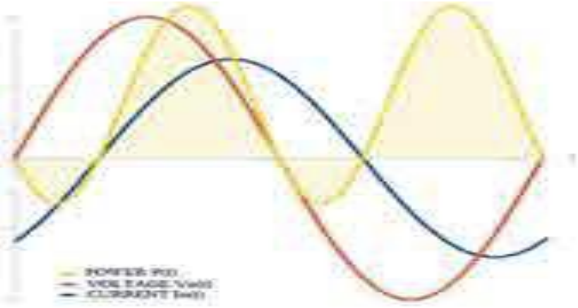


Figure 5. 14 AC output waveforms

Voltage Source Inverters can be divided into following three categories

- Pulse width modulated inverters. The DC voltage source is constant and generally it is obtained by diode rectifier or battery. The inverter must regulate magnitude and frequency of AC output voltages using pulse width modulation technique used for controlling inverter switches. Between all different schemes which are used to realize this modulation technique, sinusoidal pulse width modulation is the most exploited

- Square wave inverters. The inverter must control only frequency of output AC voltage because magnitude is controlled by acting on input DC voltage thanks to a phase-controlled rectifier. The AC voltage is characterized by a square wave

- Single phase inverters with voltage cancellation. It combines characteristics of two previous inverters, and it can only be used in a single-phase configuration.

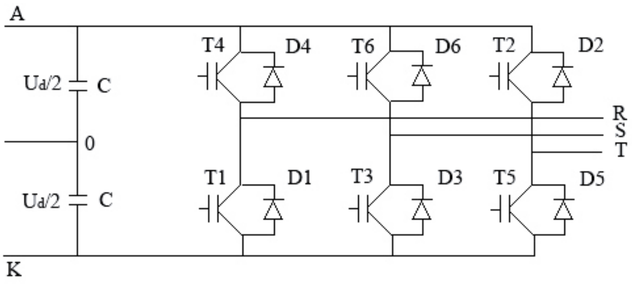


Figure 5. 15 Electrical scheme of three phase inverter

It is possible to control frequency and magnitude of AC voltage without pulse width modulation and with a constant source. Square wave modulation and Pulse width modulation will be analyzed in detail by considering a two-level inverter in three phase configurations. The scheme in Fig. 5.11 shows that converter is composed of six controllable switches and six diodes connected in antiparallel with each of them, so that current can circulate in both directions. The flow of current is free through diodes and it is controlled through switches. Each couple of opposite switches cyclically connects three terminals of AC side which are R, S, T and to the positive or negative poles which are A, K of DC side. In the scheme there are two capacitors for understanding how the inverter works, although only one is used for reducing ripple effects in DC voltage.[21]

5.10.1 Sinusoidal Pulse Width Modulation

The term Sinusoidal pulse width modulation is a technique of pulse width modulation used in inverters. An inverter generates an output of AC voltage from an input of DC with help of switching circuits to reproduce a sine wave by generating one or more square pulses of voltage per half cycle. If size of pulses is adjusted, output is said to be pulse width modulated. With this modulation, some pulses are produced per half cycle.

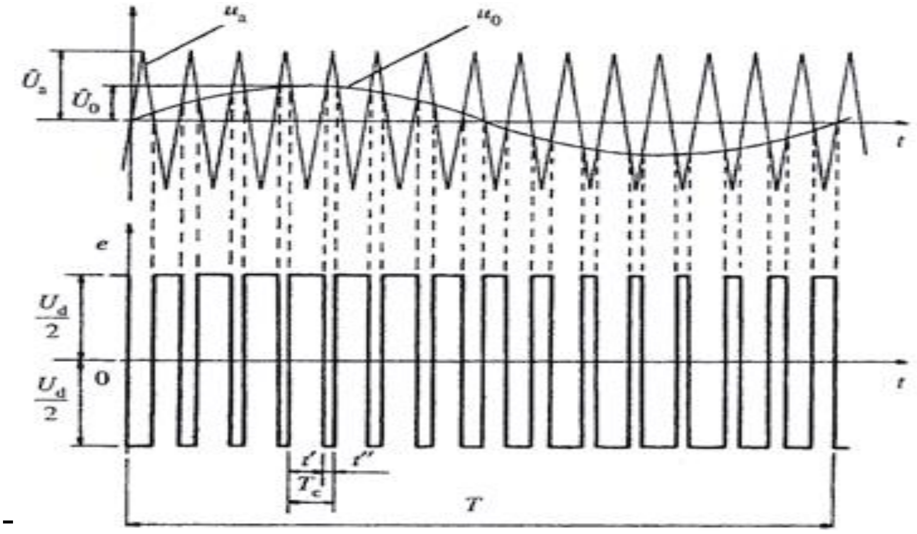


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Figure 5. 16 illustration of the sinusoidal PWM

The pulses close to ends of the half cycle are constantly narrower than pulses close to center of the half cycle such that the pulse widths are comparative to the equivalent amplitude of a sine wave at that part of cycle. To change the efficient output voltage, the widths of all pulses are amplified or reduced while keeping sinusoidal proportionality. With pulse width modulation, only on time of pulses are changed during the amplitudes.[34]

5.10.2 Rules for the provision of ancillary services

For ensuring stability of network and its safety, an active user which is equipped with storage system must provide to grid some services such as voltage and frequency regulation.

5.10.3 Participation to the frequency regulation

All active users connected to medium voltage and low voltage networks must participate to local frequency regulation, which consists in injection or absorption of active power at load buses.

As shown in Fig. 5.13, storage systems must be able to change their absorption and injection of active power depending on frequency of the network. The rectangular area between 49.7 Hz and 50.3 Hz defines possible working points in normal operating conditions. If frequency rises over 50.3 Hz (over frequency), electric storage system must absorb active power moving toward lowest quadrilateral vertex. Instead if frequency decreases under 49.7 Hz (underfrequency), electric storage system must inject active power moving toward highest quadrilateral vertex.

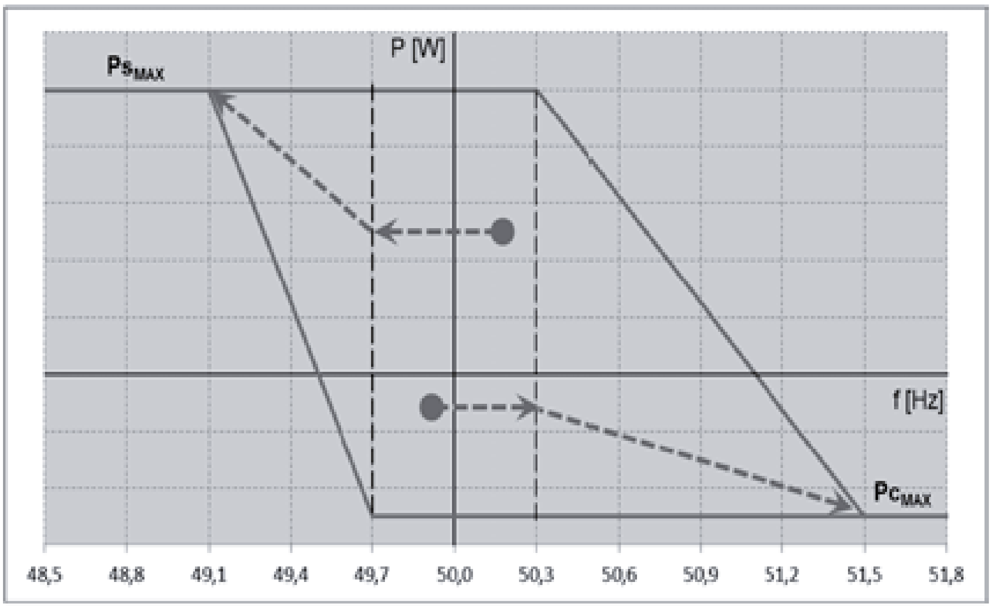


Figure 5. 17 Regulation of active power for a storage system[21]

In the case in which system is overloaded (power higher than Pc_{max} or Ps_{max}), at first a normal working point must be restored and then power has to evolve toward one of the vertexes. When frequency returns into limits, system comes back to normal conditions maintaining same power up to the moment in which the frequency band 50 ± 1 Hz is reached. When this condition is kept for at least 300 seconds, electric storage system must operate at its ordinary conditions. If the SOC does not allow to respect the power imposed (batteries are fully charged/discharged), the electric storage system must turn off itself gradually.

In a near future, with development of smart grids, plants with a power higher than 6 kW in low voltage and 100 kW in medium voltage could be managed by distributor in order for limiting the output active power in case of over frequency.[21]

5.11 Examples of commercialized Battery Energy Storage System

Many companies in world are specialized in production of modular electrochemical storage systems for improving network performances. ABB produces single and three phase systems available in several capacities (from 50 kWh to 6000 kWh) with individual modules up to 4 MW of power and an output voltage range which is from 120 V to 40.5 kV at 50 or 60 Hz. All solutions are equipped with AC and DC protections, an inverter, a supervisor control system, and a transformer combined with medium voltage switchgear. In three phase configurations and for powers between 1 MW and 4 MW, these components are installed in an independent unit called Connection Equipment Module. In addition to these devices there are Lithium ion batteries with their battery management systems which are installed in another enclosure. The overall structure of system is shown in Fig. 5.14.

Bosch is producing modular battery energy storage systems which can obtain up to 100 MW of installed power for industrial, domestic and grid applications. In Braderup (Germany), a wind farm with an installed power of 18 MW was equipped with a Bosch storage system based on LIC and vanadium redox flow batteries for a total storage capability of 3.4 MWh. This solution can avoid reduction of wind generation, for increasing local consumption and for providing ancillary services for the grid.[21]

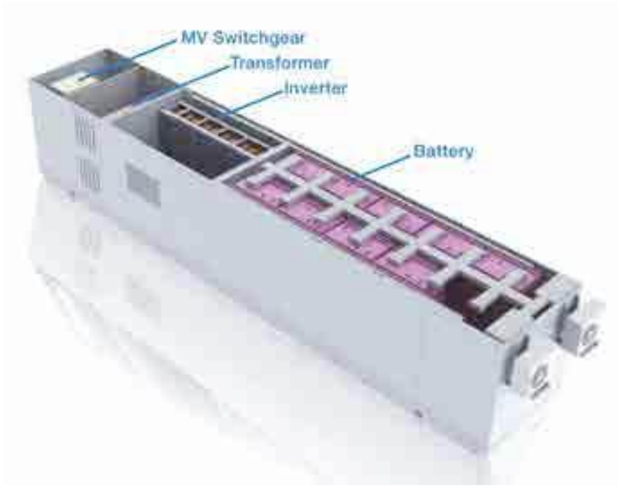


Figure 5. 18 Structure of a modular ABB battery energy storage system

Chapter 6

6. Power Converters

Battery energy storage systems and multilevel converters are key components in present and future medium voltage networks where an important assimilation of renewable energy sources takes place. The modular multilevel converter offers the potential of embedding such energy storage elements in a splitting manner, given the possibility of several sub modules operating at significantly lower voltages [25]

6.1 Modular Multi-level Converter (MMC)

The formerly mentioned drawbacks in this chapter of conventional voltage source converters are more or less significant depending on application field. For motor drive in standard industrial application up to medium voltage level VSC (2 level or 3 level topology) has become dominating technology. Where the converters are fulfilling requirements general replacement by MMC is not probable in the foreseeable future. But for many new applications like high voltage converter grid connection or large drives. Modular multilevel converter are more suitable. For HVDC it has become state of art for brand new applications. Recently there are some interesting applications in lower power range that are getting into focal point of the research.[4]

One feature of Modular Multilevel Converter (MMC) is its uniform implementation from basic building blocks. These are 2 terminal switching cells containing an internal DC-storage capacitor. In an abstract view, the structure of an MMC can be divided into three layers [3]

- Upper Layer: Main circuit
- Medium Layer: Submodule
- Lower Layer: Semiconductor switches

Compared to a conventional VSC, the “medium layer” is new. It enables decoupling of semiconductor requirements from main circuit requirements of application. The most important main circuits are AC/DC-Converters (with DC-Bus) and less frequently AC/AC-Converters (Matrix-Converters).

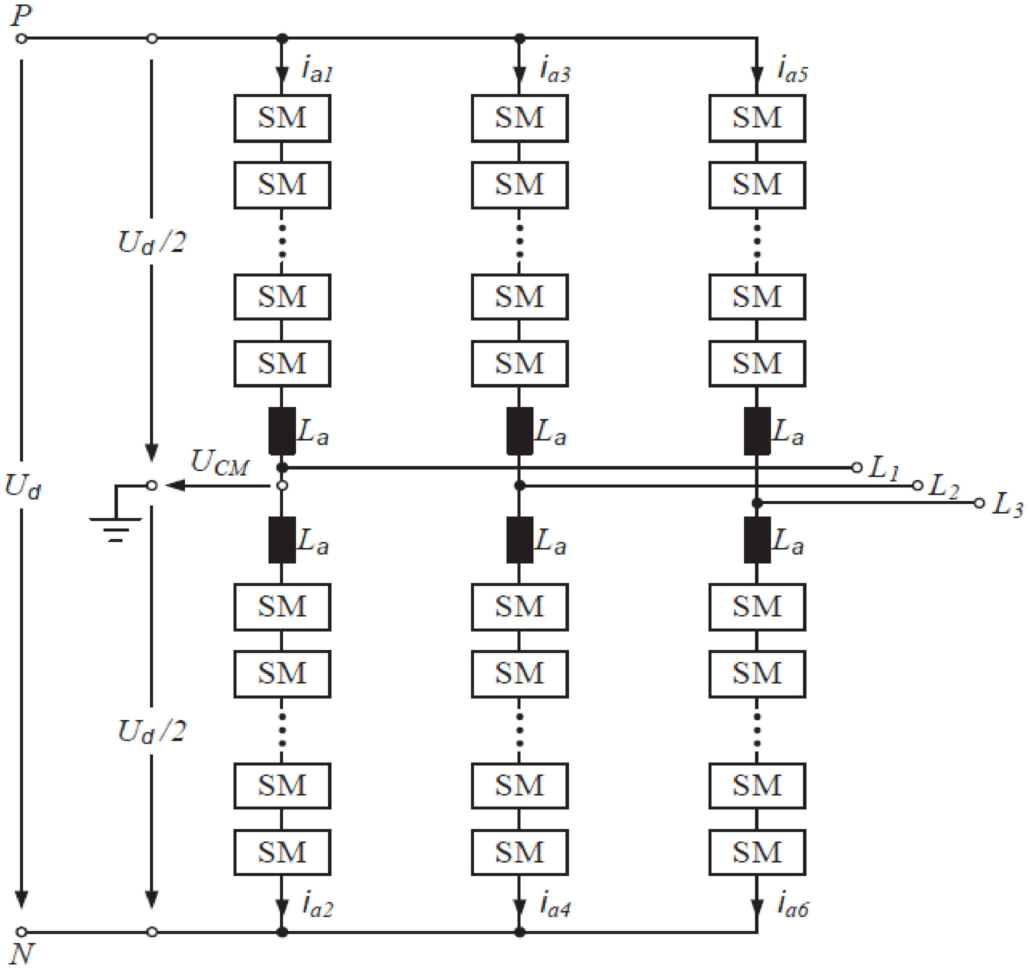


Figure 6. 1 Basic scheme of MMC

A basic analysis of circuit leads to important insight that submodules (as 2-terminal building blocks) do not need connections to energy supply. They need capacitive energy storage, however in order to be able to act like controlled voltage sources.

The total amount of required energy storage is greater than in conventional multiphase converters. This point presents a basic disadvantage of MMC originating from the idea of distributed capacitors. Future progress concerning this point will not come for free, more investment for the power semiconductors and improved control schemes will be inevitable. The first point is linked to Full Bridge Functionality of sub modules which enables other essential advantages too.

In summary when looking at the MMC concept from industrial and technical point of view significant points are in particular:

- The submodules are 2-terminal devices with simple non-critical interface conditions.
- There is no need for any form of power supply or floating power supply to the submodules.
- The critical commutation loops, important for high-speed switching semiconductors are kept internally in submodules.

At first glance some features of MMC seems to be strange, because nothing very much alike was known from conventional VSC or multilevel VSC. Essential differences, to be noticed are

- The internal arm currents (i_a) of the converter are not chopped , they are flowing continuously. They can be controlled to given set values by the converter control system.
- Stray inductances and additional chokes (L_a) distributed in the converter arms are not a complication. Some level of inductance is useful, in order for limiting high frequency circulating currents.
- The DC side of the converter does not contain a DC link capacitor. The elimination of capacitors and filters from DC Bus is an essential progress.
- The DC Bus voltage is controlled and impressed by converter control system fastly and directly (like multilevel voltage at AC side).[25]

The last two mentioned points enable much better and faster control of values of DC side and the (directly related) instantaneous real power flow.

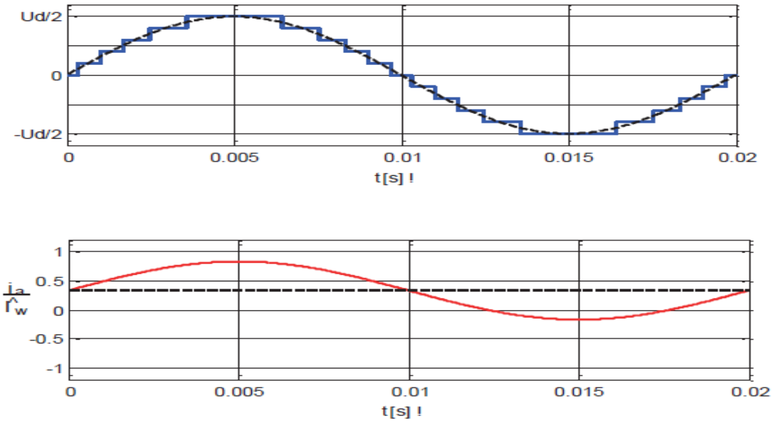


Figure 6. 2 current and phase voltage of MMC

Furthermore severe fault conditions particularly short circuits at the DC Bus can be managed in a safe manner. These new degrees of freedom are very valuable but commonly not seen because conventional VSC and Multilevel VSC do not have these features.

6.2 Basics Principles of MMC

Figure 6.3 is showing MMC's circuit configuration. The point 0 represent zero voltage reference. The converter consists of six arms three of them are upper arms and other three are lower arms in which each arm contains a series connection of an identical sub module and converter reactor (2L)[26].

Each upper and lower arm are connected to same phase. The upper and lower arms in same phase comprise a phase unit. One sub module contains an IGBT half bridge as a switching element and includes a storage capacitor. Owing to its modular design, the MMC is well scalable and flexible in structure.[4]

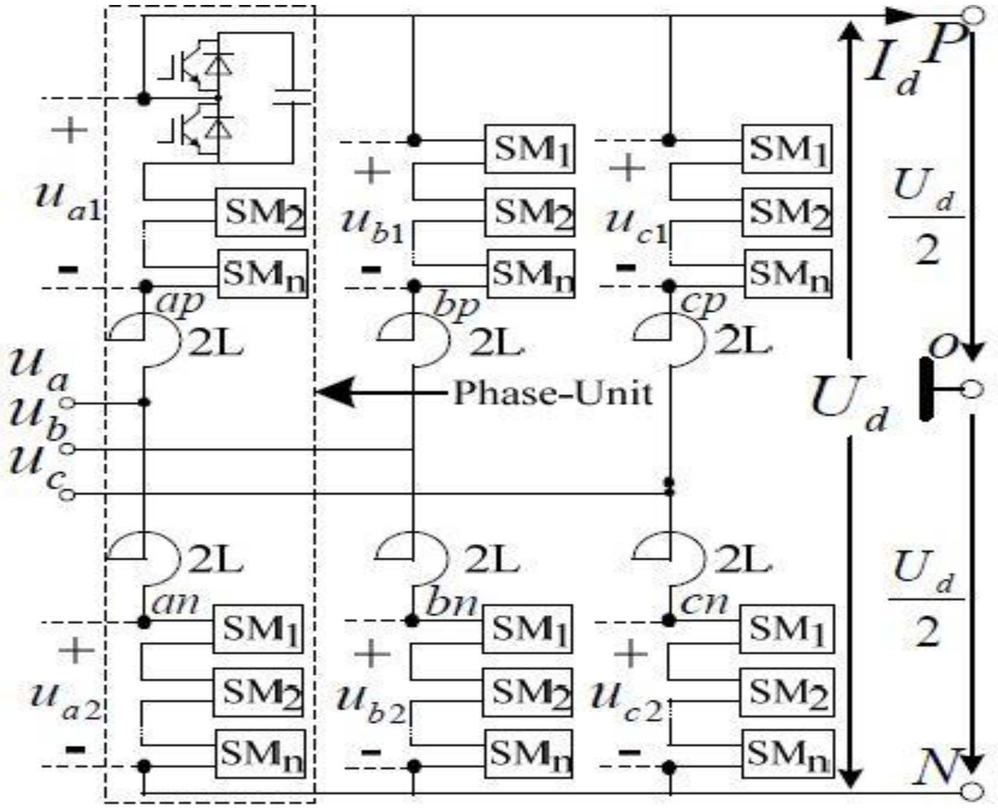


Figure 6. 3 Circuit configuration of MMC

For each sub module there are three different switching states related to the proper operation:

- On-state: the upper IGBT is switched on and lower one is switched off. Thus, capacitor voltage is applied at terminal of SM, charging and discharging of capacitor depends on direction of flowing current.

- Off-state: the upper IGBT is switched off and the lower one is switched on, in this case the voltage applied to sub module terminal is zero.

MMC Sub Circuit Module

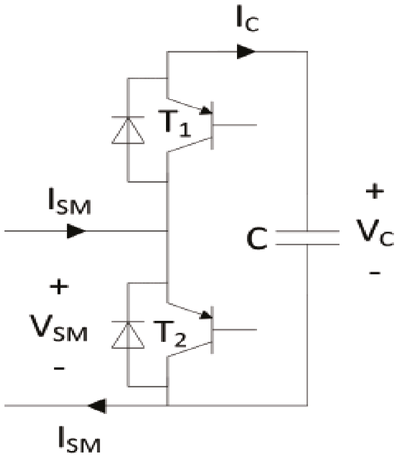


Figure 6. 4 MMC Sub Circuit Module

- Block-state: Both IGBTs are off, this state occurs when start up or in series failure conditions.

By alternating the on-state and off-state, we can control sub modules output voltage. Usually the SM’s at On-state in one phase unit are half the SM’s in each phase unit. By dividing the sub modules between upper and lower arms (n+1) output voltage levels are available at AC side.

In conventional three-phase AC/DC converter, each phase is connected to the AC side through one reactor. But in MMC, six converter reactors are needed for connecting six converter arms with the grid. That the reason, the control strategies for conventional AC/DC converter cannot be used exactly in the control of MMC. In any case MMC has better performance.

Let us see an example, if there is an MMC with n=6, where SM switches are replaced by equivalent two-pole switchers. So, number of output voltage levels are (7) which seems like a sinusoidal wave form [27]

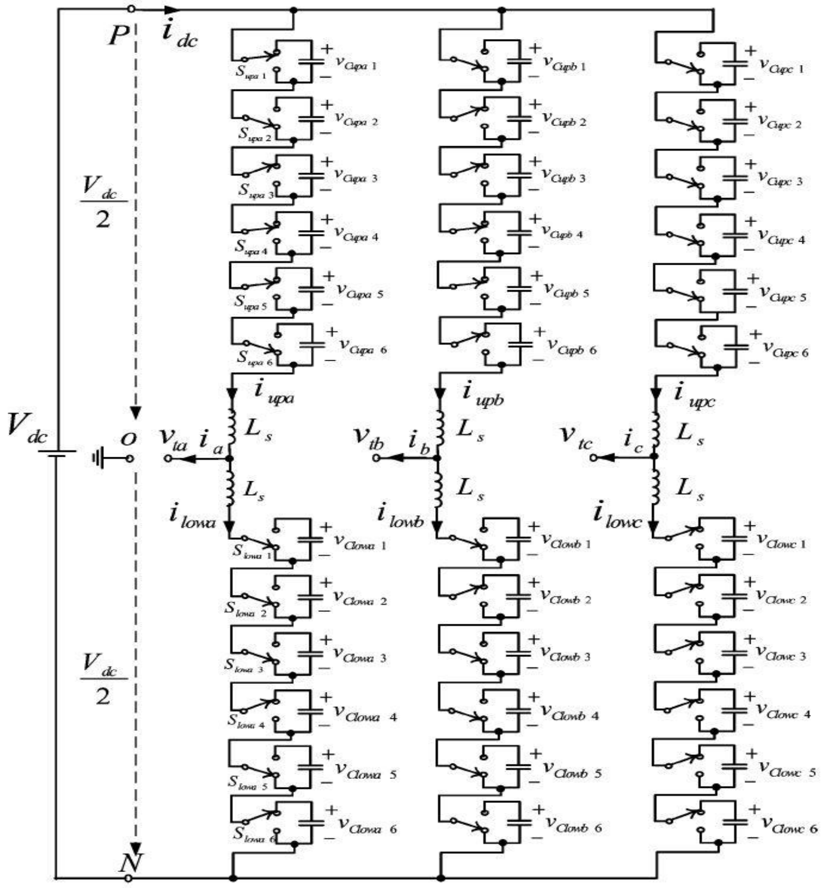


Figure 6. 5 MMC with 6 SMs[4]

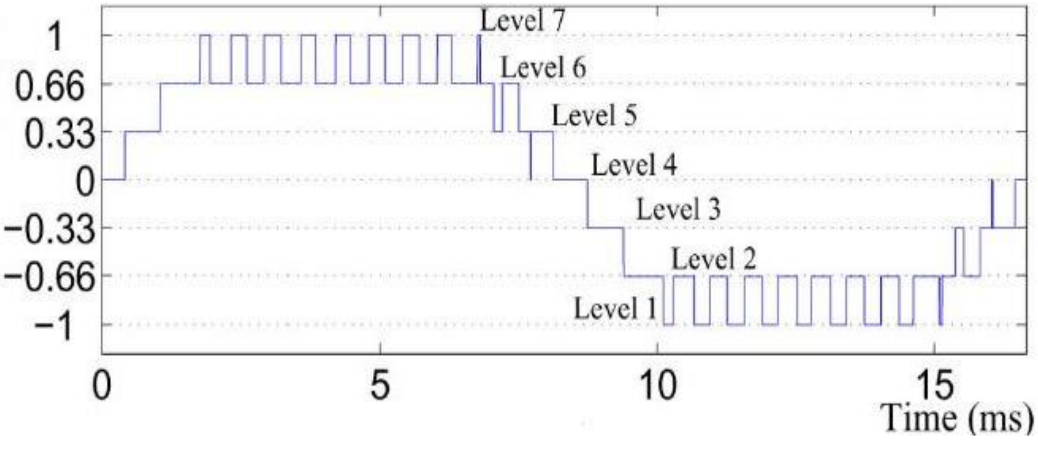


Figure 6. 6 MMC Output phase voltage with 6 SMs in (p.u)

6.2.1 Sub-Module Topologies

The Sub modules of MMC can be realized by the following circuits [26][28]:

1) **The half-bridge circuit or chopper-cell:**

As shown in Figure 5.7(a), output voltage of half-bridge sub module is either equal to its capacitor voltage V_c (switched on/ inserted state) or zero (switched-off/bypassed state), depends on switching states of complimentary switch pairs, i.e. S1 and S2 [29]

2) **The full-bridge circuit or bridge-cell**:

As shown in Figure 5.7(b), the output voltage of a full-bridge sub module is either equal to its capacitor voltage V_c (switched-on/inserted state) or zero (switched-off/bypassed state), depends on switching states of four switches S1 to S4. Since number of semiconductor devices of a full-bridge sub module is twice of half-bridge sub module, the power losses as well as the cost of an modular multilevel converter based on the full-bridge sub modules are significantly more than that of an modular multilevel converter based on the half-bridge sub modules [29].

3) **The clamp-double circuit:**

As shown in Figure 5.7(c), a clamp-double sub module consists of two half-bridge sub modules, two additional diodes and one extra integrated gate bipolar transistor (IGBT) with its anti-parallel diode. During normal operation, switch S5 is always switched ON and clamp double sub module acts equivalent to two series connected half bridge sub modules. Compared to half and full bridge modular multilevel converters with same number of voltage levels, clamp-double has more semiconductor losses than half bridge modular multilevel converter and lower than full bridge modular multilevel converter [29].

4) **The three-level converter circuit:**

As shown in Figure 5.7(d) and (e), a three-level sub module is comprised of either a three-level neutral point clamped or three-level flying capacitor converter. The three-level flying capacitor modular multilevel converter has similar semiconductor losses with half-bridge modular multilevel converter. However, three level neutral point clamped modular multilevel converter has more semiconductor losses than half-bridge modular multilevel converter and less than full bridge modular multilevel converter. From a manufacturing perspective and control this sub module circuit is not very attractive.

5) The five-level cross-connected circuit:

As shown in Figure 5.7(f), a five-level cross-connected sub module also consists of two half-bridge sub modules connected back to back by two extra IGBTs with their anti-parallel diodes. Its semiconductor losses are same as clamp double sub module [30].

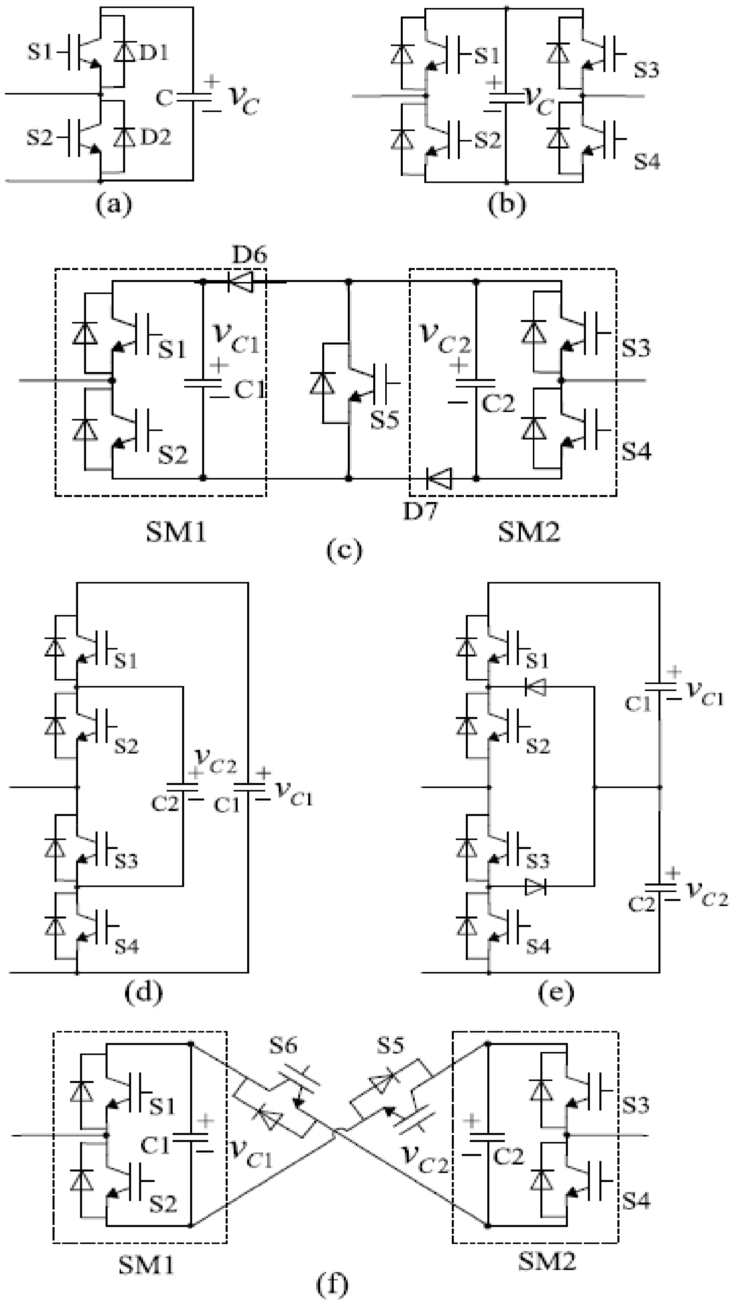
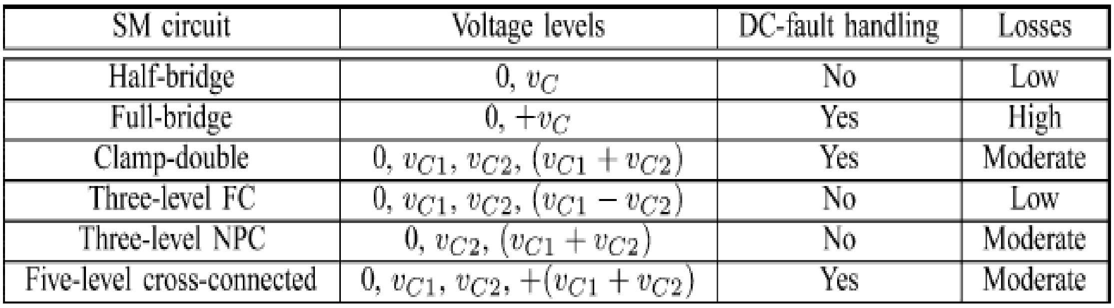


Figure 6. 7 Various SM topologies: (a) the half-bridge, (b) the full-bridge, (c) the clamp-double, (d) the three-level FC, (e) the three-level NPC, and (f) the five-level cross-connected SM

A comparison of various sub module circuits, in terms of voltage levels, DC side short-circuit fault handling capability, and power losses, is provided in Table 5. The dc side short circuit fault is one of the major challenges associated with the MMC HVDC system. Among all the sub module circuit configurations, the half-bridge sub module has been the most popular sub module adopted for the modular multilevel converter. This is due to the presence of only two switches in the sub module which results in lower number of components and higher efficiency for modular multilevel converter. Hereafter, the half-bridge sub module based modular multilevel converter is considered. [4]



SM circuit	Voltage levels	DC-fault handling	Losses
Half-bridge	0, v_C	No	Low
Full-bridge	0, $+v_C$	Yes	High
Clamp-double	0, v_{C1}, v_{C2}, $(v_{C1}+v_{C2})$	Yes	Moderate
Three-level FC	0, v_{C1}, v_{C2}, $(v_{C1}-v_{C2})$	No	Low
Three-level NPC	0, v_{C2}, $(v_{C1}+v_{C2})$	No	Moderate
Five-level cross-connected	0, v_{C1}, v_{C2}, $+(v_{C1}+v_{C2})$	Yes	Moderate

Table 4 Various SM topologies comparison

Chapter 7

7. BESS providing primary frequency control with wind penetration

7.1 INTRODUCTION

Global concerns on greenhouse gas emission incentives and codes of practice set by governments have resulted in an upward trend in penetration level of distributed generation mainly from renewable energy sources. However renewable energy sources come with some inherent disadvantages such as its dependency on weather conditions for generating electricity and its lack of inertia for damping system oscillations. With an increased amount of intermittent renewable energy sources, power system planning and operation is becoming more complex and difficult for ensuring reliability of network. Wind energy source is one of most popular forms of renewable energy source in present day power system. The dynamic response of wind integrated power system is greatly affected by type of wind generators connected to system. Among several types of generators, doubly fed induction generator based wind farm has been widely installed due to their cost benefit and flexibility of regulating output power. With different dynamics and operational features than synchronous generators, penetration of wind farm may affect negatively on damping out power system oscillation resulting from decrease of available system inertia by the shutting down of synchronous generator based conventional units of generation.

The foremost technical challenges with distributed generation penetration are on system stability. Since renewable energy systems are reducing system inertia, system may not be able to compensate frequency oscillations within permissible limit in presence of disturbance. Therefore necessity of system inertial response is very demanding. In near future, wind farm may be required to take part in in certain level of frequency regulation with large distributed generation penetration level.

Significant research efforts are dedicated for improving frequency regulation and frequency response of wind farm by using rotating mass of wind turbine

[22], power and torque droop control, optimal dispatch, power oscillation damper, pitch angle controlling for de loading and droop control. However, such control methods will require adjustment of power extraction from wind farm which is not desirable by owner of wind farm as this will be affecting wind farm revenue. Dispatchable energy source based on synchronous generator has been used for restoring system frequency. In order to drive for 100% renewable energy source, entire dependency on frequency regulation by wind farm is not fully reliable as technology itself is dependent on weather conditions. Therefore reliable and dispatchable alternative energy source is required for ensuring stability of system with increased penetration level of wind and other renewable energy sources in existing power system.

Battery energy storage system is an important and broadly studied alternative for supporting frequency stability challenges related to fluctuating and intermittent renewable energy source. Since Battery energy storage system offers fast active power response, it is a perfect choice for compensating for negative impacts of distributed generation by reducing oscillations of power system. Application of battery energy storage system significantly improves transient stability response in a micro grid [23] in an increased distributed generation penetration environment. Battery energy storage system can improve and affect positively in reducing rotor speed deviation at different distributed generation penetration levels following disturbances in system. This study discusses contribution of Battery energy storage system in supporting increased distributed generation penetration level in existing power system. The objective is maintaining system frequency within a restricted boundary of ±1% of nominal value for complying with standards of power quality according to Australian National Electricity Market .

The main interest of this study is monitoring transient stability phenomena with renewable energy penetration in electrical grid. This approach is of specific interest of future large scale renewable sources integrated power system in which system would be susceptible to power oscillation due to lower system inertia. This technique is able to obtain more information on system inertia reduction with replacement of current synchronous generator unit by renewable energy source unit. In addition important role of Battery energy storage system power and energy is also investigated in this study. The impact and improvement of system inertia by using rapid responsive battery energy storage system for facilitating increased distributed generation penetration level will be investigated through a case study.[31]

7.2 Distributed generation penetration and system inertia

The main technical concern with renewable energy source based distributed generation is its reduced inertia as it significantly affects system stability in case of power imbalances in system. Distributed generation penetration level is defined by following expression [26]

$$\%DG = \frac{\sum P_{DG}}{\sum P_{DG} + \sum P_{SG}} \tag{7.1}$$

P_{DG} and P_{SG} are total active power output from synchronous generator and distributed generation units. There are two major aspects that define severity of distributed generation penetration level and its impact on overall system inertia. These are detailed as follows:

- Existing synchronous generators remain connected to system with increased distributed generation penetration.
- Existing synchronous generators are permanently shut down with increased distributed penetration.

Considering sustainability concern, existing thermal synchronous generator unit based on fossil fuel could be shut down permanently with increased distributed generation penetration level while small hydro, biomass, geothermal etc will remain in operation in future market. In this study, replacement of existing synchronous generator is considered with increased penetration level of distributed generation unit. The idea is assimilating more renewable energy sources in grid and increasing renewable energy sources penetration level by means of using battery energy storage systems.[31]

The battery energy storage system is equipped with bidirectional DC/AC converter and can be controlled for releasing or absorbing energy. Grid frequency and power system oscillation support can be provided by controlling P_{BESS} for regulating grid power according to operational requirements. Primary focus of this study is reducing frequency oscillation under disturbance conditions with increased distributed generation penetration level. For providing inertial control, required power reference of battery energy storage system converter is adjusted according to capability of the system to respond and can be simplified as follows [32]

$$P_{ref-1} = P_{ref-0} - H_v f_{nom} \frac{df}{dt} \tag{7.2}$$

where P_{ref-1} and P_{ref-0} are power reference with and without frequency control, H_v is the inertia constant that defines battery energy storage system capability to respond in providing frequency control, f_{nom} is the nominal system frequency (pu) and df/dt is rate-of-change-of-frequency (pu/s) following any contingency. Primary frequency control needs to be activated within a very short time and for a very small period of time. Generally fossil fuel power plants deliver such frequency control. However, closing down of conventional power plants with increased penetration of renewable energy introduces stability threat in power system. Therefore, battery energy storage system is designed for providing primary frequency control with respect to changes in system frequency via droop control method. To provide frequency control through droop method, battery energy storage power is adjusted as follows:

$$P_{ref-1} = P_{ref-0} + K_r df \tag{7.3}$$

where, K_r is droop gain of battery energy storage system and df is the frequency deviation. In this study, battery energy storage system is shown to provide frequency response with respect to changes in system frequency via droop control method. The maximum deviation of system frequency is controlled by regulating primary frequency control gain i.e. droop gain (1/R) where R is droop value. Apart from droop value, parameters of other controllers such as battery energy storage converter rating and PI controller parameters also play important roles in controlling frequency response and regulating system oscillations.[31]

7.3 The control diagram of Battery energy storage system (BESS)

Battery energy storage system mainly provides frequency oscillation damping by absorbing excess power and supplying shortfall of power. The basic battery energy storage system structure consists of a battery bank, bidirectional DC/AC converter and a grid connected transformer. The detail control technique of battery energy storage is shown in Fig 6.1. There are 5 individual control sections in battery energy storage control:

- Frequency controller.
- Voltage controller.
- Active Power (P) and Reactive Power (Q) control.
- Charge controller.
- Current controller on direct (d) and quadrature (q) axis.

- **Frequency controller**

The frequency controller acts when the grid frequency differs from nominal value as per expression in (4)

$$df = f_{ref} - f_{grid} \tag{7.4}$$

Battery energy storage system absorbs energy if df is negative and supplies energy if df is positive. The dead band is included for avoiding battery energy storage operation during small change in frequency and complying with grid code. The droop sets limits of battery full active power activation in response to certain amount of frequency deviation from nominal value as per following expression in (5)

$$P_{BESS} = \frac{\pm df}{droop(R)} \tag{7.5}$$

- **Voltage controller**

The voltage controller takes action when grid voltage differs from nominal value as per expression in (6)

$$dv = V_{ref} + V_{bus} \tag{7.6}$$

Battery energy storage absorbs reactive power if dv is negative and provides reactive power if dv is positive. The droop sets limits of battery full reactive power activation in response to certain amount of voltage deviation from nominal value as per following expression in (7)

$$Q_{BESS} = \frac{\pm dv}{droop(R)} \tag{7.7}$$

- **Active power (P) and reactive power (Q) control**

In PQ control, active and reactive power at battery energy storage output terminal P_{in} and Q_{in} are compared against incoming active and reactive power reference from frequency and voltage controller. The signal Δ_{id} which is difference between charge controller input and output current on d axis is added with active power difference and then a PI controller is used for generating active current reference on d axis. The deviation between reference voltage value and voltage at battery energy storage system connection point is used as an input to another PI controller for generating reactive current reference on q axis. The difference between charge controller input and output current on q axis Δ_{iq} is added with reactive power difference in PQ controller.

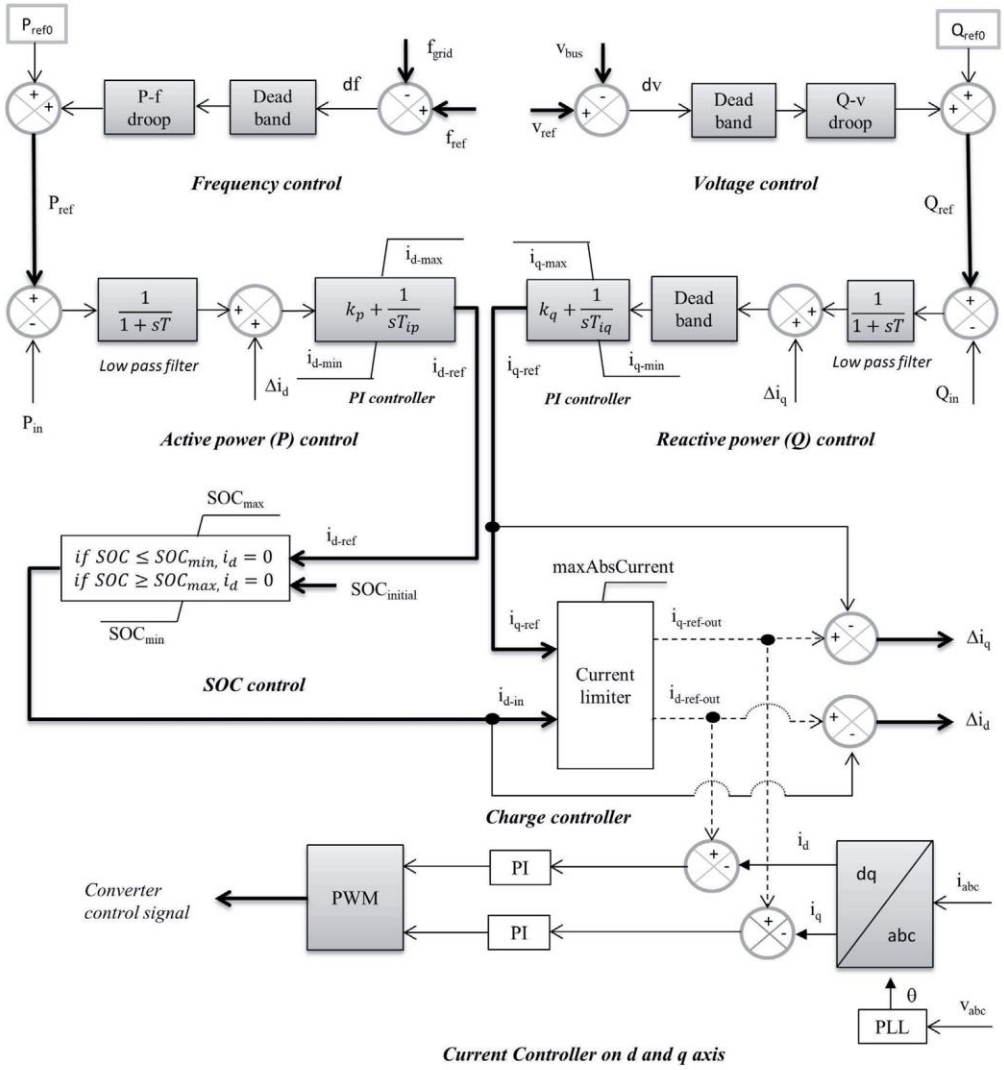


Figure 7. 1Detailed BESS control techniques[31]

However, since purpose of this study is acquiring frequency oscillation support, active power is given preferences over reactive power via dead band and lower gain for reactive power activation. A first order low pass filter is used for smoothing out input. Time constant in low pass filter defines dynamic behavior of output with respect to input. Thus a large time constant value results in large energy storing component that causes slower change in transient response. To avoid integrator windup, PI controller with an anti-windup limiter is used. The PI controller is described by Fig 7. 2 where x. can be expressed by following expression[31]

$$x = \frac{K_i}{T_i} \tag{8}$$

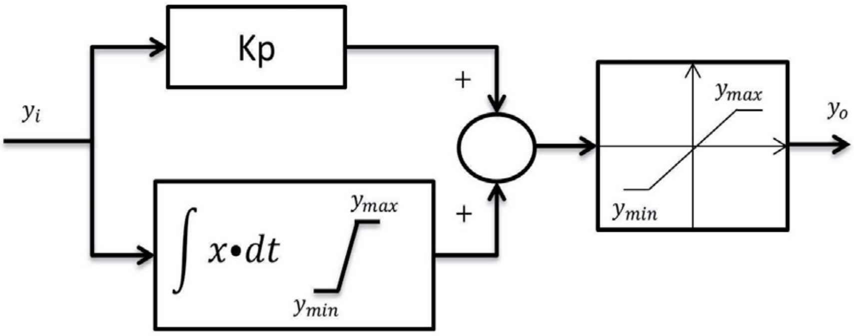


Figure 7. 2 Block diagram of PI Controller

The controller is bounded by maximum and minimum value and parameters tuned by trial and error method for reducing frequency undershoot (f_{nadir}), frequency settling time (t_{st}) and overshoot (f_{max}). Even though maximum rate of change of power (ROCOP) is not implemented in this study, a rate limiter can be added at active power current reference output to control ROCOP value.

- **Charge controller**

Charge controller generates a charging/discharging signal based on available state of charge of battery and incoming current reference value of d axis. The battery energy storage system regulates active power if battery SOC satisfies defined operating conditions. The SOC conditions are outlined in (9). Since reactive power is not dependent on battery, reactive current is not considered in charge control. However, current limiter restricts total amount of current flow through d and q-axis within design limits for avoiding overloading of battery energy storage converter. Hence, total current would be maximum absolute value of 1. The SOC control in charge controller is delimited as follows:

$$i_{d-in} = \begin{cases} i_{d-ref} & \mathrm{SOC}_{min} \le \mathrm{SOC} \le \mathrm{SOC}_{max} \\ 0 & \text{otherwise} \end{cases} \tag{7.9}$$

The battery can be charged when frequency is within grid defined deadband region. Battery can be charged if SOC is less/equal than SOC_{max} and discharged if SOC is greater/equal than SOC_{min}. Battery cannot be charged if SOC is greater than SOC_{min} and discharged if SOC is lower than $SOC\ _{min}$. The current limiter regulates active and reactive power output reference within total battery energy storage converter capacity. The active power reference regulates within maximum battery energy storage converter capacity (±1 pu). Based on remaining battery energy storage system converter capacity, the reactive power output reference is executed i.e. within ±Y, where Y varies between 0 to 1 and can be calculated as in

$$Y = \sqrt{|1 - (i_{d-ref-out}^{2})|} \tag{7.10}$$

The maximum and minimum battery energy storage converter value can be adjusted individually for positive and negative current.

- **dq current controller**

The input to current controller is AC current at battery energy storage converter output in dq reference frame. Phase locked-loop is used for synchronizing battery energy storage with grid. PI controller regulates d and q axis currents for regulating active and reactive power. The pulse width modulation is defined by modulation index on d and q axis, with reference to reference system defined by cosine and sin. The PI controller in current controller is expressed as:

$$K_p + {K_i}/{(sT_{ip})} \tag{7.11}$$

7.4 Battery model

Selected battery model in this study is a simple R_{int} equivalent model and shown in Fig 7.3 The battery is modeled as a SOC dependent voltage source with internal resistance (R_{int}) and can be calculated as in (12)[33]

$$U_{DC} = U_{max}\, SOC + U_{min}(1 - SOC) - I_{bat}R_{int} \qquad (7.12)$$

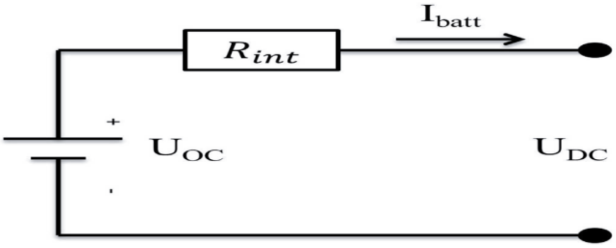


Figure 7. 3 Block diagram of R_{int}equivalent battery model

7.5 System modeling

The power system we are studying is an IEEE 9 buses, 3 synchronous Generator system as shown in Fig. 7.4 [23]. For this study, all generators are equipped with exciter, AVR and G2 is modelled as Gas turbine, G1 as hydro governor and G3 as Coal power plant with associated governor and IEEE Type AC1 Excitation System. G1 is considered as reference machine. This study was conducted on DigSILENT in the relevant paper and its results are discussed in our thesis.

The aggregated wind farm unit is installed at bus 9 via a 0.69/ 230 kV transformer and 40MW battery energy storage system is installed via a 0.4/230 kV transformer. Each wind turbine is rated as 2.2 MW. Doubly fed induction generation based generator is used for wind farm and DFIG is designed with fault-ride through capability. The total active power demand of system is 315 MW. The nominal apparent power for G1 and G2 are 250 MVA and 300 MVA with power factor of 1. For analysing impact of maximum wind penetration level, it is considered that wind farm is operating at its maximum rated output according to wind speed VS power output curve as shown in Fig. 7.5 i.e.wind speed is between 15 and 25 m/s at time of transient fault analysis. However, when wind farm operates below rated wind speed, output power of wind farm will be lower than maximum penetration limit. Therefore at lower wind penetration level, system frequency does not oscillate beyond specified grid constraints.[31]

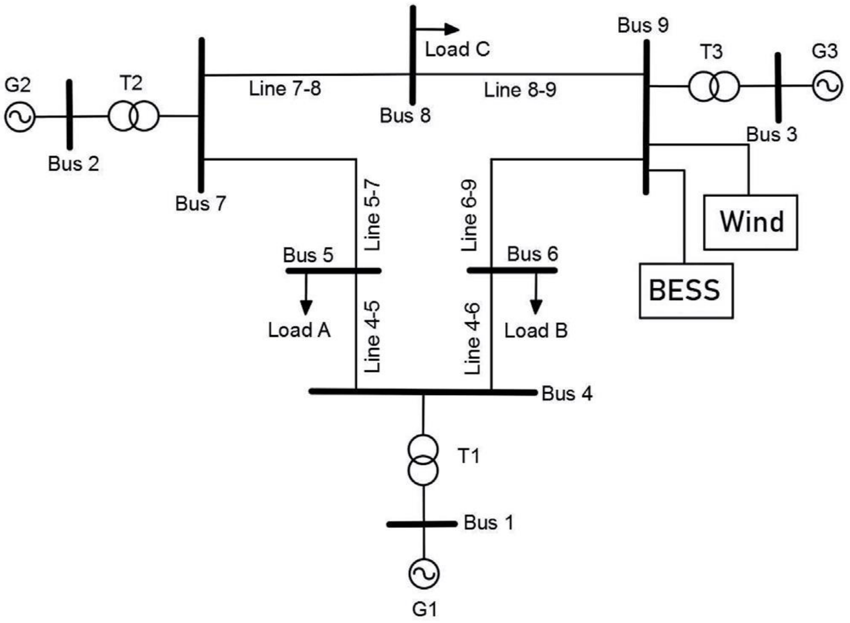


Figure 7. 4 Block diagram of Power System with installed Distributed Generation

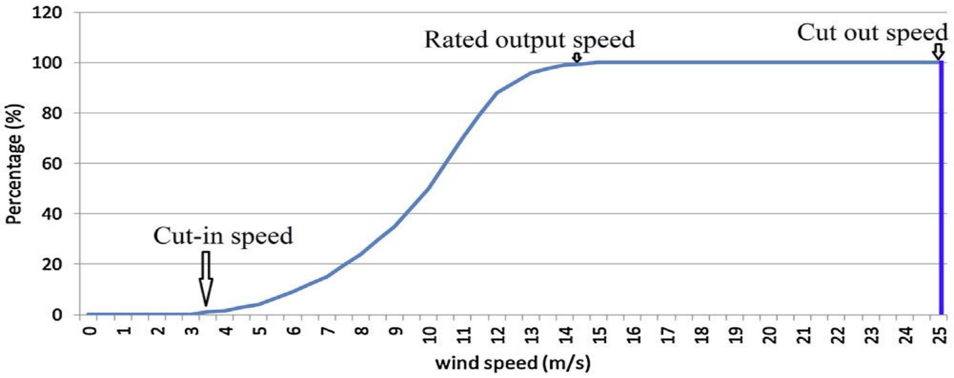


Figure 7. 5 output power of wind farm as percentage of rated capacity with varying wind speed.

7.6 Case Studies

Distributed generation penetration level and its impact on power system always depend on the nature of type and installation location of distributed generation, as well as type and location of faults. In order to gain an understanding of distributed generation penetration, one case study is analysed.

• Case Study: Load event.

Based on different scenarios, frequency operation limit is checked. The impact of distributed generation units is studied depending on four different states of affairs

- Without any wind power penetration.
- Wind penetration limit with the removal of G3 unit.
- Higher level wind penetration without battery energy storage.
- Higher level of wind penetration with battery energy storage.

To verify effectiveness of battery energy storage in reducing oscillation and supporting increased distributed generation penetration, results of simulations carried out in DigSilent in the relevant paper are studied. The target is replacing existing G3 generator and installation of wind farm of equal rating. The limit of wind farm penetration level is identified when synchronous generator unit is replaced by wind farm. Wind farm is connected to bus 9.

Case study: Distributed generation penetration and increase in load demand at load B

In order to further investigate battery energy storage performance in stability enhancement, a sudden load increment and its impact on wind penetration limit is examined. With 120MW wind power penetration, system's capability to handle amount of load demand increment is investigated. A 50% load increases at highest load point of Load A is applied for duration of 1–1.5 s and frequency response of system is observed. Simulation results in Fig. 7.6 shows that with 17.91% wind penetration and without a battery energy storage system, system fails to handle efficiently 50% sudden load upsurge according to grid code requirement. The frequency drops to a value of 0.989pu which moves out of the mandatory±1% of nominal value. However, without wind penetration, system effectively maintains grid frequency oscillations within permissible frequency corridor. This clearly defines adverse inertia impact of wind energy. On the contrary, with support of battery energy storage system, 50% load upsurge is possible to handle by the system when wind penetration is 17.91%. Battery energy storage is used to uphold frequency drop lower than the permissible limit.

Storage system is installed at two different locations in the network. It can be seen in Fig. 7.6 that when battery energy storage is installed at swing generator (bus 4), the lowest frequency drop of G1 (0.9944 pu) is slightly better than when battery energy storage is installed at wind integrated bus (0.9943 pu). A similar level of moderately improved performance is visible in case of G2 when storage system is installed at bus 4. Battery energy storage systems also minimizes active power oscillations that will arise due to load demand changing circumstance.

Storage systems active power is shown in Fig. 7.7 that illustrates quite similar performance when it is installed at buses 4 and 9 and therefore a very similar level of SOC is visible for both locations as shown in Fig. 7.8 It provides necessary power for reducing drop in frequency value during load growth periods.

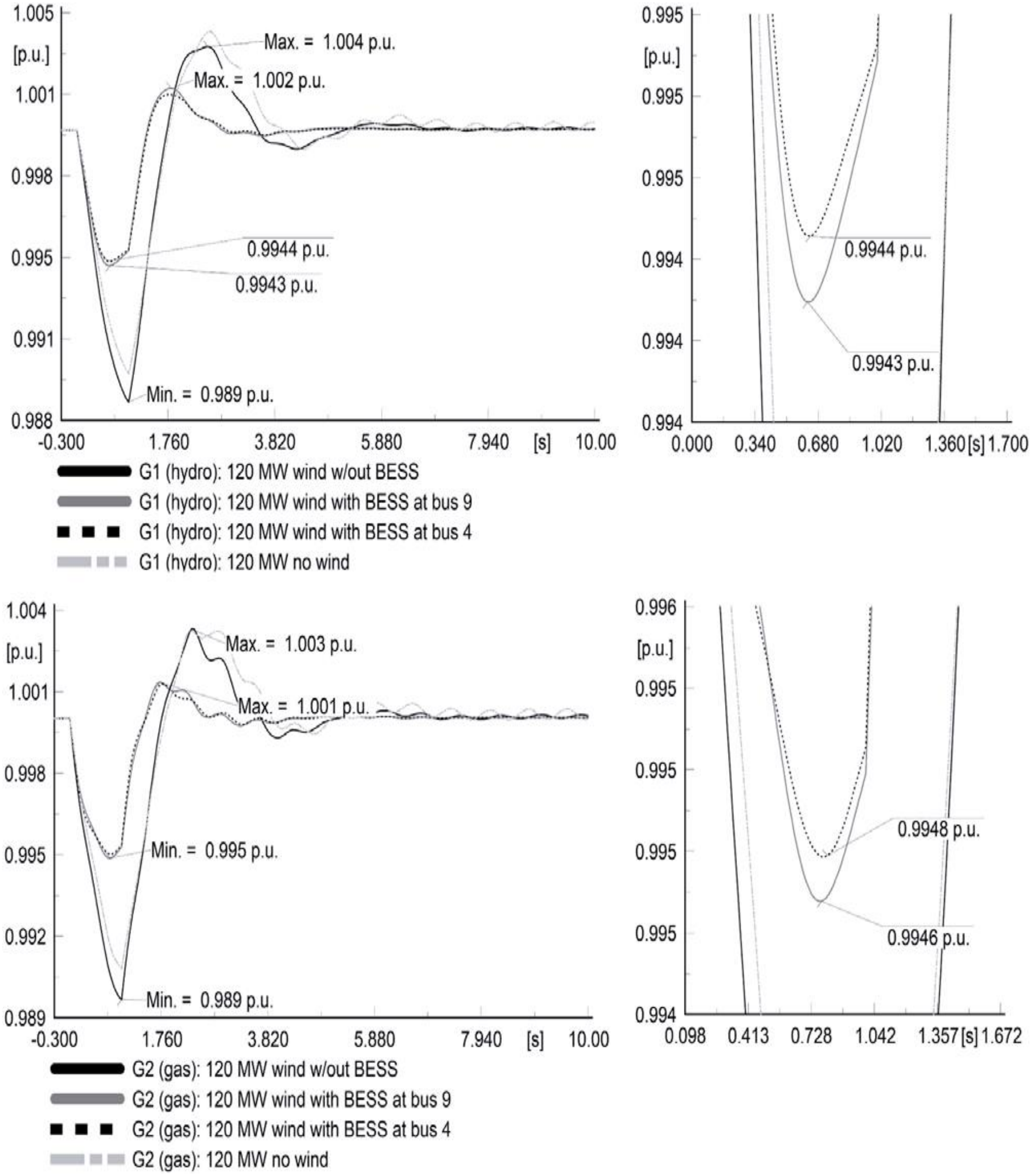


Figure 7. 6 frequency of Generators G1 and G2 with temporary load growth[31]

Since system frequency recovers to nominal value at approximately 2.8 s, the storage systems active power reduces to zero. Battery SOC goes down to a value higher than the previous cases as it provided large energy. However, steady-state battery SOC is nearly 0.77 pu at the end of simulation which shows storage systems are capable for participating in any future task. If SOC drops to minimum value or to a value that storage system operator desires to charge, it will be possible to charge the battery during storage systems inactive periods. [31]

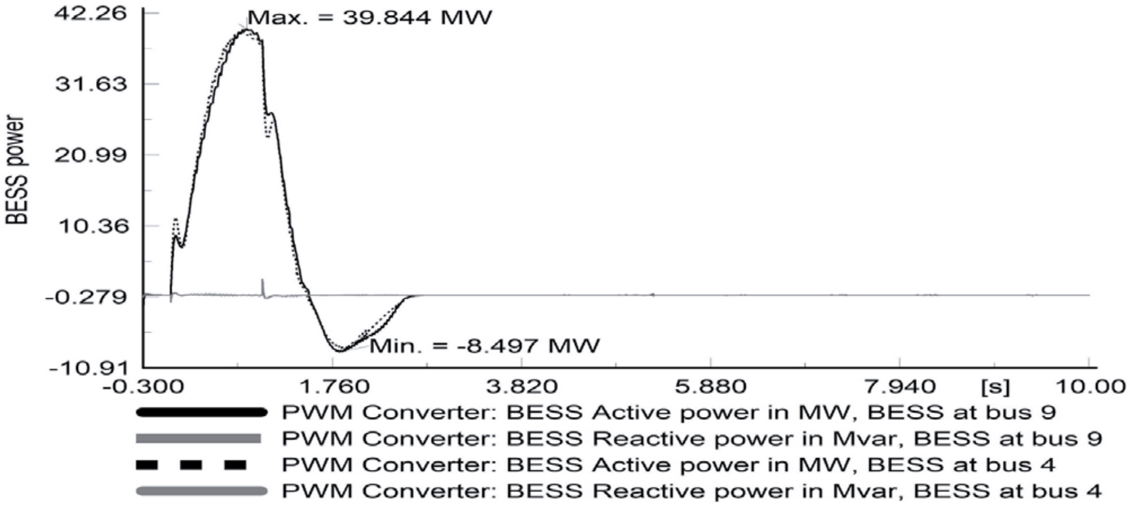


Figure 7. 7 BESS active/reactive power with temporary load growth.[31]

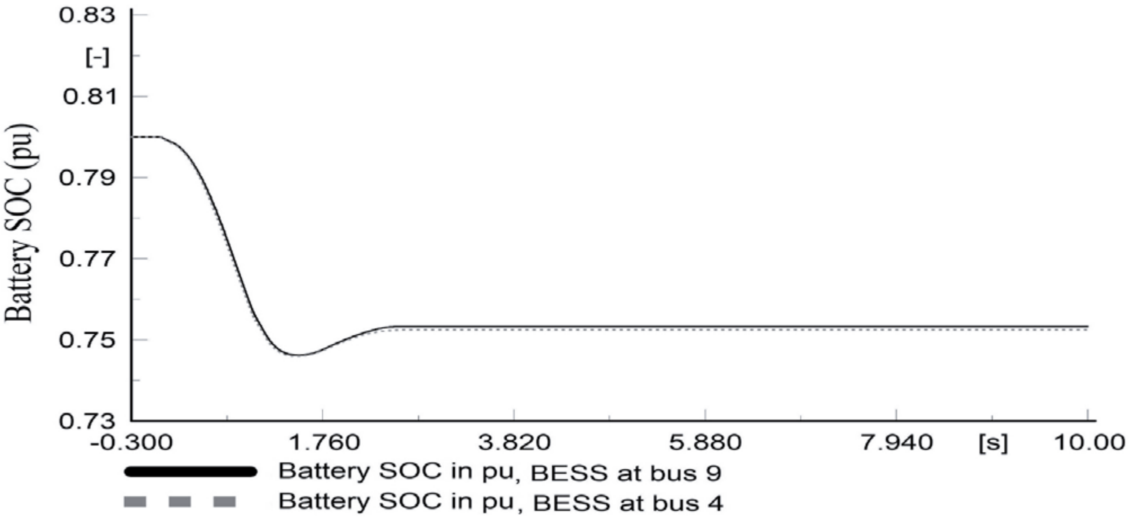


Figure 7. 8 Battery SOC with temporary load growth. [31]

7.7 CONCLUSION

Battery energy storage system as a quick responsive and reliable technology, have a remarkable prospect in regulating system frequency, particularly with large scale penetration of intermittent renewable energy sources. The limit of renewable energy sources penetration level is constrained by type of disturbance event and location. With increased wind penetration, accessible system inertia decreases and therefore system oscillation increases in case of a disturbance event. Few types of research have studied the improvement of distributed generation penetration. This case study provides an extensive investigation on battery energy storages contribution for reducing frequency oscillation, enhancing system stability and facilitating the higher level of distributed generation penetration.

It is observed that with increased penetration of wind energy, system encounters various difficulties for maintaining grid defined grid stability criteria. The incorporated storage system justifies its relevance in power system for enhancing frequency stability with increased wind energy penetration. Storage system reduces frequency oscillation by absorbing excess energy and supplying energy deficit. It also minimizes active power oscillation and the settling time of synchronous generators in system. It is also observed that wind energy penetration level is increased by 3.58–5.21% with the use of battery storage system.

With focus in a sustainable energy oriented electricity industry, the proposed use of battery storage system contribution in facilitating increased distributed generation penetration can potentially offer ample benefit for incorporating more clean energy sources with no reliability concern. In this chapter we have closely studied battery storage systems which provides a close insight of its importance in a future electric grid with 100% renewable energy penetration. However, this can be included using power oscillation damper or pitch angle controller. Comparative technical and economic benefits of utilizing oscillation damping from the wind farm and battery storage system incorporation would also be interesting.[31]

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