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ENERGY STORAGE SYSTEM WITH MULTILEVEL INVERTER FOR DISTRIBUTED GRID APPLICATION

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ABSTRACT

Solar energy is the major source of power. Renewable energy sources such as wind-turbine and photovoltaic power generators may make the power grid unstable due to their output fluctuations. Battery energy storage systems (BESSs) are being considered as a countermeasure for this issue. This study presents a battery storage system (BSS) based on a cascaded H-bridge inverter applied to a medium-voltage grid. The BSS is composed of eight equal series connected H-bridge converters, without bulky transformers, for connection to a distribution grid. The BSS is able to keep working even with a failure of one of its converters. Inverters of PV system based distributed generation (DG) are subjected to wide changes in the inverter input voltage, thus demanding a buck-boost operation of inverters. Further the inverter size, weight, and cost are increased. It is designed transformerless inverter that can be operated over a wide DC input voltage range, making it suitable for distributed generation applications.

KEYWORDS: *Battery Energy Storage Systems, Frequency Stability, Multilevel Converters, Transformer Less Inverters, Active-Power Control, SOC (State-Of-Charge) Balancing*

Article History

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1. INTRODUCTION

The need for renewable energy storage is important due to the continual climate change and the fickle nature of the weather upon which renewable energy sources depend. Although, the renewables range from photovoltaic energy to wind energy, hydroelectricity, biomass and biofuels, the photovoltaic and wind energy are the most commonly utilized systems for electricity generation for different applications in recent times. These applications can be categorized into utility -interactive, stand-alone and hybrid systems

Due to the intermittent behavior of renewable energy sources, such supply can be achieved by the support of energy storage systems. Pumped hydros, compressed air, flywheels, batteries, and supercapacitors are examples of technologies for storage systems. The choice of the storage technology depends on criteria like cost, life-cycle, energy and power density, and environmental impact. Another criterion is the voltage level of the grid where the storage is connected. A storage system connected to high-voltage grids (approximately hundreds of kilovolts) is mostly based on hydro-pumped or compressed air due to their large power capacity and long life.

A quality of an electric power supply is determined by the available reserve capacity at the energy utility. Figure 1 illustrates the distribution of the electric-system capacity expressed by a typical weekly load curve of generation for the load without storage system and generation for a load with storage system an electric utility.

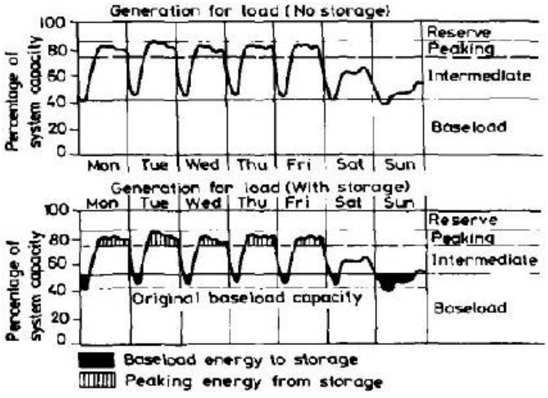


Figure 1: Typical Weekly Load Curve for an Electric Utility [19]

Low-voltage grids (approximately hundreds of volts), lead-acid batteries usually are the best choice for storage systems mainly due to their low cost and robustness. In medium-voltage grids (approximately thousands of volts), the storage tend to be made with batteries followed by a DC–AC converter and a bulk 50 Hz-transformer.

However, the output power of PV systems depends on the weather conditions and the natural environment, which cause large fluctuations in the output power, leading to an insufficient frequency adjustment capacity of the power grid. Battery energy storage systems (BESS) are being considered as a countermeasure for this issue, and the installed capacity of BESSs is expected to increase in the future. "BESS" require bidirectional AC-to-DC and DC-to- AC converters.

Multilevel inverters seem to be an attractive choice for applications in medium-voltage grids without the necessity of using bulky transformers. Additionally, their semiconductors can be controlled at low frequency, minimizing the propagation of highfrequency components. The CHB is composed of eight series-connected H-bridge converters. This number of converters allow the CHB to operate without a transformer and to keep the BSS working even when one converter fails. Moreover, the converters use PWM modulation with low switching frequency. The BSS evaluates the state-of -charge (SOC) of each battery bank in order to decide the moments when the batteries should be charged or discharged. The use of multilevel inverters would require hundreds of series-connected H-bridge converters. On the other hand, in low voltage grids, the usage of a multilevel inverter is not justified because the available transistors on the market easily handle the voltage value of these grids. Therefore, it is preferable to replace the multilevel inverter with a conventional H-bridge inverter.

2. ENERGY STORAGE SYSTEM

2.1 Types of Energy Storage System

- Superconducting Magnetic Energy Storage (SMES)
- Super Capacitor Energy Storage (SCES)
- Compressed Air Energy Storage System (CAES)

- Flywheel Energy Storage System (FESS)
- Pumped Hydro Energy Storage Systems (PHESS)
- Battery Energy Storage Systems (BESS)

2.2 Details of All Types of Energy Storage System

2.2.1 Superconducting Magnetic Energy Storage (SMES)

There is a theoretical and a technical option to store electrical energy as such, without converting it into other forms. This is possible owing to the ability of some substances to become superconducting at extremely low temperatures. Because of the conductor's electrical resistance at ambient temperature, part of the electrical energy is lost in the form of heat emission (joule losses). These losses can be compensated by adding new quantities of electricity to the power supply network. At extremely low temperatures, some alloys and ceramic materials achieve superconducting properties, i.e. they lose their electrical resistance. When direct current is fed into an electric circuit of superconductors, the current will circulate endlessly along the closed ring without energy losses. When an energy demand appears, the requested electrical power can be drawn from that closed ring.

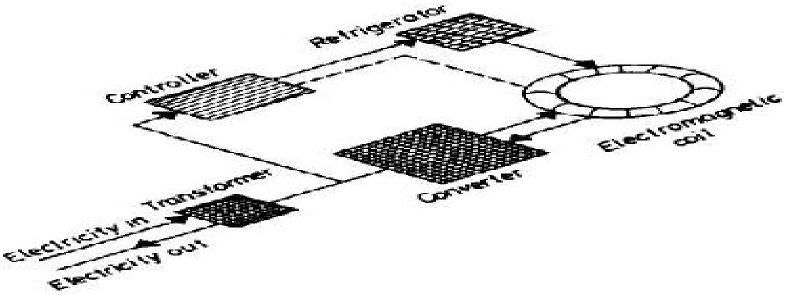


Figure 2: Schematic of a Superconducting Magnetic Energy Storage System [19]

The experimental SMES systems so far set up, operations at extremely low temperatures -269°C (4 K), the temperature of liquid helium) and the coil-wire used is made of NbTi and NbSn alloys. With the discovery of ceramic high-temperature semiconductors, it can be expected that superconducting magnetic storage plants will be constructed that are capable of operating at the temperature of liquid nitrogen (-196°C). Since the technology for liquid nitrogen production is well advanced and cost-effective, the expenses for construction and maintainance of the refrigeration system will be reduced significantly.

The current density in superconductive wires may reach extremely high values as the conductor exerts no electrical resistance leading to joule losses. This allows the wire cross-section to be decreased more than five times with respect to copper wires used at ambient temperature. This will change substantially the existing classical electric power system.

2.2.2 Super Capacitor Energy Storage (SCES)

The structure of SCESS is shown in Figure 3. Its circuit is mainly composed of three parts: rectifier unit, energy storage unit and inverter unit. Rectifier unit adopts three phase full bridge rectifier to charge the super capacitor and supply DC power energy to inverter unit. Inverter unit adopts three -phase voltage inverter composed of IGBT, it connects to the power grid via a transformer. When SCESS works normally, a voltage at DC side is converted into AC voltage with the same frequency as power grid through an IGBT inverter.

When only considering fundamental frequency, SCESS can be equivalent to the AC synchronizing voltage source with controllable magnitude and phase

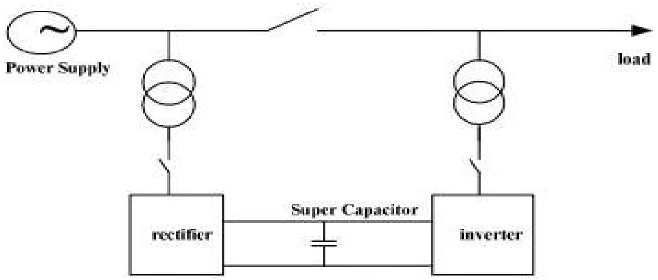


Figure 3: Structure of SCESS [20]

SCESS usually is a parallel between the power system and load, through rectifier the surplus power energy is stored in supercapacitor, when needed, the energy stored is sent into a system. When energy storage system is applied in an external power supply, power energy is converted into AC power energy via an inverter, energy is transmitted to power grid and load. SCESS based on DG connected to the power grid can be divided into three functional blocks: supercapacitor array's components stored energy, power energy conversion system in energy transformation and transmission, an integrated control system.

2.2.3 Compressed Air Energy Storage System (CAES)

A compressed-air storage plant uses inexpensive off-peak energy to drive the motor of a compressor for compressing air that is stored in a salt cavern located deep underground or in large hard rock caverns. During peak demand periods, gradual release of pressure is performed and the air coming up to the surface is heated by burning oil or gas and is then expanded through expansion turbines that drive the rotor of an electric current generator. Compressor motor and generator are combined in one machine. This leads to a two-thirds reduction in the environmental pollution caused by the combustion process of turbines which are usually located in urban areas. Always have been sought for optimization of the system operation, such as a return of the heat released during air compression back to the energy system. This energy storage option is cost-effective if operated at a power above 25 MW.

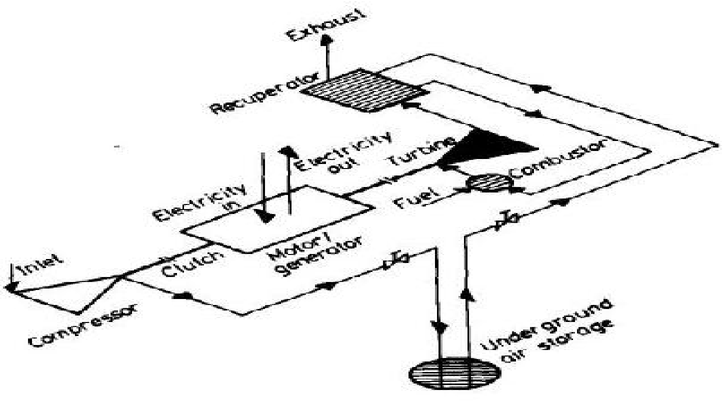


Figure 4: Block Diagram of a Compressed-Air Energy Storage System [19]

Compressed-air storage plants have a negligible environmental impact, and can be built within 2 to 5 years. They arc: fitted with modified combustion turbines of routine production. This technology can find application only in countries with natural deep underground, hard rock or salt caverns.

2.2.4 Flywheel Energy Storage System (FESS)

Flywheel energy storage uses the inertia energy of the large-scale disk, it mainly relies on three breakthrough points: electromagnetic suspension bearing, disc high sensitive materials, and power electronics technology. Flywheel energy storage exchanges energy with the outside world through motor/generator system. When flywheel stores energy, it operates as a generator, its speed is increased. When flywheel releases energy, it operates as the motor, its speed is reduced.

Disadvantages are its structure and control complex, high cost. High power flywheel energy storage needs to reduce power consumption, at present, there are a series of technical problems to solve in using high temperature superconducting magnetic bearings. As flywheel speed is very fast, needs special materials with small density and large stress, but also needs to strengthen system security and reliability.

2.2.5 Pumped Hydro Energy Storage Systems (PHESS)

Pumped storage is large centralized electrical energy storage, it needs high and low reservoir dam, long-distance transmission, mature technology. About 65% to 70% efficiency, in seconds it can rapidly respond to load; with W adjustable energy, can help future nuclear energy, large-scale wind power, and large-scale photovoltaic power.

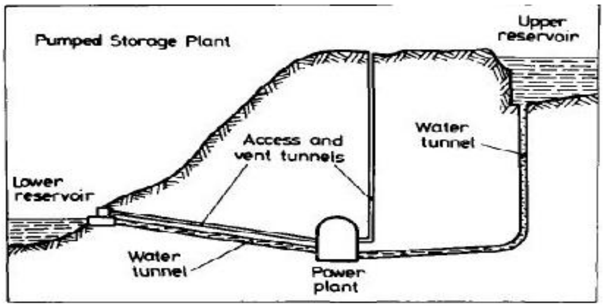


Figure 5: Schematic of a Pumped Hydroelectric Energy Storage System.[19]

2.2.6 Battery Energy Storage Systems (BESS)

In the process of development of the new generation of BES systems, lead-acid battery energy storage systems (LABESS) were widely used, which allowed the latter to exhibit a number of useful advantages leading to significant cost benefits. The features of lead-acid battery storage systems include Modular design, Short construction time, Small environmental impact, High level of recycling.

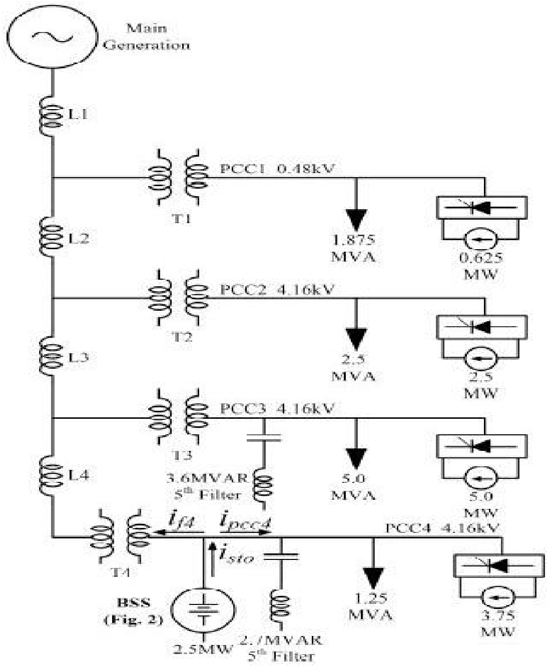


Figure 6: Simplified Single-Phase Diagram of a Medium-Voltage Distribution System with the BSS [18]

Figure 6 presents a simplified single-line diagram of a medium voltage distribution system with the BSS. The grid is composed of the main generation, distribution transformers, four feeders, linear and non-linear load and passive filters. The BSS is connected to the PCC4.

Table 1: Major Battery Energy Storage System Installed In the World

Battery Energy storage system	Location	Capacity	Battery	Application	Year
BEWAG AG	Berlin. Germany	17MW/14MWh	Lead acid	Spinning reserve. Frequency control	1986
Kansai Electric power co., Inc.	Tatsumi. Japan	1MW/4MWh	Lead acid	Multipurpose demonstration	1986
South California Edition (SCE)	Chino. CA.USA	10MW/40MWh	Lead acid	Multipurpose demonstration	1988
Puerto Rico Electric Power Authority (PREPA)	San Juan. PR.USA	20MW/14MWh	Lead acid	Spinning reserve, Frequency control. Voltage regulation	1994
GNB Technologies	Vernon. CA.USA	5MW/2.5MWh	Lead acid	Uninterruptible power supply(UPS), Peak shaving	1995
Golden Valley Electric Association (GVEA)	AK.USA	40MW/14MWh	Nickel cadmium (NiCd)	Spinning reserve. Frequency control, Voltage regulation	2003
Tokyo Electric Power co., Inc. (TEPCO)	Hitachi Factory. Japan	8MW/58MWh	Sodium sulphur (NaS)	Load leveling	2004

3. SYSTEM CONFIGURATION

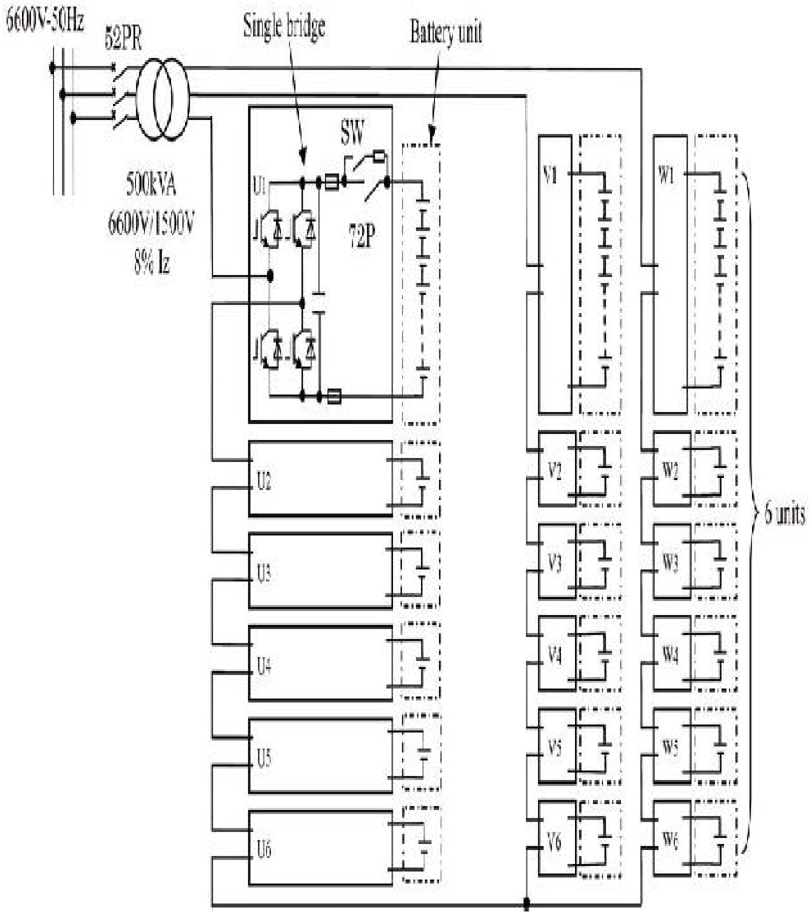


Figure 7: Main Circuit Configuration Multilevel Cascade Converter for Battery Storage System [11]

Figure 7 shows the circuit configuration of the verification test equipment. Six cells, each composed of an H-bridge IGBT unit and a battery unit, were cascade-connected in each of the U, V, and W phases to form a single-star bridge cell (SSBC)-based MMCC. In order to verify cell balancing control and suppress harmonics, the number of cascades was chosen to be six. Each cell has a pre-charge circuit consisting of a switch (SW) and a resistor. The resistor suppresses the inrush charging current to the DC capacitors of each bridge cell. After charging DC capacitors from the battery, the main switch 72P is turned on to connect the battery to the cell. In this way, it is possible to suppress the peak current, which is caused by the voltage difference between the battery and DC capacitors even though the battery no-load terminal voltage varies depending on the SOC of the battery.

The cells are equipped with fuses to limit the short-circuit current from the battery when a DC short-circuit fault such as IGBT failure occurs in the bridge cell. To ensure sufficient fault-ride-through (FRT) capability, the impedance of the converter transformer was determined to be 8% by numerical simulations. Considering 10% grid voltage fluctuations and a 5% negative phase sequence voltage, we chose 1500 V as the secondary side voltage of the transformer so that a rated power of 500 kW can be output even with the minimum battery voltage.

4. CONTROL STRATEGY

For multilevel converter BSS with the asymmetrical grid voltage condition, mainly focusing is all SOCs balanced and maintaining output power quality. The SOC balancing control is the main part of the proposed control strategy.

The grid current control block proposed control strategy to keep the grid current symmetrical and maintain power quality. In this current control block addition to the SOCs balancing among different phases and arms.

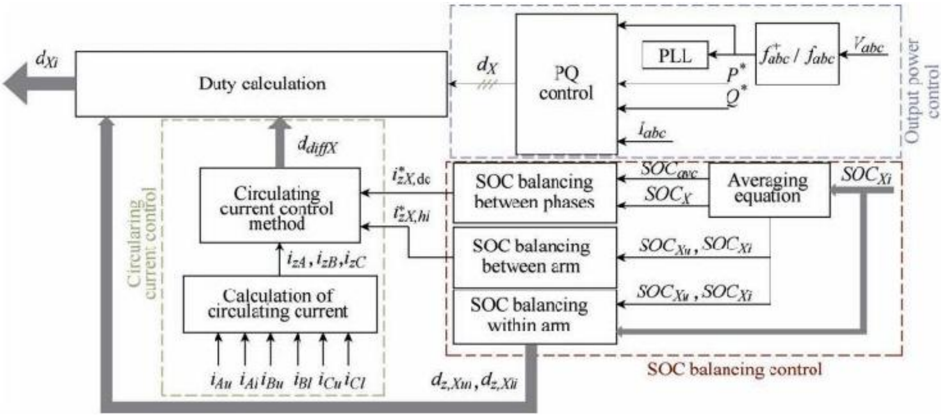


Figure 8: Control Block Diagram Multilevel Converter Battery Storage System

The above Control Block diagram is proposed that control strategy is shown in Figure 8. The grid current control the basic duty cycle for all submodules. The additional components by SOC balancing controllers and internal current controls. The discharging power of each battery stack can be individually controlled.

4.1 Grid Current Control Strategy

For Normal Conditions, grid voltages utilized to generate phase references through the phase locked loop. In asymmetrical grid voltage conditions, the grid current only positive sequence components and this component of grid voltages utilized to generate phase reference. The 90^0 phase shifting operator implemented through the calculation of second -order generalized integrator has shown below Figure 8(a).

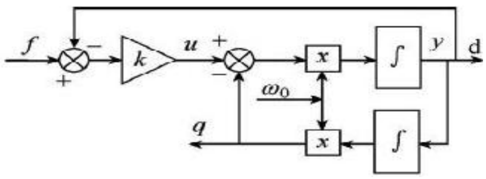


Figure 8 (a): 90 Degree Phase Shifting Operator

The positive sequence voltages can be derived and generate phase references through phase locked loop shown in Figure 8(b), where $D_\alpha = V_\alpha/2$, $Q_\alpha = V_\alpha e^{j90^\circ}/2$, $D_{\beta} = V_\beta/2$, $Q_{\beta} = V_{\beta ej90^\circ}$ /2.

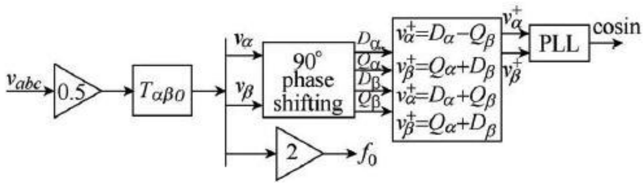


Figure 8 (b): Positive Sequence, Component Calculation

Then indicated in Figure 8 (c) besides of input of the phase locked loop, the grid current controlled strategy is similar to the traditional grid current controlled strategy. In Figure 8 (a,b,c) is The modified grid current controlled strategy.

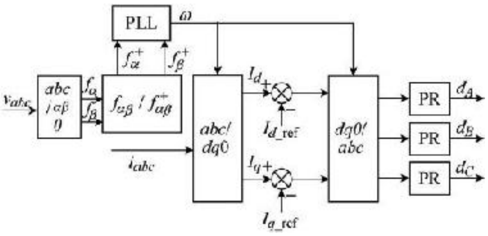


Figure 8 (c): Grid Current Controlled Strategy

4.2 SOC Balancing Control

The SOC of a battery is its percentage of its maximum available capacity, which can be expressed as below.

$$\mathrm{SOC(t)} = \mathrm{SOC(0)} = -\frac{\int_0^t \mathrm{i(t)dt}}{\mathrm{A\ h\ capacity}} \mathrm{X}\ 100\ \% \quad (1)$$

The unbalanced SOCs among all battery stacks in CHB inverter will reduce the operational capacity, the SOCs balanced in operation through balancing control strategy. Referring in Equation (1) in order to balanced SOCs the discharging current of the battery stack should controlled. In order to clarify the SOCs balancing control strategy, some variables are defined below.

$$SOCXu = \frac{1}{N} \sum_{i=1}^{N} SOCxui \quad (2)$$

$$SOCXl = \frac{1}{N} \sum_{i=1}^{N} SOCxli \quad (3)$$

Where SOC_{Xu} and SOC_{Xl} represent the averaged SOC of upper -arm and lower-arm respectively.

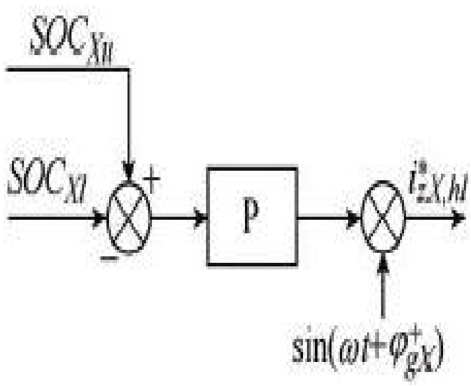


Figure 9: Between Upper Arm and Lower Arm

5. NEED OF BESS

5.1 Comparision of ESS

Table 2

ESS Features	BESS	Flywheel ESS	Super Capacitor ESS
Energy density	High	Medium	Medium
Power density	High	Low	Medium
Efficiency	85 – 95 %	70 – 80 %	80 – 90 %
Losses	Low (0.19mW)	Medium(0.5mW)	Medium(0.2 – 0.5 mW)
Maintenance	Low	High	Medium
Response Time	Very fast in few Seconds	Fast	Fast
Emergency Backup	Yes	No	No
Load Levelling	Yes	No	No
Uninterrupted Power Supply	Low	High	Medium
Max possible voltage	Max (double digit)	Low	Max (single digit)
Cost/Kwh	High	Medium	Medium

5.2 Comparison of Battery

Table 3

Specifications	Lead Acid	Nickel Cadmium	Nickel Metal Hydride	Alkaline
Specific Energy (Wh/Kg)	90 - 250	45 - 80	60 – 120	80 - 175
Cycle Life	100 – 2000	1000	300 – 500	360 - 400
Charge Time	1 – 2 hr	1 – 2 hr	2 – 4 hr	2 – 4 hr
Self discharge rate (%/days)	0.008 -0.011	0.30 – 4.00	0.07 - 0.71	0.033 – 1.10
Efficiency (%)	63 – 94 %	50 – 80 %	59 – 88 %	36 – 90 %
Life Span (yr)	3.0 – 20.0	2.0 – 15.0	2.0 – 15.0	2.50 -10.0
Power Density (Kw/m^3)	10.00 – 400.00	37.66 - 141.06	7.80 – 241.80	12.35 -101.70
Applications	Medium Scale Energy Management	Small Scale Energy Management	Small Scale Energy Management	Very Small Scale Energy Management
Environmental Impact	High	Medium	Medium	Low

6. EXPERIMENTAL RESULTS

Simulation is performed on the model system using PSIM Software. Presents the three-phase PCC4 voltage and the BSS current when the BSS is discharging the batteries, i.e. injecting real power into the PCC4. The PCC4 voltage is not purely sinusoidal due to the distribution impedance. The BSS current is sinusoidal and in-phase related to the PCC4 voltage for each phase. Current when the BSS is charging the batteries.

Similar to the previous case, the BSS current is sinusoidal, but now it is in counter-phase related to the PCC4 voltage, for each phase

Figure 10 (a) presents the charging currents for the battery banks of the H-bridge converters. Their waveforms are the same, indicating an equal distribution of power during the charging and discharging process. Figure 11 (a) presents the PCC4 voltage when charging the battery bank. The current is out of- phase related to the PCC4 voltage, showing the circulation of reactive energy and RMS Value of current & Voltage see Figure 10 (b) & Figure 11 (b).

Figure 12 (a) present the reference current Iabc & Experimental result phase Iabc see Figure 12 (b).CHB terminal voltage when the converter is bypassed into the grid see Figure 13 (a) & the experimental result see Figure 13 (b)

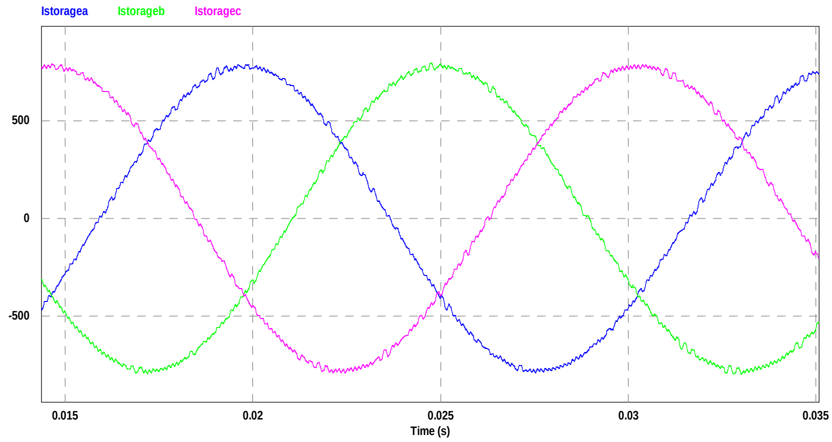
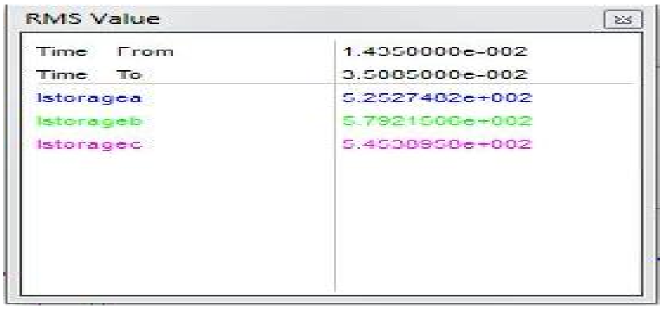


Figure 10 (a): BSS Current when the Charging the Batteries



RMS Value

Time From	1.4350000e-002
Time To	3.5005000e-002
Istoragea	5.2527402e+002
Istorageb	5.7921500e+002
Istoragec	5.4530950e+002

Figure 10 (b): RMS Value of Current

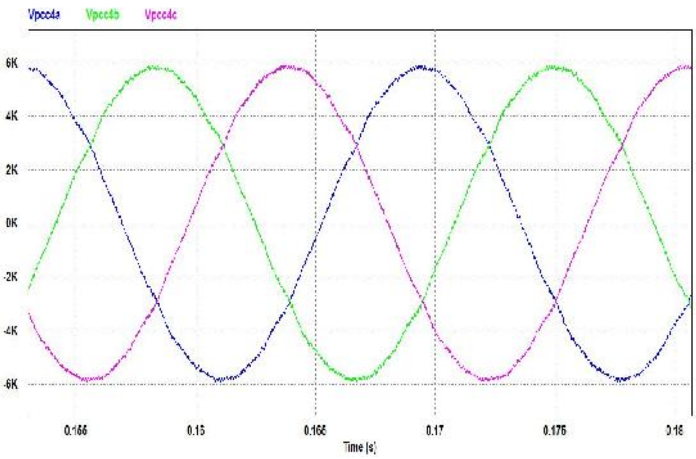
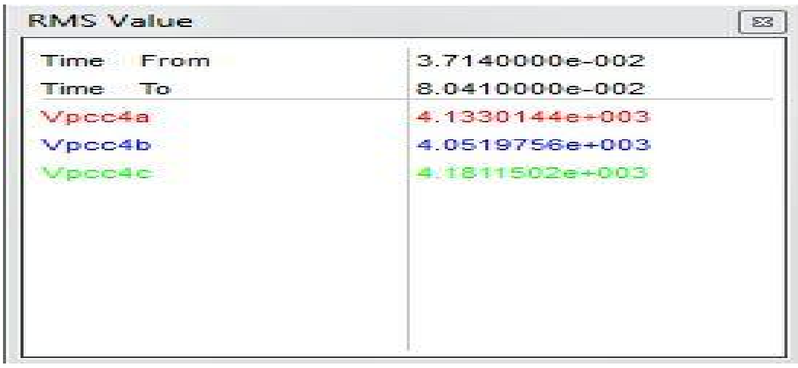


Figure 11 (a): BSS Voltage when the Charging the Batteries



RMS Value

Time From	3.7140000e-002
Time To	8.0410000e-002
Vpcc4a	4.1330144e+003
Vpcc4b	4.0519756e+003
Vpcc4c	4.1811502e+003

Figure 11 (b): RMS Value of Voltage

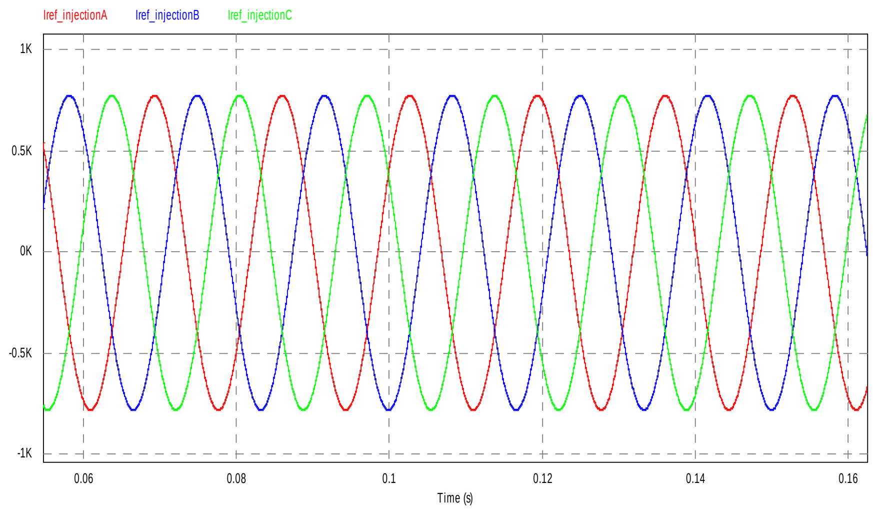


Figure 12 (a): Reference Current Iabc

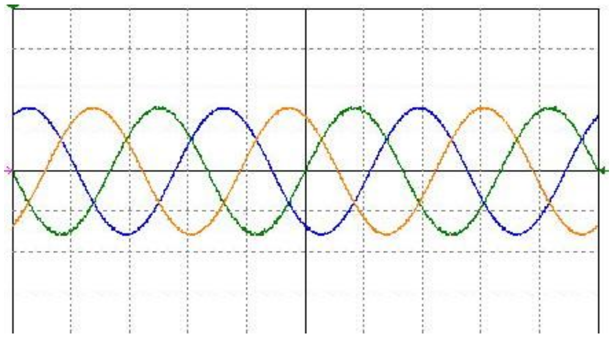


Figure 12 (b): Experiment Result for Phase A,B,C (Time base 5ms/Div, Scale 500v/Div)

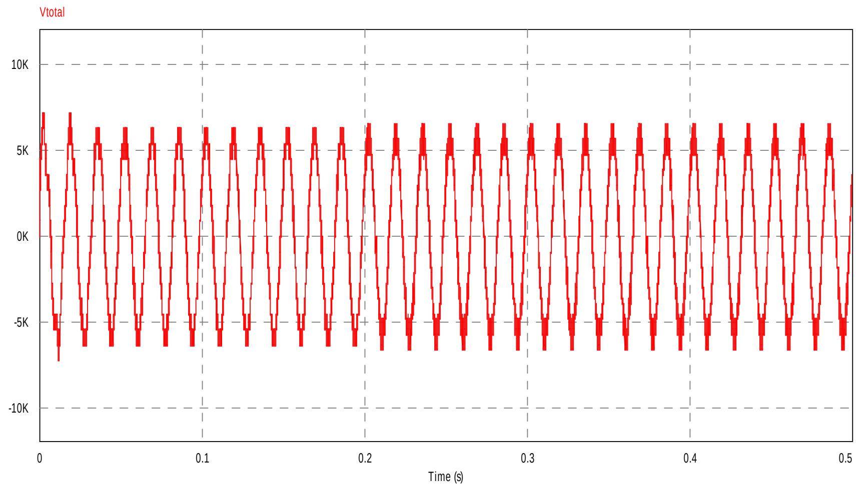


Figure 13 (a): CHB Terminal Voltage when the Converter is Bypassed

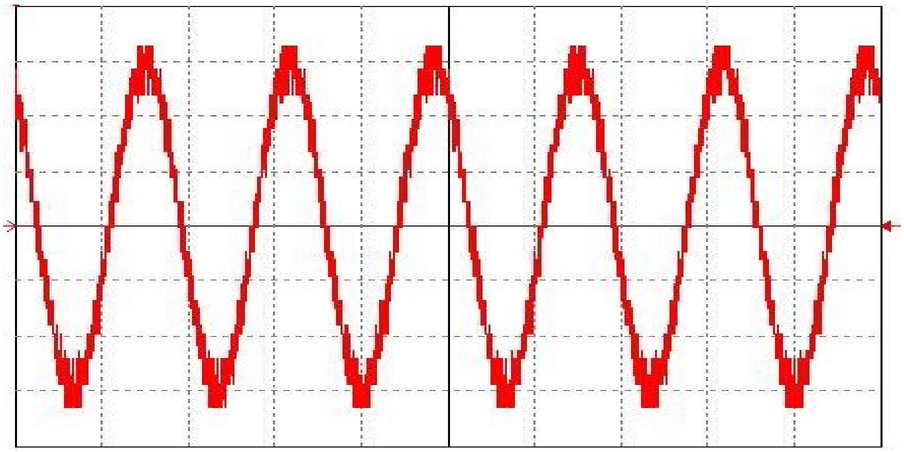


Figure 13 (b): Experiment Result for (Time Scale 10ms/Div, Scale 2kv/Div)

CONCLUSIONS

This paper presents a three-phase Battery storage system with a transformerless cascaded multilevel inverter for distribution grid applications. The BSS is composed of eight series-connected H-bridge converters, making it unnecessary to use any bulk transformer. Each converter contains a battery bank made up of 75 12 V/600Ah lead-acid batteries. The BSS is also able to keep working even if one of its converters fails. Moreover, reactive energy compensation is also performed by the proposed BSS.

A case study with simulated and experimental results in HIL system shows the performance of the BSS to be excellent. A failure in one of the H-bridge converters is emulated and the results demonstrate that the BSS kept working uninterrupted. Therefore, the proposed BSS is an attractive solution for applications in medium-voltage grids, contributing to the reliability and to the uninterrupted supply of the distribution system.

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