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Performance and Fault Analysis of an Isolated Bidirectional DC–DC Converter for Battery Energy Storage Systems

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ABSTRACT

The increasing use of Battery Energy Storage Systems (BESS) requires reliable and efficient bidirectional power conversion. This paper presents the performance and fault analysis of an isolated bidirectional DC–DC converter for battery energy storage applications. A 10 kW converter operating at 100 kHz is modelled and simulated in MATLAB/Simulink with 800 V high-voltage and 450 V low-voltage DC buses. Phase-shift control is employed to regulate bidirectional power transfer. The converter performance is evaluated under normal operating conditions, followed by a switching fault to investigate its effect on voltage, current, and power responses. The simulation results demonstrate stable converter operation under normal conditions and provide an assessment of its dynamic response under fault conditions.

Introduction

Battery Energy Storage Systems (BESS) play an important role in renewable energy integration, peak load management, and power system stability. Efficient bidirectional power conversion is essential for controlling energy transfer between the battery and the DC bus during charging and discharging operations.

The isolated bidirectional DC–DC converter provides galvanic isolation, voltage matching, and bidirectional power flow. Among various topologies, the Dual Active Bridge (DAB) converter is suitable for BESS applications due to its high-frequency transformer and phase-shift-based power control. However, switching device faults can affect power transfer and produce abnormal voltage and current responses, potentially compromising converter performance and DC-bus stability.

This paper presents the MATLAB/Simulink modeling and simulation of a 10 kW isolated bidirectional DC–DC converter operating at 100 kHz between 800 V and 450 V DC buses. The converter is evaluated under normal operating conditions and a selected switching fault condition. The voltage, current, and power responses are analyses to investigate the impact of switching faults on converter performance and dynamic behavior.

II. System Architecture

The proposed Battery Energy Storage System (BESS) employs an isolated bidirectional DC–DC converter to facilitate controlled power transfer between a high-voltage DC bus and a low-voltage battery-side DC bus. The converter is rated at 10 kW and operates at a switching frequency of 100 kHz, with DC bus voltages of 800 V and 450 V, respectively. The system consists of two active full-bridge stages connected through a high-frequency isolation transformer and an energy-transfer inductor. The transformer provides galvanic isolation and voltage matching, while the inductor regulates energy transfer between the two bridges.

Phase-shift modulation (PSM) is employed to control the magnitude and direction of power flow by adjusting the phase difference between the switching signals of the two bridges. During charging operation, power is transferred from the 800 V DC bus to the 450 V battery-side bus. Conversely, during discharging operation, power flows from the battery-side bus to the high-voltage DC bus. This bidirectional operation enables the converter to support the charging and discharging requirements of the BESS.

The proposed converter is modeled and simulated in MATLAB/Simulink using the specified system parameters. Voltage, current, and power responses are analyzed to evaluate its operating performance. Initially, the converter is investigated under normal operating conditions, followed by the introduction of a switching fault to examine its impact on the system response. This analysis provides insight into the converter's dynamic behavior and its suitability for bidirectional power conversion in BESS applications.

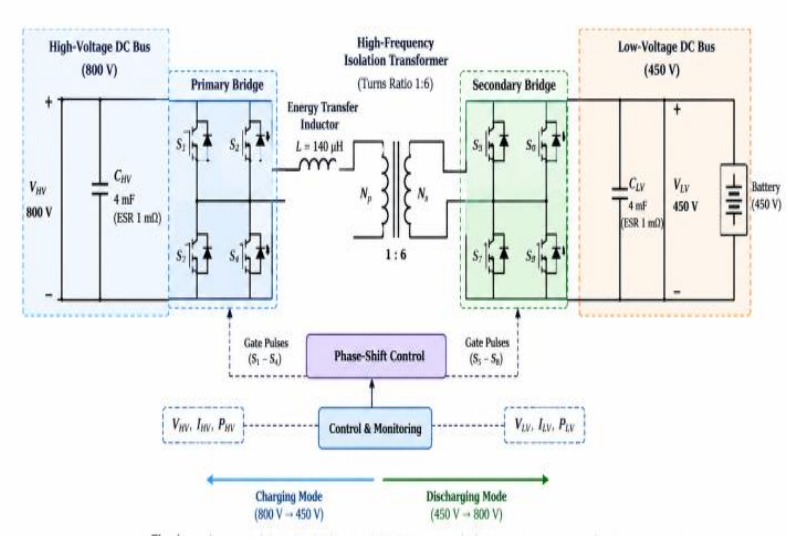


Fig.1 Configuration of the isolated bidirectional DC–DC converter for battery energy storage applications.

The Fig.1 shown the complete configuration of the proposed isolated bidirectional DC-DC Converter interfacing a high-voltage Dc bus (800v) with a low-voltage battery –side DC bus (450v)through a high-frequency transformer. The main components and control strategy used in the system are also indicated along with the key system parameters.

III. Proposed System Design

The proposed system is an isolated bidirectional DC–DC converter designed for Battery Energy Storage System (BESS) applications. The converter operates at a nominal power of 10 kW with a switching frequency of 100 kHz. It provides a controlled power interface between an 800 V high-voltage DC bus and a 450 V low-voltage battery DC bus.

The proposed topology consists of two active full-bridge converters connected through a high-frequency isolation transformer. An energy-transfer inductance of 140 µH is used to control the power transfer between the two bridges. The transformer provides galvanic isolation and voltage matching with a turns ratio of 1:6. The converter also includes the specified magnetizing and leakage parameters along with DC-side capacitors having an ESR of 1 mΩ.

Bidirectional power flow is achieved by controlling the phase difference between the switching signals of the primary and secondary bridges. During charging, power flows from the 800 V DC bus toward the 450 V battery-side bus, while during discharging, the power flow is reversed. The proposed converter is modelled in MATLAB/Simulink to investigate its normal operating performance and fault response under the specified system parameters.

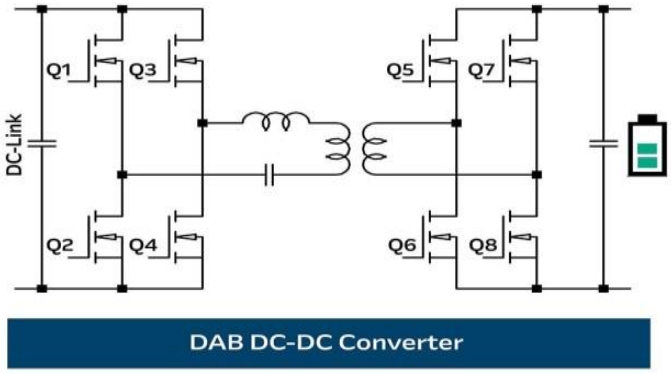


Fig.2 Proposed Dual Active Bridge (DAB) DC–DC converter topology for bidirectional power transfer in the BESS.

Figure 2 illustrates the proposed Dual Active Bridge (DAB) bidirectional DC–DC converter topology for BESS applications. It consists of two active full-bridge stages connected through a high-frequency isolation transformer and an energy-transfer inductance. Phase-shift modulation is used to control the magnitude and direction of bidirectional power transfer between the DC bus and battery side.

3.1 DAB Converter Power Transfer Model

The proposed DAB converter transfers energy between the high-voltage and low-voltage DC buses through a high-frequency transformer and transfer inductance. The power flow is mainly controlled by the phase difference between the two active bridges. The transferred power depends on the DC-side voltages, transformer turns ratio, switching frequency, transfer inductance, and phase-shift angle. This model is used to evaluate the bidirectional power-transfer characteristics of the converter.

For an ideal single-phase-shift-controlled DAB converter, a commonly used power-transfer relationship is.

$P = \frac{n\,V1V2}{2\pi fsL}\,\emptyset\,(1\text{-}\frac{|\emptyset|}{\pi})$

where (V1) and (V2) represent the DC bus voltages, (n) denotes the transformer turns ratio, (fs) is the switching frequency, (L) represents the effective power-transfer inductance, and (∅) is the phase-shift angle in radians. These parameters determine the magnitude and direction of power transfer between the two bridges.

3.2 Phase-Shift Based Power Control

Phase-Shift Modulation (PSM) is used to regulate the magnitude and direction of power flow. By varying the phase shift between the primary and secondary bridge switching signals, the transferred power can be controlled. A positive or negative phase shift enables power transfer in opposite directions, supporting both charging and discharging operation of the BESS.

The DAB converter operates using phase-shift modulation between the primary and secondary full bridges. As shown in Fig.3, both bridges operate with a 50% duty ratio, while a phase shift ϕ\phi is introduced between the bridge voltages vab and vcd. The voltage difference across the transfer inductance produces the piecewise-linear inductor current iL.The magnitude and direction of power transfer are controlled by varying the phase shift between the two bridges. For the proposed converter, the switching frequency is 100 kHz, corresponding to a switching period of Ts=10 μs.

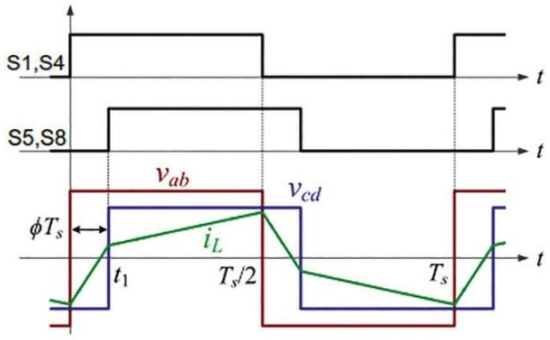


Fig.3 Switching waveforms of the DAB converter under phase-shift modulation.

For an ideal single-phase-shift controlled DAB converter, the transferred power can be expressed as a function of the DC-side voltages, transformer turns ratio, transfer inductance, switching frequency, and phase-shift angle. The approximate power relationship is given by

$$P = \frac{\mathrm{V1\ V2}}{\mathrm{n}\omega_s\mathrm{L}}\emptyset\left(1-\frac{\emptyset}{\pi}\right)$$

where V1 is the primary-side DC voltage, V2 is the secondary-side voltage referred to the primary side, n is the transformer turns ratio, L is the effective transfer inductance, ω_s=2πfs, and ϕ is the phase-shift angle. This relationship indicates that the transferred power can be regulated by controlling the phase displacement between the two bridge voltages.

3.3 Converter Control and Operating Modes

A closed-loop PI control strategy is employed to regulate the converter current and control the phase shift between the two active bridges. The controller generates the required phase-shift command based on the current error. The converter supports two operating modes: charging mode, in which power flows from the 800 V DC bus to the 450 V battery-side bus, and discharging mode, in which the power flow is reversed.

3.4 Switching Fault Modelling

To evaluate the fault response of the proposed DAB converter, a switching fault is introduced in switch S2 at t=0.2s. The converter is initially operated under normal conditions, followed by the fault condition. The resulting changes in DC-link voltage, current, output power, and phase-shift response are analyzed to evaluate the dynamic behavior of the converter..

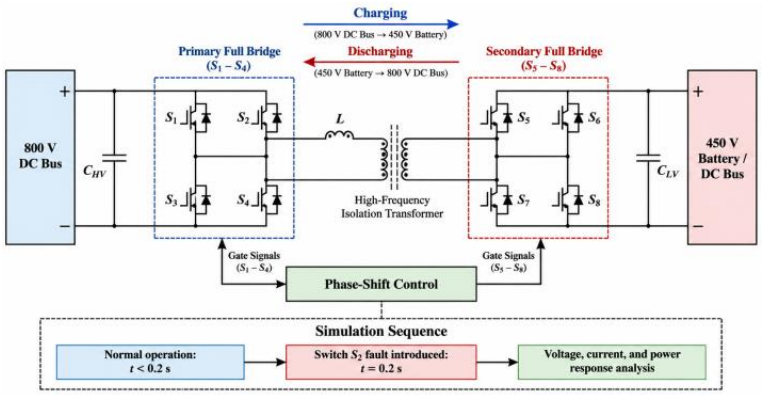


Fig.4 Configuration and fault-analysis framework of the proposed isolated bidirectional DC–DC converter for battery energy storage applications.

Fig. 4 illustrates the configuration of the proposed Dual Active Bridge (DAB) converter and its fault-analysis framework. The converter consists of primary and secondary full bridges connected through a high-frequency isolation transformer and an energy-transfer inductor. Phase-shift control regulates bidirectional power transfer between the 800 V DC bus and the 450 V battery-side DC bus. The simulation considers normal operation followed by a switching fault at t=0.2 s The resulting voltage, current, and power responses are analyzed to evaluate the converter's dynamic behaviour under fault conditions.

IV Design Parameters

Calculations:

The proposed isolated bidirectional DC–DC converter is designed with a 10 kW nominal power rating and a 100 kHz switching frequency. The converter operates between an 800 V high-voltage DC bus and a 450 V low-voltage DC bus. The selected coupling inductance, transformer parameters, DC-link capacitors, and control parameters are used to achieve controlled bidirectional power transfer and reliable high-frequency operation.

Table I-Design Parameters Of The Proposed Dab Converter.

Parameter	Value
Rated Power	10 kW
Switching Frequency	100 kHz
HV DC Bus Voltage	800 V
LV DC Bus Voltage	450 V
Transformer Turns Ratio	1:6
Coupling Inductance	140 µH
Primary Leakage Inductance	17 µH
Magnetizing Inductance	720 µH
HV-side Capacitance	4 mF
LV-side Capacitance	4 mF
Current Controller	PI
Proportional Gain (Kp)	0.1
Integral Gain (Ki)	500
Current Limit	25 A

The rated currents on the high-voltage and low-voltage sides are calculated as:

1. Rated Current

HV-side current: $I_{HV} = \frac{P}{V_{HV}} = \frac{10000}{800} = 12.5A$

LV-side current: $I_{LV} = \frac{P}{V_{LV}} = \frac{10000}{450} = 22.22A$

2. Voltage Conversion Ratio

$$M = \frac{V_{HV}}{V_{LV}} = \frac{800}{450} = 1.78$$

3. 100 kHz Switching Period

$Ts = \frac{1}{f_s} = \frac{1}{100000} = 10\mu s$

V. Simulation Results

The proposed isolated bidirectional DC–DC converter is modelled and simulated in MATLAB/Simulink using the parameters listed in Table I. The converter is evaluated under normal operating conditions followed by a switching fault introduced in switch S2 at t=0.2s. The phase-shift control, voltage regulation, power transfer, and fault response are analyzed.

A. Normal Operating Performance

Fig.5 shows the simulated phase-shift angle, output power, and current responses of the proposed converter. Under normal operation, the phase-shift angle remains approximately constant at 25°, while the output power and current increase toward their steady-state values. The responses indicate stable power transfer and satisfactory dynamic performance.

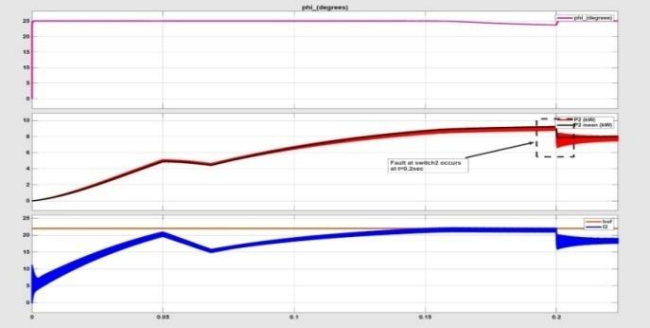


Fig.5 Simulation results of phase-shift angle, output power, and current under normal and fault conditions.

B. Output Voltage and Current Response

The simulated output voltage and current responses are shown in Fig. 6. The output voltage rises from the initial condition and approaches the reference value of approximately 450 V, while the output current settles toward its steady-state value. This response confirms the voltage regulation capability of the proposed converter.

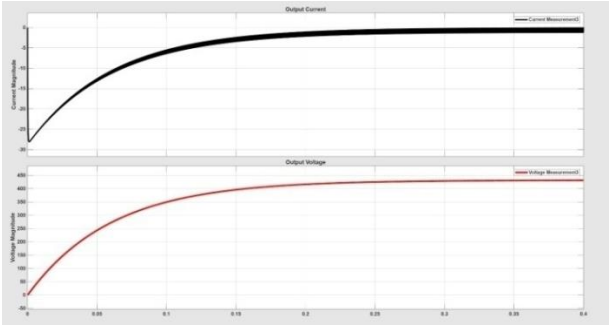


Fig.6 Simulated output voltage and current responses.

C. High-Frequency Transformer Voltage

Fig. 7 presents the simulated primary- and secondary-side voltage waveforms of the high-frequency transformer. The waveforms exhibit the expected periodic square-wave characteristics corresponding to the 50% duty-ratio switching operation of the DAB converter.

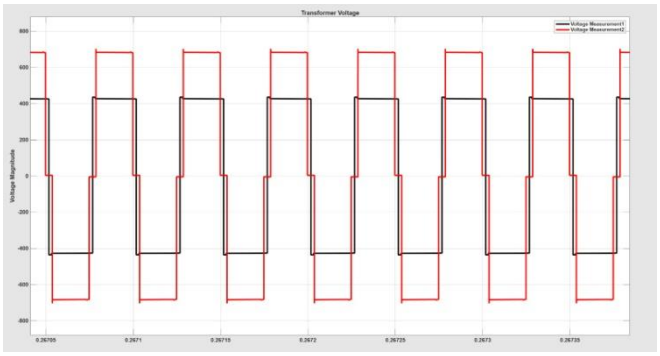


Fig.7 Simulated primary- and secondary-side voltages of the high-frequency transformer.

D. Switching-Fault Response

Fig. 8 illustrates the converter response under normal and switching-fault conditions. A fault is introduced in switch S2 at t=0.2s, resulting in noticeable changes in the voltage, power, and current responses. The transient deviations after fault initiation demonstrate the impact of the switching fault on the dynamic performance of the converter.

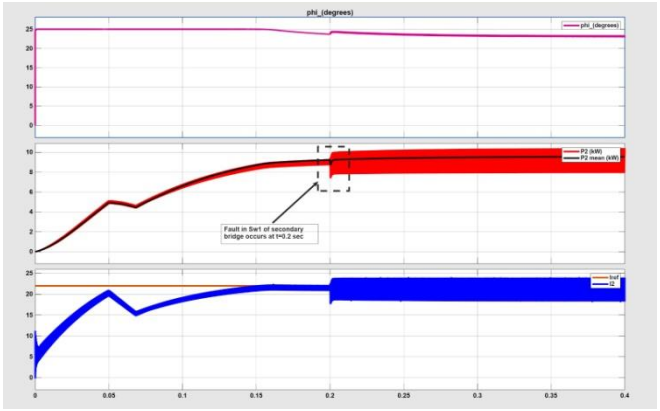


Fig.8 Simulated converter response under normal and switching-fault conditions.

Fig. 9 shows the simulated primary- and secondary-side bridge voltages along with the coupling-inductor current. The bridge voltages exhibit periodic square-wave switching characteristics corresponding to the 800 V and 450 V DC-side voltages. The coupling-inductor current shows a periodic piecewise-linear waveform, indicating controlled energy transfer between the two active bridges. The results verify the expected switching operation and power-transfer behavior of the proposed DAB converter.

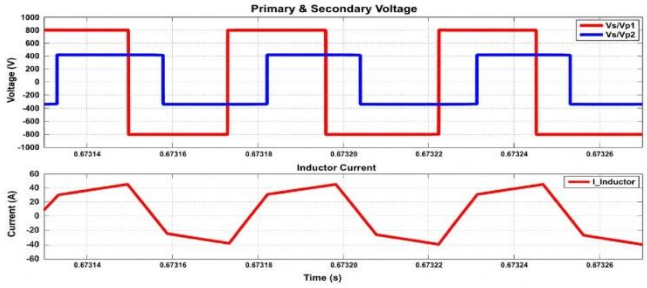


Fig.9 Primary- and secondary-side bridge voltages and coupling-inductor

VI. Conclusion

This paper presented the modelling and performance analysis of a 10 kW isolated bidirectional DC–DC converter for Battery Energy Storage System (BESS) applications. The current.

proposed DAB converter operates at 100 kHz with 800 V and 450 V DC buses using phase-shift control for bidirectional power transfer. MATLAB/Simulink results demonstrated stable voltage regulation, controlled power transfer, and satisfactory switching operation under normal conditions. A switching fault in S2 was also investigated to evaluate its impact on the converter voltage, current, and power responses. The obtained results demonstrate the suitability of the proposed DAB converter for controlled and reliable BESS power-conversion applications.

The fault analysis further provides a basis for evaluating converter behaviour under abnormal operating conditions and can support future development of fault-tolerant control strategies.

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