Topological Investigation on Interlinking Converter in a Hybrid Microgrid

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***Abstract*—Of late, the idea of hybrid microgrid has drawn immense attention among the recent researchers. Especially in a hybrid microgrid, the interlinking converter (ILC) is considered responsible for appropriate power management between the ac and dc sides. In this paper, a topological vision of ILC is presented along with its control algorithms. The proposed three-port topology, viz. dc grid, ac grid and energy storage gives operational flexibility for different bidirectional power flow modes. It offers inherent dc fault tolerance without dc-breaker, reduced volt-ampere rating of the switches and lesser conduction and switching losses. Utilization of low-voltage modular battery stacks makes the topology efficient, reliable and cost-effective. MATLAB simulation results are presented for validation of the proposed work.**

***Index Terms*—hybrid microgrid, interlinking converter, battery storage, bidirectional power flow, MOSFETs, dc fault tolerant**

I. INTRODUCTION

Now-a-days the concept of microgrid is a much investigated subject which characterize a low voltage distribution system with renewable or non-conventional distributed resources(PV, wind, fuel cells, micro-turbines, etc), energy storage units and flexible loads. Such a grid can work either autonomously (termed as stand-alone mode of operation) or in synchronization with the utility (termed as grid connected mode). From operation point of view, all the micro-sources and storage units must be integrated using controllable power electronic converters with proper co-ordinated control of power flow, reliability and power quality. Hence, power electronic converter topology, modeling and control are highly significant for proper operation of the grid. Also, power converter design issues are of great importance aiming at their economic performance as well [1], [2].

An ac microgrid is very similar to our conventional utility grid except the fact that the voltage and frequency are not dictated by the utility grid. DC microgrid has started to become relevant in the present scenario due to more and more inclination towards dc renewable sources and dc appliances (LED lighting, air conditioner, refrigerator, electric vehicle, etc), power electronic loads, etc. The hybrid microgrid signifies the coexistence of both ac and dc microgrids to incorporate the advantages of both systems. In this regard there is absolute necessity of an interlinking converter (ILC) to bridge between the ac and dc grids. The primary job of this interlinking converter is to control the transfer of power between both grids, sharing the responsibility to match supply and demand within the hybrid microgrid, and also regulate dc bus voltage and ac bus voltage and frequency [3]. The task of the ILC is more important in islanded mode of operation where there is no grid to act as infinite bus to deliver or absorb any amount of power [4]. Various control and power management strategies have been reported in literature since last decade and research progress is going on for co-ordinated power flow control. Different possible architecture of hybrid microgrid and various converter topologies and configurations of ILC are reviewed in [5].

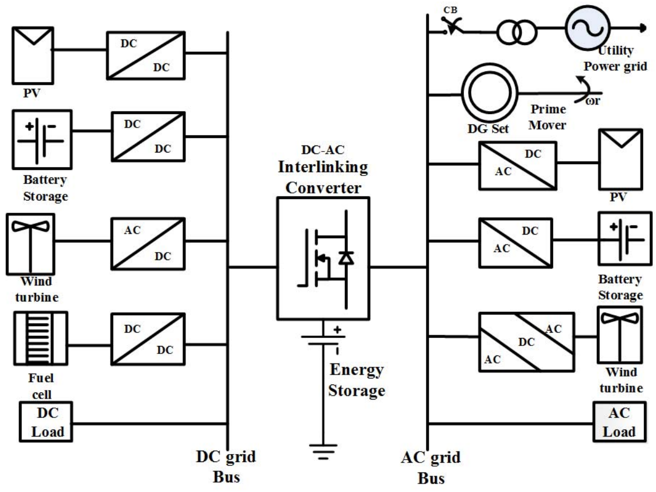

Fig. 1. Hybrid microgrid representation

Various literature have been reported on single-stage as well as double-stage voltage conversion topologies of the interlinking converter. Most of the papers on single-stage voltage conversion have been found on a single voltage source converter (VSC) used as ILC topology [6], [7]. Apart from single VSC, converters with other distinct features are also discussed. Modular Multilevel Converter (MMC) with integrated battery energy storage is employed for high voltage grid application [8]. But the complex control strategies and dc-fault intolerance demands more investigation on improved topology. The investigation reported in [9], utilizes a Z-source inverter (ZSI) which boosts the DC voltage applied to the inverter with reduced voltage stress across switches. Bidirectional Switched boost converter (BSBC) comes up as an improvement over the ZSC [10]. However, this can increase current stress and

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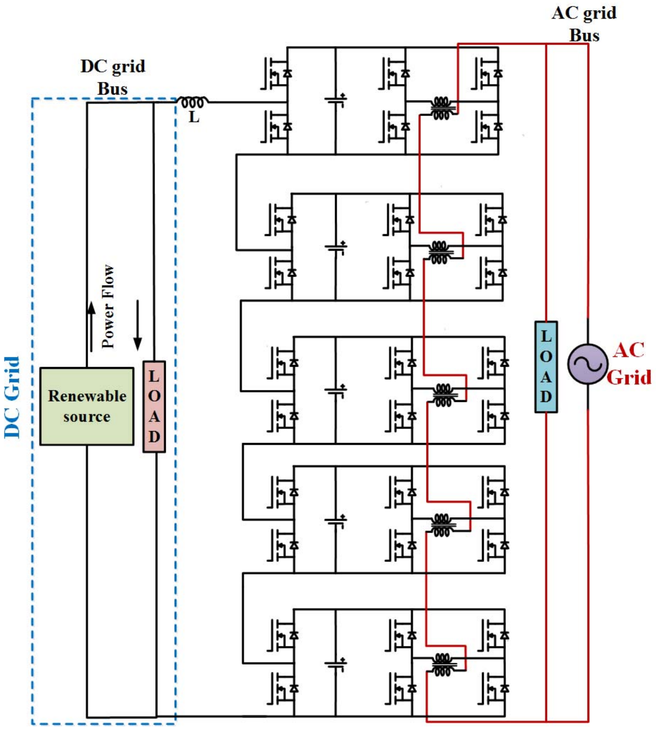

Fig. 2. Single-phase version of the proposed topology

rating of switches because of the shoot-through and also there is a limitation to boost the voltage. Multiple parallel BPCs (Bidirectional Power Converters) are used as ILCs in hybrid ac/dc microgrids [11], [12]. An asymmetrical cascaded H-Bridge (HB) Multilevel Converter (MLC) with integrated Series Active Power Filter (SAPF) is presented in [13] for interfacing energy storage systems with medium voltage grids. Here there is a limitation regarding the balancing of dc link capacitor voltages because the capability of supercapacitor energy stacks is questionable.

The most widely adopted dual-stage configuration is the use of a boost converter connected to the dc-link of a two-level three-phase dc-ac converter [14], [15]. The possibility to connect storage in the intermediate dc-link has been explored in all of these works. The use of back to back voltage source converters for connecting the dc and ac grids is described in [16], [17], whereas [18] proposes a diode rectifier with auxiliary three-level neutral-point-clamped (NPC) converter as ILC in hybrid ac/dc microgrids. However, capacitor voltage balancing issue, requirement of additional filters for power quality improvement, reduction in the cost of power electronic switches and improvement in power converter technology have led to the motivation of finding a better solution for the Interfacing Converter.

In the proposed work, a two-stage three-phase Interlinking Converter with integrated energy storage units is being proposed to connect both the ac and dc grids. Symmetrical cascaded H-bridges (CHB) are used as dc-ac converters for connecting the intermediate dc-links (energy-storages) with the ac microgrid. CHB is the appropriate choice because of modularity, extensibility and simple control. Moreover, multilevel CHB comes up as the best option particularly where low-voltage battery or supercapacitor stacks can be easily configured as separate energy sources for each module. On the other hand, bidirectional dc-dc converters link the intermediate dc-links with the dc microgrid. The interlinking dc-link acts as central energy storage unit and deals with power fluctuations(if sufficient stored energy is available) on either or both the ac and dc sides. The interlinking converter is also attributed the responsibility to control the dc side voltage magnitude at the required value and maintain the ac side desired voltage and frequency (in standalone mode). If the ac side is connected to infinite bus, then it can provide reactive power support and pulsed power support for frequency regulation purposes.

II. PROPOSED TOPOLOGY

In this paper, a hybrid microgrid system is considered as shown in Fig. 1, which comprises a dc and an ac microgrid intertied by means of a bidirectional interlinking converter. Both the ac and dc microgrids consist of various sources like renewable energy resources(PV, Wind, etc), diesel generator set, energy storage Units along with ac and dc loads. The Utility Grid is connected to the ac microgrid through a circuit breaker (CB) as shown in Fig. 1 which renders provision to operate the hybrid microgrid either as standalone (if CB is open) or as gridconnected (if CB is closed). This interlinking converter is basically a three-terminal central converter having two conversion stages combined to form a single module.In this work, a five module structure for each phase is considered, producing eleven levels in the phase voltages, for unity modulation index. The modularity enables the topology to be flexible with respect to attaining any number of levels. The multilevel output approaches sine wave in essence improving the power quality of the output waveforms and reducing filter requirements. Fig. 2 shows the single phase version of the proposed topology. As it can be seen, each module comprises of a bidirectional half-bridge dc-dc stage and a H-bridge dc-ac stage with an intermediate dc-link in between them. The intermediate dc-link is built with energy storage units like batteries which can support the ac and/or dc microgrids when there is any shortage of supply, provided the intermediate batteries have enough stored energy. The dc-ac converters of each module are connected to the ac microgrid by a single phase transformer. The secondaries of the transformers of each phase are connected in series to supply a phase, whereas the primaries are isolated. Transformers provide necessary isolation and adjust voltage levels as per requirement. The converter configuration shown in Fig. 2 is followed identically in other phases as well to build the three-phase topology. Some noticeable features of the proposed converter configuration is pointed out below:

A. Lesser conduction loss & lower VA-rating

As the combined dc-link is formed by dividing it into a number of battery stacks, the required voltage blocking

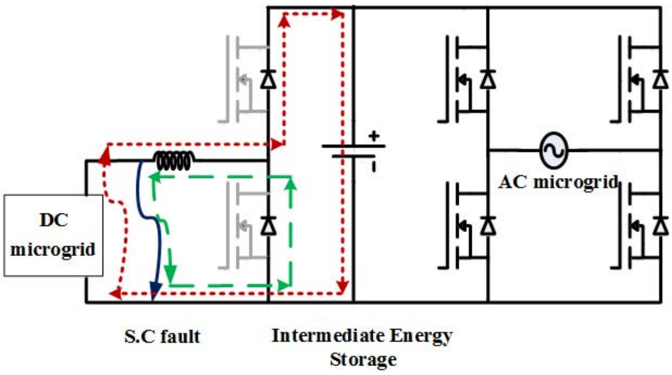

Fig. 3. DC fault current path

capability of the switches is reduced and correspondingly, the conduction losses of the switches comes down. This gives the provision of using low-voltage MOSFETs as the switching devices for the proposed configuration because of the fact that MOSFET on-state resistance exponentially falls with the decrease in its blocking voltage as depicted in (1) [19].

$$\frac{V_d}{J} = R_d * A \approx 3 * 10^{-7} BV^{n}{}_{DSS} \tag{1}$$

where, V_d = voltage drop across drift region, J = current density, R_d = on-state resistance, A = cross-sectional area, BV_{DSS} = maximum allowable drain-source voltage, n = in the range of 2.5-2.7.

In addition, the volt-ampere rating of the devices for the proposed converter configuration, is also lower as compared to other topologies. This fact can be established from the derivation of (2) and (3), referring to one module of the topology:

Equalising ac and dc side power,

$$\frac{\hat{v}_{ac}\hat{i}_{ac}}{2} = v_{dc} i_{dc} \tag{2}$$

Therefore, $\hat{i}_{ac} = 2\, i_{dc}$

Hence, VA rating of the switches for one module (consisting one half bridge dc-dc converter and one H-bridge) can be expressed as:

$$\begin{aligned} Total\ VA =& 4 v_{dc}\hat{i}_{ac} + 2 v_{dc} i_{dc} \\ =& 4\hat{v}_{ac}\hat{i}_{ac} + 2\hat{v}_{ac}\frac{\hat{i}_{ac}}{2} \\ =& 5\hat{v}_{ac}\hat{i}_{ac} \end{aligned} \tag{3}$$

where,
$\hat{v}_{ac}$ *and* $\hat{i}_{ac}$ = peak values of output ac voltage and current
v_{dc} *and* i_{dc} = dc voltage and current

With this approach, it can be found that the Total Standing Voltage (TSV) of all the switches of the proposed topology is at least 17% lesser compared to a MMC topology producing same number of levels and for same power and voltage rating.

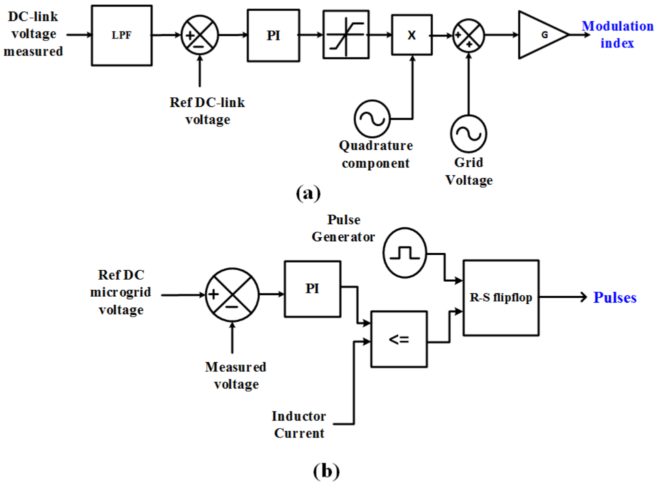

Fig. 4. Control Techniques for (a) dc-ac converter, (b) dc-dc converter

B. Inherent DC-side fault tolerant

In a situation where the ac grid is healthy and online , but a dead-short fault occurred in the dc grid, once pulses are withdrawn from dc-dc converter, two fault current paths can be derived as can be seen from Fig. 3 by red and green colour to include both directions of inductor current. In both cases the inductor current will gradually decrease and come to zero; this eliminates the need of dc breakers unlike half bridge MMC modules, making the topology inherent dc fault tolerant. Also, the operation of the ac-side converter is completely decoupled and unaffected and still power transfer between intermediate batteries and ac grid can take place.

C. Flexibility and modularity to control SOC of the battery storage

On the dc side, the dc-dc converters are connected in cascaded form to supply the dc grid. Each battery is connected to its own dc-dc converter, hence, they can be individually and independently controlled for different charging rates. Moreover, active balancing of the intermediate batteries can be achieved by means of the bidirectional dc-dc converters in the proposed Interlinking Converter without any extra switches or any dedicated converter.

D. Power flow modes

Apart from acting as an energy buffer [20] for transferring power from dc side to ac side and vice-versa, the interlinking converter can have different other power flow modes, such as: 1) between dc grid and ILC, 2) between ac grid and ILC, 3) among both the grids and ILC.

In this study, the ac grid is considered to be connected to the utility. Therefore, its voltage and frequency are assumed to be stiff. The dc grid consists of renewable sources and loads. The dc-grid is assumed to be a small dc microgrid where the voltage is not stiff. In cases, whenever, there is a generation and demand mismatch within the dc grid, the voltage will either swell or collapse (if all the Distributed

Generators (DGs) are operated at their maximum rating). Here comes the responsibility of the interlinking converter to regulate the voltage of the dc grid. It can do so in three ways: a) from/to the ac grid only (using the intermediate storage as buffer) or b) from/to intermediate storages only (if the SOC is within desired limits) or c) both from/to ac grid and intermediate storages. Here the first option is explored to show the bidirectional power transfer capability of the interlinking converter, where energy storages do not participate in active power flow. The batteries to be used in the dclink are replaced by capacitors for implementation point of view. Hence there is a need to control the dc-link capacitor voltages. The intention is to establish the fact that the developed control scheme which works for the capacitors, can be easily employed if there are batteries instead, having better dynamic performance.

III. CONTROL STRATEGY

The controller of the H-bridges regulate the dc-link capacitor voltages by indirect current control through the PI controller. The reference dc-link voltage is set to a desired value and a PLL is used to synchronize the controller with the ac microgrid Fig. 4(a). Phase Shifted Carrier modulation technique is adopted as in case of multilevel inverters. This is advantageous because of reduction in effective switching frequency which inevitably brings down the switching losses.

On the other hand, the bidirectional half bridge dc-dc converters are controlled in peak current control mode Fig. 4(b). The reference dc grid voltage and the actual inductor currents are fed to the controller to generate pulses. The system parameters are specified in Table I.

IV. SIMULATION RESULTS & DISCUSSION

Simulations are done in MATLAB/Simulink platform. Three cases have been considered to show the bidirectional power flow operation and dc grid voltage regulation. In each case, the dc-link capacitor voltages are maintained at desired value to show the effectiveness of using a battery in actual situation where it will not participate in energy transfer.

A. Case 1:

If a situation is considered when the DGs in the dc grid are operating at their corresponding Maximum Power Point (MPPT) to get full utilization of the renewable resources and the load demand at that instant is below the generation capacity, the voltage of the dc grid bus will rise. Thus appears the need to control the dc grid bus voltage by extracting the excess power from the dc grid and injecting it into the ac grid. The ILC performs the above task in times of such contingencies as shown in Fig. 5. Positive and negative power denotes delivering and absorbing power respectively. Fig. 6 (a) and (b) displays the output phase and line voltages of the inverter and three phase grid currents respectively. The modulation index being 0.96 in this mode of operation, gives eleven levels in the phase voltages and twenty-one levels in the line-to-line voltage. The inductor currents of the dc-dc converters for all the three phases is shown in Fig. 6 (c). The peak to peak ripple in the inductor current is found to be almost 3 amperes(13.2% of the rated current).

TABLE I
SYSTEM SPECIFICATIONS

System parameters	Values
AC grid voltage	220 volts (L-L rms)
DC grid voltage	110 volts
DC grid capacitance	500 microfarad
DC-link capacitance	6000 microfarad
DC-link voltage	50 volts
DC-DC converter inductance	10 mH
Switching frequency of dc-ac converter	1.2 kHz
Switching frequency of dc-dc converter	2 kHz
Transformer leakage inductance	4 mH
Transformer leakage resistance	0.25 ohms

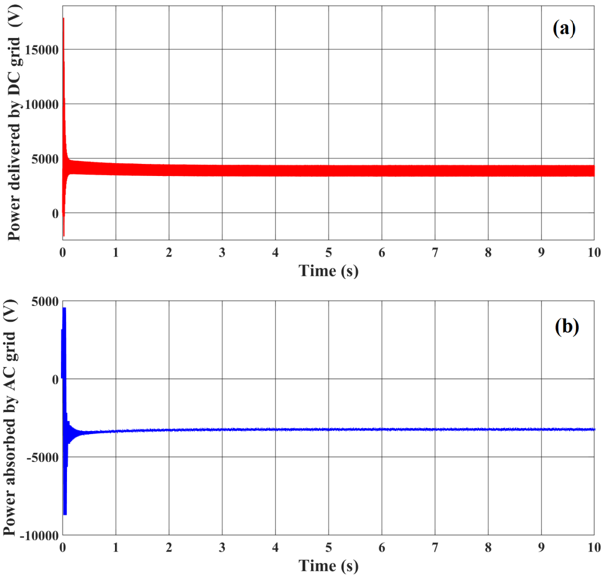

Fig. 5. (a) Power delivered by dc grid, (b) Power absorbed by ac grid

B. Case 2:

On the other hand, if the demand exceeds the generation, the voltage will fall. This situation can be dealt by the ILC by means of injecting the required amount of power from the ac grid into the dc grid, thus maintaining the dc grid voltage. The corresponding waveforms are displayed in Fig. 7 and Fig. 8. The sign of power and inductor currents signify the reversal of power flow. Also the output voltages and grid currents are shown for an operation of 0.76 modulation index. Hence, there is clear effect on the reduction of the number of levels of output voltage, which is decided by the amount of reference power to be transferred.

C. Case 3:

A changeover of the direction of power flow has been considered in this case to emphasize the dynamic performance of the controllers. It can be seen from Fig. 9, at 5 secs, a step command has been given to change the direction of power

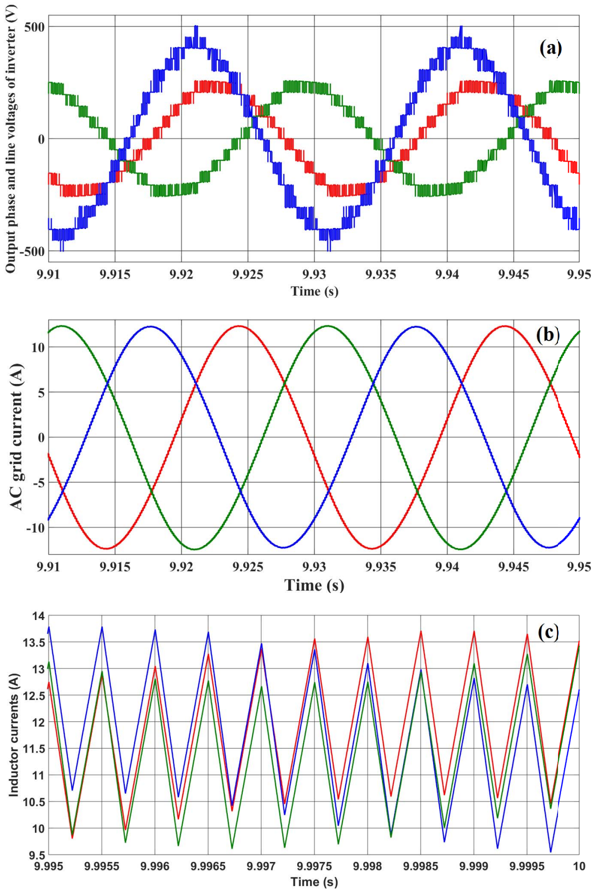

Fig. 6. (a) Output voltage of the inverter: blue- line to line voltage; red & green- line to neutral voltage, (b) AC grid current, (c) DC-side inductor currents

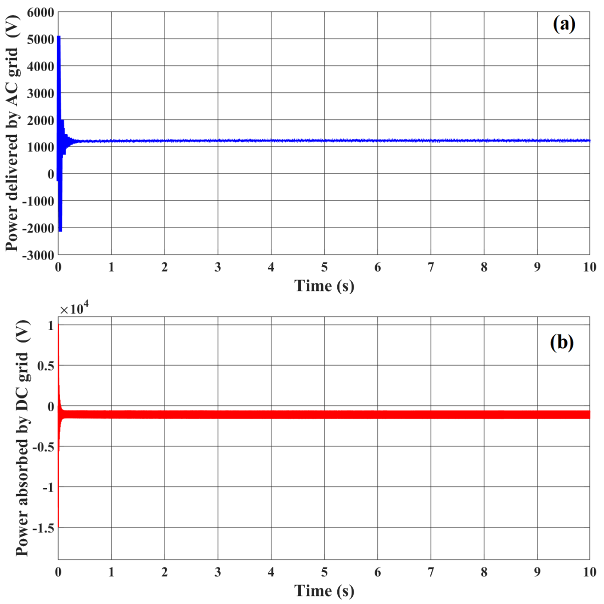

Fig. 7. (a) Power delivered by ac grid, (b) Power absorbed by dc grid

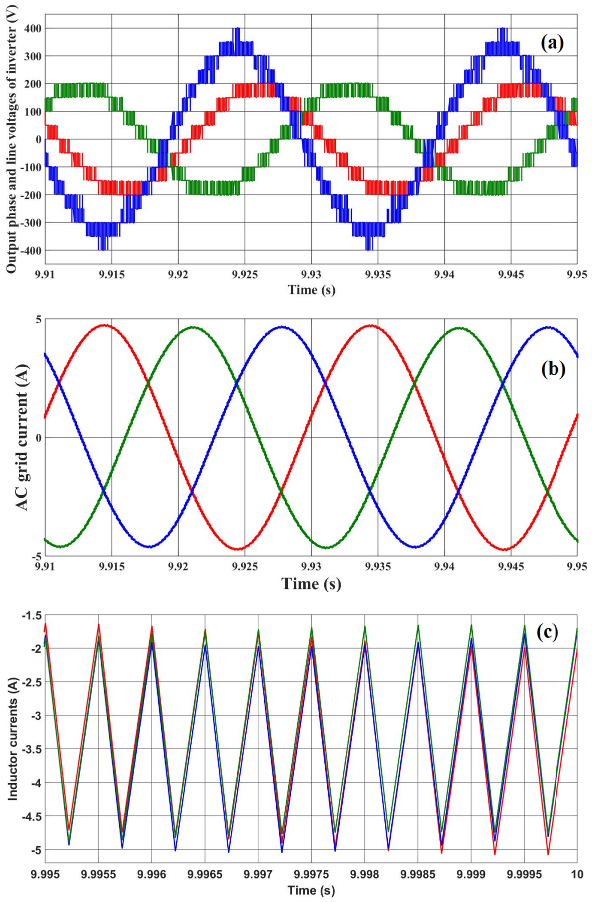

Fig. 8. (a) Output voltage of the inverter: blue- line to line voltage; red & green- line to neutral voltage, (b) AC grid current, (c) DC-side inductor currents

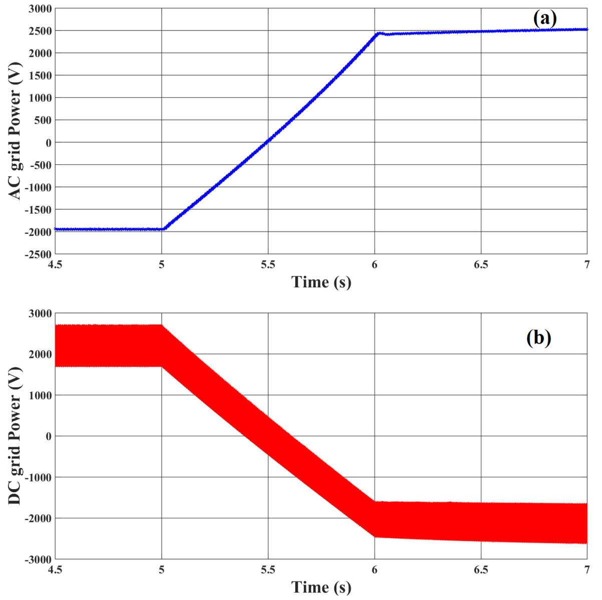

Fig. 9. Changeover of power flow direction: (a) AC grid power, (b) DC grid power

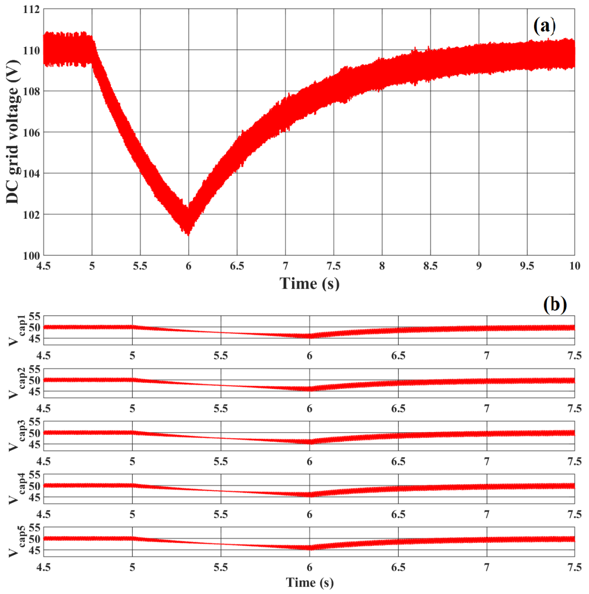

Fig. 10. Changeover of power flow direction: (a) DC grid voltage, (b) DC-link capacitor voltages

flow. Before 5 secs power was being delivered from dc grid to ac grid; whereas after the command the reverse transfer of power takes place. It can be observed in Fig. 10 (a) that the dc grid voltage was stabilized at 110 volts before and after the step command. The peak to peak voltage ripple is observed to be 2 volts (1.8% of the rated voltage). Similar case happens in case of dc-link capacitor voltages which are meant to stay at desired 50 volts as visible in Fig. 10 (b).

V. CONCLUSION

In this paper, a three-phase multilevel bidirectional interlinking converter with integrated energy storage has been proposed for hybrid ac-dc microgrid. The proposed configuration offers modularity in topology, flexible control, lesser conduction and switching losses without any need for capacitor voltage balancing like that of NPC or MMC. Intermediate low voltage battery modules are able to bring down the on-state resistance of the MOSFET switches in proportion to the required blocking voltage. Lesser VA rating of the converter switches makes the topology cost-effective as well. Most importantly, being inherent dc-fault tolerant, the ILC offers undisturbed and independent power flow modes between its three ports i.e. ac grid, dc grid and energy storage. Transformer isolation helps to avoid any possibility of short circuit operation within the converter. Bidirectional operational capability of the ILC and dc grid voltage regulation are verified by simulation results.

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REFERENCES

[1] N. Hatziargyriou, *Microgrids: Architectures and Control*, ser. Wiley-IEEE. Wiley, 2014.

[2] S. Sharkh and M. Abu-Sara, *Power Electronic Converters for Microgrids*. John Wiley & Sons, 2010.

[3] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous Control of Interlinking Converter With Energy Storage in Hybrid AC-DC Microgrid,” *IEEE Transactions on Industry Applications*, vol. 49, no. 3, pp. 1374–1382, May 2013.

[4] S. M. Malik, X. Ai, Y. Sun, C. Zhengqi, and Z. Shupeng, “Voltage and frequency control strategies of hybrid AC/DC microgrid: a review,” *IET Generation, Transmission Distribution*, vol. 11, no. 2, pp. 303–313, 2017.

[5] A. Gupta, S. Doolla, and K. Chatterjee, “Hybrid ac-dc microgrid: Systematic evaluation of control strategies,” *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1–1, 2017.

[6] H. Zhang, J. Zhou, Q. Sun, J. M. Guerrero, and D. Ma, “Data-driven control for interlinked ac/dc microgrids via model-free adaptive control and dual-droop control,” *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 557–571, March 2017.

[7] T. Ma, M. H. Cintuglu, and O. A. Mohammed, “Control of a hybrid ac/dc microgrid involving energy storage and pulsed loads,” *IEEE Transactions on Industry Applications*, vol. 53, no. 1, pp. 567–575, Jan 2017.

[8] L. Zhang, F. Gao, N. Li, Q. Zhang, and C. Wang, “Interlinking modular multilevel converter of hybrid ac-dc distribution system with integrated battery energy storage,” in *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2015, pp. 70–77.

[9] J. Khajesalehi, K. Sheshyekani, M. Hamzeh, and E. Afjei, “Maximum constant boost approach for controlling quasi-z-source-based interlinking converters in hybrid ac-dc microgrids,” *IET Generation, Transmission Distribution*, vol. 10, no. 4, pp. 938–948, 2016.

[10] M. Sahoo and K. S. Kumar, “Bidirectinal switched boost converter for ac-dc hybrid microgrid,” in *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, March 2014, pp. 2231–2236.

[11] Y. Xia, Y. Peng, P. Yang, M. Yu, and W. Wei, “Distributed coordination control for multiple bidirectional power converters in a hybrid ac/dc microgrid,” *IEEE Transactions on Power Electronics*, vol. 32, no. 6, pp. 4949–4959, June 2017.

[12] K. Sun, X. Wang, Y. W. Li, F. Nejabatkhah, Y. Mei, and X. Lu, “Parallel operation of bidirectional interfacing converters in a hybrid ac/dc microgrid under unbalanced grid voltage conditions,” *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 1872–1884, March 2017.

[13] M. Rashed, C. Klumpner, and G. Asher, “High performance multilevel converter topology for interfacing energy storage systems with medium voltage grids,” in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, Nov 2010, pp. 1825–1831.

[14] P. Wang, C. Jin, D. Zhu, Y. Tang, P. C. Loh, and F. H. Choo, “Distributed control for autonomous operation of a three-port ac/dc/ds hybrid microgrid,” *IEEE Transactions on Industrial Electronics*, vol. 62, no. 2, pp. 1279–1290, Feb 2015.

[15] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Hybrid ac-dc microgrids with energy storages and progressive energy flow tuning,” in *Proceedings of The 7th International Power Electronics and Motion Control Conference*, vol. 1, June 2012, pp. 120–127.

[16] R. Majumder, “A hybrid microgrid with dc connection at back to back converters,” *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 251–259, Jan 2014.

[17] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with ac and dc subgrids,” *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2214–2223, May 2013.

[18] C. C. Hou and Y. F. Huang, “Diode rectifier with auxiliary converter for hybrid ac/dc microgrids,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 4, pp. 1059–1069, Dec 2014.

[19] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics. Converters, Applications and Design*, 3rd ed. John Wiley and Sons, Inc, 2003.

[20] A. A. Eajal, M. A. Abdelwahed, E. F. El-Saadany, and K. Ponnambalam, “A unified approach to the power flow analysis of ac/dc hybrid microgrids,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 3, pp. 1145–1158, July 2016.