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Alternative Energy Storage Solutions for Renewable-Based Energy Systems

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Abstract—The generation of electricity from renewable sources has experienced significant global growth, including in India. However, these sources often cannot provide a consistent and easily adjustable supply to meet consumption needs. As a result, renewable energy typically cannot immediately respond to fluctuations in consumer demand, leading to greater challenges in maintaining network load stability. This situation has made energy storage systems a vital component in managing energy from renewable sources.The capacity to store energy is essential for strengthening power grids and ensuring stable load management.. Various Energy reserves methods exist, few of them are in current use and some are in development stage.This paper offers an overview of the key characteristics of different electricity storage techniques, including hybrid Energy reserves technologies and their utilization. A specific focus is given to hybrid energy storage systems that combine super-capacitors with battery energy storage devices. Additionally, the paper discusses the functionality of hybrid energy reserves systems..

Keywords-Energy storage system, Hybrid Energy Storage System, Renewable energy system, Grid system, battery

I. INTRODUCTION

Wind and solar energy sources are plentiful but are characterized by unpredictable fluctuations.. For lower levels of intermittent power, managing this variability can be done with relative ease and minimal cost. However, as dependence on renewable energy increases, the challenges and costs associated with balancing the grid become more significant. Additionally, transmission capacity can become a constraint. A promising alternative to conventional methods is the use of bulk energy reserve systems to store intermittent electricity, ensuring system reliability. As a result, a range of Energy retention technologies has been developed.[1][2].Ensuring a continuous and reliable electricity supply is critical for both power systems and power electronics. Relying on a single energy source with low reliability can negatively impact electrical and electronic systems. Factors such as rising fuel costs, decreasing reliability of traditional power sources, growing demand, and the harmful environmental impact of fossil fuels have driven the increased utilization of nonconventional energy resources. This trend encourages ongoing research and technological advancements aimed at safely and reliably integrating renewable systems into the grid. Energy reserves systems play an important role in modern as well as upcoming electric grids due to their ability to

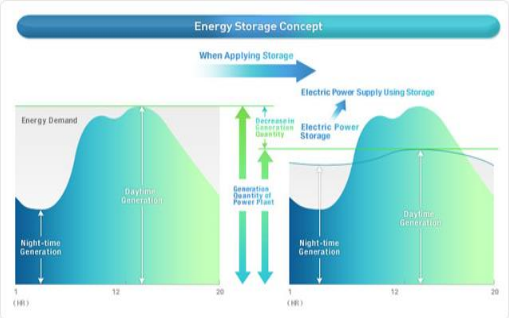

Fig.1 Concept of Energy Storage [3]

provide multiple services. Electricity generation from sources like wind and solar is influenced by variables such as solar radiation, temperature, and wind speed [3]. Hybrid power systems, which combine different energy generation methods with energy storage, can ensure a stable power supply at all

Technology	Power	Energy density	Backup time	Response time	Efficiency	Lifetime
Pumped Hydro	100mW-2GW	400Mwh-20Gwh	In Hours	12 Minutes	70-80%	50
CAES	110mW-290Mw	1.16Gwh-3Gwh	In In Hours	12 Minutes	99%	<50
BESS	100mW	1kwh-200 Mwh	In Hours	Seconds	60-80%	<10
Flywheels	5kW-100 MW	5Kwh-200 Kwh	In Minutes	12 Minutes	80-95%	20
Super capacitors	<1mW	1wh-1kWh	In Seconds	Milliseconds	>95%	>10
Pumped Hydro	100mW-2GW	400Mwh-20Gwh	In Hours	12 Minutes	70-80%	50
CAES	110mW-290Mw	1.16Gwh-3Gwh	In In Hours	12 Minutes	99%	<50

TABLE1 COMPARISON OF DIFFERENT ENERGY STORAGE TECHNOLOGY

times, regardless of fluctuations in energy generation. In such systems, the output remains constant while the input power comes from multiple sources.

The idea of hybrid energy storage systems is becoming increasingly significant, particularly in area that require load balancing,[4-5] more energy-density storage, and backup power. These systems provide an ideal platform for simulation and modeling, integration of various elements of electrical power,power electronics and control systems, Circuit-level simulations of energy reserves technologies for example batteries and super-capacitors, can be conducted using MATLAB/Simulink to analyze performance characteristics. Energy sources are connected to a DC bus through DC to DC power converters.[6]

Furthermore, a new system designed to stabilized supply and demand in deregulated energy markets may impose penalties on intermittent energy sources like wind.[7] One solution to address this issue is to incorporate storage systems that recognize wind/storage plants as unified entities. This would classify the outcome of the entire system as alternative energy, helping to solve transmission and reliability concerns. In the future, this approach could allow wind generated power to meet up to 80% of entire electricity demand.[8]

Fig.1 illustrates the concept of energy storage. A comparison of current storaging technologies, as shown in Table 1, highlights that compressed air energy storage (CAES) systems, particularly advanced variants like CASH (CAES with Humidification) and CAESSI (CAES with Steam Injection), are among the most cost-effective and environmentally friendly options. For wind energy systems, both seasonal as well as short-term storage solutions are technically and economically feasible.

II. VARIOUS TYPES OF ENERGY STORAGE SYSTEMS

A. Storage of Chemical Energy

Because the output of many renewable energy technologies, like solar and wind energy, is very much uncertain and dependent on the solar irradiation, winds speed water or currents, they cannot be used to generate base-load electricity. Therefore, any transition to these technologies depends heavily on batteries and other energy storage technology [9]. In addition to conventional batteries, the power storage industry [10] also includes hydrogen based fuel cells and mechanical options such as flywheels that have the ability to replace batteries. The topic of nanotechnology is also seeing an increase in research since nanomaterials and ultra-capacitors—high power, high energy density electrochemical devices that are simple to charging/discharging capability to greatly extend the capacity and lifespan of batteries. Certain energy sources, like wind, solar, and photovoltaic, are only utilised for power generation; others, like batteries and fuel cells, are used for storage; yet others, like pumped storage and batteries, serve two uses.

a) Hydrogen serves as a chemical energy carrier, similar to ethanol, natural gas,or gasoline. Being the only chemical energy carrier with zero emissions or zero carbon content makes hydrogen special. An industrial chemical that is frequently utilised and it is from any basic energy source i.e hydrogen. Producing hydrogen in quantities large enough to replace current hydrocarbon fuels is not feasible. Hydrogen manufacturing plants will need to be heavily invested in, and more energy than is now consumed, for such production to occur. Hydrogen is not yet widely used due to the higher expenses. Hydrogen fuels may become more appealing on the market and offer clean, effective electricity for our residences, workplaces, and cars if the prices associated with producing hydrogen were to decreases.

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b) Bio-fuel: Hydrocarbon fuels can be substituted with a variety of bio fuels, including biomass, alcohol fuels, pure vegetable oil, and bio diesel. Coal, natural gas, plant and animal biomass, and organic wastes all contain carbon and hydrogen that can be converted by a variety of chemical processes into short hydrocarbons that can replace current hydrocarbon fuels.One of the earliest solutions for energy storage in electrical applications was the development of electrochemical storage devices, such as batteries. However, their limited capacity and high cost have restricted their widespread use in electrical systems. Battery storage, with an overall efficiency of 75%, remains a viable option. While the initial installation costs per kilowatt ($/kW) are relatively low[20], the capital costs for storage are quite high, making the total installed capital costs inefficient, even for modern batteries. Moreover, large-scale installations require significant amounts of materials, raising environmental concerns, and the use of lead-acid batteries would certainly be unsuitable, even for advanced systems. Additionally, the price of a battery system does not account for replacement costs. It is evident that using batteries for industrial-scale energy storage is impractical. Oxidation occurs at the anode, where electrons are transferred from the cell to the external circuit, while reduction occurs at the cathode, where electrons from the external circuit are transferred back to the cell. In a primary cell, the anode is the negative electrode, and the cathode is the positive electrode. In a secondary cell, when discharging, the negative electrode becomes the cathode, and the positive electrode becomes the anode. In secondary batteries, the electrode roles are reversed during charging and discharging, so the electrodes are consistently referred to as positive or negative (which does not change), while the direction of current flow (charge or discharge) varies

c) Ni-Cl Battery: In 1899, Waldmar Jungner, a scientist from Sweden, developed the nickel-cadmium (NiCd) battery, which was a rechargeable battery containing nickel and cadmium electrodes immersed in a potassium hydroxide solution - the inaugural battery to utilize an alkaline electrolyte. The initial designs were sturdy and had a much higher energy density compared to lead-acid batteries, however, they came with a higher price tag.

d) Alkaline Battery:Before 1950s, the zinc-carbon battery remained a favored primary cell inspite its small battery life hindered its sales. Since 1955, Eveready (currently called Energizer) sought to prolong the lifespan of zinc-carbon batteries, but Energizer makers thought that alkaline batteries (which were much costly then) showed greater potential. They developed a fresh alkaline battery which included a manganese dioxide cathode and a powdered zinc anode with an alkaline electrolyte. The utilization of zinc powder expanded the surface area of the anode. These batteries were introduced to the market in 1959.

e) Nickel metal hydride battery: In the late 1980s, Stanford R. Ovshinsky created the nickel metal-hydride (NiMH) battery as a modified version of the NiCd, the cadmium electrode swapped with a alloy of hydrogen-absorption . NiMH batteries usually last longer than NiCd batteries (and their durability is improving with new alloy testing) and are more eco friendly as it does not contains harm full cadmium. The NiMH battery is a flexible option for a variety of uses because of its durability, eco-friendly components, strong power and energy, as well as its safe operation.

f) Lithium-ion (Li-Ion) battery: Lithium has the lowest density of all metals and offers the highest electrochemical potential and energy-to-weight ratio, making it an ideal material for battery production. American chemist John B. Good-enough led a team at Sony that developed the lithium-ion (Li-Ion) battery, which is a rechargeable and more stable version of the original lithium battery. The first Li-Ion batteries were sold in 1991, with the lithium-ion polymer battery being released in 1996. These batteries store their electrolyte in a solid polymer composite rather than a liquid solvent, with the electrodes and separators being layered together. The difference mentioned above enables the battery to be covered in a bendable covering rather than a hard metal casing, allowing these batteries to be customized to suit a specific device. Normal lithium ion batteries have lower energy density compared to them. These benefits make it a preferred battery for portable devices like cell phones and PDAs, enabling more adaptable and smaller designs.

g) Regenerative Fuel Cells: The most recent storage technology relies on the newly created regenerative fuel cell. During the system's charging, electrical energy is transformed into chemical energy in the fuel cell's electrolytic solutions and then transferred into storage tanks; the process is reversed when discharging. Fig. 2 shows schematic of Regenerative Fuel Cell.

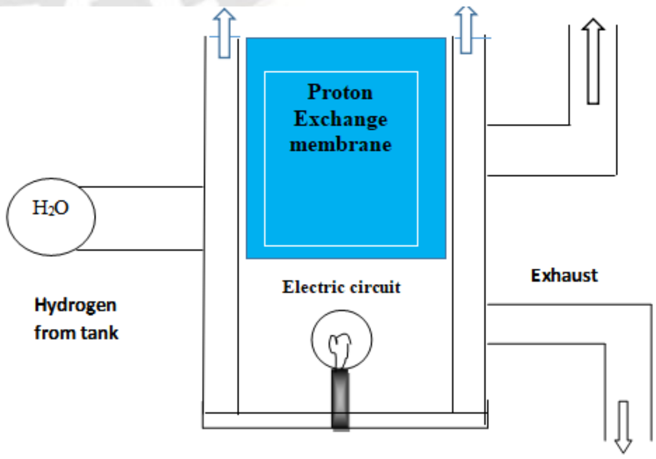

Fig.2. Regenerative Fuel Cell Energy Storage System

Fuel cell electrodes act as a selective membrane barrier; they are composed of carbon fiber, which is both inexpensive and durable. The concentrated solutions of sodium bromide and sodium poly-sulphide used as electrolytes can be easily purchased commercially. The system is expected to last more than 15 years, with an efficiency of approximately 65 percent. The technology offers numerous benefits. The system's modular design allows for easy expansion and repair; numerous modules are interconnected in both series and parallel configurations. Adjusting the power output can be done independently from adjusting the storage capacity. The system's response time is under 3 seconds, making it possible to utilize applications like spinning reserve, load leveling, and distributed generation (peak saving). This technology seems to hold potential for specific uses, but it is expected to remain considerably more costly (2-3 times) than CAES, even with substantial reductions in Cell plant and storage capital expenses, along with high fossil fuel costs for the CAES system. The result is due to the lower efficiency at which storage systems function and the higher costs of plant and storage capital in the Regenerative Cell system compared to CAES system. Fuel cell functions include:To transform a primary fuel (derived from flammable materials like hydrogen, methane, propane, and methanol) into electricity.Hydrogen serves as the fundamental fuel source for fuel cells, however, oxygen is also necessary for their operation. One major attraction of fuel cells is their ability to produce electricity with minimal pollution, utilizing a combination of hydrogen and oxygen.

B. Electrical Energy Storage

Electrical Energy Storage technologies vary based on the storage method, the amount of energy they can store, and how quickly and for how long they can release stored energy. Some EES technologies are more appropriate for providing short bursts of electricity for power quality applications, such as smoothing the output of variable renewable technologies from hour to hour (and to a lesser extent within a time scale of seconds and minutes). However, EES is not currently used specifically to smooth out renewable generation. Other EES technologies [12] are useful for storing and releasing large amounts of electricity over longer time periods (this is referred to as peak-shaving, load-leveling, or energy arbitrage). These EES technologies could be used to store variable renewable electricity output during periods of low demand and release this stored power during periods of higher demand.

a) Capacitor: Capacitors Cells use physical charge separation between two electrodes to store charge. Energy is stored on metal plastic film plates or metal electrodes. Compared to batteries and batteries, the density of batteries is very low - less than 1% of the battery, but the energy density is very high, more than the battery. This means that because of the low capacitance, the conductors can transmit or accept high currents, but only for very short periods of time.

b) Super Capacitor Energy Storage:A supercapacitor, also known as a double-layer capacitor, stores energy through charge transfer at the boundary between the electrode and the electrolyte. The amount of energy stored depends on factors such as the surface area of the electrode and electrolyte, the size of ions, and the electrolyte's decomposition voltage. Super-capacitors consist of two electrodes, a separator, and an electrolyte. The electrodes, typically made of activated carbon, offer a high surface area, which determines the energy density of the device. Current collectors with high conductivity connect the electrodes to the external circuit. A membrane separates the electrodes, allowing ions to move between them.Super-capacitors are generally classified into two types: double-layer capacitors and electrochemical capacitors. Double-layer capacitors rely on charge separation at the interface between the electrode (made of active carbon or carbon fiber) and the electrolyte. Their capacitance is directly related to the specific surface area of the electrode material. Electrochemical capacitors, on the other hand, utilize fast Faradaic redox reactions and include metal oxide and conductive polymer capacitors. These capacitors leverage highly reversible redox reactions on or within the electrode surfaces to generate capacitance, which depends on the electrode potential. Electrochemical capacitors typically operate at voltages below 3V.Hybrid supercapacitors combine features from both electrolytic and electrochemical capacitors, integrating the anode from an electrolytic capacitor with the cathode of an electrochemical capacitor. This combination results in a device with high specific capacitance and energy density. Supercapacitors have an exceptionally long lifespan, and their energy efficiency remains above 90%, provided they are operated within their design parameters. While their power density is higher than that of batteries, their energy density is typically lower. However, unlike batteries, nearly all of the stored energy in a supercapacitor is available through a reversible process.

c) Storage-Superconducting Magnets: High-efficiency (90% efficient) magnetic energy storage systems are still being developed. Even small-scale systems are used for short-term protection to reduce critical equipment such as computers that have already been deployed. Also, the high capital cost of storage for these systems ($300/kWh) makes these systems [13-14] economically unfeasible for utility scale systems. Also, the environmental effects of large solenoid valves and their unrestricted magnetic fields can be problematic

C. Mechanical Energy Storage

Various kinds of Mechanical Energy Storage technology are utilized in the present situation. These storage methods are employed for various short-term storage needs. Other energy storage technologies, such as pumped hydroelectric systems, Compressed Air Energy Storage (CAES), and flow batteries, have also been explored and utilized for utility purposes.

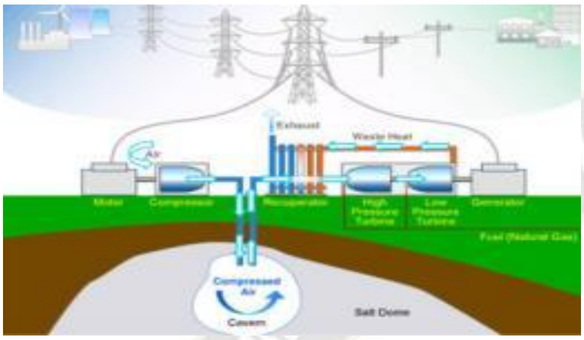

Fig 3. Compress Air Energy Storage System Energy

a) Compressed Air energy storage (CAES) : Compressed Air Energy Storage (CAES) (as in fig. 3) was first developed in Germany in 1949, with a 290 MW CAES facility operating reliably in Huntorf since 1978. In the United States, a more modern CAES plant has been operating at the Alabama Electric Cooperative in McIntosh, Alabama, since 1991. CAES utilizes gas turbine (or jet engine) technology, which has advanced significantly in recent years. A gas turbine typically consists of three main components: a compressor, a combustor, and an expander. The turbine extracts energy from fuel through a thermodynamic Joule cycle, involving isentropic compression of gas, isobaric heating in the combustor, and isentropic expansion with isobaric heat rejection in the expander.Modern single-cycle combustion turbines have an efficiency of 30 to 40 percent, meaning around 60 to 70 percent of the expander's output drives the compressor. The remaining energy, less any losses, is available for storage in a CAES system.CAES interrupts this thermodynamic cycle by storing the compressed gas in an underground reservoir instead of sending it directly to the combustor. When electricity is needed, the compressed gas is withdrawn from the reservoir, and the rest of the cycle is completed. A basic CAES system includes a compressor, a turbo expander (combining a combustor and expander), a generator, and an underground storage space such as a solution-mined cavern, a depleted gas reservoir, or a hard rock cavern. To charge the system, electricity powers a compressor that pumps air at around 80 bar into the storage reservoir. When power is required, the high-pressure air is drawn from the cavern, mixed with fuel, and supplied to the turbo expander to generate electricity.This system offers several advantages. Gas turbines are simple, reliable, and cost-effective, and air is an abundant and free storage medium. The turbo expander, which operates independently of the compressor, has a rapid ramp-up time, enabling quick response to power demands. Additionally, the system maintains a consistent heat rate over a wide range of output power. The compressor can be scaled to match a wind resource, making CAES a good match for wind energy storage. Geological surveys indicate that about 80 percent of the U.S. has suitable underground formations for CAES systems, many in areas with strong wind resources. Moreover, the environmental impact of underground storage is minimal.CAES efficiency is measured by two parameters: heat rate (HR, in Btu/kWh) and energy ratio (ER), the ratio of input to output energy.Since CAES uses fuel, the energy output is greater than the energy input, resulting in an ER of less than 1. For example, the Alabama CAES plant has a heat rate of 4100 Btu/kWh and an energy ratio of 0.82. Several methods exist to improve CAES efficiency, such as using a recuperate to preheat the compressed air with exhaust gas before it enters the turbo expander, which lowers the heat rate and operating costs. This approach is used at the Alabama plant.One possible enhancement is steam injection (CAESSI), where steam is generated and injected into the turbo expander along with compressed air. While this increases the heat rate, it also lowers capital costs. Another option is CAES with humidification (CASH), which involves heating and humidifying the air from storage before injecting it into the turbo expander. The CASH system has a lower heat rate and capital cost than CAESSI and requires a smaller storage volume, reducing total installation costs by 20 percent for both salt caverns and porous rock reservoirs. A CASH plant might have a heat rate of 5000 Btu/kWh and an energy ratio of 0.5.Wind resources vary throughout the year, often being stronger in winter and spring than in summer. A system with seasonal energy storage, such as CAES or CASH, would be highly advantageous. Seasonal storage costs for both systems, including a 250-hour storage reservoir, indicate that both CAES and CASH systems are technically and economically feasible for large-scale seasonal energy storage.

b) Flywheel energy storage: Among the energy storage devices are flywheel systems. All they are are batteries that can be recharged. In contrast to chemical batteries, which store energy electrically, they store energy mechanically in the flywheel rotor by turning the rotor. A generator is used to transform mechanical energy into electrical energy so that the stored energy in the rotor can be used. Because flywheel systems [15] function in a vacuum confinement, they are not temperature sensitive. As a result, in extremely cold or extremely hot temperatures, a hybrid car equipped with flywheel systems can operate without issue. Furthermore, compared to chemical batteries, flywheel devices have a higher energy storage capacity per unit weight. The flywheel system is an extremely effective energy storage device; it can be utilised for numerous applications.

c) Pumped storage hydroelectricity: With an overall efficiency of about 75 percent, pumped hydroelectric storage is widely used around the world, but is only economical for large installations (e.g., 1000 MW), and surface reservoirs have significant environmental impacts due to their size and dynamic behavior. Furthermore, in many regions suitable sites for reservoir construction do not exist, or exist only in areas where there is strong opposition to reservoir construction. Finally, the installed capital costs of surface pumped storage [35] are much higher than the capital costs of CAES systems. Seasonal storage, requiring storage capacity of 200-300 hours, is not cost-effective. And while the environmental impact of an underground pumped storage reservoir is minimal, the cost is high

D. Thermal energy storage:

Synthetic oil is utilized as the storage medium in thermal energy storage technology along-with with solar thermal power plants that are presently in operation in Spain [17]. Melted salts are being researched as a possible more effective TES medium.The most economical locations for end-use TES

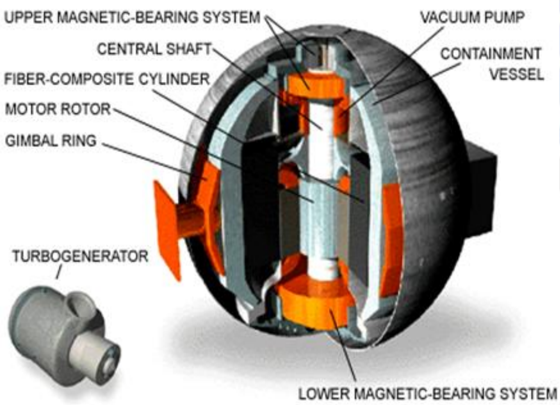

Fig.4.Flywheel Energy Storage System

are those with moderate temperatures and low humidity. Forty End-use TES technology demonstrations have taken place in Germany, the UK, the US, and Scandinavia. For instance, to heat water allover the day and lower maximum power consumption, approximately 8% of domestic water heaters in the UK use a particular TES material that is heated at night hours. This article discusses several kinds of thermal energy storage systems.

a) Molten salt batteries: A type of high temperature electric battery with both primary and secondary cells that utilizes molten salts as an electrolyte is called a molten salt battery. They provide a better power density via a high conductivity melted salt electrolyte and a higher energy density by carefully choosing reactant pairings. They are employed in services that demand high power and energy densities. Rechargeable molten salt batteries [18] are a potential technology that can power electric cars because of these properties. Operating temperatures ranging from 400°C and 700°C, however, increase the demands on the remaining battery components and cause issues with thermal control and safety.

b) Solar pond: Just put, a solar pond is a water tank that absorbs and retains solar energy [19]. At a particular distance from the surface, the solution has a high density of salt concentration. It is composed of salt layers solutions with stepup concentration. The density gradient stops heat from rising through convection from the bottom layers and exiting the pond when sunlight is absorbed. This indicates that while the temperature at the top surface of the pond [20] is typically about 30°C, while the bottom of the pond will climb to over 90°C. There are a variety of uses for the heat confined at the salty bottom layer, including heating establishments or industrial hot water or powering a turbine to produce energy.

III. COMPARISON OF STORAGE TECHNOLOGIES

Bulk power stock options include batteries, superconducting magnet made from superconducting wire for energy storage, flywheel energy storage, pumped hydro, regenerative fuel cell storage, and compressed air energy storage. The following are important factors for these systems:

- Power output cost (per capital plant cost, $/kW)
- Energy storage capacity cost (storage capital cost, $/kWh).

The cost is expressed as the storage capital cost, or $/kWh, per hour of operation at maximum output power. In order to judge

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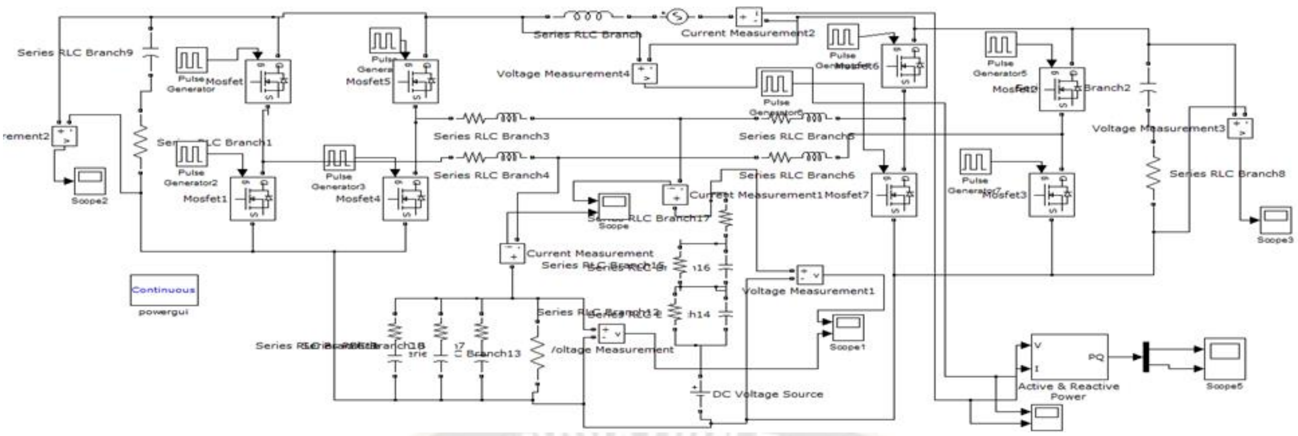

Fig.5. Model of Battery Super capacitor Hybrid Energy Storage System Connected with Boost Converter

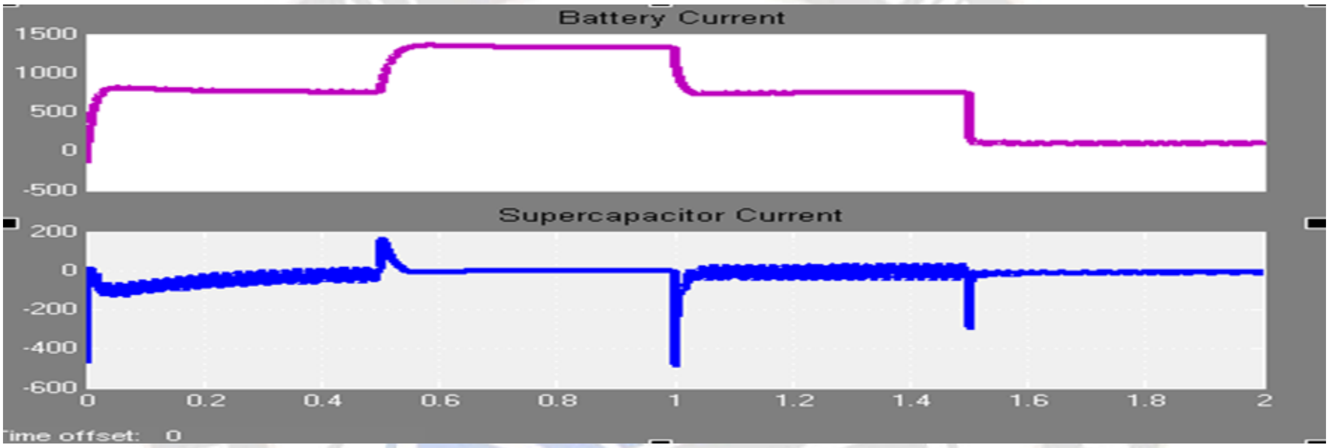

Fig.6 Output of Battery and Super-capacitor Current

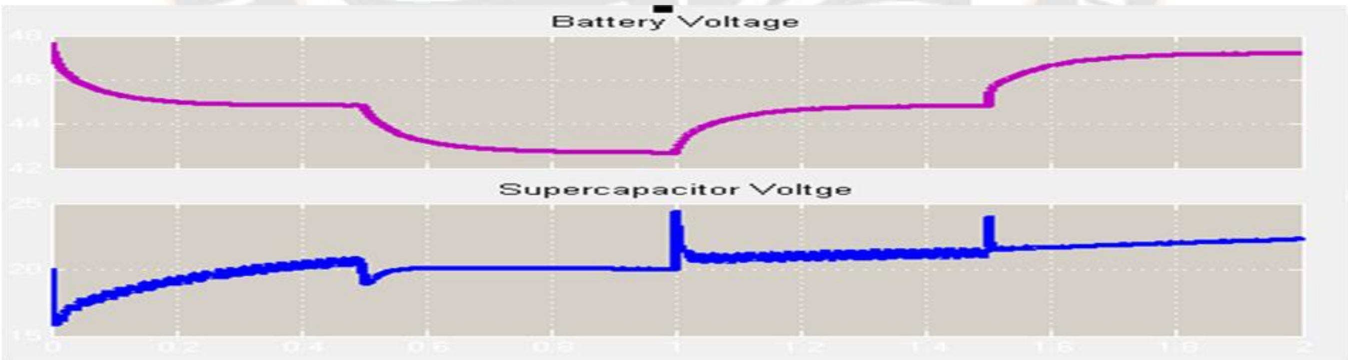

Fig.7 Waveform of Battery and Super-capacitor Voltage

Sr. No.	*Function*	*Supercapacitor*	*Lithium- ion battery*
1.	Charge Time	1 -10 Second	10-60 Minutes
2.	Life Cycle	Approx 30000 hour	500 hour
3.	Cell Voltage	2.3 volt- 2.75 volt	3.6 volt- 3.7 volt
4.	Specific Power	Upto 10000 watt/kg	1000 watt/kg- 3000 watt/kg
5.	Specific Energy	5 watt-hour	100-200 watt-hour
6.	Service Life	10 - 15 Years	5 – 10 Year

TABLE: 2 FUNCTIONS OF BATTERY AND SUPER CAPACITOR

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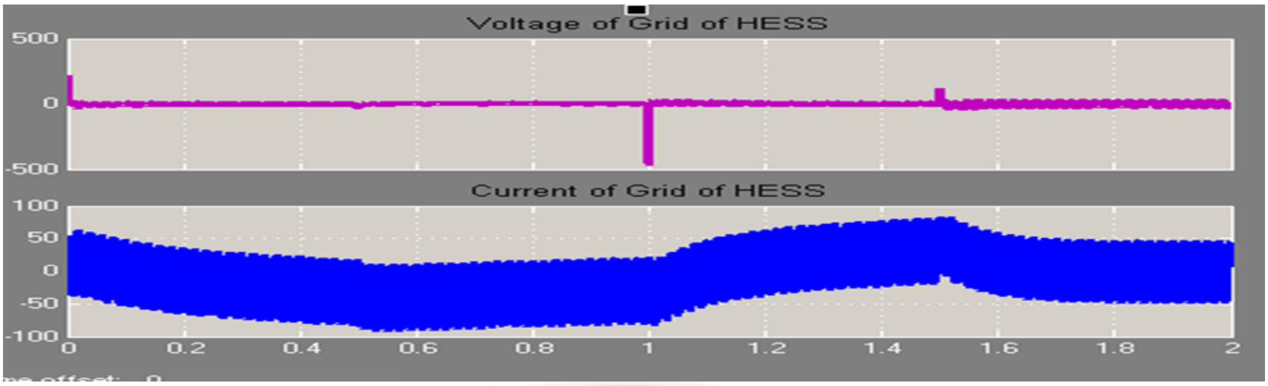

Fig.8 Voltages and Current of Single-Phase AC Grid with Hybrid Energy Storage System

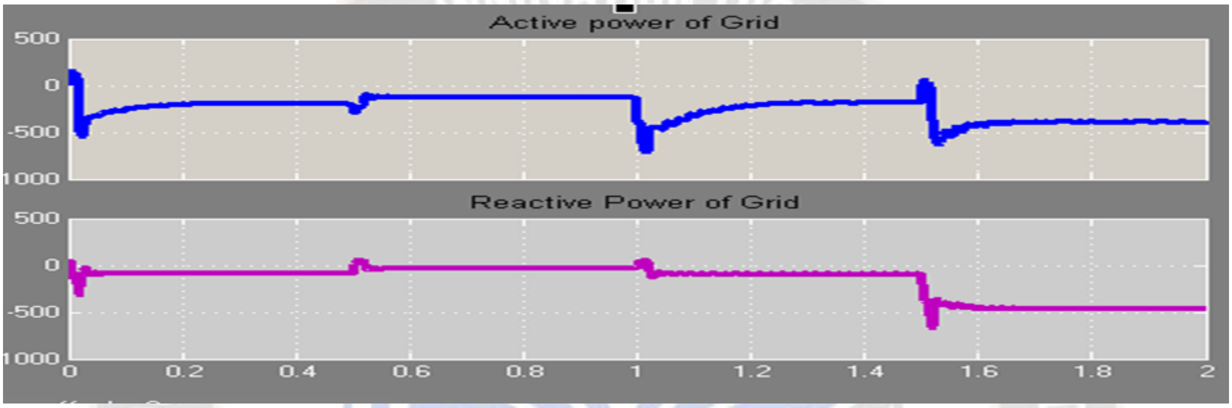

Fig 9 Active and Reactive Power of Hybrid Energy Storage System Connected to Single Phase AC Grid

the effectiveness of various storage solutions, a 50-hour reservoir size is used for comparison. This capacity allows for the conversion of intermittent wind energy [21] into base load power under a wind regime where the wind speed auto correlation time is around 8 hours. Based on a simulation of a wind farm and a CAES system, taking into account wind speed auto correlation, this reservoir size is reasonably sufficient enough for short-term baseload operation, but much smaller than what is required for seasonal storage, hence the comparison underestimates the utility of CAES..

To put this question into reference frame, it is useful to contrast the energy density of typical fossil fuels with that of other storage media [22]. Fuel has an energy density of about 38 GJ m3; a cubic meter of water at 100 m altitude - 1 MJ m^3, for comparison, a rechargeable gel battery - about 240 MJ m^3, a 25 kG magnetic field has an energy density of 10 MJ m^3, , a rechargeable fuel cell (Innogy PLC) - 120 MJ m^3 and compressed air (80 bar) - 8 MJ m^3. In this respect alone, fossil fuels have a huge advantage. When you add their extremely low cost and easy to transport and use, the advantages of fossil fuels seem overwhelming. However, intermittent renewable energies, equipped with appropriate storage systems3, can effectively compete technically and economically with fossil fuel and nuclear systems, as mentioned below. When we look at the technical competitiveness that intermittent renewable energy systems with storage must undergo the same forced and scheduled outages and all other power quality parameters as the best fossil fuel or nuclear systems. Economic competitiveness requires that the electricity market must be designed in a manner that the cost of electricity supplied is affordable to the consumers and profitable for the equipment suppliers and manufacturers. Taking into account the advantages of fossil fuel systems (low installation costs, relatively low fuel costs, no costs associated with the damage caused by extracting, burning the fuel and transporting), it is unrealistic to assume that renewable will be able to compete if markets currently operate. However, with the advent of superior renewable energy technologies, awareness of the dangers of alternatives and an increased understanding and it is clear that the rules by which markets currently operate must be balanced to permit renewals to meet a much sizeable share of demand.

Energy storage devices can generally be designated by their energy density (the energy stored per unit of mass or volume) and power (how fast the energy is delivered by the device).Here we explain the major differences between electrical and electrochemical energy storage procedures.

:• Batteries: can store high amounts of energy but take a considerable time to charge or discharge, resulting in low

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power. • The conventional capacitor has a tremendous force, but only holds a small amount of energy.

• Super capacitors provide a unique combination of high energy and power characteristics and connect the gap between the battery and the capacitor.

• Fuel cells: Operate most efficiently within a narrow range of operating parameters and at high temperatures, but become inefficient quickly when power demand is high. These can be used simultaneously with batteries or supercapacitors to provide a combination of high energy and power

IV. HYBRID ENERGY STORAGE SYSTEMS

The hybrid energy storage system (HESS) concept is attaining significant importance in applications requiring high-density energy storage, load leveling and emergency power. Energy sources used in modern HESS in automotive and avionics sectors include high performance batteries such as super capacitors, Li-Ion, and flywheels. HESS provides an excellent platform for system-level modeling and simulation while integrating aspects of, control systems, electrical power and power electronics.

a) Super capacitor and Battery based hybrid energy system

The system configuration of a boost-inverter based single-phase grid-connected battery-super-capacitor HESS. Simulation and analysis of supercapacitor hybrid energy storage system and battery gives better overall performance, improved efficiency. It is highly reliable and efficient. Hybridization benefits of an energy storage for single phase grid. Figure 8 shows matlab/simulink model of supercapacitor - battery hybrid energy storage system connected with boost converter.

The different outcomes of MATLAB simulations for a battery-based energy storage system, a Super capacitor-based energy storage system and a battery-super capacitor hybrid energy storage system are as follows:

•Findings of Super capacitor Current and voltage

•Findings on Current and voltage of the Battery.

• Findings of Active Power and Reactive Power in a hybrid energy storage system with super-capacitors and batteries.

Modeling the voltage and current behaviors of a theoretical super-capacitor and battery during charging and discharging is carried out in a single-phase AC power system. The main way reactive power control is shown is by supplying the grid with reactive power compensation. There are at least two ways to control reactive power compensation. The battery current fluctuates more smoothly than the super-capacitor current. Boost converters operate during both positive and negative cycles. When a battery-super-capacitor hybrid energy storage system is linked to a single phase AC grid system, the charging and discharging current of the battery and super-capacitor is modified based on the grid's power needs. At 0.5 seconds in active mode, both the battery and super-capacitor begin to charge in the Boost converter as shown in figure 9. The results above indicate that the charging current of the battery rises to 700 amperes before stabilizing at a certain level for a time period. When the battery charging current surpasses 700 amperes, the super-capacitor charges rapidly to 190 amperes immediately, then gradually decreases and stabilizes at a certain level. Super-capacitor current sharply decreases at a certain moment when the battery switches to discharging while the boost converter is in inactive mode. This finding demonstrates the occurrence of a Battery-Super capacitor hybrid energy storage system in a recurring manner every two seconds. According to the charging and discharging current of a Battery-Super capacitor Hybrid energy storage system in fig.7, the voltage behavior of the battery and super capacitor can be seen in fig.5 due to their inverse relationship. Hybrid energy storage system combines battery and supercapacitor to provide needed power to the grid while diverting ripple current to the super-capacitor. Fig.8 shows that the super-capacitor current and battery current demonstrate that the super-capacitor absorbs the high-frequency components. it depicts the voltage and current characteristics when a hybrid energy storage system is connected to a single-phase AC Grid system, specifically when the battery charging current is on the rise. Fig.9 shows the fluctuating current of the battery-super-capacitor and the power variations to the super capacitor as the battery provides a slowly changing average power component. The high power density of super-capacitors makes them a great option for peak power applications. The power that is currently in use.

V. CONCLUSION

Electric Energy Storage (EES) technologies are essential for advancing the large-scale deployment of renewable energy sources like wind and solar, which are critical for reducing greenhouse gas emissions. While wind and solar power generate electricity without producing carbon emissions, their output is variable and depends on factors like wind speed and sunlight intensity. This intermittency creates challenges for grid operators, who must balance electricity supply and demand in real-time. EES offers a solution, enabling better integration of these renewable resources by improving power quality, supply reliability, and overall grid stability.

Several EES technologies have evolved to address these needs. Advanced batteries serve both utility-scale applications and electric vehicles, while flywheel systems are used in uninterruptible power supplies. Capacitors ensure power quality, and emerging superconducting energy storage systems are gaining attention for utility-scale applications. Compressed air energy storage (CAES) is particularly effective, supporting wind turbine arrays and offering both environmental and economic advantages. Organic fuel cell systems also present a cost-effective option, especially in remote areas lacking grid infrastructure.

Although EES currently represents a small part of power infrastructure, its role is expanding rapidly. As renewable energy adoption increases, technological advancements in EES will drive its critical integration into the future energy landscape.

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