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Optimizing Energy Storage with the Integration of Batteries and Super Capacitors in Hybrid Systems

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***Abstract*— Renewable energy sources (RES) are widely needed because of the growing population and increased demand for energy resources. RES are also inexpensive, abundant, and free of pollution. An energy storage system (ESS) is crucial for meeting the load requirement. Because of its high energy density, BESS is generally favored. In temporary situations, it reacts slowly to abrupt changes. An energy storage system (ESS) is crucial for meeting the load requirement. Because of its high energy density, BESS is generally favored. In temporary situations, it reacts slowly to abrupt changes. Therefore, in order to build a HESS, an ESS with a high power density, such as a super capacitor, needs to be combined with a battery. The ESS and PV array are connected by a 48 V DC connector. In this work, as the solar output power rises, the HESS uses the extra power to keep the load's power supply constant and returns energy to the load when the PV is unable to meet the load's demand. An integrated control approach is suggested, which proficiently produces the bidirectional converter's switching pulses.The voltage control loop generates the entire current that goes to the HESS. In addition to designing the existing control loops, stability analysis is done. Bode plots are employed in HESS stability testing. The outcomes are encouraging, and the controller effectively shares power between the SC and battery and restores the DC link voltage. With the suggested controller, it is discovered that HESS performs well in providing average power for extended periods of time and managing transient situations for brief periods of time.**

***Index Terms*— Battery, Renewable energy, Energy Storage System, Hybrid Energy Storage System, Super Capacitor.**

I. Introduction

The power industry is shifting toward renewable energy sources (RES), which are widely available and reasonably priced, as a result of the depletion of non-renewable energy resources, increased energy consumption, and the requirement for rural electrification [1]. The industries have embraced solar and wind power as their primary renewable energy sources. Solar energy is less expensive, requires less upkeep, has a longer lifespan, and operates quietly. The electricity output from the solar panel is affected by temperature and irradiance levels, which makes it advantageous for rural electrification with lower energy usage. For all stand-alone systems to maintain appropriate power balance, ESS is necessary. An energy storage system (ESS) that is linked to a grid is referred to as a microgrid system. There are two kinds of microgrids: systems that are connected to the grid and standalone microgrids. Battery energy storage system (BESS) is the most favored ESS among all of them [2] because of its high energy density. The average load demand during a specific time period is met by BESS. During periods of

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high demand, the low power density of the battery results in an inability to meet the load requirements. An energy storage system with a high energy density and high power density is needed to make up for this. In order to maximize the power output from the PV source, a hybrid energy storage system (HESS) that combines two energy storages is used. There are various HESS combinations in the literature [1]. One of them is the battery and super capacitor (SC) combination. Because SC has a high power density, it is quite useful in temporary situations. Battery meets the average load demand, while SC balances the short-term power variations. Each storage system should receive an equal amount of power from the energy source. Equitable power sharing can be achieved through the use of a control technique.
This paper proposes a combined control technique for a DC microgrid system that uses solar and battery power to construct the HESS that is fed by photovoltaic cells as its primary source.

II. RENEWABLE ENERGY SOURCES

A. SOLAR PV GENERATION

The process of producing electricity from sunlight using solar photovoltaic technology is known as solar PV generation. Solar photovoltaic (PV) systems convert solar radiation into direct current (DC) electricity. This DC electricity can then be converted into direct current (AC) electricity, which can be used to power various electrical loads, including homes and businesses.
Solar panels, an inverter, and a mounting system are the basic parts of a solar PV system. Several solar cells in solar panels convert sunlight into DC electricity. DC energy is transformed into AC by the inverter and then used to power loads or fed back into the grid. The mounting system is in charge of holding the solar panels firmly in place and making sure they are facing the sun to produce the most energy possible.
Due to the decreasing cost and improving efficiency of solar PV systems throughout time, solar PV generation has grown in importance as a renewable energy source. Solar PV systems come in a variety of sizes, from small residential units to massive utility systems that produce megawatts of electricity, and can be mounted on rooftops or the ground.
One of the key benefits of solar PV generating is that it is a clean, sustainable energy source because it generates electricity without releasing any greenhouse gases or other pollutants into the atmosphere. Furthermore, solar PV systems can lessen dependency on fossil fuels and the grid by supplying electricity in isolated areas with expensive or limited access to the grid.

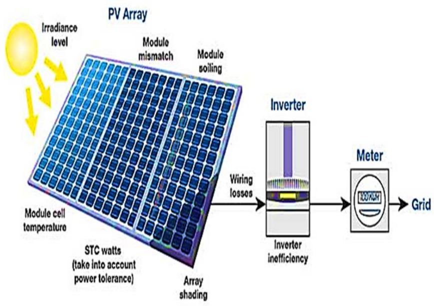

Figure 1:Solar PV Generation

B. PHOTO VOLTAIC(PV)CELL,MODULE,ARRAY

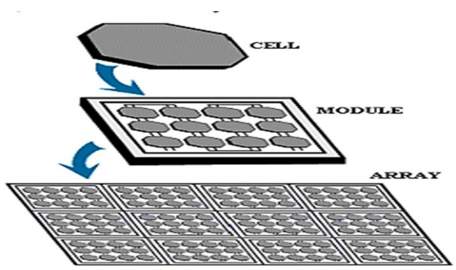

Figure 2: Cell Module and Array

PV Cell

Using the PV effect, a PV cell, sometimes referred to as a solar cell, is a device that captures light energy and transforms it into electrical power. These cells, which are essential components of solar PV systems, are often constructed of semiconductor materials like silicon.

When light energy photons are absorbed by the semiconductor material in a photovoltaic cell, the photovoltaic effect occurs. After that, the material's electrons receive this energy, which excites them and causes an electric current to flow. The current flow can then be converted into electrical energy by being collected by metal contacts on the cell.

PV Module

PV Module Also referred to as a solar panel, a PV module is a group of connected photovoltaic cells that transform light from the sun into electrical energy. Usually constructed of silicon or another semiconductor material, the PV cells are enclosed in a glass cover to provide weather protection.

The fundamental component of a solar PV system, a PV module is made to generate a certain quantity of electricity. the quantity and size of PV cells that provide power, as well as the cells' efficiency and the caliber of the production process.

In order to build a solar PV array, PV modules are intended to be connected in series or parallel.

PV Array

Designed to produce electricity from sunshine, a PV array is a group of connected photovoltaic modules. In order to generate the required electrical output, the PV modules are usually mounted on a support structure, such as a rooftop or ground-mounted system, and connected in series or parallel.

The required electrical power and the amount of area available for installation determine the size of a photovoltaic array. PV arrays come in a variety of sizes, from modest home systems producing a few kilowatts to massive utility-scale systems producing megawatts of electricity.

To construct a whole solar PV system, PV arrays are frequently utilized in conjunction with additional parts like inverters and batteries.

C. SOLAR MPPT CONTROLLER

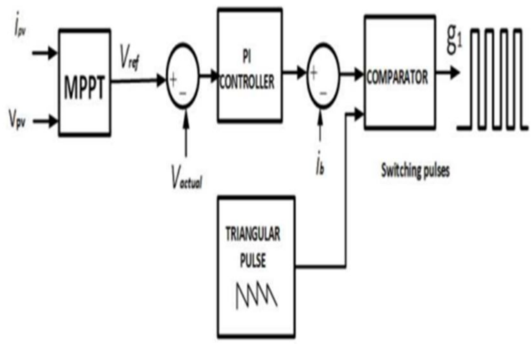

Figure 3: MPPT Controller

In photovoltaic (PV) systems, greatest output Point Tracking (MPPT) is a technique used to harvest the greatest output from a solar panel. A solar panel's power output is contingent upon several parameters, including temperature, load on the panel, and sunshine intensity.

Tracking with a maximum power point is electronic, typically digital tracking. The charge controller examines the panel output and contrasts it with the voltage of the battery. Next, it determines the optimal power output of the panel to charge the battery. It takes this and adjusts the voltage to provide the battery the greatest amount of amps. (Remember, the amount that counts is the amps into the battery). The majority of current MPPTs have conversion efficiencies between 93 and 97%. In winter, you usually receive 20 to 45% of your power back, while in summer, just 10 to 15%. The real gain could differ significantly based on the temperature, weather, battery level, and other elements.

D. BATTERIES

Devices that store and release electrical energy as needed are called batteries. They are composed of one or more anode and cathode electrochemical cells and an electrolyte that facilitates ion transport between the electrodes.

When a battery is connected to an electrical circuit, the chemical processes occurring in the cells cause electrons to flow from the negative electrode to the positive electrode (cathode) of the circuit, producing an electrical current that keeps the battery charged. Batteries are used in many different applications, including powering tiny devices like flashlights and remote controls as well as larger systems like electric cars and renewable energy systems. They are available in a variety of sizes, forms, and chemistries.

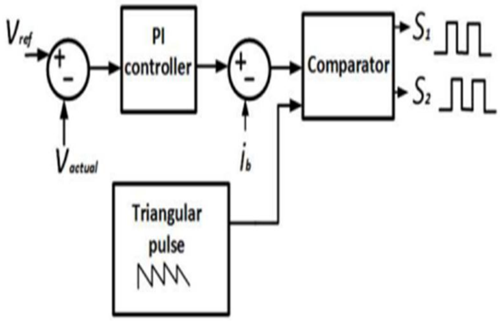

Figure 4: Batteries

Types of batteries

There exist numerous varieties of batteries, each has distinct attributes and uses. These are a few of the most typical kinds:

Lead-acid batteries

These are the most common and traditional kind of rechargeable battery. They are utilized in backup power systems as well as in automobiles, boats, and other types of vehicles.

Nickel-cadmium (NiCd) batteries

These batteries, which are also rechargeable, are frequently found in cameras, portable power tools, and other electronic equipment.

Nickel-metal hydride (NiMH) batteries

These have a higher energy density than NiCd batteries, which makes them suitable for use in hybrid vehicles and other applications.

Lithium-ion (Li-ion) batteries

Rechargeable batteries like these are frequently found in cellphones, laptops, and other portable electronics. Their extended longevity and high energy density are well recognized.

Lithium-polymer (Li-poly) batteries

These Li-ion batteries have a polymer electrolyte rather than a liquid electrolyte. They work well in tiny devices like tablets and smartphones because they are more flexible and lighter than conventional Li-ion batteries.

Alkaline batteries

These are non-rechargeable batteries that are frequently found in toys, remote controls, and torches among other household gadgets.

Zinc-carbon batteries

These batteries resemble alkaline batteries and are likewise non-rechargeable. They are frequently found in low-drain electronics like radios and clocks.

Silver oxide batteries

These are the tiny button-cell batteries that are frequently seen in hearing aids, calculators, and watches

Zinc-air batteries

These are found in certain electric cars as well as in hearing aids and other medical equipment. Numerous more battery types, such as flow, solid-state, and sodium-ion batteries, are still being researched and developed for a range of uses.

E. SUPER CAPACITORS

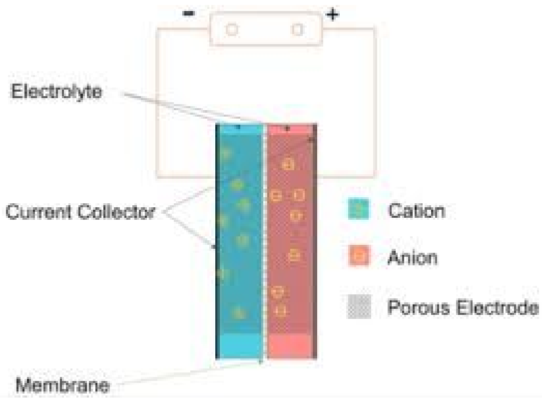

Figure 5: Supercapacitor

Supercapacitors, sometimes referred to as electrochemical capacitors or ultracapacitors, are cutting-edge energy storage technologies that fill the void left by conventional capacitors and rechargeable batteries. They are useful in a variety of applications because they provide a special set of qualities. Supercapacitors have unique advantages over regular capacitors, which store energy in an electrostatic field, and batteries, which store energy through chemical reactions and electrochemical double-layer capacitance and pseudo capacitance.

Supercapacitors are renowned for their long cycle life, which allows them to be charged and discharged thousands to hundreds of thousands of times without experiencing appreciable degradation, and their remarkable power density, which allows for quick charge and discharge cycles. They may function well in a broad temperature range and are also incredibly dependable.

II. CONTROL STRATEGIES FOR HESS

The two switches that make up the bidirectional converter are complementary to one another. As a result, their transfer function is similar. In order to develop the controller, the boost mode of operation is taken into consideration. In this work, a switching frequency of 10 kHz is employed.

a) Battery Current Control loop design

Table I displays the battery's parameters. The control to inductor current transfer function is provided by

TABLE I .PARAMETERS OF BATTERY

V_O	V_B	I_B	D_B	L_B	C_B	*Load*
48V	24 V	1.6 A	0.3	5 mH	440 µF	60 Ω

$$G_{id\_B} = \frac{0.02112s + 3}{8.8\times10^{-7}s^2 + 6.25\times10^{-5}s + 0.25}$$

The transfer function of PI controller in battery current control loop is given by

$$G_{Pi\_B} = K_{P\_B} + \frac{K_{i\_B}}{s}$$

The open loop transfer function of battery current control loop is given by

$$G_{ol\_B} = G_{ol\_B} G_{di\_B} H_B$$

At 6.34 krad/s, the PI controller is intended to achieve a phase margin of 60 degrees. The settings of the PI compensator are Kp_B = 1000 and Ki_B = 0.32 s.

b) Design of SC current control loop

Table II displays the parameters for the SC. The control to inductor current transfer function is provided by

TABLE II. PARAMETERS OF SC

V_0	V_{SC}	I_{SC}	D_{SC}	L_{SC}	R
48 V	32 V	2.25 A	0.33	1.8 mH	60 Ω

$$G_{id\_sc} = \frac{0.02112s+3}{7.92\times10^{-7}s^2+5.625\times10^{-5}s+0.4489}$$

The transfer function of PI controller in SC current control Loop is given by

$$G_{Pi\_S} = K_{P\_S} + \frac{K_{i\_S}}{s}$$

The open loop transfer function of SC current controller is given by

$$G_{ol\_s} = G_{pi\_s} G_{di\_s} H_s$$

At 10.5 krad/s, the controller parameters are tuned to achieve a phase margin of 60 degrees. The PI controller values that were utilized are Ki_s=0.34 s and Kp_s= 2021.

c) Voltage Control Loop of HESS Design

The inductor current to output voltage transfer transfer function is given by

$$G_{vi\_v} = \frac{0.00416s+32.16}{0.0221s+3.015}$$

The transfer function of voltage control loop is given by

$$G_{pi\_V} = K_{pi\_V} + \frac{K_{i\_V}}{s}$$

The open loop transfer function of voltage loop

$$G_{ol\_V} = G_{pi\_V} G_{cl\_s} G_{pi\_V} H_V$$

At 6.65 krad/s, the controller's parameters are set to achieve a 60-degree phase margin. Kp_v=674, Ki_v=0.22 s are the settings of the PI controller that is being used. Table III displays the system configuration settings.

TABLE III .CONFIGURATION PARAMETERS

Parameters	**Value**
PV Open circuit voltage	24 V
PV Short circuit current	3.5 A
Supercapacitor voltage No of cells connected in series	32 V 2
Battery voltage No of cells connected in series Ah capacity	24V 2 17 Ah
Load resistance	60 Ω
Inductance	L_{SC}=1.8 mH, L_{pv}=10 mH, L_b=5 mH
DC capacitance	440 µF

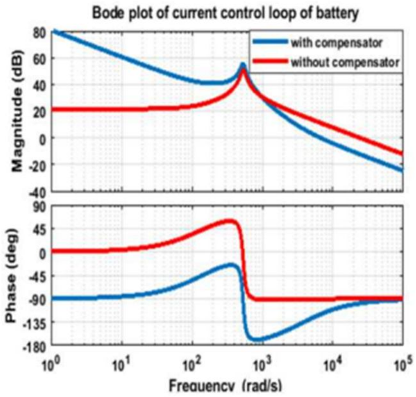

Figure 6: Bode plot of current control loop of battery

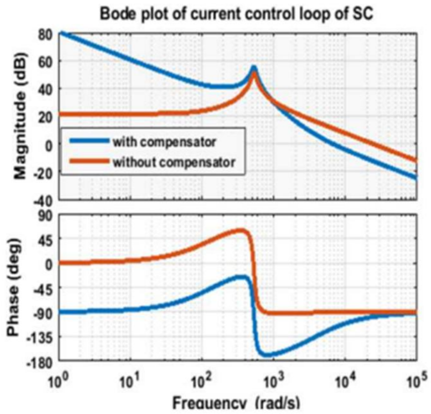

Figure 7: Bode plot of current control loop of SC

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