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A REVIEW ONUSAGE OF BESS TO MITIGATE TRANSMISSION LINE CONGESTION AND TO IMPROVE POWER SYSTEM EFFICIENCY WITH RENEWABLE ENERGY

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Abstract: Battery energy storage is crucial in power transmission system. The generation, storage and transportation of are all examined in this article. Power generated from renewable energy sources like wind, solar is the main focus. Batteries are the main components for energy storage. Study of battery energy storage system (BESS) and its characteristics is very prominent for transmission planning. Several case studies and operating modes pertaining to BESS have been studied. The current state of battery energy storage technology, as well as methodologies for evaluating its economic viability and impact on power system operations is studied. Battery energy storage transportation (BEST) is a novel approach for enhancing variable renewable use and load shifting, as well as providing a potential option for reducing transmission congestion. The goal of this paper is to reduce the total system planning cost, which includes load shedding penalty, and BEST transportation costs

INTRODUCTION

Now a day's increase in population, industrialization and transportation the energy demand is increasing. The consumption of the energy changes with loads, day to day consumption depending upon domestic, individual and industrial loads. World demand for energy is projected to more than double by 2050 and to more than triple by the end of the century. Incremental improvements in existing energy networks will not be adequate to supply this demand in a sustainable way. Finding sufficient supplies of clean energy for the future is one of society's most daunting challenges.

The supply and demand of energy is determining the course of global development in every sphere of human activity. Sufficient supplies of clean energy are intimately linked with global stability, economic prosperity and quality of life. Finding energy sources to satisfy the world's growing demand is one of the societies' foremost challenges for the next half century. So in order to solve this problem Renewable energies are getting increase day by day. The Renewable energy supplies the energy as load demand requires.Renewable energy is crucial for being able to reduce the amount of CO2 we are pumping into the atmosphere and oceans to be able to mitigate dangerous levels of climate change. Climate change mitigation is a huge concern for governments around the world and with an ever-increasing energy demand, especially in newly industrialized countries. We need to adopt the Renewable energy for producing energy that is sustainable for future generations.Renewable energy is derived from renewable resources that are renewed naturally on a human timeline. Sunlight, wind, rain, tides, waves, and geothermal heat are all examples. In contrast to fossil fuels, which are depleted significantly faster than they are regenerated, renewable energy is rapidly renewed. Some renewable energy sources are not sustainable, despite the fact that the majority are. Some biomass sources, for example, are deemed unsustainable at current utilisation rates. Renewable energy is expected to surpass coal and natural gas as a source of electricity by 2040.

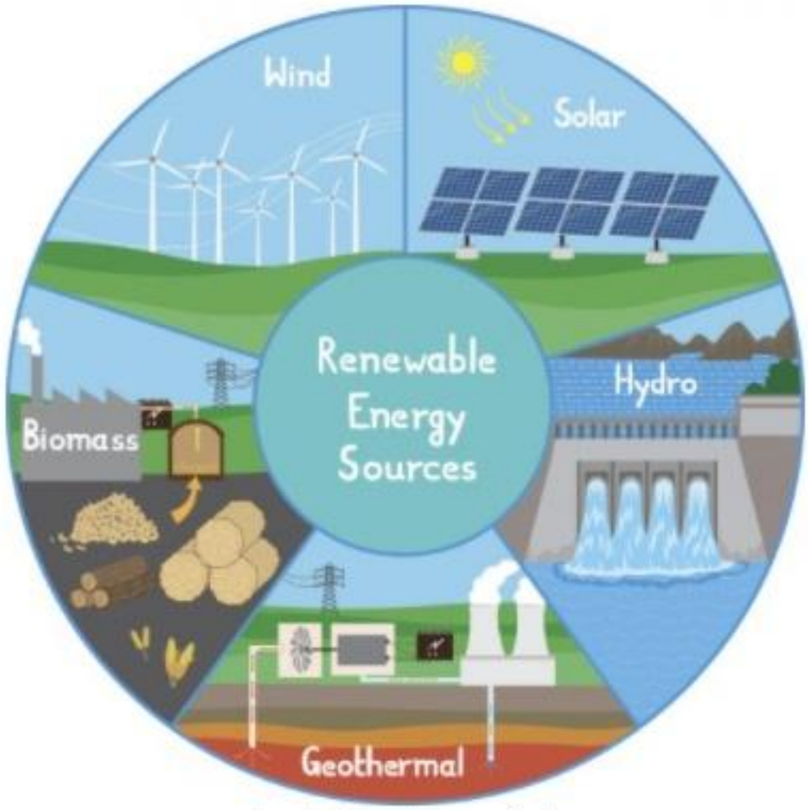

Figure 1.1 Block diagram of renewable energy

1.1 LITERATURE SURVEY

The line congestion to mitigate system has been done by several researches. Sun et al. [11] established a spatiotemporal network to optimize locational and hourly charging/discharging schedule of BEST. In [8], an efficient SCUC with integrated BEST model was presented and solved using Benders Decomposition approach. A stochastic programming model was proposed in [9] to optimize the schedules of power system with battery transportation under high share of wind energy, taking into account both load and wind energy forecasting uncertainties. Battery energy storage approach can be looked at as a promising planning tool for achieving the optimal sizing of transmission networks [7]. So, [11] the stationary transmission has been facing many challenges to solve this problem we have adopt BEST.

Lu & Li proposed a long-term planning with BEST in power system considering the investment cost of power generation, transmission line and BESs [9]. The obtained results showed that, the proposed mixed integer linear

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programming model could not solve large problems. In [10] a new approach, called Battery Transportation and Logistics was proposed to investigate the transportation and logistics (T&L) model for delivering green energy to end users.

In that respect, we note that in literature there is still a lack concerning BEST integration in the transmission grid. On the one hand, several papers investigate BEST optimal operations and locations [4], [8], and on the other hand, a few works consider mobile storage systems in the expansion planning problem [9].

The Literature pertaining to the mitigation of line congestion on power system & improvement of efficiency is tabulated as Table-1.

Table-1 Literature survey

S:No	Title of the paper	Year	Remarks
1	Giorgia Pulazza, Ning Zhang, Chongqing Kang, "Transmission planning with battery –based energy storage transportation with high penetration of renewable energy"	2021	Discussion regarding both stationary and battery energy storage transportation. This paper proposes long-term transmission-planning model coordinated with both stationary and mobile storage units.

2	G. Pulazza, N. Zhang, C. Kang, and C. A. Nucci, “Expansion Planning Model Coordinated with both Stationary and Transportable Storage Systems for Transmission Networks with High-RES Penetration”	2020	Transmission expansion planning model with BEST has been presented. The proposed mathematical model includes also stationary battery energy systems (BESs) in the planning scheme; hence the model output is the optimal set of transmission lines, BESs and BEST.
3	H. Abdeltawab and Y. A. I. Mohamed, "Mobile Energy Storage Sizing and Allocation for Multi-Services in Power Distribution Systems,"	2019	This paper proposed a sizing and allocation algorithm for a MESS in a power distribution system. The sizing problem aims at maximizing the distribution company profit by considering the participation of the MESS in multi grid-support services including energy arbitrage, voltage regulation.
4	P. P. Gupta, P. Jain, S. Sharma, K. C. Sharma and R.Bhakar, "Scheduling of Energy Storage Transportation in Power System Using Benders Decomposition Approach"	2018	This paper discussing the efficient SCUC with integrated BEST model was presented and solved using Benders Decomposition approach.

5	J. Yan et al."A new paradigm of maximizing the renewable penetration by integrating battery transportation and logistics"	2018	This paper proposes to investigate the transportation and logistics (T&L) model for delivering green energy to end users.
6	D. Lu and Z. Li, "Long-Term Planning with Battery-Based Energy Storage Transportation in Power System"	2018	Long-term planning with BEST in power system considering the investment cost of power generation, transmission line and BESs.
7	j. A. Aguado, S. de la Torre, A. Trivino "Battery energy storage systems in transmission network expansion planning"	2017	This paper proposed electrical energy storage approach can be looked at as a promising planning tool for achieving the optimal sizing of transmission networks.
8	H. H. Abdeltawab and Y. A. I. Mohamed, "Mobile Energy Storage Scheduling and Operation in Active Distribution Systems,"	2017	This paper proposes a dayhead energy management system (EMS) for a MESS that aims to minimize the cost of the power imported from the grid. The MESS does not only shift renewable energy power to load peak-hours but also can provide localized reactive power support.

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9	Y. Sun, J. Zhong, Z. Li, W. Tian and M. Shahidehpour, “Stochastic scheduling of battery-based energy storage transportation system with the penetration of wind power”	2017	This paper discusses to optimize the schedules of power system with battery transportation under high share of wind energy, taking into account both load and wind energy forecasting uncertainties.
10	S. Lumbreras, A. Romas, “The new challenges to transmission expansion planning”	2016	This paper discussing challenges faced in transmission.
11	Y. Sun, Z. Li, M. Shahidehpour and B. Ai, “Battery-Based Energy Storage Transportation for Enhancing Power System Economics and Security”	2015	This paper discusses to optimize locational and hourly charging/discharging schedule of BEST.
12	A. Poulikkas, “A comparative overview of large-scale battery systems for electricity storage”	2013	This paper proposes the different types of batteries used in BESs.

1.2WIND POWER GENERATION:

The utilization of wind turbines to generate electricity is known as wind power or wind energy. Wind energy is a popular, renewable energy source that has a far lower environmental effect than burning fossil fuels. Many individual wind turbines are linked to the electric power transmission network to form wind farms. A wind farm is a group of wind turbines in the same location. A large wind farm may consist of several hundred individual wind turbines distributed over an extended area. The land between the turbines may be used for agricultural or other purposes. For example, Gansu Wind Farm, the largest wind farm in the world, has several thousand

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turbines. A wind farm may also be located offshore. Almost all large wind turbines have the same design a horizontal axis wind turbine having an upwind rotor with 3 blades, attached to a nacelle on top of a tall tubular tower.

Equation for Wind Power

$$P = \frac{1}{2}\rho A V^3$$

Where

ρIs the Air density

A Is the Swept area

V Is the Wind speed

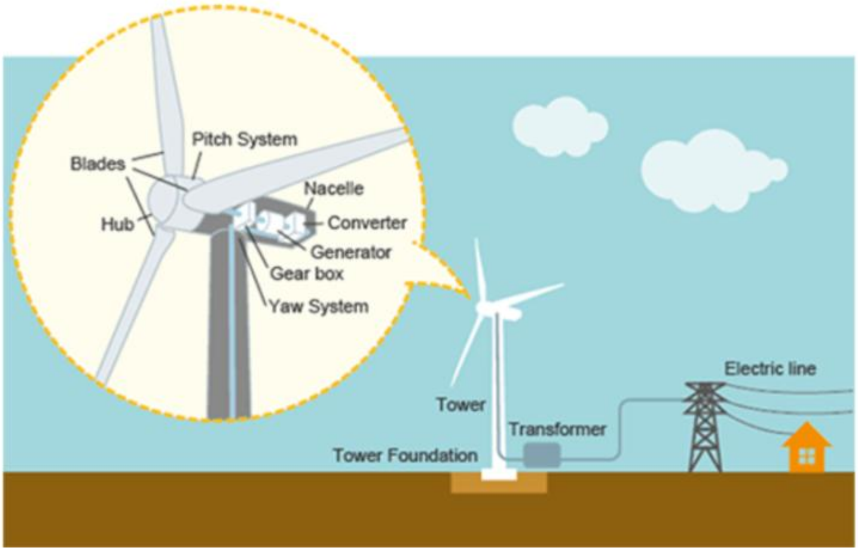

Figure 1.2.1 Wind power generation

1.2.1 Wind Farm Development

1. Understand your wind resource
2. Evaluate distance from existing transmission lines
3. Determine benefits of and barriers to allowing your land to be developed

4. Establish access to capital
5. Identify reliable power purchaser or market
6. Address site and project feasibility considerations
7. Understand wind energy's economics
8. Obtain zoning and permitting expertise
9. Establish dialogue with turbine manufacturers and project developers
10. Secure agreement to meet O&M needs.

1.3 SOLAR POWER GENERATION:

Solar energy is the conversion of light energy into electrical energy. Solarpower plants use one of two technologies 1) Photovoltaic systems (PV) and 2) Concentrated solar power.

1.3.1Photovoltaic cells:

A solar cell, often known as a photovoltaic cell (PV), is a device that uses the photovoltaic effect to convert light into electric current. Although the prototype selenium cells converted less than 1% of incoming light into energy, German engineer Bruno Lange created a photo cell utilizing silverselenide instead of copper oxide in 1931. Gerald Pearson, Calvin Fuller, and Daryl Chapin invented the silicon solar cell in the 1940s, and it was first used in 1954.

A photovoltaic power system, or PV system, provides direct current (DC) electricity that varies with the intensity of sunshine. Inverters are often used to convert this to certain required voltages or alternating current (AC) for practical usage. Inside the modules, many solar cells are linked. Modules are joined together to form arrays, which are then connected to an inverter, which generates electricity at the specified voltage and frequency/phase for AC.

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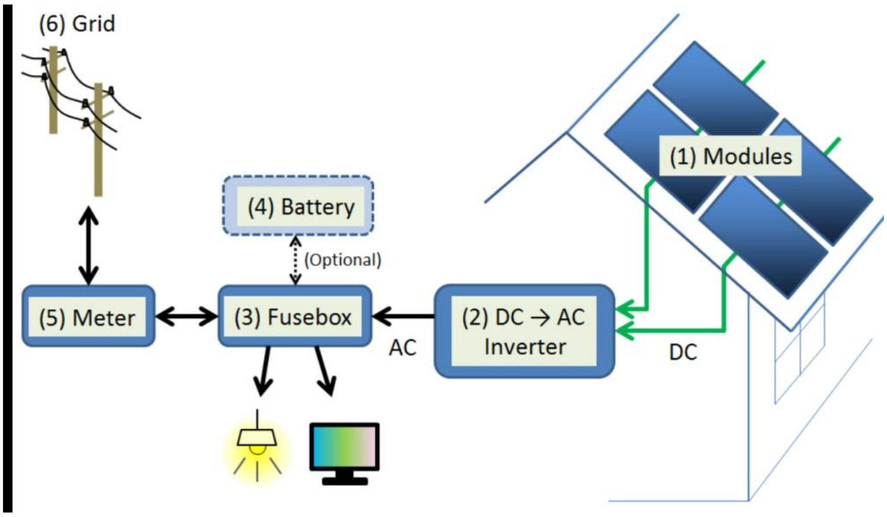

Figure 1.3.1 Photovoltaic cell solar power systems

1.3.2 Concentrated solar power (CSP)

Concentrated solar power (CSP), also known as "concentrated solar thermal," concentrates sunlight using lenses or mirrors and tracking systems, then utilizes the generated heat to create electricity using traditional steam-driven turbines. The parabolic trough, the small linear Fresnel reflector, the dish Stirling, and the solar power tower are among the most well-known concentrating devices. To monitor the sun and concentrate light, a variety of approaches are utilized. In all of these systems, concentrated sunlight heats a working fluid, which is subsequently employed for power generation or energy storage. Thermal storage efficiently enables for power generation for up to 24 hours.

A linear parabolic reflector focuses light onto a receiver positioned along the reflector's focal line in a parabolic trough. The receiver is a tube that is filled with a working fluid and is positioned at the focus points of the linear parabolic mirror. During daytime hours, the reflector tracks along a single axis to follow the sun. The best land-use factor of any solar technology is provided by parabolic trough systems.

A solar power tower concentrates light on a central receiver atop the tower using an array of tracking reflectors (heliostats). Power towers have a higher efficiency (thermal-to-electricity conversion) than linear tracking CSP schemes and can store more energy than dish stirling technologies.

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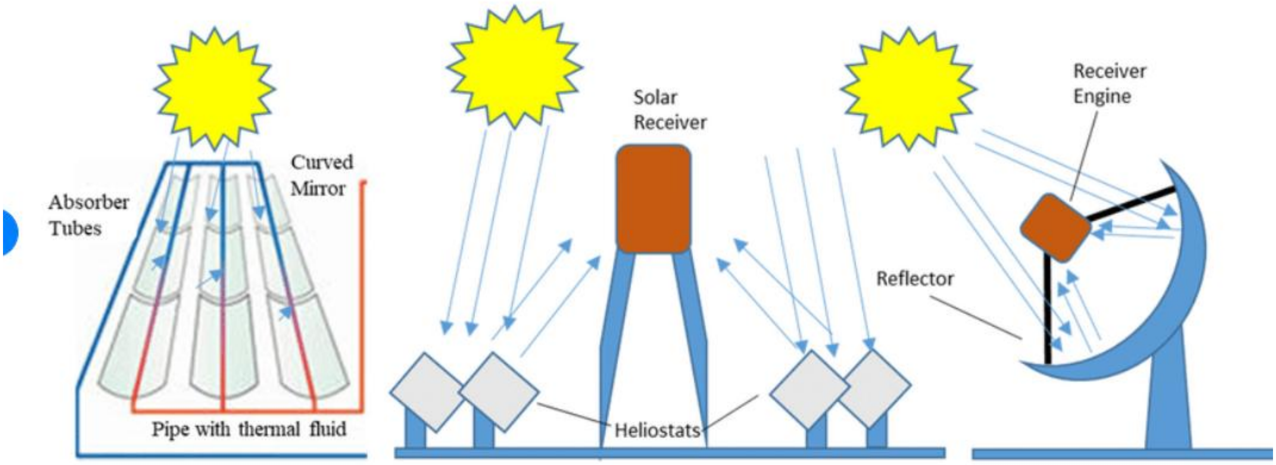

Figure 1.3.2 Concentrated solar power systems

BATTERY ENERGY STORAGE SYSTEM

Variable Renewable energy is not only high penetration but also non dispatch able. So, it causes several challenges for power system operation and planning has several challenges to ensure reliability, flexibility and security of supply. There are two major challenges i.e., 1) how to transmit large sums of renewable energy to load centers; and 2) how to accommodate the variability of renewable energy resources (RES) at load points. Energy storage system (ESS), which is rapidly improving, might provide a well-established solution to the two difficulties explained above. ESTs are divided into four types for grid-scale applications, including mechanical,

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electrical, chemical, and thermal. Mechanical storage, which includes pumped-hydro and compressed-air systems, provides for 99% of global storage capacity, although tight constraints prevent significant development for power system applications.

The storage systems are relevant and important to change to energy generation and consumption is being driven by three powers they are 1) Decarbonization, 2) Digitization and 3) Decentralization. Energy storage systems are capture energy and store it for use at a later time or date. A Battery Energy Storage System (BESS) is a device that uses specifically built batteries to store electric charge. The basic concept is that such energy can be used at a later date. A significant amount of research has resulted in battery advancements, which have helped to turn the notion of a Battery Energy Storage System into a commercial reality. The ability of a system to store energy via thermal, electro-mechanical, or electro-chemical solutions is referred to as an energy storage system. An electro-chemical solution is commonly used in a BESS.A battery energy storage system (BESS) is an electrochemical device that charges (means collects energy) from the grid or a power plant and then discharges that energy at a later time to provide electricity or other grid services when needed. Battery energy storage system is one of several technology options that can enhance power system flexibility and enable high levels of renewable energy integration. Several types of batteries are used for battery energy storage system all consist of electrochemical cells only.

2.1 CLASSIFICATION OF BESS BY BATTERY TYPES

2.1.1 Lithium-ion

Lithium-ion batteries, which have a large market share in portable consumer devices and are making the move to hybrid and electric vehicle applications, have grid storage potential as well. If the sector can achieve advancements and manufacturing economies of scale in the automotive and consumer electronics segments, they will most likely make their way into grid storage applications as well.

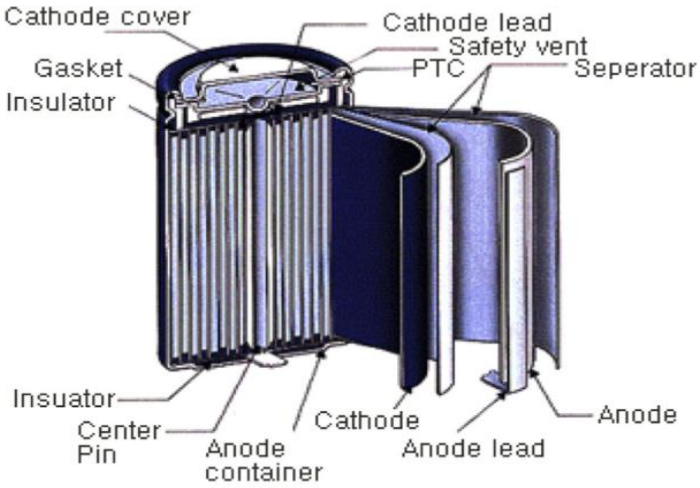

Fig. 2. Structure of lithium-ion battery [89]

Figure 2.1.1 Structure of Lithium-ion battery

Developers are aiming towards decreased maintenance and operating costs, excellent efficiency, and the ability to handle huge banks of batteries. For this battery chemistry to spread into various grid applications, continued cost reductions, longevity, and state-of-charge improvements will be important. In commercial usage, there are three varieties of lithium-ion batteries: cobalt, manganese, and phosphate. When lithium-ion batteries are employed for utility-scale applications, they are used for minutes of runtime and to provide regulation and power management service.

2.1.2 Lead-acid

The earliest form of rechargeable battery is the lead–acid battery, which was created in 1859 and uses a liquid electrolyte. Lead–acid batteries have a simple technology and inexpensive production costs; nevertheless, due to their poor energy-to-weight and energy-to-volume ratios, they are sluggish to charge, cannot be fully drained, and have a limited number of charge/discharge cycles. Lead and sulfuric acid are both very poisonous and hazardous to the environment, which is paradoxical when used in conjunction with clean energy sources like PV systems.

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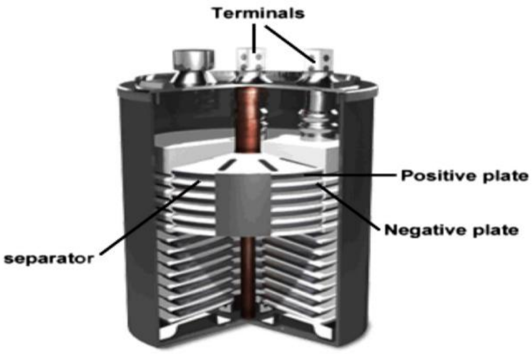

Fig. 1. Structure of lead–acid battery [88].

Figure 2.1.2 Structure of Lead-acid battery

By modifying the electrode configurations, the lead–acid battery chemistry may be adjusted for grid storage purposes beyond stability. The purpose of lead–carbon electrodes is to combine the high energy density of a well-designed battery with the high specific power generated by charging and discharging the electrochemical double layer. The expansion of cycle life durability and specific power has been the focus of lead–carbon electrode research. Carbon is added to the negative electrodes, and while it has no effect on the nature of the charge transfer processes, it boosts specific power and minimizes the occurrence of sulfating during charging cycles, which is one of the most common failure mechanisms in traditional lead–acid batteries.

2.1.3 Sodium Sulfur

Sodium–sulfur batteries are high-temperature rechargeable batteries that use metallic sodium and provide appealing solutions for a variety of large-scale electric utility energy storage applications. Load balancing, power quality, and peak shaving, as well as renewable energy management and integration, are some of the applications. A sodium–sulfur battery is a form of molten metal battery made up of sodium and sulfur. This type of battery has a high energy density, good charge/discharge efficiency, extended cycle life, and is made of low-cost components.

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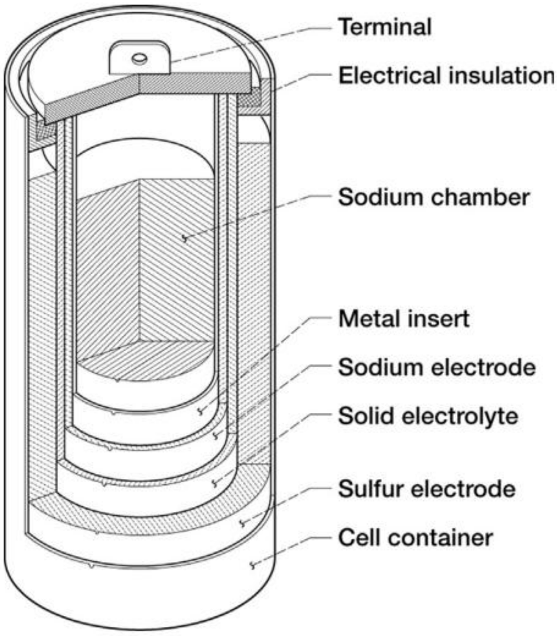

Fig. 5. Structure of sodium–sulfur battery [63].

Figure 2.1.3 Structure of Sodium-Sulfur battery

Sodium $\boldsymbol{\beta}$-Alumina (beta double-prime alumina) is a rapid ion conductor material that is utilized as a separator in molten salt electrochemical cells of various sorts. The main disadvantage is that temperature control is required to keep the ceramic separator and cell seal in good working order. The sodium/metal-chloride system was developed beginning in the mid-1980s. This technique might help solve some of sodium/development sulfur's problems.

2.1.4Flow batteries

A flow battery is a rechargeable battery in which an electrolyte containing one or more dissolved electro-active species flows through an electrochemical cell, which converts chemical energy to electricity directly. Additional electrolyte is often kept outside, in tanks, and pumped through the reactor's cell (or cells), however gravity feed systems are also available. Flow batteries can be quickly recharged by replenishing the electrolyte liquid (similar to how fuel tanks for internal combustion engines are refilled) while collecting the used material that would otherwise be

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recharged separately.

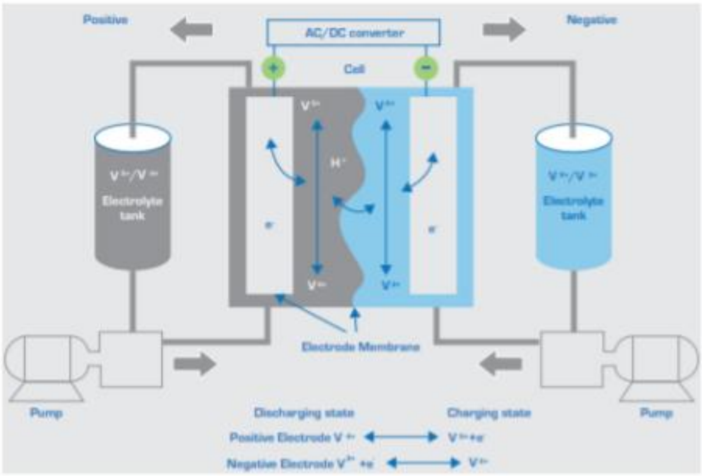

Figure 5. Schematic overview of operation of flow batteries [EASE]

Figure 2.1.4 Structure of Flow batteries

2.2MAIN COMPONENTS OF BESS

The BESS is a modular, Scalable solution that can be configured for different applications. The components are individually designed and manufactured to meet the specific demands of each installation.

1. Special E-house for BESS
2. Bidirectional converter
3. Battery bank
4. Power transformer
5. DC switchboards
6. AC switchboards
7. HVAC and fire control system
8. Energy Management System (EMS)

2.3 CHARACTERISTICS OF BESS

2.3.1 Round-trip Efficiency

It indicates the amount of usable energy that can be discharged from a storage system relative to the amount of energy that was put in. This accounts for the energy lost during each charge and discharge cycle.

2.3.2 Response Time

Amount of time required for a storage system to go from standby mode to full output. This performance criterion is one important indicator of the flexibility of storage as a grid resource relative to alternatives. Most storage systems have a rapid response time, typically less than a minute. Pumped hydroelectric storage and compressed air energy storage tend to be relatively slow as compared with batteries.

2.3.3 Ramp Rate

Ramp rate indicates the rate at which storage power can be varied. A ramp rate for batteries can be faster than 100% variation in one to a few seconds. The ramp rate for pumped hydroelectric storage and for compressed air energy storage is similar to the ramp rate of conventional generation facilities.

2.3.4 Energy Retention or Standby Losses

Energy retention time is the amount of time that a storage system retains its charge. The concept of energy retention is important because of the tendency for some types of storage to self-discharge or to dissipate energy while the storage is not in use.

2.3.5 Energy Density

It is the amount of energy that can be stored for a given amount of area, volume, or mass. This criterion is important in applications where area is a limiting factor, for example, in an urban substation where space could be a limiting constraint to site energy storage.

2.3.6 Power Density

Power density indicates the amount of power that can be delivered for a given amount of area, volume, or mass. In addition, like energy density, power density varies significantly among storage types. Again, power density is important if area and/or space are limited or if weight is an issue.

2.3.7 Safety

Safety is related to both electricity and to the specific materials and processes involved in storage systems. The chemicals and reactions used in batteries can pose safety or fire concerns.

2.3.8 Depth of Discharge (DoD)

It is refer to the amount of the battery's capacity that has been utilized. It is expressed as a percentage of the battery's full energy capacity. The deeper a batteriesdischarge the shorter the expected life time. Deep cycle is often defined as 80% or more DoD.

2.4 ADVANTAGES OF BESS:

1. Modular and customizable systems

2. Parallel operation with different power sources

3. On-grid and off-grid operation

4. Remote monitoring and control

5. Complete energy management

6. Real-time operation settings

7. No pollution generation

8. High energy density

9. High storage capacity

10. Low maintenance

BATTERY ENERGY STORAGE TRANSPORTATION

Transmission network expansion is commonly required to meet current or emerging energy demands. Transmission network expansion planning is traditionally enabled by the building of new power lines. However, in most cases, growth is not possible right once since the installation of new lines may necessitate the acquisition of facilities or authorizations that are not readily available. The transportation of modular BESs modules by rail cars or trucks is known as BEST. The potential of BESs in terms of load shifting and VRE use may be further utilized with such an innovative approach. BEST is the transportation of modular BESs modules via train cars or trucks. BEST can be charged and discharged only in one bus because it seems reasonable not to allow intra-day BEST routes when dealing with transmission networks. BEST is postponing or reducing the investment of transmission lines, but they also increase the support on frequency and voltage enabling higher transmission capability. BEST can act as generator or load when it is connected to the grid.

3.1 THE CHALLENGES OF TRANSMISSION

3.1.1 Deregulation

The deregulation of the power sector has meant that Generation Expansion Planning (GEP), which was once centrally performed, is now a decision taken privately by the companies participating in the generation market. This is especially important considering that, while building a power plant can take around one to three years for some technologies, transmission projects have a much longer lead-time. Therefore, TEP must anticipate generation investments, but there is no longer a binding, coordinated generation expansion plan that can guide transmission decisions. In addition, there are new objectives of transmission expansion that have been brought by deregulation, the most important one being facilitating competition.

3.1.2 Renewable penetration

The European Union has set aggressive targets for greenhouse gas (GHG) emission reductions. It should lead to large amounts of renewable generation being installed in the coming decades. A large part of this new generation will be installed in the areas were its resource (namely, wind and solar) abounds. This often coincides with relatively remote areas for which connection capacity to the bulk system should be either reinforced or built altogether. A particularly good example of this is offshore wind, which requires the Greenfield design and construction of a new transmission system from the plant to the onshore grid. In addition, an important part of this generation will be no controllable, which brings additional problems to the operation of the system. When performing TEP, several operation situations should be considered when assessing the possible benefits of network reinforcements an average scenario is not sufficient. Moreover, long-distance flows are needed in order to export any excess generation or provide a backup when renewable are not available. This means that the transmission network should increase the connection capacity between different zones in order to even their unbalances.

3.1.3 Large-scale generation projects

Usually in relation to renewable, there is currently a wide arrange of extremely ambitious projects that contemplate the installation of large amounts of new generation capacity, such as Deserter or Med grid. These schemes extend across borders and require large transmission investments in order to support the long-distance flows they would cause.

3.1.4 Market integration and regional planning

The European Union established three main objectives in its energy policy: affordable and competitive pricing, sustainability and reliability. It has been said that “A well-integrated internal energy market is a fundamental pre-requisite to achieve these objectives in a cost-effective way. “The fundamental rules for this market are set

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out in the Internal Market in Electricity Directive [10]. One of the main obstacles to the creation of the internal electricity market is the lack of sufficient interconnection capacity among the Member States. It is necessary to study how to increase this connection capacity in a cost-efficient way, therefore performing TEP at a joint level.

So, these are challenges of transmission expansion planning in this case, energy storage systems, particularly battery energy storage systems, may be a viable option since they decrease the need for extra capacity to deal with demand peaks, preventing wasteful network development.

The integrated security-constrained unit commitment (SCUC) solution will give the BEST charging/discharging schedule on a location and hourly basis in order to save power system running costs. The BEST application in SCUC will take into consideration thermal unit constraints, power transmission constraints, BEST charging/discharging constraints, and BEST transportation constraints Battery-Based Energy Storage Transportation (BEST) can be utilized by Independent System Operate (ISO) to compensate issues. BEST can act as load as well as source and needs to be modeled adequately in Security Constrained Unit Commitment (SCUC) formulation with adequate reserve constraint to gain the reliable performance.

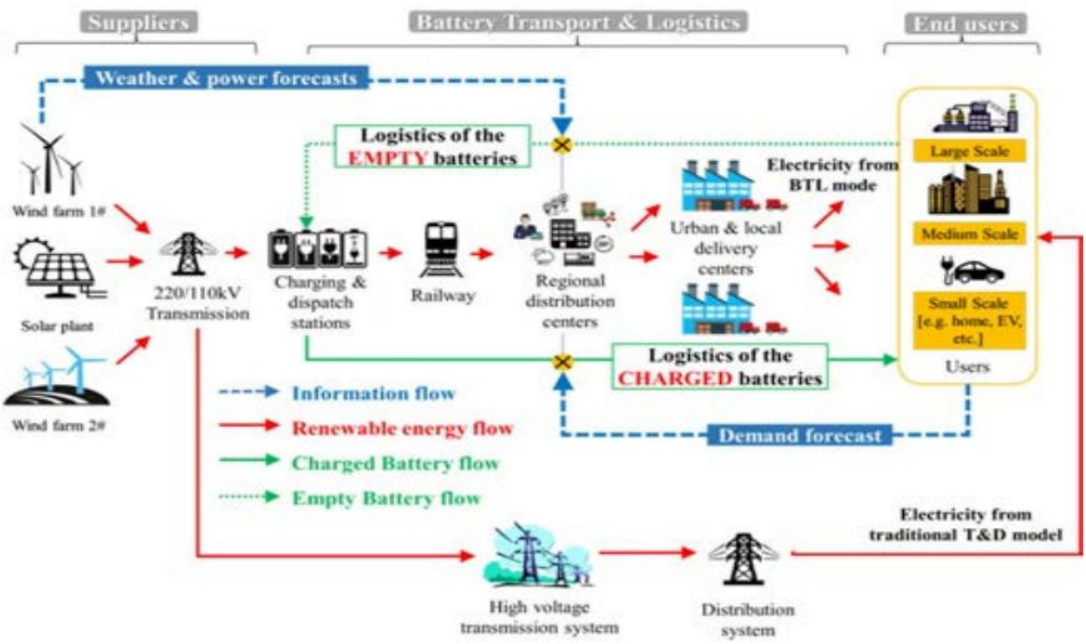

Figure 3.1.1 Battery energy storage transportation

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3.2 ASSUMPTIONS OF BEST

• The model is static (single-stage planning). It only considers the investment decisions to supply the demand of a target year.

• DC power flow representation is adopted, and line losses are neglected.

• The generation planning is given as a boundary condition.

• To represent daily storage cycles, demand and VRE production correlations, and each operation condition is described by 1 day with hourly resolution.

• A daily energy balance is set for both transportable and stationary storage units.

• No BEST intra-daily routes are allowed. This paper proposes BEST displacements only between different operating conditions, i.e. operating days.

• Dynamic planning and long-term uncertainties are beyond the scope of this paper.

• VRE uncertainty in spinning reserve requirement is represented through a Gaussian distribution.

3.3 THE OBJECTIVE OF BEST

1. Reducing the total system cost

The objective to minimize the total cost, which is the sum of the annualized investment costs and the operation costs of the system under study

$$OF = \min C^{inv} + C^{oper}$$

$$C^{inv} = \sum C_l^{Line} X_l + \sum C_{ibes}^{Storage} Y_{ibes} + \sum C_{ibes}^{Best} V_{ibes}$$

$$C^{oper} = \tau \sum d_j \sum C_i^{gen} \sum P_{i,j,t}^{gen} + \tau \sum d_j \sum \sum L_{ib,j,t}^{shed} C^{shed}$$

C^{inv} It denotes the annualized investment cost of transmission lines, BESs and BESTs.

C^{oper} It includes only variable costs and, it is given by the sum of three components: the fuel consumption of conventional generating units, the load shedding penalty and the BEST operation cost, respectively.

2. Increasing Efficiency
3. Decreasing Transmission line utilization
4. To decrease the renewable energy curtailment

METHODOLOGY

4.1 BEST MODEL

Constraints (1) enforce the energy limits for the transportable storage systems in each time period and operating condition.

$$V_{i_{best}} S_0^{i_{best}} + \sum_{ib} \sum_{t=1}^{t_n} (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - \frac{P_{i_{best},ib,j,t}^{best,dis}}{\eta_{dis}^{i_{best}}})\tau \geq V_{i_{best}} S_{min}^{i_{best}}$$

$$V_{i_{best}} S_0^{i_{best}} + \sum_{ib} \sum_{t=1}^{t_n} (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - \frac{P_{ibest,ib,j,t}^{best,dis}}{\eta_{dis}^{ibes}})\tau \leq V_{i_{best}} S_{max}^{i_{best}} \text{ .... (1)}$$

$\forall i_{best}$, j, t_n = 1, 2,…..,T

Constraints (2) enforce the transportable storage energy balance per day.

$$\sum_{ib} \sum_{t=1}^{T} (\eta_{ch}^{i_{best}} P_{i_{best},i_b,j,t}^{best,ch} - \frac{P_{i_{best},i_b,j,t}^{best,dis}}{\eta_{dis}^{i_{best}}})\tau \text{ ....}$$

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(2)

Constraints (3) are the charging and discharging bounds for the transportable storage systems.

$$V_{i_{best}} P^{i_{best}}_{min,ch} \leq P^{best,ch}_{i_{best},i_{b},j,i} \leq V_{i_{best}} P^{i_{best}}_{max,ch}$$

$V_{i_{best}} P^{i_{best}}_{min,ch} \leq P^{best,dis}_{i_{best},i_{b},j,i} \leq$

$V_{i_{best}} P^{i_{best}}_{max,ch}$……………………………………………………........................ (3)

$\forall i_{best}$, j, i_{b}, t

Constraints (4) set the mutual exclusion constraint of the charge and discharge state of the BEST. It enforces the BESTs to be only in one bus of the network in each time period and operating condition.

$NZ\left(P^{best,ch}_{i_{best},i_{b},j,t}\right) + NZ\left(P^{best,dis}_{ibest,ib,j,t}\right) \leq 1$

……………………………………………………………. (4)

$\forall i_{best}$, j, t   NZ= number of non zeros

As we are dealing with a transmission network, we feel it reasonable to enforce BESTs to be in one bus only of the network in each operating condition, which in our case refers to a day.

$NZ(\left(\sum P^{best,ch}_{i_{best},i_{b},j,t}\right) + \left(\sum P^{best,dis}_{i_{b},ib,j,t}\right) + P^{best,ch}_{i_{best},i_{b},j,t} + P^{best,dis}_{i_{best},i_{b},j,t}) \leq 1$

………………. (5)

$\forall i_{best}$, j, t = 1,2 ,………T−1

It should be noted that the application of the number of nonzero function (NZ) as done in (4) and (5) (which in the equations and in the following has been referred to as NZ function for simplicity) makes it possible to successfully model the transportable storage systems avoiding the use of additional binary variables, which could increase drastically the computational burden, especially for large scale power network.

Concerning the BEST operation cost, the following equations.

$n^{i_{best}}_{dist} = n^{0}_{dist} \sum_{j=1}^{n_{oc}} n^{i_{best}}_{dist,j}$ ……………………………………………………….

(6)

$n^{i_{best}}_{j} = find \sum_{t=1}^{T} (P^{best,ch}_{i_{best},i_{b},j,t} + P^{best,dis}_{i_{best},i_{b},j,t})$

……………………………….…. (7)

$n_j^{i\ \ best} = n_{oc} - \sum_{j=1}^{n\ \ oc} n_{0,j}^{i\ \ best}$

…………………………………………………… (8)

Where:

1. $n_{dist}^{i\ best}$ It is the distance to be covered for the transportation of the BEST system ibest.
2. $n_{i\ \ best}^{0}$ It is represents the distance between adjacent buses,
3. $n_{dist,j}^{i\ best}$ It is denotes the non-dimensional 'bus distance' between operating conditions j and j +1 of the BEST system,
4. $n_j^{i\ \ best}$ It is represents the bus number of the BEST system $n_j^{i\ \ best}$ in operating condition j,
5. $n_0^{i\ \ best}$ It is the number of operating conditions where the BEST system is not used, and
6. $n_{0,j}^{i\ best}$ It is Indicates whether the BEST system t is operative in operating condition j.

4.2 BES MODEL

Constraints () enforce the energy limits for the stationary storage systems in each time period and operating condition.

$$\mathrm{Y}_{\mathrm{i}\ \ bes} S_0^{i\ \ bes} + \sum_{t=1}^{t\ \ n} ((\eta_{ch}^{i\ \ bes} P_{i\ \ bes,ib,j,t}^{bes,ch} - \frac{P_{ib\ \ bes,i\ \ b,j,t}^{bes,dis}}{\eta_{dis}^{ibes}})\tau \geq Y_{i\ \ bes} S_{min}^{i\ \ bes}$$

$$Y_{i\ \ bes} S_0^{i\ \ bes} + \sum_{t=1}^{t\ \ n} ((\eta_{ch}^{i\ \ bes} P_{i\ \ best,i\ \ b,j,t}^{bes,ch} - \frac{P_{i\ \ bes,ib,j,t}^{bes,dis}}{\eta_{dis}^{i\ \ bes}})\tau \leq$$

$Y_{i\ \ bes} S_{max}^{i\ \ bes}$ ………….. (9)

$\forall i_{bes}$, j = 1,2 ,………T

Constraints (10) enforce the stationary storage energy balance per day.

$$\sum_{t=1}^{T} \left(\eta_{ch}^{ibest} P_{ibes,j,t}^{bes,ch} - \frac{P_{ibest}^{bes,ch}}{\eta_{dis}^{ibes}}\right)\tau = 0 \text{ ……………………………………. (10)}$$

Constraints (11) are the charging and discharging bounds for the stationary storage systems.

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$$Y_{i_{bes}} P^{i_{bes}}_{mi,ch} \leq P^{bes,ch}_{i_{bes},j,i} \leq Y_{i_{bes}} P^{i_{bes}}_{max,ch}$$

$$Y_{i_{bes}} P^{i_{bes}}_{min,dis} \leq P^{bes,ch}_{i_{bes},j,i} \leq Y_{i_{bes}} P^{i_{bes}}_{max,dis} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

4.3 TEP AND NETWORK CONSTRAINTS

The energy balance at each node of the system is represented in constraint (12).

$$\sum P^{gen}_{i,j,t} + \sum P^{wind}_{wj,t} + \sum P^{solar}_{pv,j,t} + \sum (P^{best,dis}_{i_{best},j,t} - P^{best,ch}_{i_{best},ib,j,t}) + \sum (P^{dis}_{i_{bes},j,t} - P^{ch}_{i_{bes},j,t}) = L_{ib,j,t} - L^{shed}_{ib,j,t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Constraint (13) enforces the transmission capacity limits for existing and prospective lines, respectively.

$$-F^{max}_{l} \leq F_{l,j,t} \leq F^{max}_{l}$$

$$-X_l F^{max}_{l} \leq F_{l,j,t} \leq X_l F^{max}_{l} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$\forall l$, j, t= 1,2 ………T

Constraints (14), (15) and (16) refer to the production bounds of thermal units, wind units and solar ones, respectively.

$$P^{gen,min}_{i} \leq P^{gen}_{i,j,k} \leq P^{gen,max}_{i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$\forall$ i, j, t = 1,2 ………T

$$0 \leq P^{wind}_{w,j,t} \leq P^{f}_{w,j,t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

$\forall$ w, j = 1,2 ………T

$$0 \leq P^{solar}_{pv,j,t} \leq P^{f}_{pv,j,t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

$\forall$pv, j = 1,2 ………T

Constraints (17) enforce the load shedding bound, when allowed.

$$0 \leq L^{shed}_{i_b,j,t} \leq L_{i_b,j,t} L^{shed}_{param} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

$\forall i_b$, j, t = 1,2 ………T

4.4SCUC FORMULATION WITH BEST

The SCUC model with BEST is described as follows.

1. Objective Function of SCUC
2. Thermal Unit Constraints
3. BEST Constraints

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4.4.1Objective Function of SCUC

The objective function (18), which is the overall cost, is composed of two parts. The first part is the total power production cost which includes fuel costs for producing electric power and startup and shutdown costs of individual units over the scheduling horizon.
$\min \sum_t \sum_{u \in G} [F_{C,u}(P_{u,t}) + SU_{u,t} + SD_{u,t}] + \sum_k \sum_s C_{k,ij} I_{k,ij,s}$ ……… (18)

4.4.2Thermal Unit Constraints

The thermal unit constraints include capacity limits of generating units (19), ramping up limits (20), ramping down limits (21).

$P_{min} I_{u,t} \leq P_{u,t} \leq P_{max,u} I_{u,t} \forall u, \forall t$ ……………………………(19)

$P_{u,t} - P_{u,t-1} \leq UR_u(1 - y_{u,t}) + P_{min,u} y_{u,t} \forall u, \forall t$…………….(20)

$P_{u,t} - P_{u,t-1} \leq DR_u(1 - y_{u,t}) + P_{min,u} z_{u,t} \forall u, \forall t$……………..(21)

4.4.3 BEST Constraints

Equation (22) represents BEST state constraints. Each BEST k can only be on one arc in time span s. Equation (23) represents BEST connection constraints..

$\sum_{ij \in A} I_{k,ij,s} = 1 \forall s, \forall k$……………………………………………………………..(22)

$\sum_{ij \in A_i^+} I_{k,ij,s+1} = \sum_{ij \in A_i^-} I_{k,ij,s} \forall s=1 \ldots N-1, \forall i, \forall k$ ……………………… (23)

The BEST charging/discharging power constraints are given in (24). BEST k charges from the grid when$P_{k,i,t} > 0$ and discharges to the grid when $P_{k,i,t} < 0$. Note that, is negative. As mentioned before, a BEST state can only exchange power with the grid when it is in horizontal TSN arcs, which means that the BEST stops at a certain station when it is connected to the grid at that station. The BEST energy capacity constraints are given in (25). The BEST energy balance constraints are given in (26). The BEST terminal energy capacity constraints are given in (27).

$I_{k,ij,s} P_{min,k} \leq P_{k,i,t} \leq I_{k,ij,s} P_{max,k} \forall t \in T_s, \forall s, \forall k, \forall i$ …………………….. (24)

$E_{min,k} \leq E_{k,t} \leq E_{max,k} \forall k, \forall t$ ……………………………………………….(25)

$E_{k,t} = E_{k,t-1} + \sum_i P_{k,i,t} \forall k, \forall t$ ……………………………………………….(26)

$E_{k,t} = E_{k,NS} = NS \quad \forall k$ …………………………………………………….(27)

4.5 PROBLEM SOLVING

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Initially, the optimization problem by expressing the investment cost of stationary and mobile storage units through binary variables. Subsequently, when increasing the complexity of the mathematical model due to the introduction of spinning reserve, we had to relax these binary variables and turn them into continuous ones, in order to achieve the numerical solutions in a reasonable computational time. It is worth noting that this provides as output also the size of both stationary and transportable storage units and not only their locations.

This methodology presents a novel mathematical approach for the transportable storage systems scheduling, which allows us to avoid the inclusion of additional binary variables, and therefore to decrease the complexity of the problem. To accomplish that, we have made use of the NZ function, which output is the number of nonzero elements of a generic input matrix. The application of NZ function allowed us to add two constraints only, and, to successfully implement the scheduling of each transportable storage systems, which we feel represents a novel contribution to the subject.

MOBILE ENERGY STORAGE IN POWER DISTRIBUTION SYSTEMS

A mobile energy storage system (MESS) is a localizable transportable storage system that provides various utility services. These services include load leveling, load shifting, losses minimization, and energy arbitrage. A MESS is also controlled for voltage regulation in weak grids. The MESS mobility enables a single storage unit to achieve the tasks of multiple stationary units at different locations. The MESS is connected to the grid at specific substations (or buses) known as MESS stations. This paper proposes an optimization algorithm for sizing and allocation of a MESS for multi-services in a power distribution system. The design accounts for load variation, renewable resources intermittency, and market price fluctuations. A realistic dynamic model for the MESS is adopted to consider the capacity and lifetime constraints.

The distribution power system structure is evolving to fit the increasing renewable energy sources penetration. Recent research shows that for every 10% wind penetration, a 2-4% balancing generation is needed for stable operation [1]. The renewable energy future goes hand in hand with energy storage systems (ESSs). An ESS can provide various grid support services due to its fast time-response and various power and energy density in different technologies. As a result, ESSs have various applications for both the energy and transport sectors as explained in [2]. The economic benefit of ESSs is feasible when combined with renewable resources, such as PV or wind farms for power regulation. Optimal sizing of ESS for these applications is key for a successful investment. With the increasing number of RESs dispersed in the system, a large number of ESSs is needed to support grid stability and reliability. Because ESSs are relatively expensive for their lifetime, distributed ESSs represent an expensive RES integration solution.

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For instance, the ESS power conversion system per-unit cost. Thus, a significant saving is achievable if a single bulk ESS can replace a large number of smaller ESSs. On the other side, distributed ESSs provide essential services that a single centralized ESS cannot provide, such as voltage regulation and power losses minimization. A MESS can provide a solution for the aforementioned trade-off. A MESS is a single ESS plugged into the system at different locations during different times [8]. It can be regarded as a distributed ESSs working at different times but a cheaper alternative. The main advantage of the MESS is the transportability that enables delivering a localized reactive/active power support for voltage regulation, power loss reduction, and dispersed RESs integration.

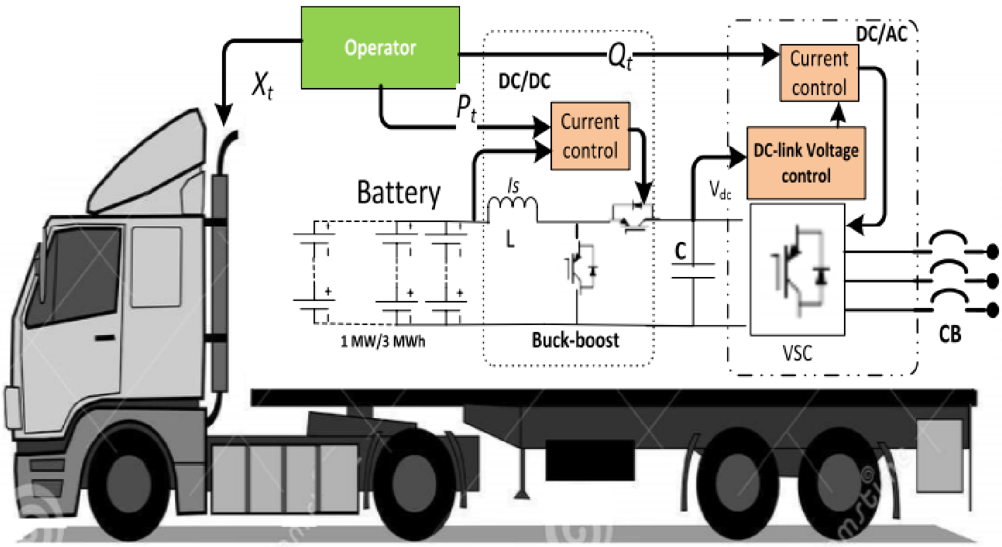

Figure 5.1 MESS Structure

The MESS is a promising storage technology that will contribute to solve many issues in active distribution systems. Optimal scheduling and energy management algorithms for a MESS in an active distribution system are not developed in the current literature. This work proposes a day-ahead energy management system (EMS) for a MESS owned by a DNO. The DNO uses the MESS for minimizing the day-ahead cost of power imported from the grid. Further, MESS provides a reactive power support for the system for voltage regulation at critical loads. The authors want to emphasize that this work does not compare by any mean the fixed ESS with the Mobile one from the economic point of view, rather this work presents a management system if the DNO found a MESS investment is a profitable one.

5.1 MESS Model

The feeder has RESs set $\mathcal{N}r$ at different locations of the feeder, such as wind energy conversion systems (WECS) and photovoltaic (PV) power generators. Furthermore, other dispatch able resources (such as micro turbines) exist at different buses and defined by the set $\mathcal{N}g$. Moreover, the feeder has a load set $\mathcal{N}l$ with some smart houses (net-zero houses) that may use a rooftop PV, heat pumps, electric storage, and electric vehicle. RESs have different profiles that can be forecasted efficiently using both numerical and physical techniques. Moreover, electrical loads can be accurately predicted for the day-ahead operation planning. It should be emphasized that even with a 10-15% power prediction error, a day-ahead EMS.

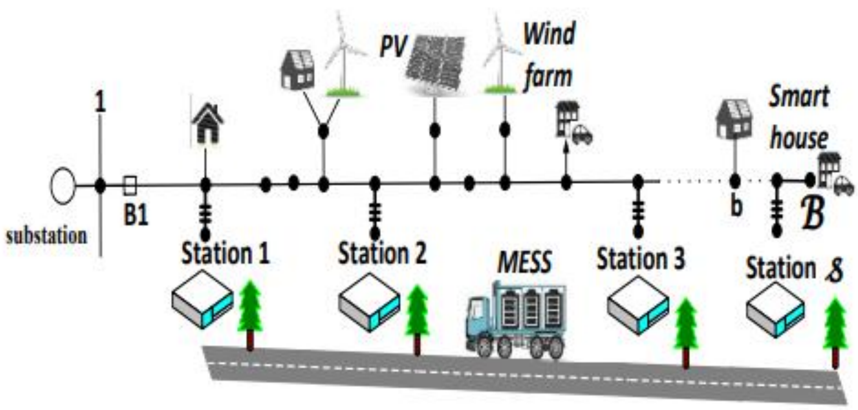

Figure 5.1.1 Radial feeder with multi-MESS stations.

For instance, a day-ahead EMS decides the reactive power set point; however, due to unpredictable real-time changes (sudden load change, faults or outages, RES intermittency), the actual reactive power is tuned by a real-time on-line voltage controller that measures the bus voltage and tunes the reactive power accordingly. This multi-level control scheme has been adopted widely in the literature such as in [28]. In power system dispatch, the system operator adopts the same strategy when it comes to frequency control.

The DNO can schedule a MESS to move between different positions for multi-services. Different MESS positions ($\mathcal{N}s$ ={1,2,..,$\mathcal{S}$}) define the buses at which the MESS can be connected to the system which will be designated as the MESS stations. Fig. 3 depicts the structure of a MESS which consists of two parts: the ESS and the truck. The ESS consists of an array of battery cells.

While the battery bank terminal voltage is determined by the number of series cells in the same string, the total current is the sum of the parallel strings currents. The reader is referred to IEEE standards 485 for further sizing details. The ESS is connected to the grid via a DC/DC/AC bidirectional VSC. The DC/DC converter is a current-controlled buck-boost controller.

CONCLUSION

This paper has addressed the long-term transmission planning problem including stationary and transportable battery energy system (BES and BEST, respectively), adopting a novel mathematical approach for the BEST vehicle scheduling problem, which can be suitable for extended portions of large-scale power systems. In particular, the number of non-zero function is included in the optimization model set of constraints, avoiding the use of additional binary variables, as generally accomplished for addressing vehicle scheduling, which would considerably increase the computational burden.

Depending on the variables indicating whether to settle the stationary or transportable battery system, binary or continuous, the model allows us to identify either the storage system's optimal location or both optimal location and size of storage systems.

The model application to the above systems allows us to infer that:

1) BEST system is a suitable alternative to manage transmission congestion in power networks with high penetration of renewable energy.

2) BEST application allows the reduction of renewable energy curtailment almost in all cases and its contribution will be reasonably even more relevant when renewable energy curtailment penalties would be applied. It is worth noting that for one of the

examined cases, case I, the adoption of BEST results not only in a lower operation cost (1.3 109 CNY), but also in a reduced wind and PV curtailment of 35% and 8% respectively.

3) When technically feasible, both position and size of storage systems should be allocated in the coordinated planning problem. The proposed approach is more convenient with respect to the case where storage system size has a fixed value, and it allows load shedding to be equal to zero.

The developed methodology can find useful applications also in problems where BEST is investigated as a promising tool for facing emergency situations, and for enhancing power grid resiliency. Moreover, the application of the above-mentioned NZ function can bring interesting benefits also to other optimization problems involving a consistent number of binary variables.

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