Performance Analysis of Interleaved Converter with Voltage Multiplier Module for High Efficiency Conversion and High Step-Up Voltage Gain

[1]Mr.M.Rajavelu, [2]Mr.K.B.Bhaskar, [3]Ms.D.Jasmine Susila
[1]Assistant Professor, [2]Head of the Department, [3]Assistant Professor,
Electrical and Electronics Engineering,
Adhi College of Engineering and Technology, Kanchipuram, India.

Abstract – This paper proposes the performance analysis of interleaved converter with voltage multiplier module. In previous days, the high step-up DC-DC converters were used to produce a high step-up gain. Due to the single switch operation of the converter, the power level is limited and the input current ripple is large. Therefore, it is unsuitable for high power application. In order to overcome this problem, the interleaved boost converter with a PWM scheme was proposed. To achieve a high step-up voltage, gain, the voltage multiplier module is integrated with the interleaved converter. Thus, the voltage multiplier module is based on the concept of the switched capacitor and coupled inductor technique. However, the leakage inductor causes voltage transients across the switches. In order to eliminate the voltage spike, the lossless passive clamp circuit was introduced. Thus, the leakage energy is recycled and reverse recovery problem is eliminated. By selecting the low voltage rated power devices, the cost and voltage stress is reduced with improving efficiency. The proposed converter will be analyzed in PSIM model in continuous conduction mode (CCM) of operation and the converter analysis will be presented.

Index Terms - Coupled inductor, renewable energy sources, high step-up interleaved converter, voltage multiplier module, PSIM.

I. INTRODUCTION

Renewable energy plays an important role in day-to-day life applications. Thus, renewable energy sources causing harmful problems like global warming, the greenhouse effect, and fossils exhaustions are completely avoided. When considering the secure, robust, reliability and pollution - free environment [1-2]. The photovoltaic system becomes the better contribution for generating electricity among the renewable energy sources [3-5]. In general, the front stage conversion process will be the high step-up dc-dc converter. In recent years, the boost converter is widely used to produce high conversion ratio. However, in practical consideration, it is not possible to achieve a high conversion ratio without using a large duty cycle. Due to the larger duty ratio and higher components rating, the series problems like reverse recovery, voltage stress, and conduction losses will occur [6-11]. In order to avoid the large duty ratio, the better solution to use a transformer or coupled inductor [12-14]. Due to the disadvantages of the two switches in a conduction state, a single power device using high step-up dc-dc converter have been developed [15-16].

To achieve a high step-up voltage, gain and conversion ratio, the boost flyback converter with clamp mode coupled inductor was introduced. But the output voltage will be equal to the voltage stress [17-20]. In order to reduce the current ripple and magnetic component size with low cost, the interleaved structure was introduced. Then, the interleaved converter added with some switched capacitor cell was proposed. But the magnetic component size will be larger and volume occupied also increased. Thus, the high step-up boost converter with Winding Cross-Coupled Inductors (WCCI) was developed to extend the step-up voltage with proper turn ratio. In WCCI, the second and third winding will be act as dc input voltage source and are connected in series to the circuit. To overcome this problem, the passive lossless clamp scheme was introduced. Then, the voltage multiplier cell is inserted in between the winding cross-coupled inductor (WCCI) for voltage gain extension. But the circuit is complex and difficult to handle. By simplifying the circuit, the interleaved high step-up dc-dc converter with voltage multiplier cell was introduced. To increase the efficiency of the converter, the voltage multiplier module is added on the interleaved converter.

The proposed interleaved converter consists of a voltage multiplier module. It is based on the concept of the switched capacitor and coupled inductor technique. In this converter, the conduction loss is reduced by the current sharing of energy stored in the magnetizing inductor. Then the diode reverse recovery problem also eliminated by making the current flow through the diode will become zero before the switch turned off.

II. PROPOSED TECHNOLOGY

The proposed topology consists of the voltage multiplier module which is integrated with the interleaved boost converter. In this voltage multiplier module, it consists of four diodes and four capacitors with the secondary side winding of the coupled inductor. The proposed interleaved converter consists of two capacitors and two diodes which are added on the coupled inductor secondary side. So, the coupled inductor makes the capacitor to discharge in series and also to charge in parallel. Moreover, there is a problem of using a coupled inductor. Because of the leakage inductor of the coupled inductor may produce high voltage transients on the

power switch. In order to reduce the voltage spike across the switches and to recycle the leakage energy, the lossless passive clamp circuit is proposed. During heavy load conditions, the voltage stress and input current ripple are larger. Further, the reduction of current ripple and voltage stress of the proposed converter introduce the interleaved PWM scheme for gate signal and that makes the components to be rated with low voltage. Thus, by selecting the low voltage rated power devices makes the voltage stress and conduction loss to be lower.

2.1. Circuit Configuration

The circuit configuration of the interleaved converter with voltage multiplier is shown in Fig. 2.1. It consists of dc input voltage source Vin, two coupled inductors, two power switches S1 and S2, two clamp capacitors Cc1 and Cc2 and two clamp diodes Dc1 and Dc2, three output capacitors C1, C2, and C3. Thus, the output diodes for boost operation with switched capacitors are represented as Db1 and Db2. Then, the output diodes for flyback-forward operation are represented as Df1 and Df2.

The equivalent model of circuit configuration consists of leakage inductors Lk1 and Lk2, magnetizing inductors Lm1 and Lm2, serious leakage inductor Ls and an ideal transformer instead of coupled inductor. The turn ratio of the coupled inductor n is defined by the same turn ratio Ns/Np.
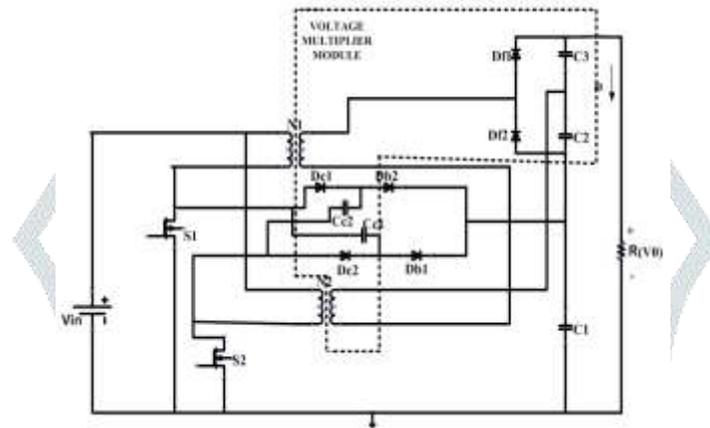

Figure. 2.1. Circuit Configuration of the Proposed Converter System.

In order to achieve the high voltage gain, the switched capacitor technique was proposed in the earlier days. In this topology, the high step-up voltage gain can be achieved without using a large duty cycle. From this switched capacitor technique, that the capacitor can charge in parallel and discharged in series. Based on this technique, the proposed converter introduced the combination of a coupled inductor and switched capacitor technique.
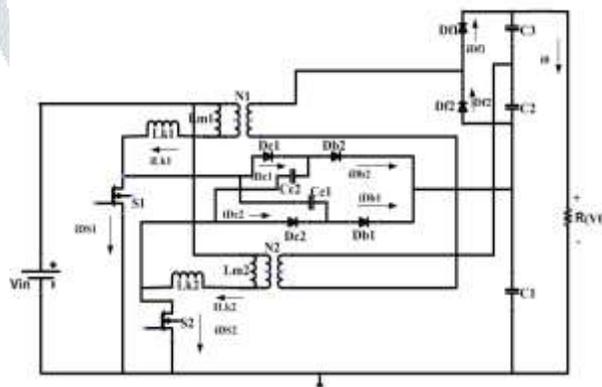

Figure.2.2 Equivalent Circuit of the Proposed Converter System.

The passive clamp circuit is used to recycle the leakage inductor energy to capacitor Cc1 and Cc2 and also the voltage spikes occur in the power switches S1 and S2 can be clamped. So, the voltage stress is reduced when compared to the other conventional boost converter topology. By selecting the low resistance Rds(ON) of the switch, the conduction loss is reduced significantly. From this concept, we can reduce the voltage stress, cost, and conduction loss. By recycling the energy, the reverse recovery problem is reduced and also high efficiency is achieved. In addition, the high step-up voltage gain is achieved.

2.2. Operational Principle

The operating principle of the proposed interleaved converter describes in different modes of the switching period. To form an asymmetrical interleaved structure, two coupled inductors and two switched capacitors are proposed in the voltage multiplier module. The dashed block of the circuit configuration is a voltage multiplier module. By turn, the power switches S1 and S2 is in ON state. It will act as a forward converter. When the power switches S1 and S2 is in OFF state. It will act as a flyback converter. In order to simplify the circuit analysis, the following assumptions are made as follows.
1. By neglecting the leakage inductor like Lk1, Lk2, and Ls.

2. The proposed interleaved converter utilizing components are made to be ideal.

3. Due to the infinite large capacitor, assume the voltage across all the capacitors should be constant.

The proposed topology will be operated only in continuous conduction mode (CCM) of operation.

2.3. Continuous-Conduction Mode (CCM) Operation

The current flow path of operating modes during each switching cycle at CCM will consist of eight modes as shown in Figure.2.3
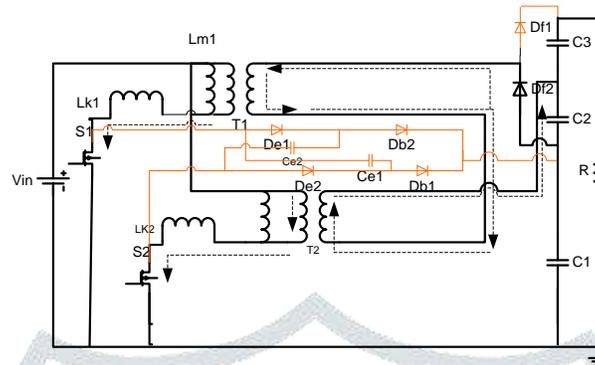

Figure 2.3. Current flow path of operating modes during one switching period at CCM mode-I
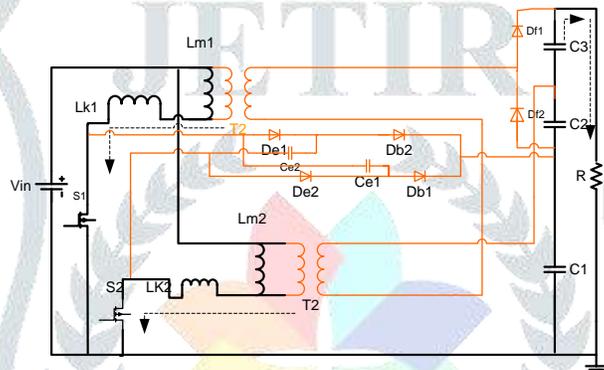

Figure 2.4. Current flow path of operating modes during one switching period at CCM mode-II
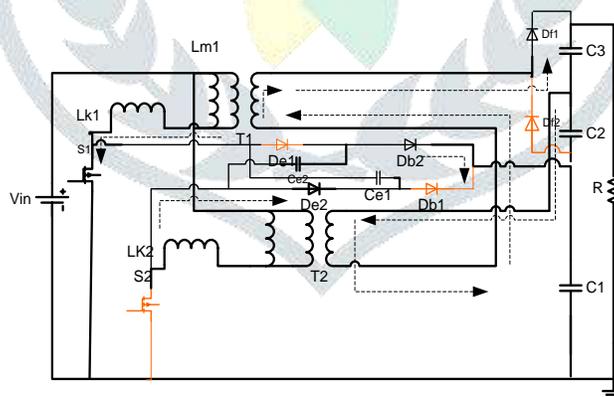

Figure 2.5. Current flow path of operating modes during one switching period at CCM mode-III.
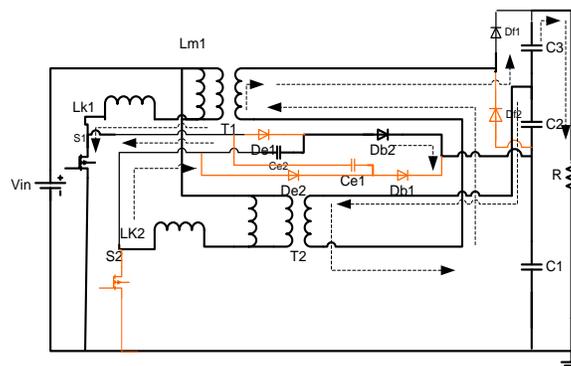

Figure 2.6. Current flow path of operating modes during one switching period at CCM mode-IV.
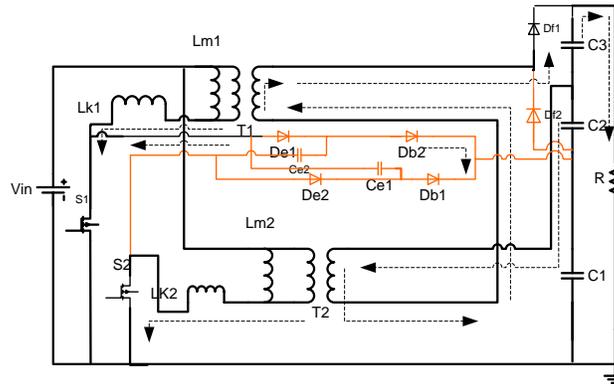
Figure 2.7. Current flow path of operating modes during one switching period at CCM mode-V.
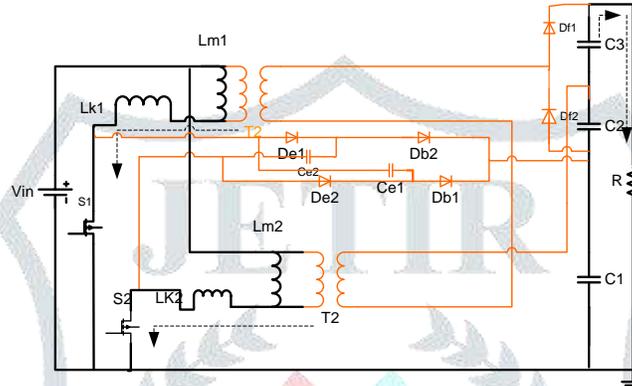

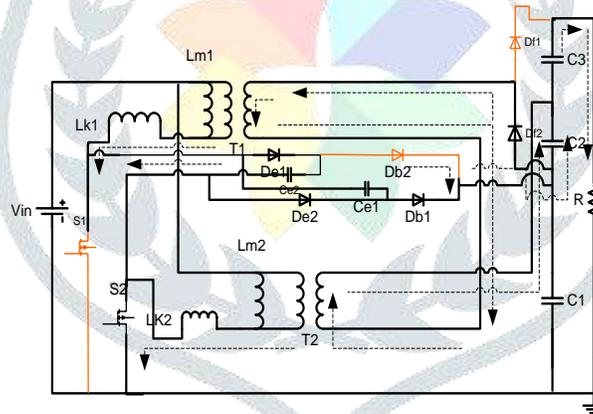Figure 2.8. Current flow path of operating modes during one switching period at CCM mode-VI

Figure 2.9. Current flow path of operating modes during one switching period at CCM mode-VII
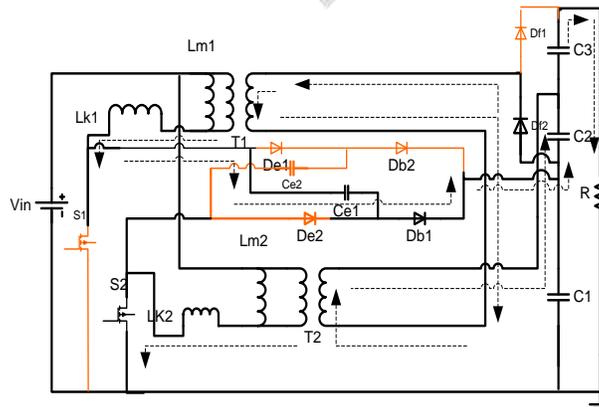

Figure 2.10. Current flow path of operating modes during one switching period at CCM mode-VIII

Mode-I [t0-t1]: In mode-I operation, the stored energy of the series leakage inductors Ls will be quickly discharged to the load R0 through the output diode of flyback-forward Df2 and makes Ls current to become zero. The dc voltage source Vin charges

magnetic inductor Lm1 and some amount of energy will be transferred to the coupled inductor secondary side. Thus, the current passes through leakage inductor Lk1 and Lk2 will be increases and decreases linearly.

Mode-II [t1-t2]: In mode-II operation, the dc source Vin charges the leakage inductor Lk1 and Lk2; and make iLk1 and iLk2 to increase linearly.

Mode-III [t2-t3]: In mode-III operation, the stored energy of magnetizing inductor Lm2 will transfer its energy to the secondary side coupled inductor. Thus, makes the is to flow through the output capacitor C0 by output diode Df1. The output voltage of the boost converter will be equal to the voltage-clamped by clamp capacitor Cc1 across the power device S2. The energy of the dc input voltage Vin, leakage inductor Lk2, magnetizing inductor Lm2, and clamp capacitor Cc2 will be discharged to the load R0. Thus, the voltage across the capacitor C1 (Vc1) will be twice the output voltage of the boost converter.

Mode-IV [t3-t4]: In mode-IV operation, due to the current distribution of magnetizing inductor, the current flow through the clamp diode Dc2 will become zero by nature. So, the conduction losses are reduced and reverse recovery problems are eliminated. Except for the clamp diode, Dc2 all remains the previous state.

Mode-V [t4-t5]: In Mode-V operation, the stored energy of the series leakage inductors Ls will be quickly discharged to the load R0 through the output diode of flyback-forward Df1 and makes Ls current to become zero. The dc voltage source Vin charges magnetic inductor Lm2 and some amount of energy will be transferred to the coupled inductor secondary side. Thus, the current passes through leakage inductor Lk2 and Lk1 will be increases and decreases linearly.

Mode-VI [t5-t6]: In mode-VI operation, the dc source Vin charges the leakage inductor Lk1 and Lk2; and make iLk1 and iLk2 to increase linearly.

Mode-VII [t6-t7]: In mode-VII operation, the stored energy of magnetizing inductor Lm1 will transfer its energy to the secondary side coupled inductor. Thus, makes the is to flow through the output capacitor C0 by output diode Df2. The output voltage of the boost converter will be equal to the voltage-clamped by clamp capacitor Cc2 across the power device S1. The energy of the dc input voltage Vin, leakage inductor Lk1, magnetizing inductor Lm1, and clamp capacitor Cc1 will be discharged to the load R0. Thus, the voltage across the capacitor C1 (Vc1) will be twice the output voltage of the boost converter.

Mode-VIII [t7-t8]: In mode-VIII operation, due to the current distribution of magnetizing inductor, the current flow through the clamp diode Dc1 will become zero by nature. So, the conduction losses are reduced and reverse recovery problems are eliminated. Except for the clamp diode, Dc1 all remains the previous state. This mode of operation will be end at t=t8 and the switching period will start to repeat.

From table 1 of CCM operation, we can describe the time interval, switch turn on and off period and also the devices should turn on and off sequences for the certain switching period.

During steady-state circuit analysis, the duty ratio of power switches will be interleaved with a 180° phase shift and greater than 0.5.

Table 1 CCM operation

Stages	Switch (S1)	Switch (S2)	Devices On	Devices Off	Reverse Biased
t0-t1	ON	ON	D_{f2}	$C_{c1} C_{c2} D_{c1} D_{c2} D_{b1} D_{b2} D_{f1}$	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f1}$
t1-t2	ON	ON	-	$C_{c1} C_{c2} D_{c1} D_{c2} D_{b1} D_{b2} D_{f1}, D_{f2}$	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f1} D_{f2}$
t2-t3	ON	OFF	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f1} D_{f2}$	$C_{c1} C_{c2} D_{c1} D_{b1} D_{f2}$	$D_{c1} D_{b1} D_{f2}$
t3-t4	ON	OFF	"	"	"
t4-t5	ON	ON	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f1} D_{f2}$	$C_{c1} C_{c2} D_{c1} D_{c2} D_{b1} D_{b2} D_{f2}$	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f2}$
t5-t6	ON	ON	-	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f1} D_{f2} C_{c1} C_{c2}$	$D_{c1} D_{c2} D_{b1} D_{b2} D_{f1} D_{f2}$
t6-t7	OFF	ON	$D_{c1} D_{b1} D_{f2} C_{c1}$	$C_{c2} D_{c2} D_{b2} D_{f1}$	$D_{c2} D_{b2} D_{f1}$

The waveform of continuous conduction mode (CCM) of operation is shown in Figure 2.11.
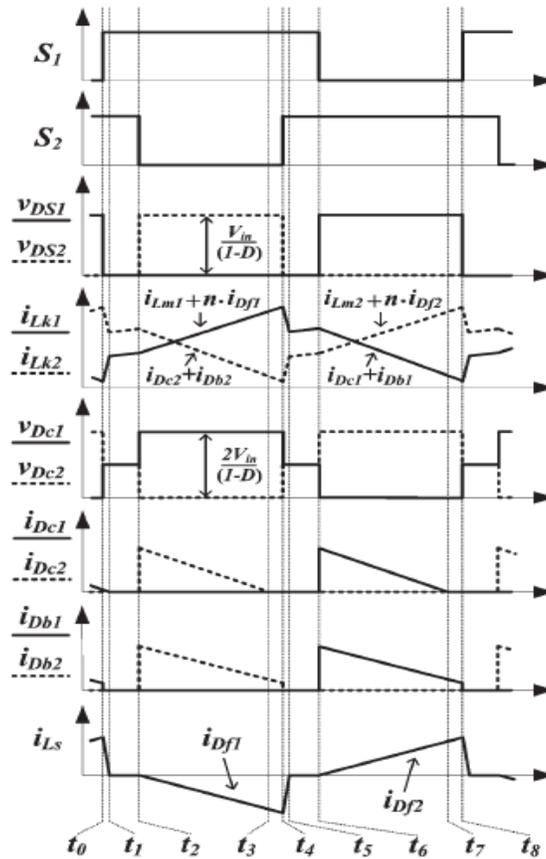
Figure.2.11 Typical waveform of the proposed converter at CCM operation.

III. CONVERTER PERFORMANCE ANALYSIS

To achieve a high step-up voltage, gain with reduced voltage stress and higher efficiency, the following interleaved converter is analysed as follows.

3.1. Voltage Gain

The output voltage of the boost converter is depending on the voltage across the clamp capacitor Cc. so it can be derived in equation (1) as follows,

$$V_{co} = \left(\frac{1}{1-D}\right) V_{in} \tag{1}$$

The output voltage of the boost converter will be twice when one of the power devices is turned off as shown in equation (2),

$$V_{c1} = \left(\frac{1}{1-D}\right) V_{in} + V_{cc} = \left(\frac{2}{1-D}\right) V_{in} \tag{2}$$

The energy stored in the primary side winding will be charged the output capacitor C2 &C3.

When the power switch s1 is off state and s2 in on state, thus the voltage induced on the secondary side coupled inductors Ns1 &Ns2 will be equal to Vc2.

The voltage across the capacitors C2 and C3 can be derived in equation (3),

$$V_{c2} = V_{c3} = n.V_{in} \left(1 + \left(\frac{D}{1-D}\right)\right) = \left(\frac{n}{1-D}\right) V_{in} \tag{3}$$

The output voltage can be equated in equation (4) as follows,

$$V_0 = V_{c1} + V_{c2} + V_{c3} = \left(\frac{2n+2}{1-D}\right) V_{in} \tag{4}$$

Then, the voltage gain of the proposed interleaved converter is derived in equation (5),

$$\left(\frac{V_0}{V_{in}}\right) = \left(\frac{2n+2}{1-D}\right) \tag{5}$$

From this equation (5), we can conclude that the proposed converter can extend the voltage gain without using the large duty cycle.

3.2. Switch Voltage Stress

To simplify the converter analysis, the capacitor voltage ripples are neglected. The voltage stress on power switches S1&S2 is clamped and it can be derived as,

$$V_{s1} = V_{s2} = \left(\frac{2}{1-D}\right)V_{in} = \left(\frac{1}{2n+2}\right)V_0 \qquad\qquad (6)$$

To reduce the conduction loss and cost of the power converter by selecting the low voltage rated device with low RDs on is confirmed by equation (6).

This feature says that the proposed converter is suitable for high power applications. The curve of the relation between switched voltage stress and turns ratio is shown in figure 3.1.
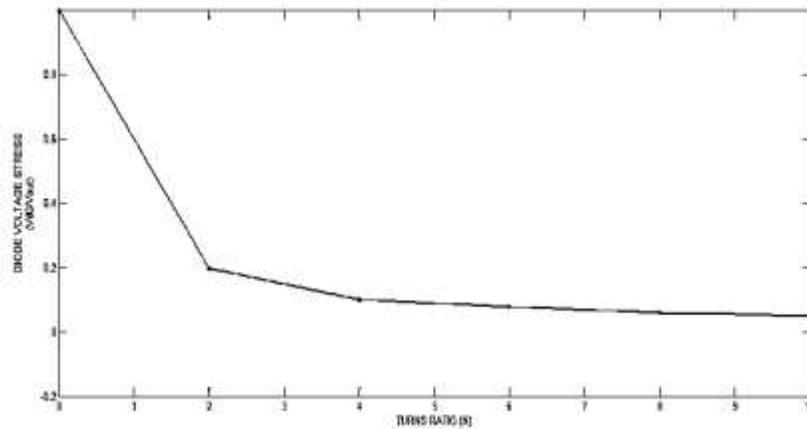

Figure 3.1. Relation between switched voltage stress and turns ratio

3.3. Diode Voltage Stress

In order to eliminate the reverse recovery problem of the proposed converter, the following equations (7-12) are derived as follows.

$$V_{Dc} = V_{Dc1} = V_{Dc2} = V_{C1} \qquad\qquad (7)$$

$$V_{Dc} = V_{in}\left(\frac{2}{1-D}\right) = \left(\frac{V_0}{1+n}\right) \qquad\qquad (8)$$

$$V_{Db} = V_{Db1} = V_{Db2} = V_{c1} - V_{c2} \qquad\qquad (9)$$

$$V_{Db} = \left(\frac{V_{in}}{1-D}\right) = \left(\frac{V_0}{2n+2}\right) \qquad\qquad (10)$$

$$V_{Df} = V_{Df1} = V_{Df2} = V_{c2} + V_{c3} \qquad\qquad (11)$$

$$V_{Df} = \left(\frac{2n}{1-D}\right)V_{in} = \left(\frac{n}{n+1}\right)V_0 \qquad\qquad (12)$$

When turn ratio n increases with the voltage stress on the diode D_f. The voltage relationship between diode voltage stress and turns ratio n is shown in figure 3.2.
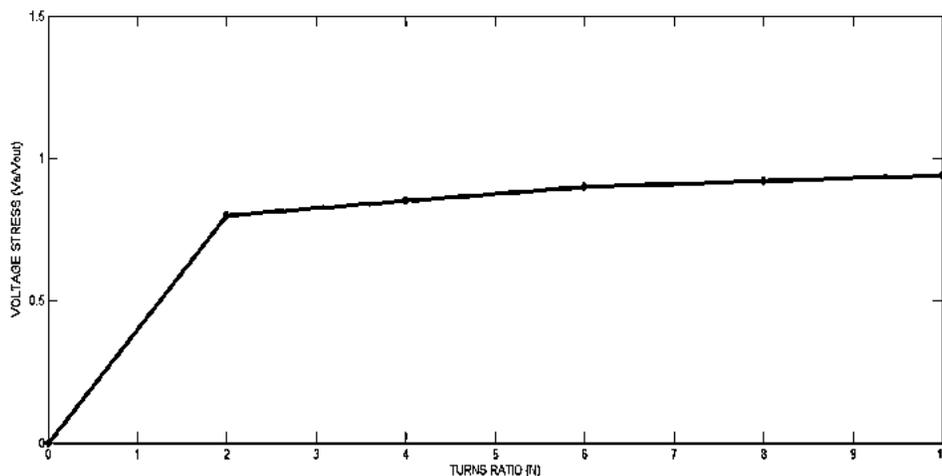

Figure 3.2. Relation between diode voltage stress and turns ratio

3.4. Performance Analysis for Phase Shift Interleaved PWM Scheme

For a high step up and high power applications, the input current ripple should be lower. But in single phase operations, the ripple current will be higher and not suitable for high power applications. During a converter analysis, the duty ratio of the power system will be interleaved with 180¬ degree phase shift for higher duty ratio.

3.5. Current Sharing Performance

When one of the power switches is turned off, the stored energy of the magnetizing inductor will transfer the current through the three different paths. The current sharing performance makes the conduction loss and power capacity to decreases and increases by lowering the effective value and peak value of the current. This feature makes the proposed converter from reverse recovery problems and also reduces the switching loss made by conduction.

3.6. Advantages of the Interleaved Converter

When comparing the advantages and feature of other interleaved converter, the proposed converter is efficient and consists of the following advantages,

1. Low conduction loss and low input current ripple make the lifetime of the converter to increase and it is suitable for high power applications.
2. Mostly the renewable energy sources require the high step-up gain which obtained in the proposed topology.
3. The high-efficiency converters are used for the effective application. So, the leakage energy is recycled by a lossless passive clamp circuit.
4. By selecting the low voltage power device with low Rds(on), the voltage stress is reduced.
5. By using the current sharing performance, the conduction loss and reverse recovery losses are eliminated.

IV. DESIGN SPECIFICATIONS AND SIMULATION RESULTS OF THE PROPOSED CONVERTER

Table 2 - Specification for the proposed converter

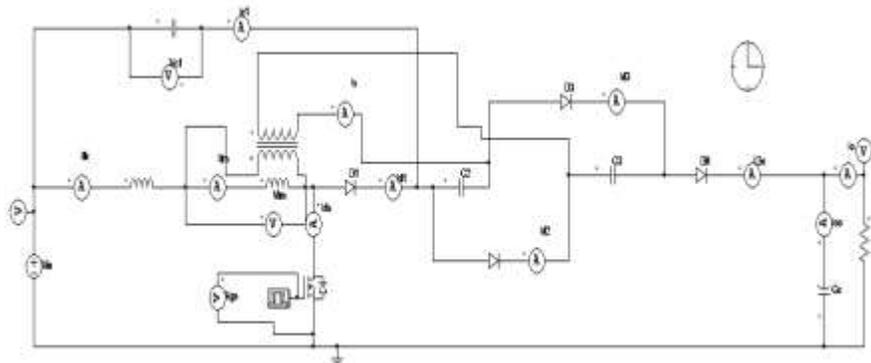| Attributes	Ranges
Input voltage (V_{in})	24V
Switching frequency(f_s)	50kHz
Maximum output power	200W
Magnetizing inductor(L_m)	48μH
Leakage inductor(L_k)	0.25μH
Capacitors C_1	56μF/100V
Capacitors C_2/C_3	22μF/200V
Capacitors C_0	180F/450V
Output voltage (V_0)	400V

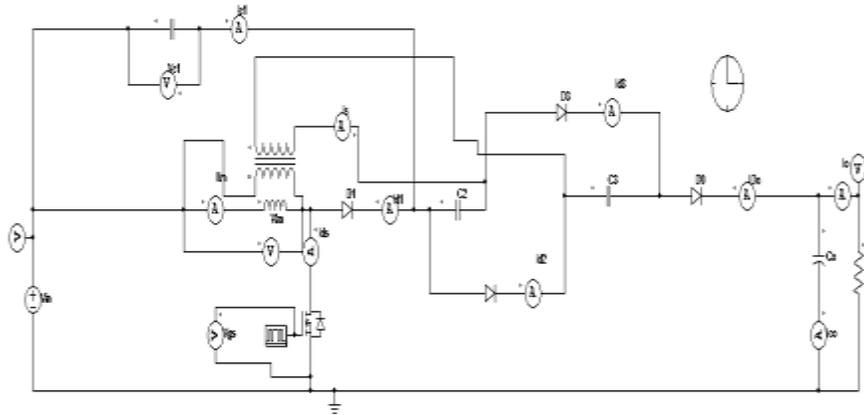Figure 4.1. PSIM circuit for CCM operation.

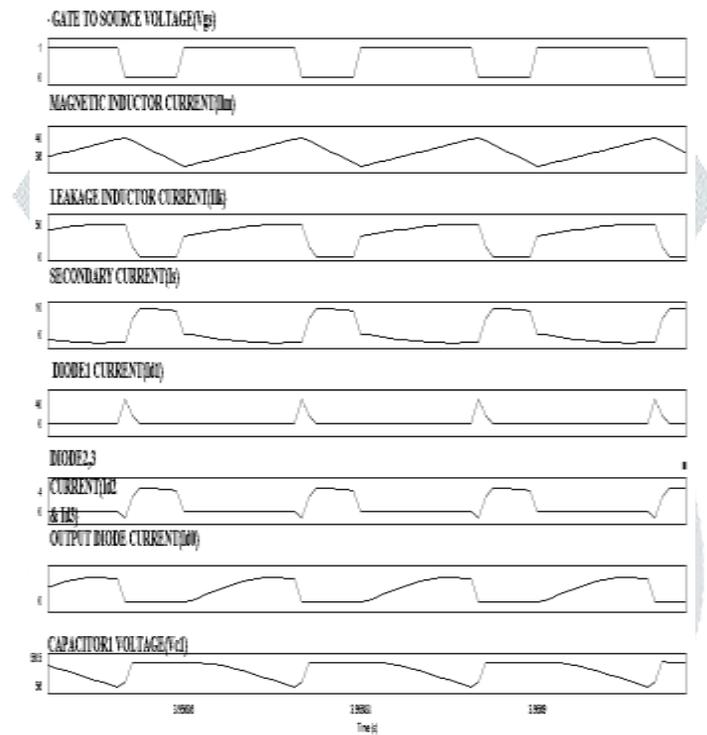Figure 4.2. PSIM circuit for DCM operation.

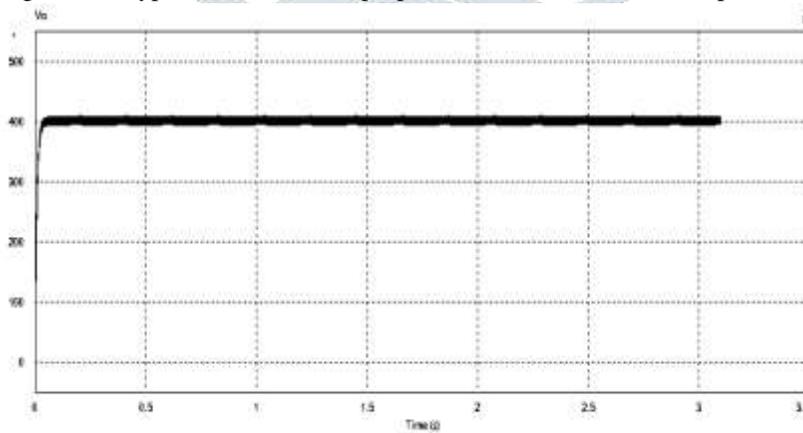Figure 4.3. Typical waveform for proposed converter under CCM operation.

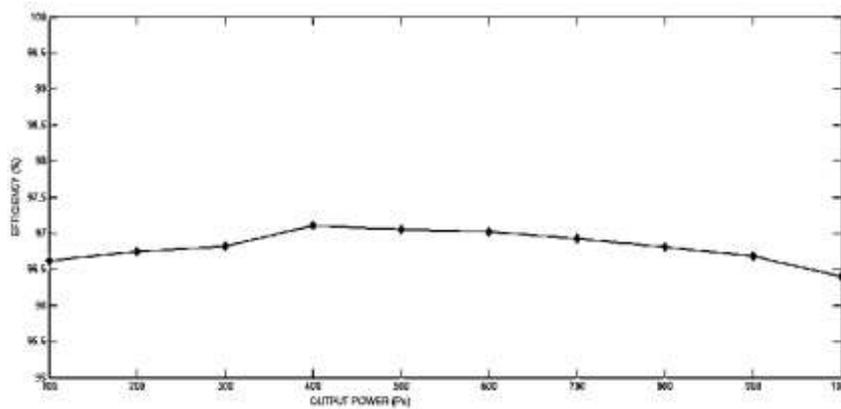Figure 4.4. Output voltage of the proposed converter

Figure 4.5. Converter Efficiency

V. CONCLUSION

In this work, we analyzed the interleaved converter using coupled inductors and switched capacitor technique. High step-up interleaved converter voltage multiplier module is presented for high step-up voltage gain and efficiency conversion. The converter is simulated in PSIM package and results are verified. The principle and experimental results for an interleaved converter are presented. The operation principle and modes of operation are discussed thoroughly. The voltage multiplier module is integrated with the interleaved converter to increase the voltage gain and efficiency conversion ratio without using a large duty cycle is presented. Then by using the lossless passive clamp circuit leakage inductor energy is recycled and voltage stress is reduced. Thus the phase shifted interleaved PWM 180° degree the input current is reduced in the proposed topology. The reverse recovery losses and conduction losses are eliminated by current sharing performance and it was analyzed thoroughly. For a full load condition and light load condition, the efficiency obtained will 96.4% and 97.11%. From this topology, high voltage gain and efficiency are achieved. The analysis of the interleaved converter has been discussed in detail. Finally, a 40V – 380V had been achieved.

REFERENCES

[1]   Erickson, R.W., and Maksimovi!c, D.: 'Fundamentals of power electronics'', 2nd Edn. (John Wiley, New York, USA,1950), pp. 39–55.

[2]   Mohan, N., Undeland, T.M., and Robbins,W.P.: 'Power electronics', 2nd Edn. (John Wiley & Sons Inc., New York, USA, 1995), pp. 172–178.

[3]   Hart, D.W.: 'Introduction to power electronics'', (Prentice-Hall, New York, USA, 1964), pp. 212–214.

[4]   J. T. Bialasiewicz, "Renewable energy systems with photovoltaic power generators: Operation and modeling," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2752–2758, Jul. 2008.

[5]   S. M. Chen, T. J. Liang, L. S. Yang, and J. F. Chen, "A safety enhanced, high step-up DC–DC converter for AC photovoltaic module application," Cheng, D.K.W., Liu, X.C., and Lee, Y.S.: 'A new improved boost converter with ripple free input current using coupled inductors'. IEE Int. Conf. on Power electronics and variable speed drives, London, UK, 1998, pp. 592–599.

[6]   Bhaskar, K. B., Sivakumaran, T. S., & Devi, M. (2016). Analysis of asymmetrical cascaded multi-cell multilevel inverter employing multicarrier level shifting pwm technique on different loads. IDNJST, (31).

[7]   C. L. Chen, Y. Wang, J. S. Lai, Y. S. Lee, and D. Martin, "Design of parallel inverters for smooth mode transfer micro grid applications," *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 6–15, Jan. 2010.

[8]   A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of current controllers for distributed power generation systems," *IEEE Trans. Power Electron.*, vol. 24, no. 3, pp. 654–664, Mar. 2009.

[9]   Y. A.-R. I. Mohamed and E. F. El Saadany, "Hybrid variable-structure control with evolutionary optimum-tuning algorithm for fast grid-voltage regulation using inverter-based distributed generation," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1334–1341, May 2008.

[10]   A. M. Salamah, S. J. Finney, and B. W. Williams, "Single-phase voltage source inverter with a bidirectional buck–boost stage for harmonic injection and distributed generation," *IEEE Trans. Power Electron.*, vol. 24, no. 2, pp. 376–387, Feb. 2009.

[11]   Bhaskar, K. B., & Alagumariappan, P. (2020). Energy Channeling Led Driver Technology to achieve Flicker Free Operation with Zeta Converter for Power Quality Improvement. International Journal of Automation and Smart Technology, 10(1), 401-407.

[12]   A. Cid-Pastor, L. Martínez-Salamero, C. Alonso, A. El Aroudi, and H. Valderrama-Blavi, "Power distribution based on gyrators," *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2907–2909, Dec. 2009.

[13]   Q. Zhao and F. C. Lee, "High-efficiency, high step-up dc–dc converters," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 65–73, Jan. 2003.

[14]   Bhaskar, K. B., Sivakumaran, T. S., & Devi, M. (2014), "Implementation of 11 level cascaded multilevel inverter using level shifting pulse width modulation technique with different loads" IPASJ International Journal of Electrical Engineering, 2(10), 20-31.

[15]   R. J. Wai and R. Y. Duan, "High-efficiency DC/DC converter with high voltage gain," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 152, no. 4, pp. 793–802, Jul. 2005.

[16]   L. S. Yang, T. J. Liang, and J. F. Chen, "Transformer-less dc–dc converter with high voltage gain," *IEEE Trans. Ind. Electron.*, vol. 56, no. 8, pp. 3144–3152, Aug. 2009.

[17]   K. C. Tseng and T. J. Liang, "Analysis of integrated boost–flyback step-up converter," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 152, no. 2, pp. 217 225, Mar. 2005.

[18]   Singh, R.K., Joshi, A., and Ghosh, A.: 'A modified flyback DC-DC converter topology'. Proc. IEEE-APEC Conf., 1998, pp.

[19]   K. C. Tseng and T. J. Liang, "Novel high-efficiency step-up converter," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 151, no. 2, pp. 182–190, Mar. 2004.

[20]   Bhaskar, K. B., Devarajan, S. V., & Karthick, R. (2018). Implementation of improved cascaded multi-cell 15 level inverter for induction motor using level shifting multicarrier PWM. Int J Pure Appl Math, 119(16), 1121-1138.