A Novel Topology for High Voltage Battery Energy Storage Systems

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***Abstract*—This paper introduces a novel topology for high voltage battery energy storage systems (BESS), addressing the challenge of achieving necessary power and voltage for effective energy storage without exposing cells to harmful high voltages stress. Such exposure risks accelerated degradation and electrical faults. This research presents a scalable and simple solution using high frequency power transformers (HFPT) in a cascade configuration, allowing the use of low voltage cells in high voltage applications and avoiding the issues common to traditional series-parallel cell setups. The key advantages of the proposed topology include its simplicity, scalability, and ability to significantly reduce voltage stress, thereby enhancing system efficiency and reliability. Simulation results from MATLAB-Simulink support the effectiveness of the presented topology, suggesting its potential to improve high voltage battery storage systems.**

Keywords—Battery energy storage system, cell, circuit topology, electrical safety, insulation, voltage stress

NOMENCLATURE

$a = U_1 / U_2$	Transformation ratio
C	Capacitance
C_1	1st degree capacitor of an internal battery cell model
C_2	2nd degree capacitor of an internal battery cell model
f_1	Fundamental frequency
f_{com}	Commutation frequency
L_{1t}	Dispersion inductance of the primary winding of a transformer
L_{2t}	Dispersion inductance of the secondary winding of a transformer
L_m	Magnetizing inductance of a transformer
N	Number of battery modules
P_n	Rated power
R_1	1st degree resistance of an internal battery cell model
R_{1t}	Primary winding resistance of a transformer
R_2	2nd degree resistance of an internal battery cell model
R_{2t}	Secondary winding resistance of a transformer
R_{gnd}	Grounding resistor
R_{load}	Load resistance
R_m	Iron loss resistance of a transformer
$R_{n1} = R_{n2}$	Artificial midpoint resistors
R_{pol}	Polarization resistance of a cell
U_{Cell}	Voltage of a single cell
U_{DC}	Output DC voltage of a battery module

I. INTRODUCTION

The global shift towards greener energy solutions has led to increased adoption of renewable energy sources (RES), but their intermittent nature poses challenges. Solar and wind energy's fluctuating output underscores the vital role of efficient energy storage systems in ensuring reliable power supply. Among these technologies, direct current (DC) systems play a crucial role, comprising sources like solar panels, batteries, and electrochemical cells powered by hydrogen (H_2).

However, to achieve substantial power and operating voltages for storing electrical energy from dispersed generation, these systems often require multiple cells configured both in series and parallel. The primary goal is to maximize the number of cells connected in series to enable higher voltage operation and, consequently, more efficient installations. Nevertheless, this approach presents a significant challenge: cells exposed to the highest voltage in the circuit relative to the ground can suffer from accelerated wear and become more susceptible to electrical faults. Studies have shown that when photovoltaic (PV) panels are exposed to high voltage levels, they experience increased rates of cell degradation, leading to a decline in power output over time [1]-[2]. Likewise, battery units are similarly afflicted,

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enduring shortened lifecycles and heightened failure rates under these conditions [3]-[4]. These issues not only compromise the reliability of renewable energy systems but also contribute to higher operational costs due to the need for more frequent maintenance and component replacement. By addressing the high voltage stress problem, we can significantly enhance the durability and operational efficiency of PV and battery storage systems, reducing long-term costs and improving the sustainability of renewable energy infrastructure.

The literature reveals various strategies to address the challenges associated with integrating Battery energy storage systems (BESS) into high voltage applications, including modular reconfigurable systems, active cell voltage balancing, and dynamic reconfiguration frameworks [6]-[13]. However, a critical examination of these proposed solutions uncovers a consistent gap: the issue of voltage stress on cells, which significantly impacts system durability and limits the potential for series expansion of cells.

Authors in [5] proposed cell balancing technique using symmetrical switched capacitors structure with equal amount of stress on all the switches and capacitors, yet the impact on voltage stress on cells is not fully mitigated.

In [6], it is proposed a new type of battery systems topology to improve the fault response capability of the system, which has a lower cost, particularly in scenarios involving single or multiple battery cell failures. Nevertheless, the study does not investigate the voltage stress on the cell. Paper [7] proposes switchable series topologies for charging and discharging by means of electronic DC/DC converters, but still presents the above problem.

The dynamic reconfiguration framework, featuring energy storage cells surrounded by ON/OFF switches, enabling flexible interconnections in series, parallel, or combinations is presented in [8]. While [8] focused on reconfigurable topologies at the cell level, [9] proposed extending these concepts to module-level applications where individual cells within a cell pack are replaced by energy storage modules along with module switching elements. This architecture of a reconfigurable battery pack is suited for high-power applications. However, the persistent problem of voltage stress on cells remains unaddressed.

A modular multi-technology energy storage system connected to a combined DC-link via DC/DC converters is presented in [10]. This approach can lead to a higher flexibility in the system design and enhance lifetime and safety at the same time. However, this approach requires more power electronics, potentially increasing costs, and complexity. Adapting modular multilevel converters for low voltage battery storage systems has led to the development of Alternating Current (AC) batteries [11]. These systems are more efficient, can be easily scaled up, and offer flexible configuration options. However, the drawback is that they require more complex control systems to manage them effectively.

Review [12] discusses how Re-configurable Battery Management Systems are becoming a promising way to make battery systems more energy-efficient, last longer, and be more reliable. It looks into and compares different reconfigurable setups. However, none of these setups provide a way to reduce the stress on battery cells caused by high voltage.

In addition, [13] provides an in-depth analysis of power converter applications for linking battery storage systems to medium voltage grids. The study reveals that most of the examined topologies employ Buck/Boost DC/DC converter systems, which elevate the voltage to match grid output levels, followed by an AC inverter that facilitates the transmission of current to a transformer. This transformer then further increases the voltage to integrate the battery bank with the high voltage circuit efficiently. Additionally, alternative topologies incorporate phase-to-phase cells evenly distributed across the three phases of the AC system, referred to as cascaded systems, or utilize modular multilevel converters for a direct grid connection.

The review highlights a crucial gap in addressing excessive voltage stress on cells within BESS, which diminishes system durability and restricts the use of additional cells in series. This paper proposes a novel system design and topology aimed at integrating storage cells into the grid while mitigating voltage stress. This design introduces a simple topology that extends operational life and reduces maintenance costs by lowering voltage stress on battery cells. We introduce High Frequency Power Transformers (HFPTs) in order to galvanically isolate the cells of each module of batteries from the high voltage DC side of the circuit to connect the modules in series. Furthermore, HFPTs allow to reduce the current on the high voltage DC side of the converter, resulting, a priori, in a decrease of energy losses and an overall enhancement in system efficiency.

The proposed topology solution is validated with simulations conducted in MATLAB-Simulink. The promising results from these simulations demonstrate the effectiveness of the proposed configuration.

The paper is structured as follows: Section II explains the connection topology for battery storage systems with multiple cells in series. Then, Section III defines the simulation setup while Section IV discuss the results obtained from it. Finally, Section V concludes the manuscript with its main highlights and further research lines.

II. Operating Principles of the Proposed Topology

In traditional configurations of PV arrays or battery storage systems, as depicted in Fig. 1(a) to 1(c), several inefficiencies and operational challenges are identified:

- Fig. 1(a): In this configuration, every cell is exposed to a different voltage stress between its terminals and the ground, located in the negative pole of the electric system. Cells located at an upper position in the array experience a higher voltage stress, and therefore, the uppermost cell is exposed to the highest voltage stress. Besides, the higher the array voltage is, the higher the voltage stress of all cells will be, and particularly, that of the uppermost cell. This excessive voltage stress accelerates the aging process of the insulation, compromising the longevity and safety of the system.
- Fig. 1(b): In this configuration, the grounding is performed in the DC midpoint of the electrical system. While this configuration mitigates voltage stress by approximately half, it does not eliminate the underlying issue. In order to better understand this configuration, a numerical example is given: In a scenario with an array operating at 1000 Vdc, comprised of 10 V cells, the last cell is subjected to insulation stress at both 490 V to 0 V

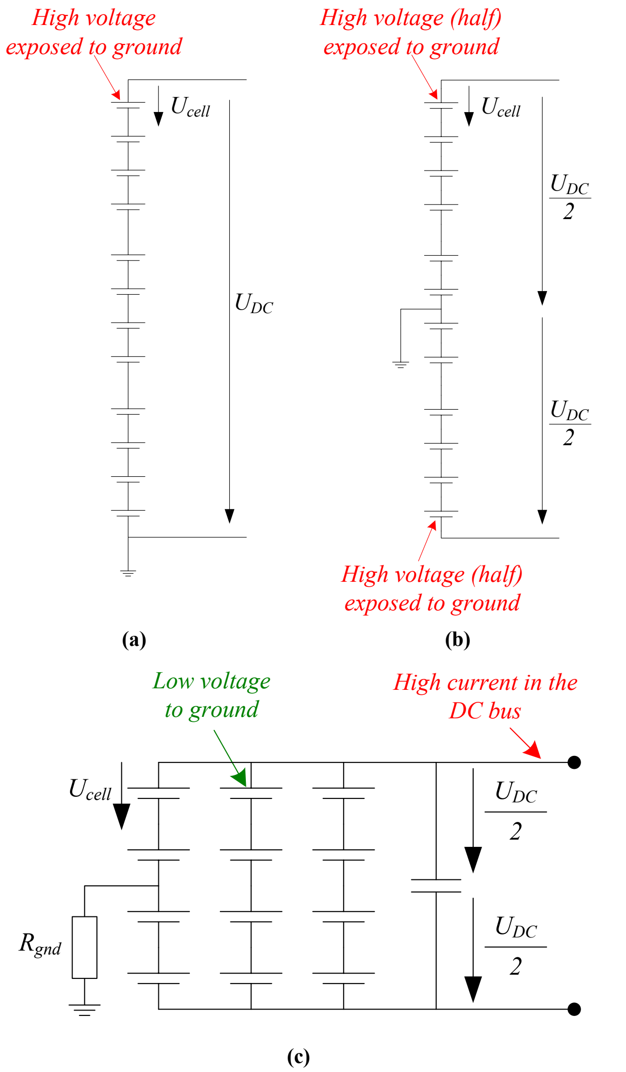

Fig. 1. Electrical schemes of conventional battery-solar photovoltaic array connections [(a): Series array with the negative pole grounded; (b): series array with the midpoint grounded; (c): parallel array with the midpoint (or negative pole) grounded].

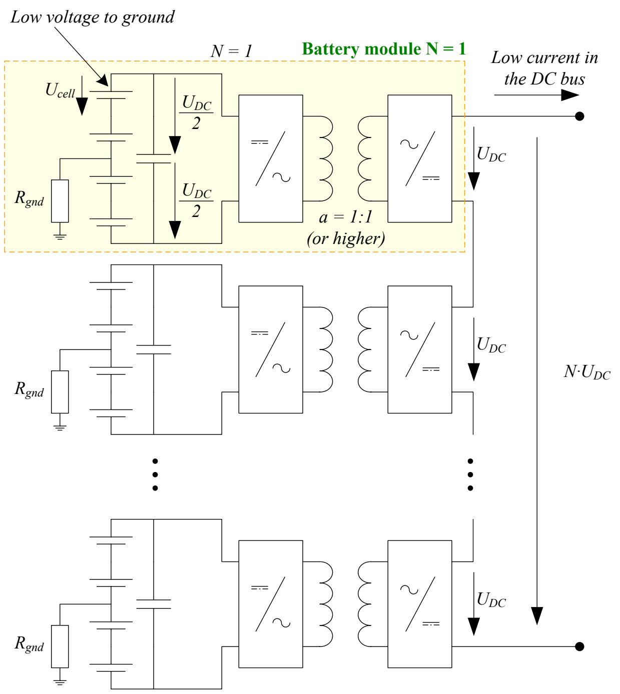

Fig. 2. Proposed configuration for array connection with HFPT.

and 500 V to 0 V, a marked improvement from the 990 V to 0 V and 1000 V to 0 V observed in the previous configuration. Nonetheless, this configuration introduces contrary stress on the first cell, with -490 V to 0 V and -500 V to 0 V in the insulation of the cell terminals, illustrating a reversal of the problematic condition.

- Fig. 1(c): This configuration also grounds the system in the DC midpoint and significantly reduces insulation stress by shorting the number of cells in series and placing them in parallel to reach the same energy capacity. However, it leads to a tripling of the current in the DC bus. Consequently, the system incurs a ninefold increase in energy losses, reducing its overall efficiency. This type of systems (also grounded in the negative pole) is the most common installed in real facilities.

The proposed configuration, illustrated in Fig. 2, synthesizes the advantages of the previous setups while addressing their limitations. The incorporation of a midpoint grounding strategy effectively reduces insulation stress and the most critical voltages in the battery packs (upper and lower cells) do not exceed U_{DC} / 2 in any case. It maintains a low DC bus current, allowing for an increase in bus voltage without incurring additional losses. Importantly, the insulation of the cells is preserved due to the low voltage at the secondaries, which cumulatively contribute to the primary voltage of each module. Furthermore, the cells of each battery module become galvanically isolated, which allows to place different groundings along the series array. This innovative approach not only enhances the system's operational efficiency but also its safety and resilience against degradation induced by voltage stress.

III. Simulation Setup

In order to validate the proposed topology, some simulations have been carried out in MATLAB-Simulink. The setup considers a battery storage system, but other applications with electrical cells such as H_2 storage systems or PV solar systems could be also considered.

The simulation setup is depicted in Fig. 3. It consists of two battery modules connected to a high voltage side. Both modules are connected in series in order to add their output voltages in the high voltage side of the system. Additionally, two capacitors have been installed in order to reduce the voltage ripple. The high voltage side emulates the power consumption downstream by means of a load resistor, R_{load}.

Inside each battery module, there is a battery pack consisting of "*N*" cells in series. The equivalent circuit of one cell is shown in Fig. 3, in blue color. The output of the battery pack is connected to an AC single-phase IGBT-based inverter, which is Pulse Width Modulation (PWM) controlled, to provide an AC waveform to the transformer, that allows the galvanic insulation of each battery pack. In the output of the transformer, the AC current is rectified with a non-controlled single-phase rectifier. Consequently, DC voltage emerges between each module's terminals. The sum of all these DC voltages will conform the pole-to-pole voltage of the high voltage side of the circuit. This configuration can be scaled up to "N" battery modules, but still the insulation of the battery packs will remain constant.

On the other hand, in order not to stress the insulation of the circuit, a midpoint grounding strategy was considered.

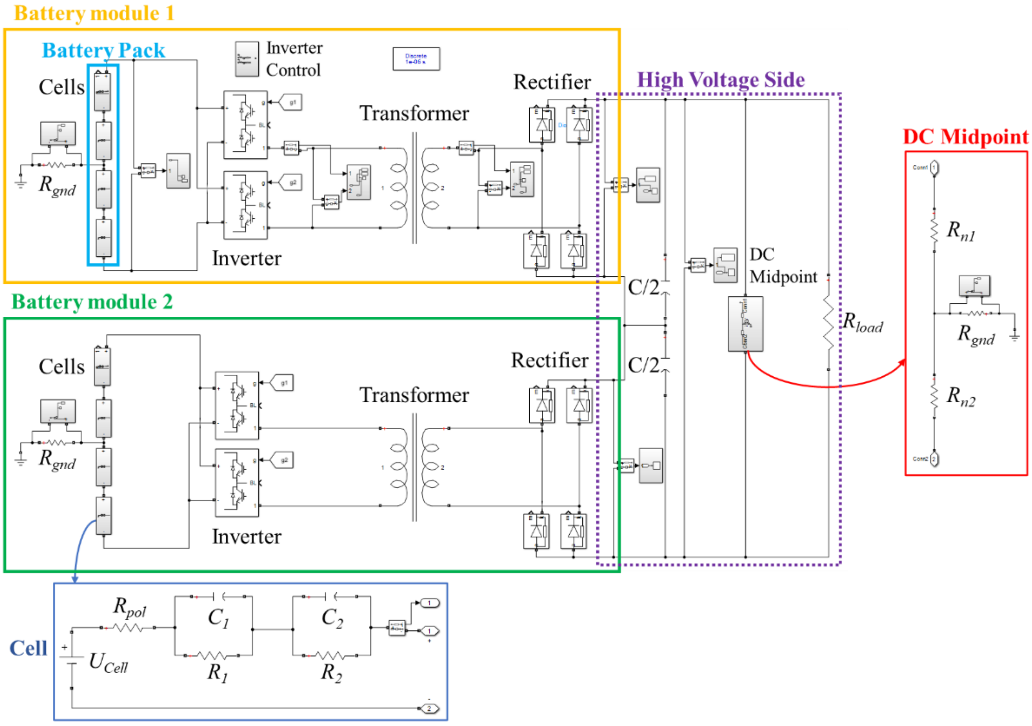

Fig. 3. Simulation setup.

TABLE I. SIMULATION SETUP PARAMETERS

Element	Parameter	Magnitude	Units	Element	Parameter	Magnitude	Units
Battery cells	U_{Cell}	1.5	V	***Power transformers***	P_n	1.5	kW
	No. of cells	160	Cells		$a = U_1 / U_2$	220 / 220	V / V
	R_{pol}	0.005	Ω		R_{1t}	0.5	Ω
	R_1	0.01	Ω		L_{1t}	1.273	mH
	C_1	10^4	F		R_{2t}	0.8	Ω
	R_2	0.305	Ω		L_{2t}	1.273	mH
	C_2	1.5×10^4	F		R_m	1427.7	Ω
Inverter	f_1	50	Hz		L_m	1.9713	H
	f_{com}	5×10^3	Hz	***DC capacitor***	C	10^{-3}	F
Grounding systems	$R_{gnd} = R_{n1} = R_{n2}$	4.7	kΩ	***DC Load***	R_{load}	500	Ω

Inside each battery module, a grounding resistor, R_{gnd}, has been placed. As a result, the dielectric stress of each terminal cell has been reduced to the half (compared to the case where the grounding was in the negative pole). The same strategy has been adopted for the high voltage side of the circuit (Fig. 3, red color), where an artificial DC midpoint has been installed using two identical high value resistors, $R_{n1} = R_{n2} = R_{gnd}$. The high value resistors act as current limiters in case of a fault. Finally, the parameters of the entire simulation setup can be seen in Table I.

IV. SIMULATION RESULTS

Once the simulation setup has been assembled, different study cases have been performed in order to examine the DC and AC voltages and AC currents at both sides of the transformers. Additionally, phase-to-ground voltages have been measured in order to verify the insulation stress of each element.

To validate the operation principles of the system, Fig. 4 shows the different DC voltages considered in the simulation. The blue line corresponds with the output of the battery pack at the inverter side, which is 240 V_{DC}. The red line is the DC voltage at the rectifier side. It can be seen that a voltage drop of 14 V appears in each module (5.8% of voltage drop per module). Finally, the green line is the pole-to-pole voltage in the high voltage side of the circuit, which corresponds to the addition of the two modules' output voltages.

Analyzing the AC side, on the one hand, Fig. 5 shows the simulation results of the AC voltages at both sides of the power transformer of the battery module 1. It can be seen that the amplitude of the voltage is reduced in the secondary. However, the transformer actuates as a filter for the commutation frequency pulses caused by the inverter. Additionally, the currents are analyzed in Fig. 6, where an inrush current can be seen at the beginning of the simulation, but afterward, it decreases up to 5 A. The difference between primary and secondary currents is given by the magnetizing current of the power transformer, which is almost negligible.

However, inrush current dampers or smooth starters should be considered in real applications.

To corroborate the phase-to-ground insulation stresses, the voltages of different parts of the circuit to ground have been measured and their Root Mean Square (RMS) values were calculated. Table II collects the simulation results of the study.

As stated in Section II, the most critical voltages in the battery packs (upper and lower cells) do not exceed $U_{Cells}/2$ (= 120 V in the simulation setup) in any case. The simulation values are slightly smaller than the theoretical values due to the voltage drop in the internal components of the battery. In the AC side, the RMS value of the inverter side corresponds to $U_{Cells}/2$. In the AC rectifier side, the voltage drop to ground increases because the pole-to-pole voltage of this side is twice the battery module voltage, as there are two battery modules. The RMS voltage value does not correspond to $U_{DC}/2$ (= 240 V in the simulation) due to the transformer filtering. However, the commutation frequency pulses fall within the expected range between $U_{DC}/2$ and 0 V. In case of having more than two modules, the voltage to ground will be comprised between the upper and lower voltages in the output terminals of the module, i.e., for three modules the upper module will be comprised between $U_{DC}/2$ and $U_{DC}/6$. Besides, despite the number of modules, the battery packs have the same results in the isolated part of the module.

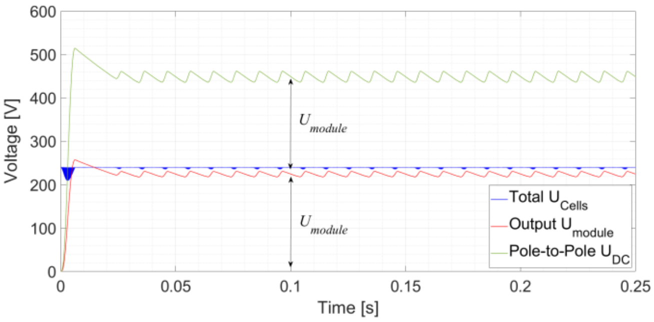

Fig. 4. DC Voltage measurement, including cells´ pole-to-pole voltage, the module 1 output voltage and the pole-to-pole voltage.

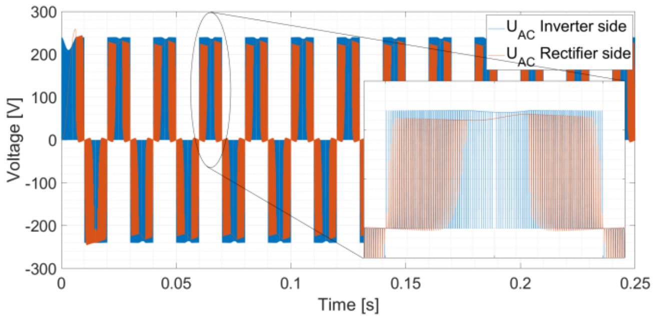

Fig. 5. AC Voltage measurement, including the inverter and rectifier sides of the power transformer at battery module 1.

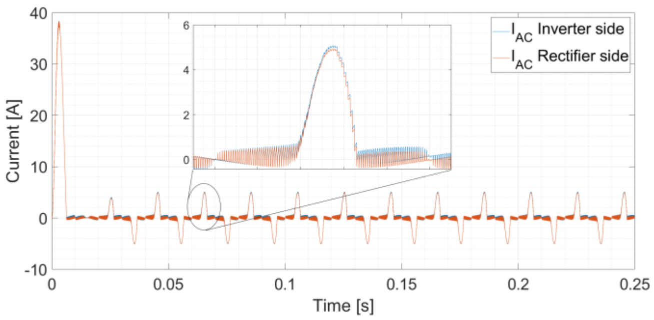

Fig. 6. Current measurement of the inverter and rectifier sides of the power transformer at battery module 1.

TABLE II. POTENTIAL TO GROUND OF DIFFERENT ELECTRICAL POINTS OF THE PROPOSED CONNECTION TOPOLOGY

Electrical point description	Magnitude	Units
Upper cell voltage to ground (module 1)	119.6	V
Lower cell voltage to ground (module 1)	-119.6	V
AC terminals of the inverter (module 1)	119.6	V_{RMS}
AC terminals of the rectifier (module 1)	143.9	V_{RMS}
DC output of module 1 (positive pole)	224.1	V
DC output of module 1 (interconnection with module 2)	≅0	V
Upper cell voltage to ground (module 2)	119.6	V
Lower cell voltage to ground (module 2)	-119.6	V
AC terminals of the inverter (module 2)	119.6	V_{RMS}
AC terminals of the rectifier (module 2)	143.9	V_{RMS}
DC output of module 2 (negative pole)	-224.1	V
DC output of module 2 (interconnection with module 1)	≅0	V

Finally, regarding the pole-to-pole DC voltage, the upper and lower pole-to-ground voltages are $U_{DC}/2$ and $-U_{DC}/2$ to ground, respectively. The interconnection point in this example corresponds with the DC midpoint; thus it is 0 V to ground because of symmetry with the grounded point of the high voltage DC side.

Once analyzed the data from simulations, it can be stated that the validation of the system has been successfully achieved, but its experimental validation is required and will be developed in further works.

V. CONCLUSIONS

This paper has introduced a novel topology for high voltage battery storage systems, addressing the critical issue of voltage stress on cells. By utilizing high-frequency power transformers in a cascade configuration, the proposed topology offers a scalable and efficient solution to mitigate voltage stress, thereby enhancing system reliability and efficiency. Simulation results from MATLAB-Simulink have provided compelling evidence of the effectiveness of the proposed configuration.

While the proposed topology has demonstrated promising results through simulation, future research efforts should address several key areas to further enhance the proposed topology's effectiveness and practical implementation. These include:

- Experimental validation to corroborate the simulation findings.
- Investigation into transformer’s inrush current attenuation for improved system performance.
- Development of robust protection mechanisms to protect the system against potential faults and failures.
- Exploration of efficient control strategies for the converters to optimize system operation.
- Conducting an energetic study to assess the overall energy efficiency and performance of the proposed topology under varying operating conditions.

By addressing these key areas in future research, the proposed topology can be further refined and optimized for widespread adoption in high voltage battery storage systems.

References

[1] W. Luo *et al.*, “Potential-induced degradation in photovoltaic modules: A critical review,” in *Energy and Environmental Science*, vol. 10, no. 1. 2017, https://doi.org/10.1039/c6ee02271e.

[2] S. Pingel *et al.*, “Potential induced degradation of solar cells and panels,” in *Conference Record of the IEEE Photovoltaic Specialists Conference*, 2010, https://doi.org/10.1109/PVSC.2010.5616823.

[3] Y. Sun, S. Saxena, and M. Pecht, “Derating guidelines for lithium-ion batteries,” in *Energies (Basel)*, vol. 11, no. 12, 2018, https://doi.org/10.3390/en11123295.

[4] Y. Gao, J. Jiang, C. Zhang, W. Zhang, Z. Ma, and Y. Jiang, “Lithium-ion battery aging mechanisms and life model under different charging stresses,” in *Journal of Power Sources*, vol. 356, 2017, https://doi.org/10.1016/j.jpowsour.2017.04.084.

[5] S. Singirikonda and Y. P. Obulesu, “Active cell voltage balancing of Electric vehicle batteries by using an optimized switched capacitor strategy,” *Journal of Energy Storage*, vol. 38, p. 102521, Jun. 2021, https://doi.org/10.1016/J.EST.2021.102521.

[6] Y. Sun *et al.*, “A novel reliable and economic topology for battery energy storage system,” in *Journal of Energy Storage*, vol. 45, 2022, https://doi.org/10.1016/j.est.2021.103523.

[7] M. Ceylan and A. Balikci, “An Intermodular Active Balancing Topology for Efficient Operation of High Voltage Battery Packs in Li-Ion Based Energy Storage Systems: Switched (Flying) DC/DC Converter,” in *Energies (Basel)*, vol. 16, no. 15, 2023, https://doi.org/10.3390/en16155608.

[8] H. Kim and K. G. Shin, “On dynamic reconfiguration of a large-scale battery system,” in *Proceedings of the IEEE Real-Time and Embedded Technology and Applications Symposium,* San Francisco, CA, USA, 2009, pp. 87-96, https://doi.org/10.1109/RTAS.2009.13.

[9] F. Baronti, G. Fantechi, R. Roncella, and R. Saletti, “Design of a module switch for battery pack reconfiguration in high-power applications,” in *IEEE International Symposium on Industrial Electronics*, 2012, https://doi.org/10.1109/ISIE.2012.6237283.

[10] S. Rothgang, T. Baumhöfer, H. van Hoek, T. Lange, R. W. De Doncker, and D. U. Sauer, “Modular battery design for reliable, flexible and multi-technology energy storage systems,” in *Appl Energy*, vol. 137, 2015, https://doi.org/10.1016/j.apenergy.2014.06.069.

[11] F. Helling, J. Glück, A. Singer, H. J. Pfisterer, and T. Weyh, “The AC battery – A novel approach for integrating batteries into AC systems,” in *International Journal of Electrical Power and Energy Systems*, vol. 104, 2019, https://doi.org/10.1016/j.ijepes.2018.06.047.

[12] V. Viswanathan, L. N. Palaniswamy, and P. B. Leelavinodhan, “Optimization techniques of battery packs using re-configurability: A review,” in *Journal of Energy Storage*, vol. 23. 2019. https://doi.org/10.1016/j.est.2019.03.002.

[13] L. S. Xavier, W. C. S. Amorim, A. F. Cupertino, V. F. Mendes, W. C. do Boaventura, and H. A. Pereira, “Power converters for battery energy storage systems connected to medium voltage systems: a comprehensive review,” in *BMC Energy*, vol. 1, no. 1, 2019, https://doi.org/10.1186/s42500-019-0006-5.