A New Multi-port DC/DC Converter for PV/battery/DC gird Energy Systems

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Abstract

Interfacing multiple low-voltage energy storage devices with a high-voltage dc bus efficiently has always been a challenge. In this article, a high gain multiport dc–dc converter is proposed for low voltage battery-supercapacitor based hybrid energy storage systems. The proposed topology utilizes a current-fed dual active bridge structure, thus providing galvanic isolation of the battery from the dc bus, wide zero voltage switching (ZVS) range of all the switches, and bidirectional power flow between any two ports. The dc bus side bridge uses voltage multiplier cells to achieve a high voltage conversion ratio between the supercapacitor (SC) and the dc bus. Moreover, as the proposed topology employs only one two-winding transformer to achieve a three-port interface, the number of control variables are reduced, which decreases control complexities. The operation of the proposed converter is analyzed in detail, including the derivation of ZVS conditions for the switches and transformer power flow equations. A decoupled closed-loop control strategy is implemented for the dc bus voltage control and energy management of the storage devices under different operating conditions

1. INTRODUCTION

Due to recent developments in renewable energy source based distributed generation systems, integration of energy storage systems (ESSs) is gaining increasing attention. These ESS can improve the overall system reliability against the intermittent nature of renewable energy sources such as solar and wind energy. However, energy storage using a single technology such as batteries or supercapacitors (SCs) faces difficulties in supplying large power and large energy demands simultaneously . For example, energy density and decent lifespan, but low specific power and slow dynamic response. On the other hand, SCs have a higher specific power, short charging/discharging times, and long life cycle, but low energy density. Hence, combined battery and SC-based hybrid ESSs are very appealing for loads that have moderate average power demand and relatively high peak power demand [3]. Conventionally, separate dc–dc converters are used to interface different sources or storage elements with a common dc bus. As a result, power transfer between the sources and storage elements becomes a two-stage process, which reduces the overall efficiency of the system. In contrast, a multiport converter (MPC) provides an interface for different energy sources or storage elements utilizing a single dc–dc converter. MPCs, thus, cut down the redundant power conversion stages, which increases the system efficiency and provides a more compact structure. MPCs can be divided into two main categories: non isolated and isolated. Non isolated MPCs [6] are simpler in design and more compact due to the lack of a transformer; however, voltage levels of the ports are not flexible, and soft switching cannot be realized easily. On the other hand, isolated MPCs [7]–[9] provide buck or boost capability utilizing the transformer turns ratio. Isolated MPCs remain the popular choice owing to their flexibility in routing the power flow between the different ports as well as their superior performance . Most of the isolated MPCs described in the literature are derived from the dual active bridge (DAB) [11] converter, as it provides high- frequency galvanic isolation, bidirectional power flow, and soft switching. Compared to the traditional voltage-fed DABs [11], current-fed DABs provide benefits such as wide zero voltage switching (ZVS) range with varying port voltages and increased voltage conversion ratio, thus making them suitable for application in ESS. Isolated MPCs can be subdivided into two main groups based on their construction. Fully isolated MPCs combine three or more ports using a single multi winding high-frequency transformer, which provides isolation for all ports [7]. Several three port converter topologies have been reported in the literature that utilize a triple active bridge (TAB) structure (either half-bridge or full- bridge). However, control of these converters is complicated, since there are several coupled control variables. Moreover, the fully isolated MPCs have a higher device count, and the multi winding transformer handles the entire output power; thus efficiency and power density are reduced [10]. Partially isolated MPCs, which are the main focus of this article, utilize a single-core two-winding transformer, and two or more ports are coupled either at the primary or the secondary terminals of the transformer .They provide galvanic isolation while reducing the component count, making them cheaper and more efficient.

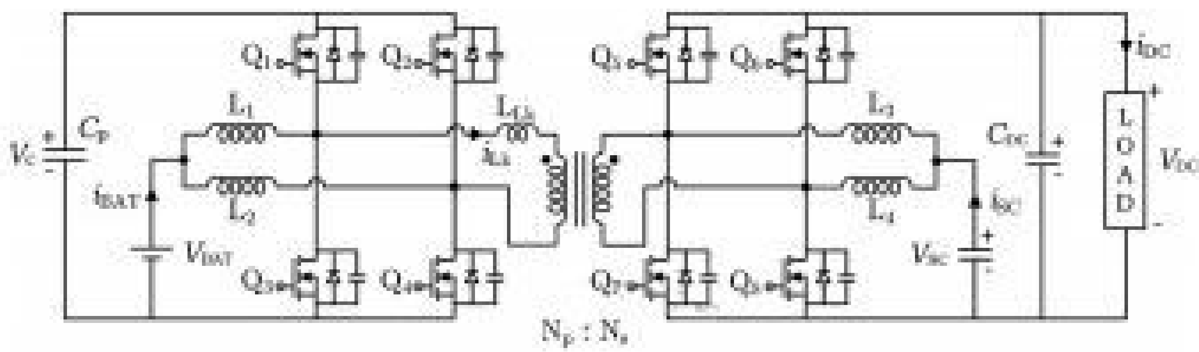

Fig 1: Topology of the multiport dc–dc converter proposed

2. PROPOSED CONTROL PHILOSOPHY

In a battery-SC-based hybrid ESS, the purpose of the MPC is to dynamically allocate the load between the battery and the SC. Under pulsed load conditions, the SC acts as a filter that relieves peak power stresses on the battery. Hence, it is appropriate that the SC current essentially controls the dc bus voltage VDC. However, then under normal operating conditions, the SC voltage VSC will vary drastically. Therefore, the phase shift φ between the two voltages vab and vcd (see Fig. 3) is used to control the average SC voltage.

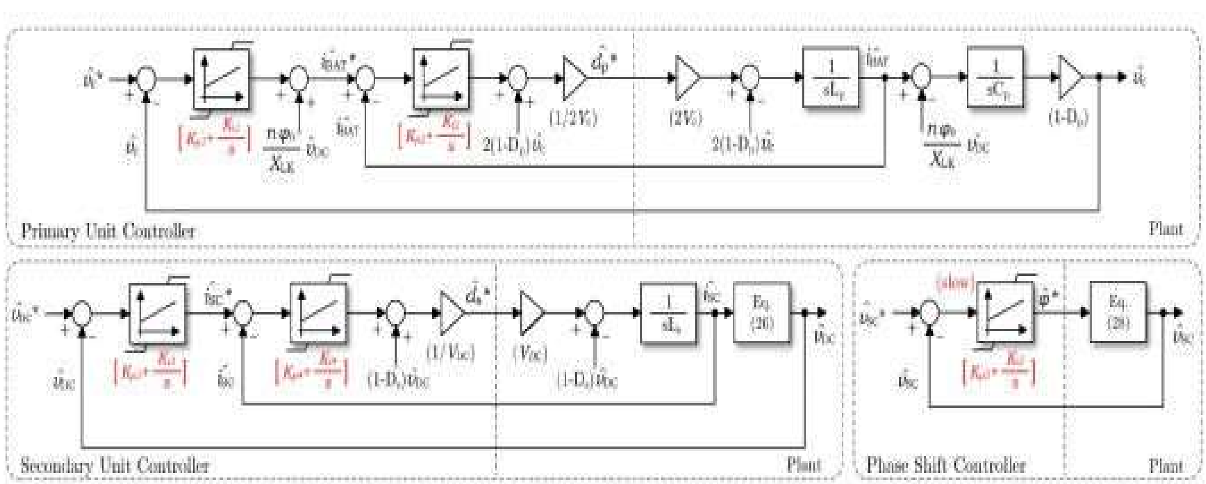

Fig 2: Detailed schematic of the control block diagram for the proposed high gain MPC

To reduce the RMS value of the leakage inductor current iLk and the losses, voltage Vc must also be controlled such that proper voltage matching is ensured The detailed control block diagram for the proposed high gain MPC (along with the plant model) is shown in Fig. 9, which consists of three parts: the primary unit controller, the secondary unit controller, and the phase shift controller. The primary unit controller ensures that the primary side clamp capacitor voltage remains regulated, so that voltage matching is achieved; whereas, the secondary unit controller ensures that the dc bus voltage remains regulated with fast dynamic performance. Both the controller units have a conventional nested two-loop structure with an outer voltage control loop and inner current control loop. Proportional-Integral (PI) controllers are used throughout with appropriate feed-forward compensation terms (see Fig. 9). The phase shift controller also employs a slow PI controller to control the average SC voltage, which, in turn, generates the reference phase shift command. The proportional and integral control gains of the different PI controllers are chosen based on the desired bandwidth and phase margin. The choice of the proportional and integral control gains of the various PI controllers along with the resulting bandwidths.

3. BIDIRECTIONAL DC TO DC CONVERTERS (BDCS)

Generally buck-boost converter can manage the power flow in one direction only but power can flow in both the direction in a bidirectional converter. BDCs are capable of stepping-up or stepping-down the voltage level with ability of flowing of power in either forward directions or in backward direction. BDCs work as regulator of power flow of the dc link voltage in both the directions. In the power generation by wind mills and solar power systems, output fluctuates because of the changing atmospheric situations. These energy sources are not reliable to feed the power in a standalone system because of the large fluctuations in output and hence these energy sources are always connected in conjunction to energy storage systems like batteries and super capacitors as shown in Fig. 1. These energy storage devices store the surplus energy during low load demand and provide backup in case of system failure and when the output of energy sources reduces due to weather conditions. Thus, a BDC is needed to permit power flow in both forward as well as backward directions. A normal unidirectional dc to dc converter is transformed into a BDCs using bidirectional switch by using diode in anti-parallel with MOSFET or IGBT allowing current flow in both the direction using controlled switching operation.

4. SIMULATION AND RESULTS

The circuit has been designed and implemented using MATLAB Simulink. Fig. 12 shows the steady-state waveforms with VBAT = 60 V and VSC = 48 V. Based on the value of φ ($\varphi > 0$), the operation of the converter is shown in Mode I respectively. The operation of the converter with PSC < 0 (i.e., SC being charged). For this, an additional rheostat was connected across the SC port (since diode rectifiers are unidirectional). Here, the converter operates in Mode I, hence profile of the leakage inductor current however, the average SC current remains negative (VBAT = 62 V and VSC = 48 V). With negative phase-shift angles ($\varphi < 0$), the operation of the converter, with VBAT = 57 V and VSC = 52 V. Here, the converter operates in Mode IV, with PBAT < 0 (additional rheostat connected across the battery port). the battery current is negative, which indicates that the battery is being charged. Zero voltage turn- ON is achieved by all switches, even for small values of φ. switches Q1, Q4, Q7, and Q9 get ZVS for $\varphi = 8.1^\circ$.

Due to symmetry of the proposed converter, ZVS of the other switches can be guaranteed for similar operating conditions. The filter inductor currents of the primary and secondary units (with PDC = 480 W). the battery current is the sum of the filter inductor currents iL1 and iL2 , and, thus, have a ripple of frequency 50 kHz (double the switching frequency). Similar argument holds true for the SC current The performance of the controller during load transients, with a step-change in load varying initially from 480 to 700 W, and finally settling to 480 W (with VBAT = 59 V and VSC = 47 V). For both the primary and secondary unit controller, the bandwidth of the inner current loop is kept at 2.5 kHz, while the outer voltage loop bandwidth is kept at 80 Hz. Dc bus voltage vDC remains well regulated with maximum overshoot/undershoot of 6 V and a settling time of 40 ms, Proper voltage matching is ensured, since the primary unit clamp capacitor voltage vc also remains constant. The difference in the voltages of the switched capacitors vcs1 and vcs2 are insignificant, even during transients, the performance of the battery and the SC during load transients (iBATf and iSCf represents the filtered values of iBAT and iSC, respectively). The SC compensates for the load transients by delivering or absorbing the additional power, whereas the battery current remains almost constant, which eventually improves battery life. The performance of the phase shift controller, with an SC voltage reference of VSC ∗ = 46 V (with additional rheostat connected across the SC port). The phase- shift controller is designed much slower, having a bandwidth of approximately 5 Hz. At time t = t1, the phase shift controller is enabled. As a result, the SC voltage tracks the reference command and eventually settles at time t = t2. The transients are observed to settle within 150 ms (the ripple observed in the SC voltage vSC is due to the three-phase diode bridge rectifier).

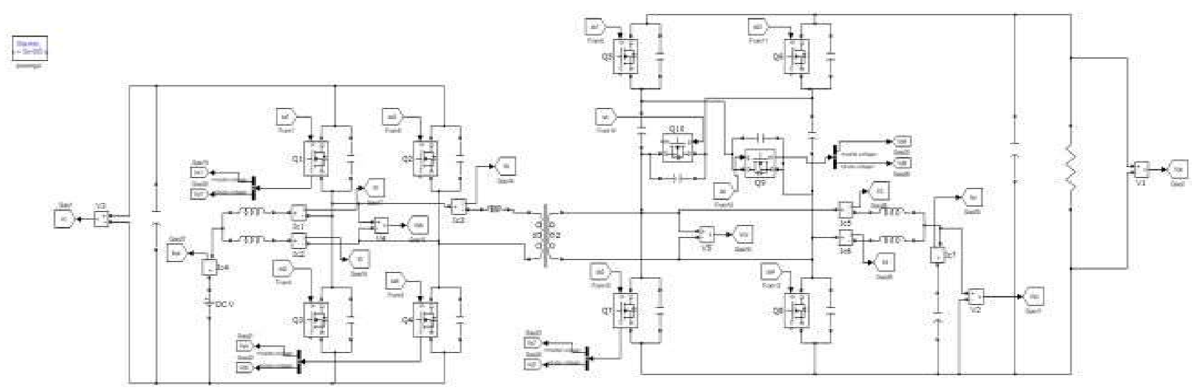

Fig 3: Simulation model

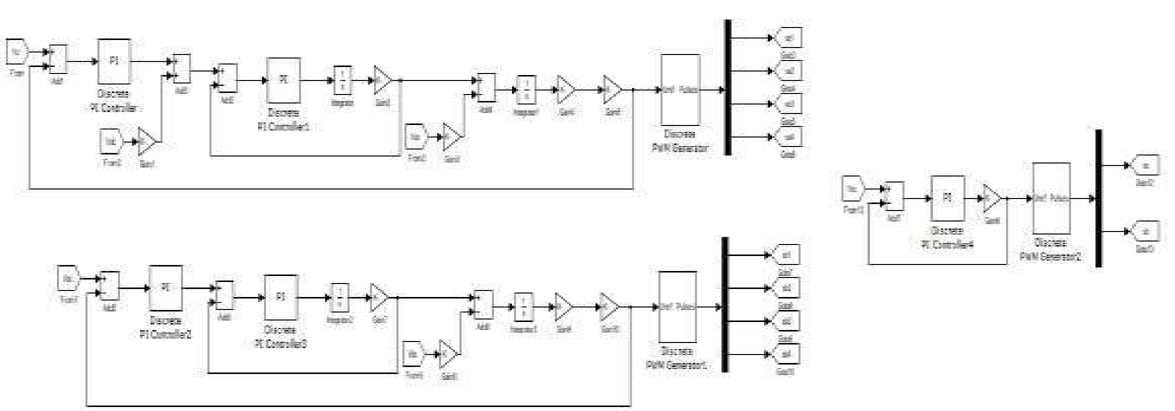

Fig 4: Control block diagrams

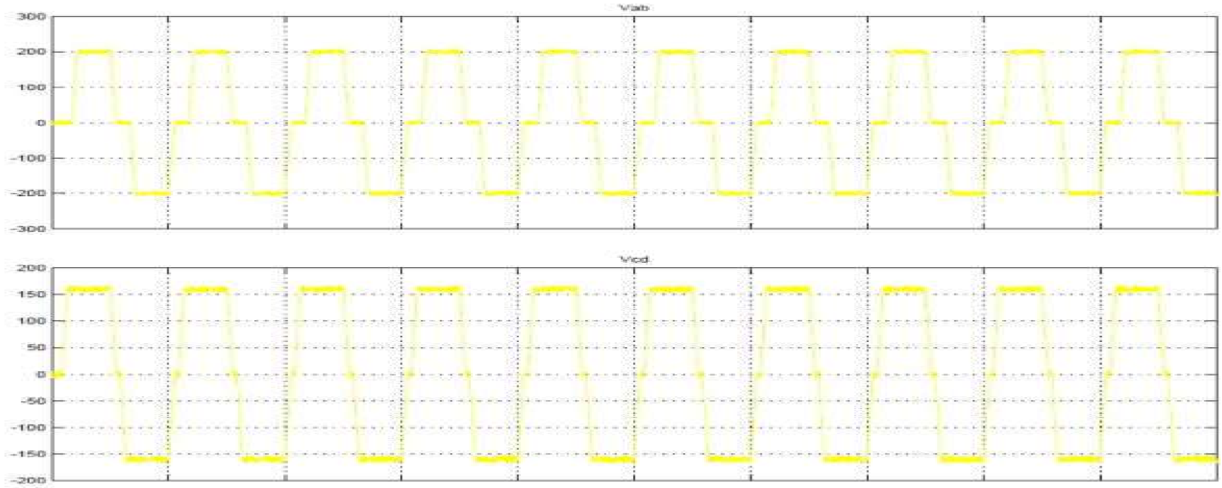

Fig5: Steady-state operating waveforms with different phase-shift

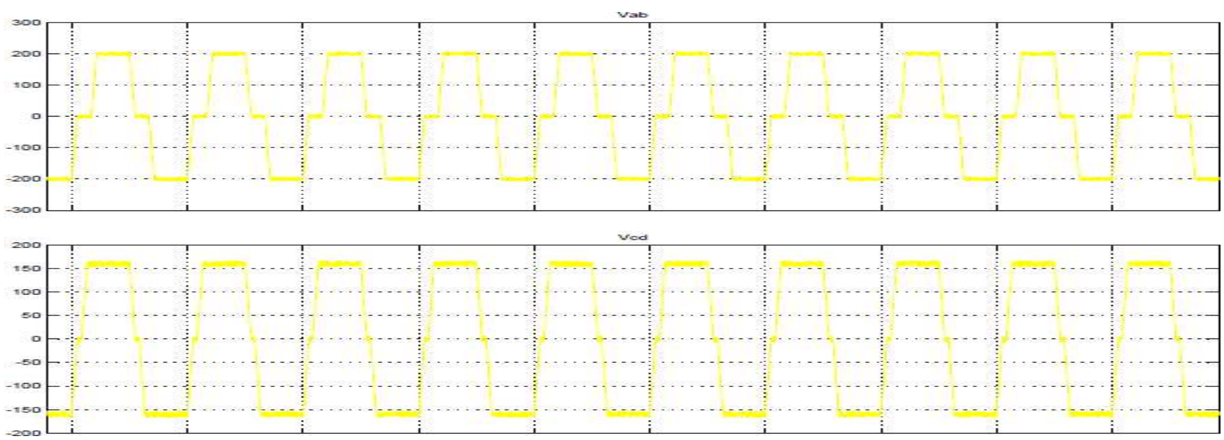

Fig 6: ZVS turn-ON of switches on the primary and secondary units

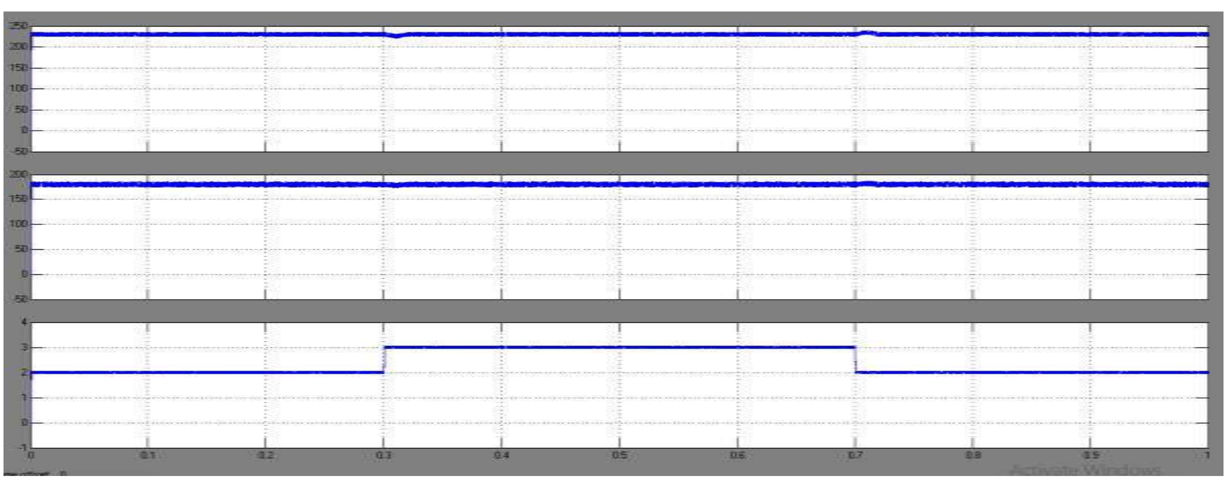

Fig 7: Performance evaluation of the proposed controller (a, b, c) Transient response with the load

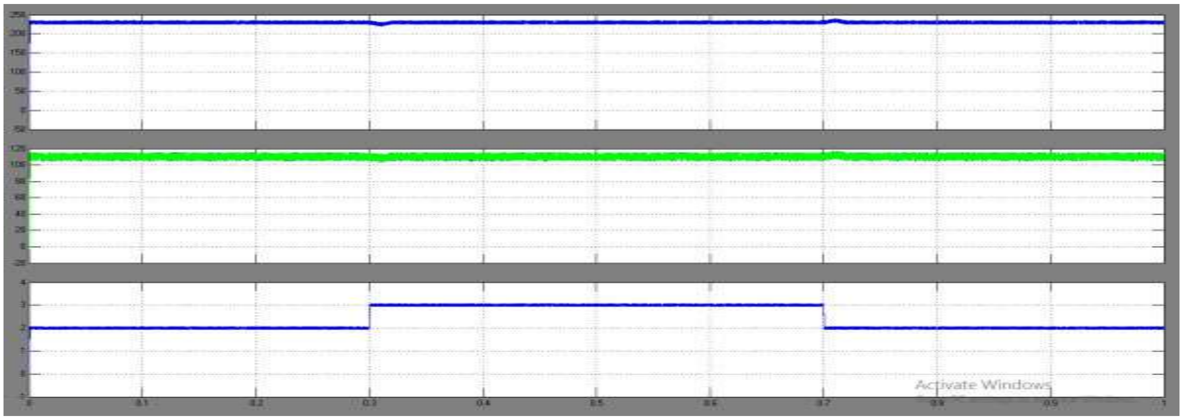

Fig 8: Performance evaluation of the proposed controller (a, b, c) Transient response with the load, initially varying from 480 to 700 W and finally settling to 480 W.

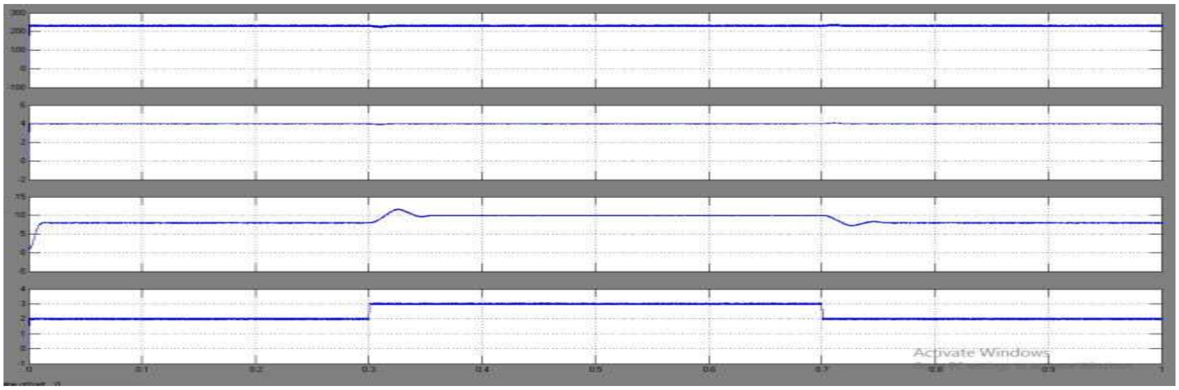

Fig 9: Performance evaluation of the proposed controller (a, b, c) Transient response with the load, initially varying from 480 to 700 W and finally settling to 480 W.

5. CONCLUSIONS

In this article, a novel high gain multiport dc–dc converter, suitable for integrating low voltage energy storage devices in a dc microgrid, is proposed. The proposed topology provides a three-port interface utilizing only one two-winding transformer, which significantly reduces control complexities. The inclusion of a VM module helps to increase the voltage conversion ratio between the SC and the dc bus. With careful choice of the primary unit clamp capacitor voltage and filter inductors of the respective converter units, it is possible to achieve ZVS operation of all switches over the entire operating range. A decoupled closed-loop control strategy is proposed, which ensures dc-link voltage control with fast dynamic performance and energy management of the SC under different operating conditions. Effectiveness of the proposed topology and the control strategy are verified experimentally on a 1- kW laboratory prototype. The developed hardware prototype achieves a peak efficiency of 95.96%, which is superior in comparison with the existing MPCs in literature. Experimental results also verify that the proposed converter provides a fast dynamic response against load variations along with energy management of the SC under different operating conditions. Performance comparison of the proposed high gain MPC with the existing solutions confirms that the proposed converter has advantages such as reduced voltage stress across some of the power devices, ZVS turn- ON for all the switches over the entire operating range, and a much simple control structure. Although ZVS turn-ON reduces the switching losses, conduction losses of the different switches are not balanced. Besides, the power density is low due to the use of several discrete magnetic components. Hence, future work will include efficiency optimizations and operation of the converter at higher switching frequencies to extract the benefits of soft- switching in improving power density without increasing switching loss.

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