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PMDC MOTOR SPEED CONTROL USING BATTERY SOURCES FOR ECONOMICAL APPLICATIONS

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ABSTRACT

Battery Energy Storage Systems (BESS) play a critical role in stabilizing voltage and frequency fluctuations caused by renewable energy variability. A key application of BESS is enabling autonomous power system operation, independent of the main transmission network, while maintaining high-quality, reliable three-phase voltage to protect plant equipment. This study investigates various multilevel inverter topologies for BESS applications through simulation. It includes both quantitative analyses, evaluating output performance, and qualitative analysis, assessing reliability, modularity, and functionality. Multilevel converters are state-of-the-art for medium-voltage (MV) high-power systems, widely used in industries such as mining, marine, and oil and gas, and in integrating renewables into the grid. The focus is on three-level and five-level converter topologies with a common DC-link, supporting bidirectional energy flow. New hybrid topologies and modulation techniques are developed to optimize cost, reliability, and efficiency. All simulations are conducted under identical conditions using MATLAB/Simulink.

1. INTRODUCTION

As renewable energy sources like solar and wind become more integrated into power systems, maintaining grid stability has become increasingly challenging due to their intermittent and unpredictable nature. Battery Energy Storage Systems (BESS) offer a promising solution by storing excess energy and supplying it during periods of high demand or low generation. Beyond stabilizing voltage and frequency, BESS also enable peak shaving, load leveling, and black-start capabilities, making them vital for future smart grids.

Power electronic converters are crucial for interfacing BESS with the grid or loads. Among them, multilevel converters are favored for medium-voltage and high-power applications due to their superior voltage quality, efficiency, and reduced electromagnetic interference compared to traditional two-level converters. They offer advantages like lower total harmonic distortion (THD), reduced voltage stress, and improved scalability.

Key multilevel converter topologies—Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB)—each have distinct benefits and trade-offs affecting system cost, complexity, and control. This study analyzes these topologies, focusing on their suitability for bidirectional power flow, modularity, and high efficiency. Performance factors such as switching losses, waveform quality, control complexity, and thermal management are evaluated.

Simulations using MATLAB/Simulink are conducted under uniform conditions to identify the most suitable inverter architecture for BESS integration, balancing cost, reliability, and performance. Special focus is given to five-level converters with a common DC-link, highlighting their advantages for advanced energy storage applications. This research aims to optimize BESS power electronic interfaces, contributing to more resilient and sustainable energy systems.

In recent years, the transition from traditional fossil-fuel-based power systems to renewable-energy-based power grids has garnered significant scientific interest. Consequently, multilevel converters have emerged as a contemporary and noteworthy topic within the field of power electronics, facilitating the integration of renewable energy resources into the grid [1]. Renewable energy sources, such as wind and solar photovoltaic (PV) systems, are inherently intermittent due to their reliance on weather conditions. To mitigate this variability, Battery Energy Storage Systems (BESS) can provide supplementary energy during periods of peak demand or when renewable sources are unavailable. Furthermore, BESS can swiftly deliver active power to the grid, thereby supporting ancillary services including spinning reserve, peak shaving, load leveling, and frequency regulation [2]. Current energy storage technologies encompass batteries, flywheels, ultracapacitors, and superconducting systems.

Black start restoration represents a critical application of Battery Energy Storage Systems (BESS) within contemporary power systems [3]. In recent years, several large-scale blackouts have underscored the necessity of dependable restoration methods. For example, the North American blackout on August 14, 2003, resulted in extensive damage, with power restoration efforts extending nearly two weeks [4]. Other significant incidents include the European outage on November 4, 2006 (lasting up to two hours), the Brazil-Paraguay blackout on November 10, 2009, and the shutdown of Japan's Fukushima nuclear plant following the earthquake and tsunami on March 11, 2011 [11].

Black start restoration denotes the procedure of reactivating a power plant or a small grid independently of the external transmission network. This process necessitates a local DC source to supply energy to auxiliary systems—such as protection, monitoring, excitation, and lighting—for a duration exceeding 10 hours. Traditionally, this service is facilitated by specially-equipped generators; however, various energy storage technologies, including Battery Energy Storage Systems (BESS), can effectively fulfill this role [5]. A pertinent example is the 5 MW battery storage system located in northeast Germany, which possesses the capability to restore a regional power grid in the event of a significant outage [6].

Voltage-sourced converters can be integrated with Battery Energy Storage Systems (BESS) to facilitate power system restoration efforts [7]. A typical BESS installation comprises two primary hardware components: a power conversion system (PCS) and a network of battery storage units [2]. In the event of a blackout, station batteries sustain the operation of critical control and protection systems for a limited duration, typically around 30 minutes. Subsequently, a small diesel generator is generally employed to recharge the batteries and provide backup power to essential components, such as the converter valve cooling system [14].

- To study the multilevel inverter topologies for BESS using quantitative and qualitative analyses.
- To study the performance comparison of Cascaded Multilevel Inverter (CMLI), The modular structure of CMLI, along with the Z-Source Multilevel Inverter (ZsMLI) and Quasi-Z-Source Multilevel Inverter (QZsMLI) with single-input inverters.

2. GRID CONNECTION OF BATTERY MANAGEMENT CONVERTER SYSTEM

When integrated with the electrical grid, the Battery Management and Control System (BMCS) fulfills a dual function: it regulates the power exchange between the battery pack and the grid, and it ensures the safe and efficient operation of the batteries. The embedded power converters, typically voltage-sourced inverters, enable the system to manage both charging and discharging processes, synchronize with the grid, and support grid functions such as peak shaving, load leveling, frequency regulation, and black start restoration.

Stability is a major challenge for all Grid-Connected Converters (GCCs). Depending on the application, GCCs can operate in all four quadrants, controlling both active and reactive power. Grid-connected battery systems typically focus on active power regulation, operating at unity power factor, with two main modes: inverter mode (power injection) and rectifier mode (power absorption), the latter often used for Power Factor Correction (PFC).

Impedance or admittance modeling is a common method for analyzing GCC stability, treating the converter as a controllable admittance at the Point of Common Coupling (PCC). In rectifier mode, the converter behaves like a positive resistor, ensuring stable, resistive behavior across frequencies. In inverter mode, however, the converter mimics negative resistance to inject power, which can amplify high-frequency resonances and cause instability.To prevent this, negative resistance is restricted to the grid’s fundamental frequency. Phase-Locked Loops (PLLs) are commonly used to isolate the line frequency, keeping converter admittance neutral elsewhere. Alternatively, Opposed Conductance Control (OCC) maintains broadband resistive behavior while shaping negative conductance near the line frequency using a low-pass-filtered voltage signal. Crucially, the control crossover frequency must stay below potential grid resonances to preserve stability.

The control system from Figure 1 and the circuit in Figure 1 were simulated in PSIM using parameters from Table 1. Figure 2 shows simulation results without an EMI filter. Initially, the converter operates in full-power inverter mode (negative conductance), then switches to full-power rectifier mode (positive conductance). The 20 kHz voltage filter enables a fast response to this transition. Despite a low current THD (~1%), high-frequency switching noise appears on the grid voltage due to grid impedance.

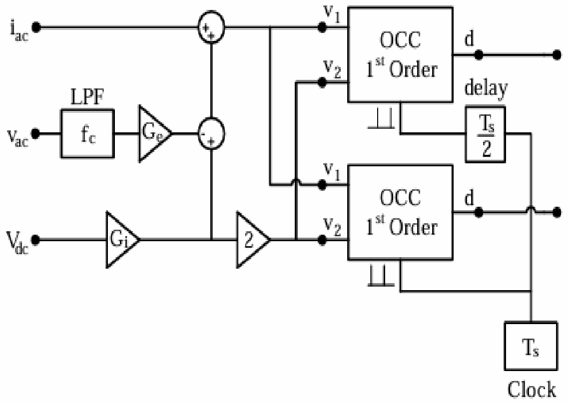

Figure 1. Block diagram of OCC for grid-connected single Full-Bridge Buck converter.

Switching noise on the grid voltage can interfere with nearby devices at the Point of Common Coupling (PCC), making an EMI filter necessary.

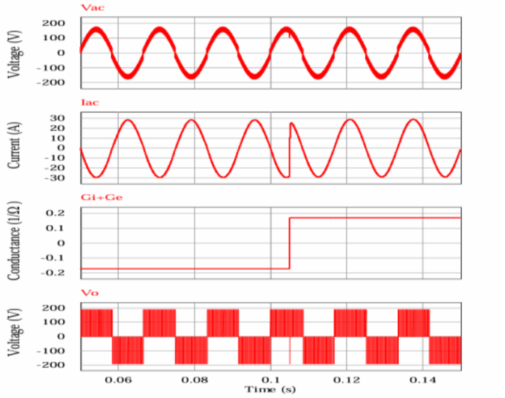

Figure 2. Simulated waveforms of grid-connected single Full-Bridge Buck without EMI filter.

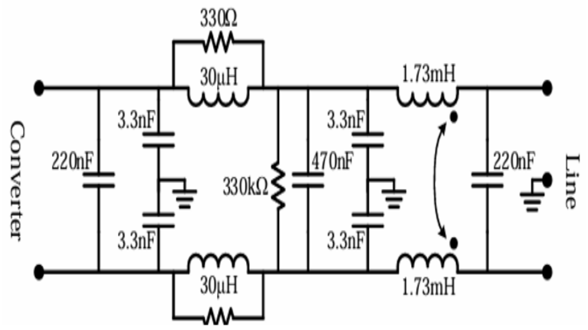

Figure 3. The schematic of an EMI filter with typical values for 20A rated filter.

Table 1. Simulation parameters of the grid-connected single Full-Bridge Buck converter.

Parameter	Symbol	Value
Grid Nominal Voltage	v_g	120 V_rms
Grid Fundamental Frequency	f_o	60 Hz
Grid Inductance	L_g	93.4 μH
Grid Resistance	R_g	7.2 mΩ
Battery Voltage	V_{dc}	192 V
Coupling Inductance	L_{ac}	500 μH
Coupling Resistance	R_{ac}	1 mΩ
EMI Filter		See Figure 3.8
Clock Frequency	f_{clk}	50 kHz
LPF Cut-Off Frequency Without EMI Filter	f_c	20 kHz
LPF Cut-Off Frequency With EMI Filter	f_c	5 kHz
Conductance via Current Loop	G_i	0.17 Ω^{-1}
Conductance $0 \leq t < 105$ ms via Voltage Loop $105 \leq t < 150$ ms	G_e	-0.32Ω^{-1} 0 Ω^{-1}

Figure 3 shows a typical 20A EMI filter, where differential mode noise is filtered by series inductors and X capacitors, and common mode noise by a common mode choke and Y capacitors. However, the filter introduces new resonant frequencies through interactions with grid and converter inductances, with the lowest around 6.5 kHz. Without damping, these resonances could destabilize the system. To ensure stability, the converter must behave resistively at and above this frequency. In simulation, the low-pass filter bandwidth was reduced to about 5 kHz, effectively suppressing switching noise while maintaining stability in both inverter and rectifier modes (Figure 4). Though the reduced bandwidth slightly slows the converter's response to mode transitions, system stability is preserved.

3. OCC OF CASCADED FULL-BRIDGE BUCK GC-BMCS

BMCS architectures often use cascaded Full-Bridge Buck converters to achieve higher voltages. Interleaved modulation, as previously discussed, reduces voltage distortion, improves waveform quality, and allows lower switching frequencies, minimizing losses and boosting efficiency. This section presents grid connection control using a four-stage cascaded Full-Bridge Buck converter Each stage carries the same AC current and contributes to the total series conductance (Ge + Gi) through its individual conductance (Gex + Gix), managed by the OCC control block.

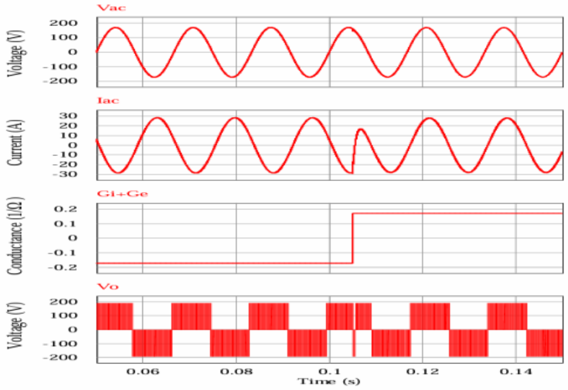

Figure 4. Simulated waveforms of grid-connected single Full-Bridge Buck with EMI filter.

4. DIFFERENT MULTILEVEL CONVERTER TOPOLOGIES FOR BATTERY ENERGY STORAGE APPLICATION

In this work, five well-known battery-source multilevel inverter topologies shown in Fig. 5 and Figure 6 are evaluated through both quantitative and qualitative analyses using MATLAB/Simulink. All scenarios are simulated under identical conditions, utilizing the same energy storage source and load setup. Each inverter uses IGBT switches, and a Nickel-Metal Hydride (NiMH) battery system is employed as the energy source, providing a total nominal voltage of 1664 V for both single- and multi-input configurations. A low-pass filter is connected to the inverter output to suppress high-frequency harmonics. Additionally, the load is modeled as a balanced three-phase resistive load (R = 10 Ω) to accurately assess the real efficiency of the inverters.

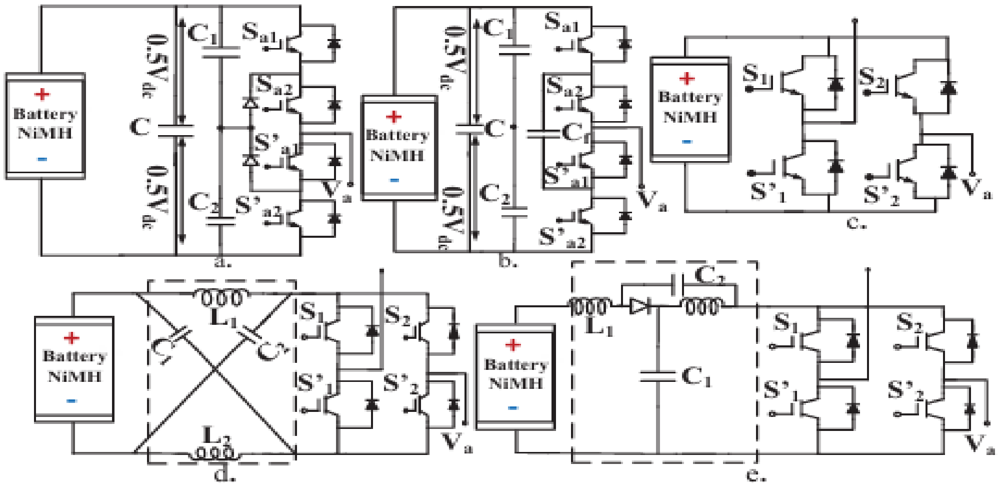

Figure. 5. Single-leg representations of various multilevel inverter topologies: (a) NPC-MLI, (b) CCL-MLI, (c) CHB-MLI, (d) Z-source MLI, and (e) Quasi Z-source MLI.

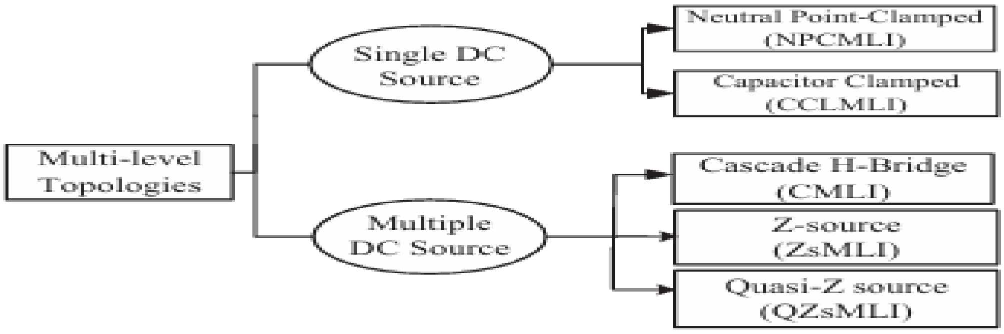

Figure.6. Multi-level topologies classification.

4.1. Quantitative Study

In this section, the output waveform characteristics of each battery-sourced inverter topology are analyzed in terms of line-to-line Total Harmonic Distortion (THD), power losses (Ploss), and efficiency (η). Efficiency for each topology is defined as the ratio of the electric power delivered from the battery system to the electric load, as shown in Equation (1).

$$\eta = \frac{P_{\text{output}}}{P_{\text{input}}} = \frac{P_{\text{output}}}{P_{\text{output}} + P_{\text{loss}}} \tag{1}$$

4.2. Battery-Sourced NPCMLI

The Neutral Point Clamped (NPC) inverter is the first and most widely used multilevel topology, originally patented in 1975. Figure 5 (a) illustrates a single-leg diagram of a three-level NPC inverter powered by a battery energy storage system and connected to predefined loads. The modulation strategy used is Level-Shifted Sinusoidal Pulse Width Modulation (SPWM), with carrier signals arranged in In-Phase Disposition (IPD), as detailed in The voltage and current waveforms of the inverter capacitor clamped inverter are shown in Figure 7 and 8. According to Table 4.1, this topology exhibits a line-to-line voltage Total Harmonic Distortion (THD) of 15.23%, an efficiency (η) of 94.26%, and total power losses of 3.953 kW.

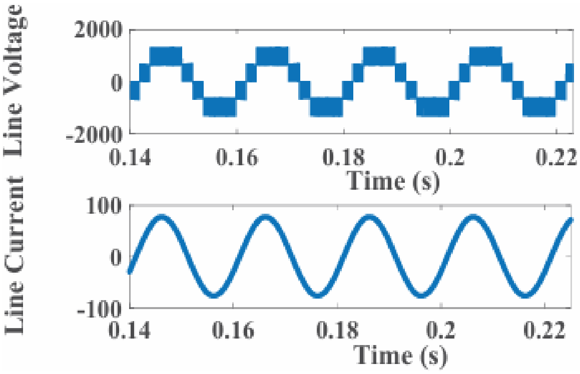

Figure. 7. Voltage and current waveforms of three level battery source NPC inverter.

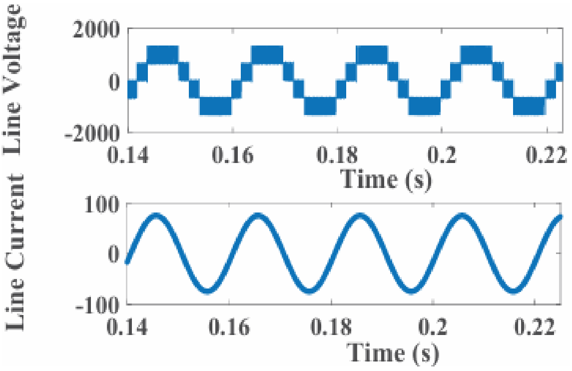

Figure.8. Voltage and current wave forms of three level battery source capacitor clamped inverter

Table 2. Quantitative Study

Topology	THD %	Efficiency%	Power loss (KW)
NPCMLI	15.23	94.26	3.953
CCMLI	17.48	95.80	2.892
CMLI	16.77	99.92	0.055
ZsMLI	17.66	92.27	5.323
QZsMLI	17.34	94.77	3.602

4.3. Qualitative Study

In this section, the battery-sourced multilevel inverter topologies are evaluated based on key qualitative characteristics, including **reliability**, **modularity**, and **functionality**. Figure9 represents the voltage and current wave forms of three level Quasi-Z source battery connected inverter.

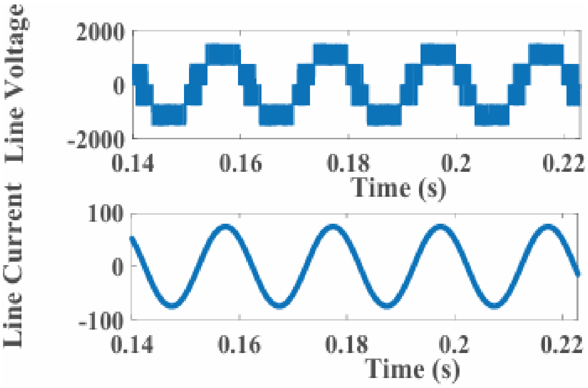

Figure.9. Voltage and current wave forms of three level Quasi-Z source battery connected inverter.

Table 3. Qualitative Study

Topology	M1	M2	M3	M4	M5	M6	M7
NPCMLI	12	3	0	6	Y	N	Y
CCMLI	12	6	0	0	Y	N	Y
CMLI	12	0	0	0	N	Y	Y
ZsMLI	12	6	6	0	N	Y	Y
QZsMLI	12	6	6	3	N	Y	Y

Reliability reflects an inverter's ability to operate correctly over time, considering commutation accuracy, safe operation, and proper switching. Key indicators are failure rate and lifetime, both tied to component reliability.
Two main metrics are: - MTBF (Mean Time Between Failures) = 1 / λ_s, where $\lambda_s = \Sigma \lambda_j$ (sum of component failure rates) - Lifetime (LT) = minimum component lifetime

The reliability factor (R.F) is:
R.F = MTBF / MTBF_max × LT / LT_max

The CMLI has the highest reliability, while NPCMLI shows the lowest, restricting its scalability. NPC's numerous clamping diodes limit scalability beyond five levels. CCLMLI replaces diodes with capacitors but requires pre-charging. CMLI, with modular full-bridge units and independent DC sources, reduces components, boosts efficiency, and cuts losses compared to NPCMLI and CCLMLI. ZsMLI and QZsMLI further enhance reliability and functionality. While ZsMLI offers voltage boost, its capacitor stress is resolved in QZsMLI.

5. CONCLUSION

In this study, the most prevalent multilevel inverter topologies were examined to identify the most suitable topology for Battery Energy Storage System (BESS) applications. The investigation comprised both quantitative and qualitative analyses. The quantitative analysis focused on the critical output parameters of inverter topologies, while the qualitative analysis assessed features such as reliability, modularity, and functionality. Additionally, various inverter topologies were evaluated in terms of the required capacity at a consistent operating point. The simulation results demonstrated that the optimal BESS power conversion system, among the reviewed multilevel topologies, is the Cascaded topology. This topology was selected for three primary reasons. First, efficiency and reliability assessments indicated that the Cascaded Multilevel Inverter (CMLI) is the most efficient and reliable topology, exhibiting minimal power loss compared to other topologies. Second, it subdivides the battery string and enhances high-voltage functionality. Finally, studies on capacitor volume, cost, and Total Harmonic Distortion (THD) further confirmed the effectiveness of this topology in battery energy storage systems.

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