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A Bidirectional Photovoltaic Inverter without a Transformer

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Abstract: The high frequency leg (HFL) technology is used to create a revolutionary bidirectional transformer less photovoltaic (PV) inverter that can operate in both continuous and discontinuous current modes while having much improved dependability. With the high-frequency Leg, the smooth ac current is made possible because the higher equivalent switching frequency may lessen inductor current ripple, which in turn reduces the volume of passive components. There is no problem with dead time that would prevent complete pulse width modulation from transferring all the energy to the grid and raising the duty cycle to its maximum possible level. Adding more high-frequency legs to the PV inverter also makes it simple to increase its capacity. Additionally, the suggested topology can operate in the rectifier mode with the capacity to transfer power in both directions, which is appealing for the PV application. The suggested transformer less PV inverter's viability and effectiveness in standalone mode have been confirmed by the experimental findings of an 8-kW laboratory prototype.

Keywords: Bidirectional capability, high frequency leg (HFL), N-Cell, P-Cell, Transformer less photovoltaic (PV) inverter.

1. Introduction

Nowadays, grid-connected photovoltaic (PV) systems, particularly low-power transformer less single phase systems [1]–[11] (The national standard GB/T 30427– 2013 of the People's Republic of China [12] rules that the maximum out-put power of single-phase PV systems is 8 kW) are becoming more important worldwide. There is a small PV power generation system as shown in Fig. 1, which consists of the PV panel, the battery, the inverter, the ac grid, and the users' load. Among them, the inverter is the core of the whole system PV panels generate electricity during the day that is sent to the grid or directly to customers, and any excess energy is simultaneously sent to the battery to be charged. In the evening, PV panels cease to function in the absence of sunshine, while the grid and users depend on the battery to provide power. There is a need for the grid to charge the battery through the inverter when the PV panels and battery are both malfunctioning. The central inverter must therefore have the capability of bidirectional power flow. But currently, the majority of PV inverters without transformers are also capable. Transformer-less PV grid-tied inverters provide numerous advantages over those with transformer galvanic isolation, including higher efficiency, lower cost, smaller volume, and less complexity [13]–[15].

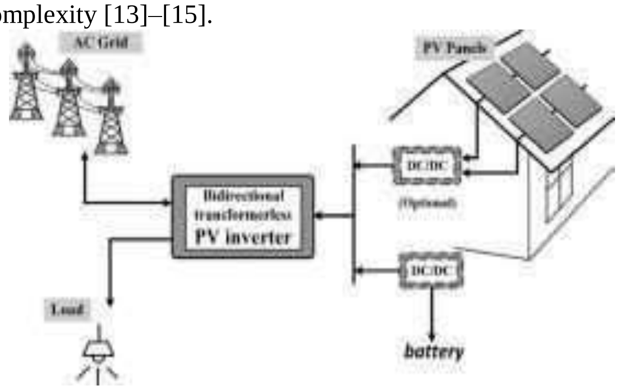

Figure 1. System block diagram of the PV grid-tied system.

One key issue for the transformer less PV inverter with high efficiency and reliability is that in order to achieve high efficiency over a wide load range, it is necessary to utilize MOSFETs or some switches with better performance for all switching devices because of its low conduction and switching loss [16]. Another key issue is that the inverter should not have any shoot through issues for higher reliability. In addition, an important problem of leakage current must be solved to utilize transformer less PV inverters for safety. Common-mode (CM) voltages must be avoided since they will cause a significant amount of current to partially flow through the inverter and out to earth. The current harmonics, losses, safety hazards, and electromagnetic interference problems caused by this CM ground current will all rise [17]–[21].In order to fulfil the promise of assuring reliable operation, it is the goal to increase efficiency as much as possible, while also taking into account cost concerns. In order to resolve these problems, a unique high-frequency leg (HFL) concept-based transformer-less PV single-phase inverter topology is developed, which may easily enhance the power capacity. The proposed transformer less PV inverter has the following

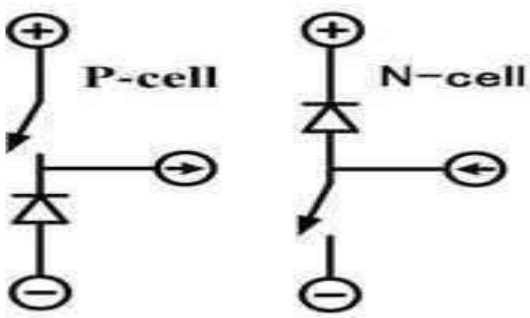

Figure 2. (a) Structure of basic switching cells

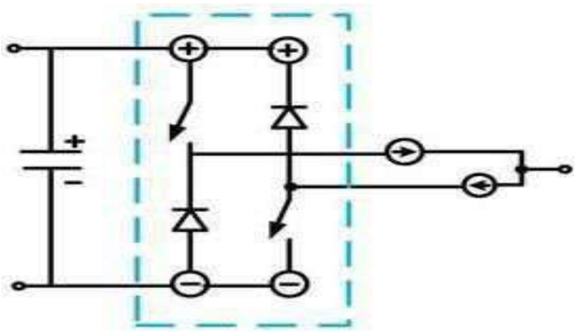

Figure 2. (b) Parallel combination of the P- andN-cells form a bidirectional phase leg

1) High reliability because there are no shoot throughissues.

2) Due to the two single loops that disconnect the PV array from the grid during the freewheeling phases, there is a reduction in CM leakage current.

3) Since the proposed converter never has the chance to cause MOSFET body diode reverse recovery, all of its high-frequency active switches can dependably use MOSFETs. The suggested inverter's ability to operate at higher switching frequencies while maintaining high system efficiency is made possible by the MOSFETs' low conduction and switching losses. A reduced inverter volume can be achieved by increasing switching 3.)Frequency, which can also reduce the size of passive components. Increasing the capacity of system according to demand by increasing the number of legs with the technology of interleaving modulation.

2) It has the capability of bidirectional power flowing, which it works as an inverter when the power is transferred from dc source to grid. Alternately, it can workas a rectifier when the power is transferred from grid to dc source. The bidirectional function will play a huge role in the future PV generation system

2. HFL Techniques Concept

2.1 Two Basic Switching Cells

All power electronics circuits are based on two simple switching cells and a combination of the basic switching cells defined as P-cell and N-cell as shown in Fig. 2 [22],

[23]. each cell consists of a switching device (a MOSFET, IGBT, or other switching device) and a diode connected to three terminals: (+), which is connected to the positive of a voltage source or capacitor, (), which is connected to the negative of a voltage source or capacitor, and a common terminal denoted by (←) or (→). In addition to their excellent utility in the inverter and rectifier techniques, they can be employed directly as dc converters. The advantage is that using P-cell and N-cell in the inverter topologies can avoid the problem of shoot- through. By using the fundamental switching cells, any inverters may be built similarly. To avoid a short circuit of the dc link, there must typically be dead time between the switching periods of the two switches. There is no need for the dead time when using the paralleled P-cell and N-cell phase leg, which has an inductor inserted between the common terminals. Since the load current only passes through the P-cell during the positive half cycle of the current and the N-cell during the negative half cycle, IGBT-diode modules designed as the P-cell and N-cell are better suited for inverter operation.

2.2 HFL Methodologies based on Simple Switching Cells

In some power-level applications, MOSFET-diodes modules based on P-cell and N-cell perform better than IGBT-diodes modules because MOSFET has lower switching and conduction loss than IGBT, and IGBT can only function at a lower switching frequency than MOSFET, resulting in a bigger filter size. For power conversion, the high-switching frequency topology is therefore required [24]. The HFL technology that is suggested in this

Paper integrates the multiple bridge legs together, switches the high-frequency control signals to the switches, and replaces the IGBT switches of the cells with high-frequency switches, such as MOSFETs or other switches with greater performance. In order to decrease current ripple and the size of passive components, the HFL can increase their equivalent switching frequency with phase-shift PWM control technology. As a result, system efficiency is significantly increased

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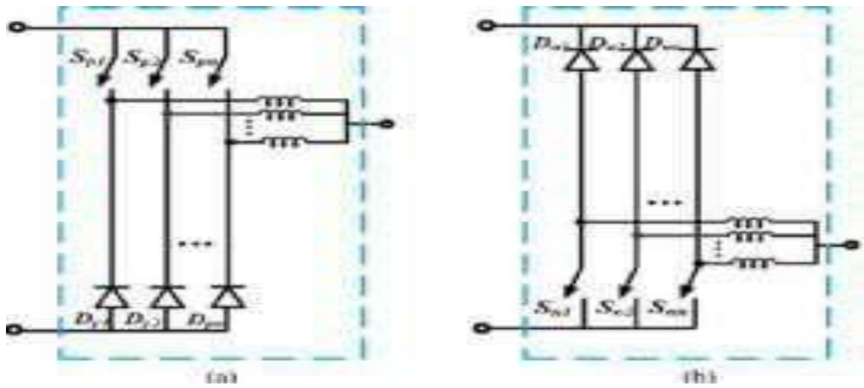


Figure 3. (a) High-frequency P-Cell Leg. (B) High frequency N-Cell Leg.

The inductors are positioned between the P-cell and N-cell legs' common terminals in Fig. 3, where they can be built as integrated linked inductors. Using the dual-buck half-bridge inverter structure as an illustration, increasing a group of P cell and N cell legs, as shown in Fig. 4, can double its capacity and the equivalent operating frequency by modulating the switches in each group of legs with a 180° phase shift, which can decrease the inductor volume.. By analogy, in order to achieve greater capacity, it is possible to continue increasing the number of legs, with each group of legs with 360°/n phase shift to modulate.

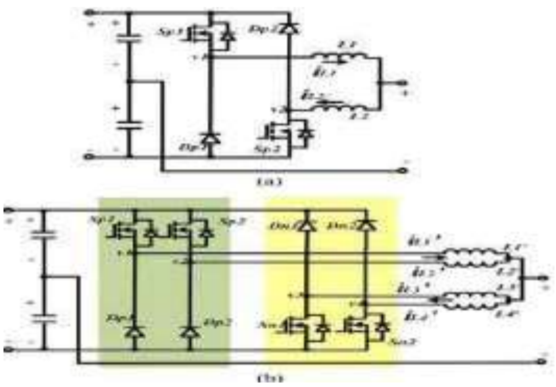
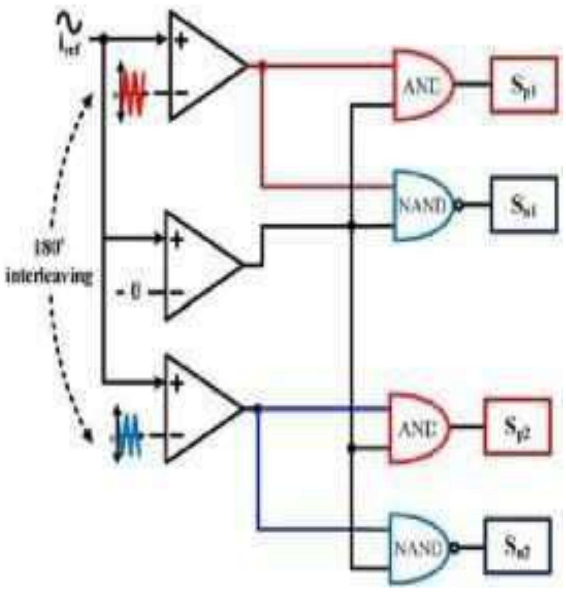


Figure 4. (a) Configuration of the dual-buck half-bridge structure. (b) Dual-buck structure based on HFLs.

As shown in Fig.4 the dual-buck half bridge inverter structure is displayed in Fig.4 (a) and the dual buck structure based on HFL is displayed in Fig.4(b), Fig.5gives the modulation.



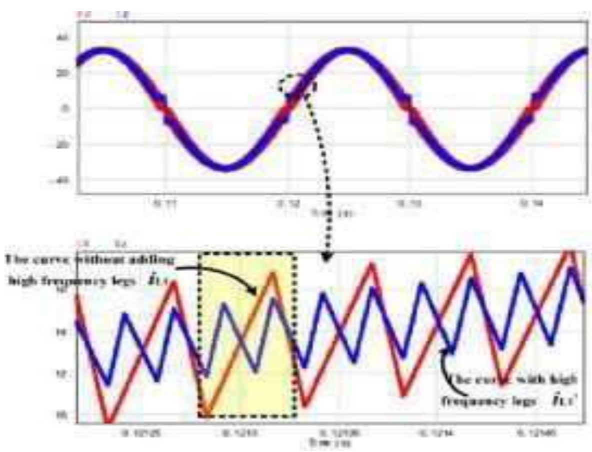


Figure 5. Modulation block diagram of the HFL-based dual-buck half-bridge inverter

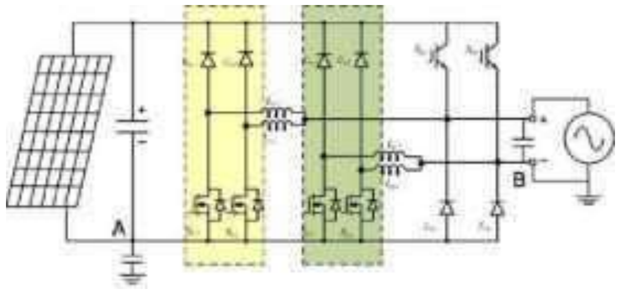


Figure 6. Shows the total output inductor

Current waveforms of the dual-buck half-bridge inverter before and after adding the HFLs. The current curve with higher ripple is the dual-buck inverter without adding HFLs and the later ripple frequency is two times of the former. Neither adding HFLs nor with it, the zero- crossing distortion of the ac current cannot be resolved in the dual-buck inverter. But after adding HFLs, the smaller current ripple is received and the frequency of the current ripple is also doubled.

3. Customary PV Inverters with No Transformer

The classic full-bridge inverter structure [25] would be a first example of the transformer less PV inverter with bipolar modulation avoiding the CM leakage current. Although the traditional topology can complete the function of PV inverter, it has the shoot-through issue, the most dominating failure of voltage source inverters. Inaddition, at higher dc bus voltage, it loses the benefit of using power MOSFETs as the active switching devices for efficiency improvement and fast switching speed because of the reverse recovery issues of the body diodes.

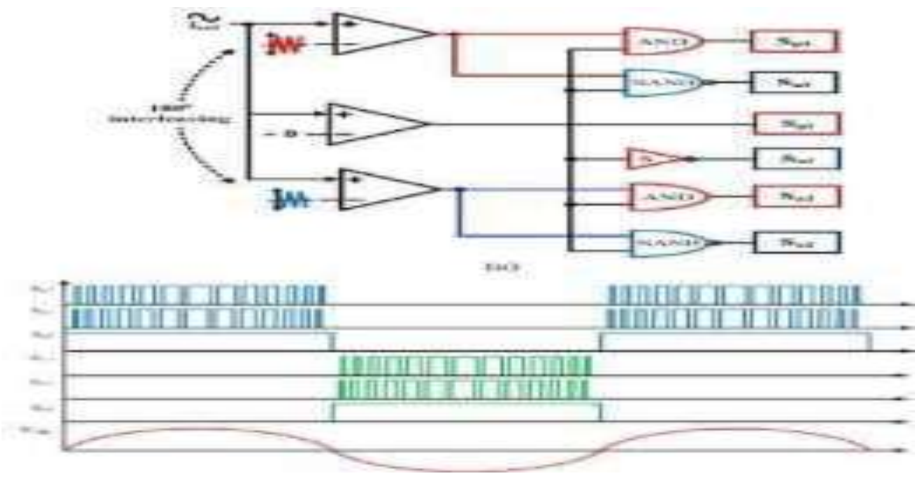
Figure 7. Proposed bidirectional transformerless PV inverter topology based on HFLs.

The HERIC topology [26] consists of a normal full-bridge circuit with each group of diagonal switches being operated at high frequency during one half-wave of the output voltage. An additional branch placed in parallel with the filters and load has two switches in opposite directions, each one is active during one whole half-period of the grid waveform. The drawbacks here are the increased quantities of semiconductors and the reactive power incapability. Examples of commercial products with such topology are the NT-series of inverters from the manufacturer Sun ways. The H5 inverter structure basically consists of a full bridge with the upper switches operating at grid frequency and the lower ones operating at high frequency, while the additional switch operating at both half-waves together with the same high-frequency signals of the lower switches. The disadvantages of this topology are the higher conduction losses due to the series association of three switches during the active powering period. This circuit is employed by the manufacturer SMA on the Sunny Mini Central series and the new Sunny Boy TL series [27]. As shown in Fig. 4, the dual-buck converter [28] consists of two of that composition (shown in Fig. 2) eliminates the problem of shoot through in the traditional full-bridge inverter.

The dual-buck structure can also utilize the HFL by using MOSFETs and increasing the number of leg to expand the capacity. But the number of the switches in the dual-buck topology needs to increase in multiples when the capacity is expanded by times. It will cost large number of switches so that the economic efficiency is poor. And it also has the problem of the current zero- crossing distortion. Fig. 7 shows intuitively that the proposed transformer less PV inverter topology based on HFL can not only expand its capacity easily by increasing leg numbers, but also can work as two modes, called PV mode and storage mode.

3. PV Inverter with HFL-Based Transformer instead

This paper proposes a new bidirectional transformer less PV inverter topology by utilizing the N-Cell HFLs consisting of MOSFETs and silicon carbide diodes, and two P-Cell legs based on IGBTs without anti parallel diodes and the silicon car-bide diodes. Fig. 7 shows the proposed topology where the high-frequency leg adopts two N-Cell legs and four inductors L_{p1}, L_{p2}, and L_{n1}, L_{n2}. The two P-Cell legs are used for the selection of grid voltage directions. The common terminal of the P- Cell leg with S_{pf} and D_{pr} choosing the positive direction is connected with the positive port of the ac side and the negative N-Cell HFL with L_{n1} and L_{n2}. The common terminal of the P Cell leg with S_{nf} and D_{nr} choosing the negative direction is connected with the negative port of the ac side and the positive N-Cell HFL with L_{p1} and L_{p2}. S_{pf} and S_{nf} would work at power frequency in switching cycle under inverter mode (PV mode), and the



role of Dpr and $Dn\ r$ is to choose direction legs under the rectifier mode (storage mode).

Figure 8. Modulation block and switching patterns in the HFL PVinverter.
(a) Modulation block diagram of the HFL-based PVinverter.
(b) Waveform of the switches modulation signal

4.1 PV Mode (Inverter Mode)

Fig. 8 shows the modulation signals of the proposed inverter where Spf and Snf are, respectively, controlled by the grid frequency pulse signals. Because there is no antiparallel diode of the IGBTs in the P-Cell legs, a small dead band between the low-frequency switches Spf and $Sn\ f$ is not needed to avoid the grid short circuit.

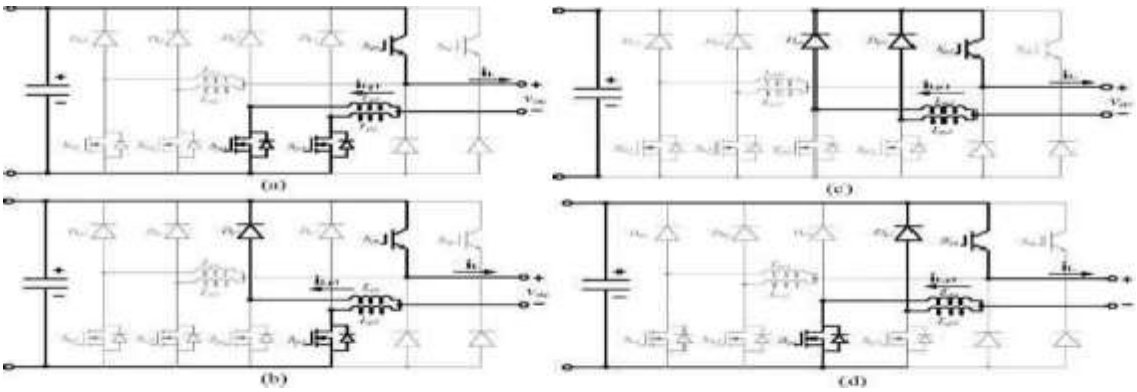


Figure 9. Operation modes in the positive half-line cycle in the PV mode.
(a) Sp 1 , $S\ p$ 2 turned ON, called as Mode 1.
(b) Dp 1 free-wheeling, $S\ p$ 2 turned ON, called as Mode 2.
(c) Dp 1 free-wheeling, Dp 2 free-wheeling, called as Mode 3.
(d) Sp 1 turned ON, Dp 2 free-wheeling, called as Mode 4.

In the positive half-line grid cycle, the switch Spf turns ON, Sp 1 and Sp 2 are controlled by the PWM signals. And in the negative half-line grid cycle, the switch $Sn\ f$ is ON, Sn 1 and Sn 2 are controlled by the PWM signals. At the same time, in order to reduce the current ripple of the ac side, two switches working in the same half-line cycle are modulated employing two triangular carriers with 180° phase shift, namely interleaving modulation technology. Fig. 9 shows the detailed operation modes taking the positive half-line cycle of the ac side for example. There are four operation modes (Mode 1, Mode 2, Mode 3, and Mode 4) that, respectively, Sp 1 , Sp 2 are ON or OFF at the same time, one of the two switches conducts and the other is OFF. At this time, the current flowing through Lp 1 and Lp 2 changes the paths associated with the state of Sp 1 , Sp 2 .When Sp 1 is ON, the voltage value of the inductor Lp 1 is the difference between the dc side and the ac side, and the inductor is charged so that the current value is rising. When Sp 1 is OFF, the voltage value of the inductance Lp 1 is the reverse ac voltage and the inductor is discharged so that the inductor current value is falling. It is the same analysis to Sp 2 and Lp 2 . According to the four operation modes shown in Fig. 9

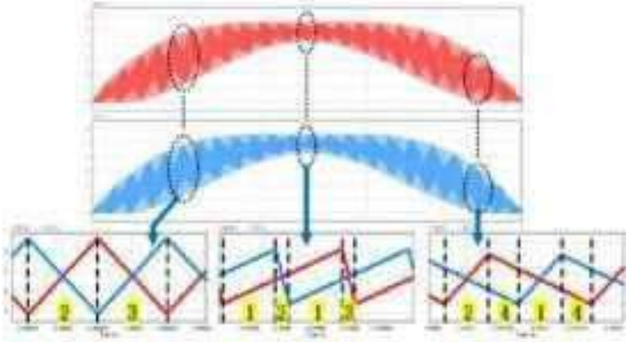


Figure 10. Inductor current ripple waveforms in the positive half-line cycle.

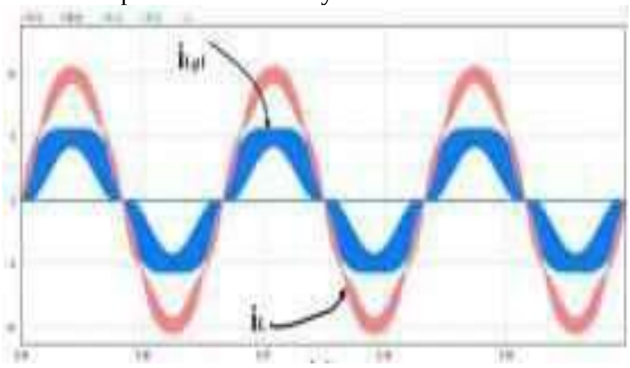


Figure 11. Waveforms of the total ac current and each inductor current.

As shown in Fig. 11, by paralleling two high- frequency legs in the proposed PV inverter under unipolar modulation employing two triangular carriers with 180° phase shift, the total ac cur-rent ripple can be reduced effectively, especially under d = 0.5, although each inductor current ripple is maximum, the total ac output current is smooth without any ripple. As is shown in Fig. 12, the No.1 straight line is Vdc , the No.2 curve is $v$ac , and the inductor voltage is changed between Vdc – $v$ac and –$v$ac shown in the No.3 region. The efficient calcu- lation based on (4) and (5) is capable of calculating the amplitude of current ripple through a single inductor. The total ac current will be the sum of the currents flowing through the two inductors, by the interleaving modulation, and the frequency of the ac current ripple will be doubled.

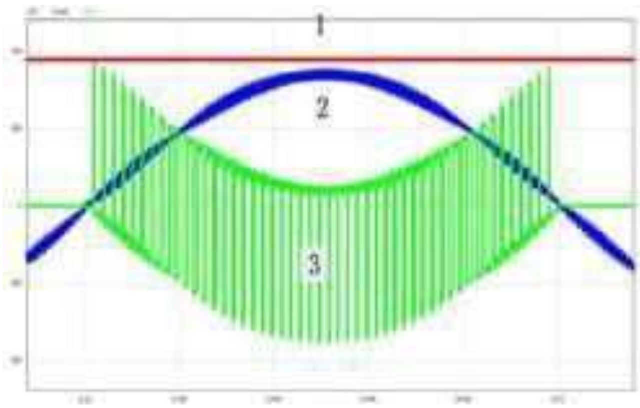
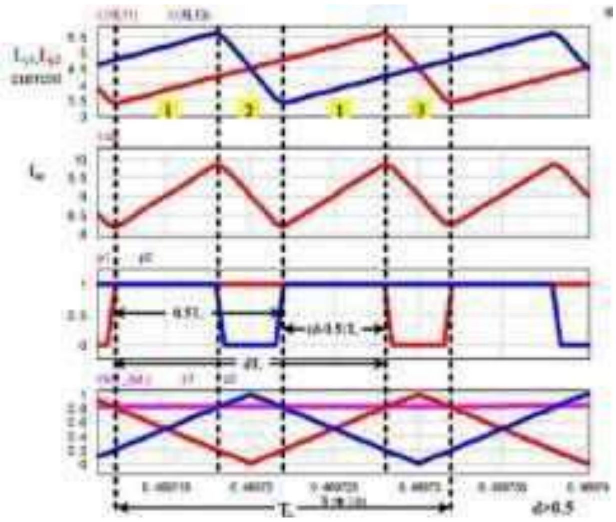


Figure 12. Voltage drop through inductor`

As shown in Fig. 13, the relationship between the inductors’ current ripples and the total ac current ripple is exhibited, respectively, under the operating conditions of $d > 0.5$ $d = 0.5$ and $d < 0.5$.



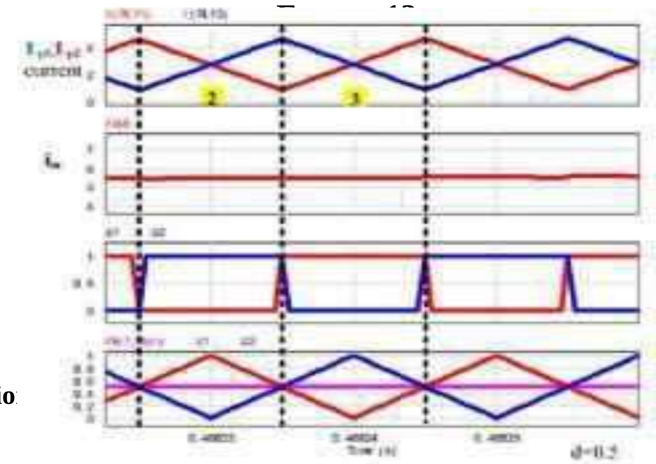


Figure 14

Leakage currents are avoided due to the absence of high frequency oscillations since the positive output of the PV array is directly connected to and to the phase positive output the phase negative output (the neutral), respectively, during the positive and negative half-waves. In the experiment, the waveforms of the CM voltage are monitored. Fig. 23 as the experiment monitor results confirmed the leakage currents is limited successfully in this circuit.

4.2 Efficiency Calculation and Analysis of the Proposed Transformer less Inverter

The major losses of an inverter are conduction loss and switching loss. First, the conduction loss is considered including the conduction loss of the power MOSFET, the IGBT, and the diode in the proposed inverter shown in Fig. 7. The specifica-tion of power devices for efficiency evaluation and the circuit parameters of the experimental system are shown in Table I.

3. EXPERIMENTAL RESULTS

An 8-kW, 50-kHz prototype circuit has been developed, built, and tested to demonstrate the viability and benefits of the suggested trans-former-less PV inverter architecture. Fig. 16 displays a picture of the test-bed hardware prototype. Two inversely coupled inductors are built for (Lp1, Lp2) and (Ln1, Ln2), with a self-inductance of 150 H and a mutual inductance of 16.8 H, respectively. The dc-side nominal voltage is 380 V. The load voltage is 220 Vrms, the filter capacitor has a value of 2 F, and the switching frequency is 50 kHz. The L-C filter's cutoff frequency is approximately 9 kHz, or 10% of 100 kHz, which is the comparable frequency. Typically, the large voltages cause the discontinuous conduction mode (DCM).

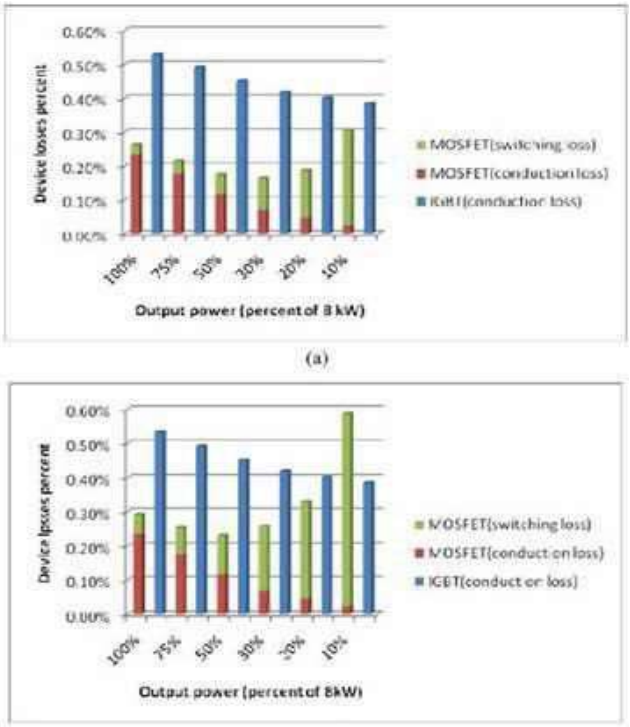


Figure 15. Power semiconductor device losses Distribution comparison for the proposed inverter at the different output power conditions. (a) 25-kHz switching frequency. (b) 50-kHz switching frequency.

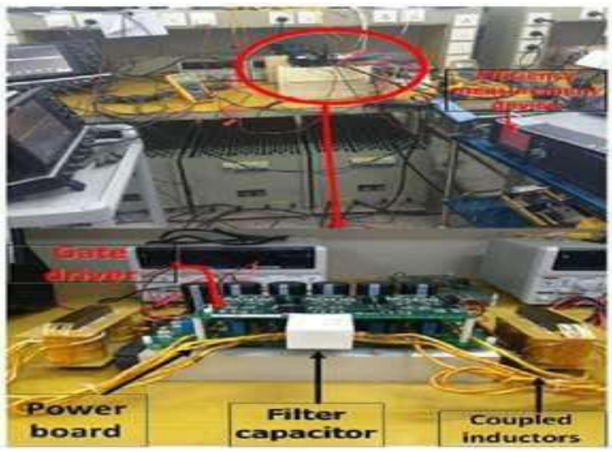


Figure 16. Test-bed hardware prototype

Fig. 17 shows the discontinuous inductor current i_{Lp1}, the continuous total inductor i_{out}, and the output voltage v_{out} under the 1.8-kW load condition. The waveforms i_{Lp1} are the inductor L_{p1} current at the negative half-line cycle. The two inductor currents are i_{Lp1} and i_{Lp2} operating at the positive half-line cycle, and the sum of them can be found in Fig. 18. As shown, i_L is the sum of the two inductor current waveforms, and the total current ripple is reduced obviously compared with either one.

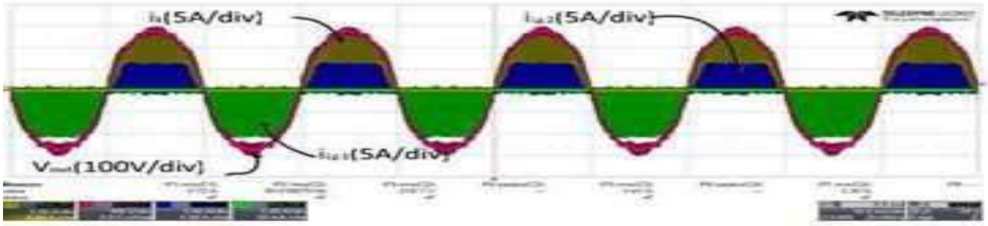


Figure 17. Experimental waveforms of the proposed

Inverter when the load power is 1.8 kW with Dm = 0.7It can be obviously seen that the circuit operates in the DCM at this time as the inductor currents are discontinuous shown in Fig. 18.

However, the total current *iL* is continuous and it canbe inferred that the proposed PV inverter topology can operate well in the DCM. When the circuit operates in the DCM, the switches can be turned ON under ZCS condition, so that the losses of the switches are reduced and the efficiency of the system is improved.

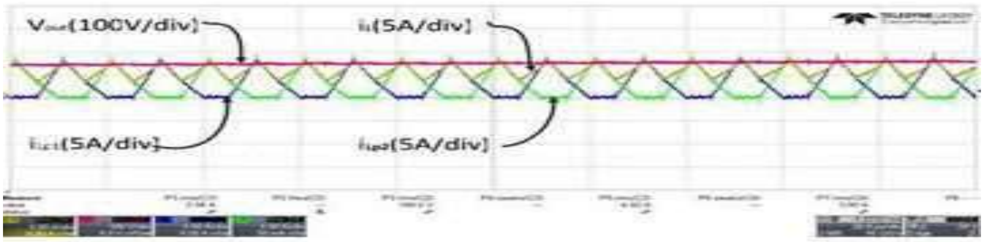


Figure 18. Comparison between the sum inductor current and the single inductor current when the load power is 1.8 kW with D = 0.7.

Fig. 19 shows the efficiency of the power stage for an in-put voltage of 380 V with the 50 kHz switching frequency based on NORMA5000. According to (20), the CEC efficiency of the proposed transformerless inverter at 50 kHz is, respectively, 98.78%. In the end, the feasibility and effectiveness of the proposed transformerless PV inverter can be verified from the above experimental results of 8-kW laboratory prototype.

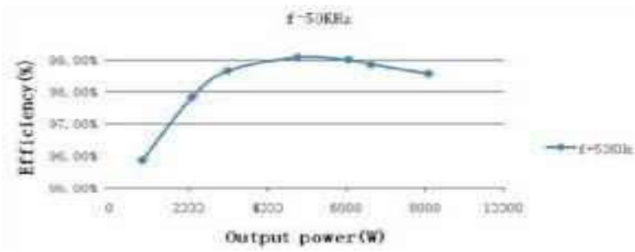


Figure 19. Efficiency curve of the power stage for an input voltage of 380 V with the 50-kHz switching frequency.

4. Conclusion

The interleaving the HFL concept has been used in this paper to present a novel bidirectional transformerless PV inverter with DCM/CCM operation. As a result of the high-switch frequency and DCM/CCM operation, the HFL allows for the smooth generation of ac current. Dead time at PWM is unnecessary when using the proposed architectureCommutation instants are switched, resulting in reduced ac output current distortion. Additionally, increasing the quantity of HFL can quickly increase the inverter's capability. In addition to being a bidirectional inverter that can also function as a rectifier, the topology suggested in this research is one. The proposed topology is extremely appealing for applications involving transformer-free PV inverters due to the benefits listed above.

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