

# X-Y Converter Family: A New Breed of Buck Boost Converter for High Step-up Renewable Energy Applications

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**Abstract**—A New breed of a buck boost converter, named as the XY converter family is proposed in this article. In the XY family, 16 topologies are presented which are highly suitable for renewable energy applications which require a high ratio of DC-DC converter; such as a photovoltaic multilevel inverter system, high voltage automotive applications and industrial drives. Compared to the traditional boost converter and existing recent converters, the proposed XY converter family has the ability to provide a higher output voltage by using less number of power devices and reactive components. Other distinct features of the XY converter family are i) Single control switch ii) Provide negative output voltage iii) Non-isolated topologies iv) High conversion ratio without making the use of high duty cycle and v) modular structure. XY family is compared with the recent high step-up converters and the detailed description of XY converter family and its topologies are presented. The simulation results are provided and it confirms the feasibility, functionality and validity of the concepts of the proposed XY converter family.

**Index Terms**— DC-DC converter topologies; High Conversion ratio; Non-isolated; Renewable Energy.

## I. INTRODUCTION

IN THE CURRENT scenario, the rising energy demand increases the need for renewable energy sources. The rapidly rising energy demand has reached a level where the world will face severe crisis of energy. This is because the energy sources required for the massive power generation are exhaustible. On the other hand, renewable energy sources are reliable and plentiful and can be locally produced and therefore are not vulnerable to any kind of risks [1]-[4]. Hence energy management focus on the widespread use of renewable energy resources for power generation. Several renewable energy applications such as a photovoltaic multilevel inverter system, high voltage automotive applications and industrial drives require a high step-up and non isolated converter [1]-[35]. Series connection of solar arrays is not practical solution to achieve high voltage. Generally for applications involving

photovoltaic systems, DC-DC converters with high conversion ratio are employed. The performance of a boost converter deteriorates with the increase in the duty cycle of the power switch and also due to the leakage resistance of the inductor. Because of these practical difficulties, the traditional DC-DC converter is not a suitable solution to achieve high voltage. Hence it is impossible to use traditional converters when the required conversion ratio is greater than four [3]-[35]. Another major drawback of using the traditional buck-boost converter is discontinuous input current which proves the minimum utilization of input source. A classical approach to overcome the problem of leakage resistance is by increasing the converter's switching frequency for a certain value of acceptable ripple. The finite switching time in a normal power device limits the switching frequency if the duty ratio is either too high or too small. In order to overcome the above drawback and to simultaneously increase the voltage without using the extreme values of duty cycles, isolated converters can be employed.

Numerous isolated converter topologies that make use of transformers and coupled inductors have been proposed in the literature [15]-[19]. The switching losses and electromagnetic interference (EMI) problem are caused by high voltage stress due to transformer leakage inductance, overall reducing the converter efficiency. Comparing the hard switching converter the voltage stress is higher, thus increasing the cost and circuit complexity. Hence, for isolated topologies size, weight and losses of power transformer are limiting factors. In [15]-[19], Switched capacitor (SC) and Switched Inductor (SI), Voltage Lift Switched Inductor (VLSI), modified VLSI principles are used along with a combination of coupled inductors, voltage multipliers or Switched capacitor multipliers [21]-[25]. Fig.1 (a)-(d) shows the inductor, SI, VLSI and modified VLSI. In order to attain a higher boost ratio, cascaded approach is used. Several industries are required to design a Cascaded Boost Converter (CBC) which is the most complex part and quite hard to encapsulate [20, 21]. In addition to that, high ripple current and losses prove to be obstacles to attain the high conversion ratio and efficiency [26, 27]. Quadratic Boost converter (QBC) is proposed to obtain high voltage gain by just using a single switch. However, in Quadratic Boost converter, the voltage stress on the switch is equal to the total output voltage. This requires high voltage rated power switch with higher  $R_{DS,ON}$  [20, 21]. In the recent past, several DC-DC multilevel topologies have been proposed to overcome the limitations of cascaded converter

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TABLE I. CONVERSION RATIO

New Buck Boost Converter	Voltage Conversion Ratio
BBC or L Converter	$D/(1-D)$
SI BBC or 2L Converter	$2D/1-D$
VLSI BBC or 2LC Converter	$1+D/1-D$
modified VLSI or 2LCm Converter	$1+D/1-D$

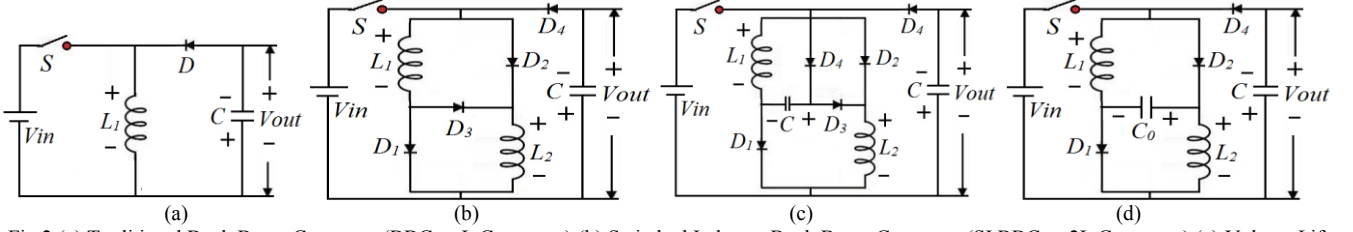
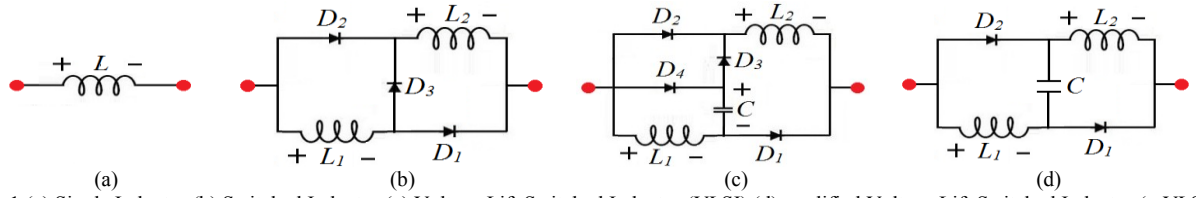


TABLE II. XY CONVERTER FAMILY

XY Converter		Y DC-DC Converter			
		BBC (L)	SI (2L)	VLSI BBC (2LC)	Modified VLSI BBC (2LC <sub>m</sub> )
X DC-DC Converter	BBC (L)	L-L Converter	L-2L Converter	L-2LC Converter	L-2LC <sub>m</sub> Converter
	SI BBC (2L)	2L-L Converter	2L-2L Converter	2L-2LC Converter	2L-2LC <sub>m</sub> Converter
	VLSI BBC (2LC)	2LC-L Converter	2LC-2L Converter	2LC-2LC Converter	2LC-2LC <sub>m</sub> Converter
	Modified VLSI BBC (2LC <sub>m</sub> )	2LC <sub>m</sub> -L Converter	2LC <sub>m</sub> -2L Converter	2LC <sub>m</sub> -2LC Converter	2LC <sub>m</sub> -2LC <sub>m</sub> Converter

and isolated topologies. However, a large number of capacitors and diodes are required to design DC-DC multilevel converter [22]-[35].

In this paper a new breed of a buck boost converter, named as the XY converter family is proposed. In the XY family, 16 topologies are presented which are highly suitable for renewable energy applications which require a high ratio of DC-DC converter. The proposed XY converter family has the ability to provide a higher output voltage by using less number of power devices and reactive components. Other distinct features of the XY converter family are i) Single control switch ii) Provide negative output voltage iii) Non-isolated topologies iv) High conversion ratio without making the use of high duty cycle and v) modular structure.

## II. XY Converter Family

### A. Generalized structure of XY converter Family

New Buck Boost Converters are designed by using inductor, SI, VLSI and mVLSI for boost applications. Fig.2 shows (a) traditional Buck Boost Converter (BBC or L Converter) (b) Switched Inductor Buck Boost Converter (SI BBC or 2L Converter) (c) Voltage Lift Switched Inductor Converter (VLSI BBC or 2LC Converter) and (d) modified Voltage Lift Switched Inductor Converter (modified VLSI or 2LC<sub>m</sub> Converter). The voltage conversion ratio of above designed Buck Boost Converters is determined and provided in Table-I. The generalized structure of the XY converter family is shown in Fig.3. XY converter consists of two separate converters named as X converter and Y converter. The input voltage source is directly attached to the X converter and input of Y converter is a series connection of input voltage source and output voltage of X converter. The total output voltage of the XY converter family is equal to the inverting sum of output voltage of X converter and Y converter as in (1).

$$V_o = -(V_x + V_y)$$

(1)

### B. XY Converter topologies

Various suitable combinations of the new Buck Boost Converter are designed and total 16 topologies are formed named as the XY family. The detail description of suitable combinations of X converter and Y converter is provided in Table-II. Fig.4 (a)-(p) shows the XY converter topologies. The operation mode of XY converter topologies is divided into mode two modes-one when the switch is conducting and other when switch is not conducting. To explain the modes of operation 2LC<sub>m</sub>-2LC<sub>m</sub> converter topology is considered.

### C. 2LC<sub>m</sub>-2LC<sub>m</sub> converter topology

2LC<sub>m</sub>-2LC<sub>m</sub> converter topology is shown in Fig.4 (p). The 2LC<sub>m</sub>-2LC<sub>m</sub> converter is a combination of two 2LC<sub>m</sub> converters. 4 inductor, 4 capacitors and 7 diodes along with single switch are needed to design the 2LC<sub>m</sub>-2LC<sub>m</sub> converter. In order to analyse converter, it is assumed that the converter is operating in steady state and following assumptions are considered during one switching state: i) Pure DC input supply ii) All power devices are ideal, thus 100% efficient component iii) L<sub>X1</sub> and L<sub>X2</sub> are inductors with the same rating and identical iv) L<sub>Y1</sub> and L<sub>Y2</sub> are inductors with the same ratings and identical v) All capacitors have very small ripple at the operating switching frequency  $f_s$ . When switch S is conducting, input voltage charges the inductors L<sub>X1</sub> and L<sub>X2</sub> in parallel through diode D<sub>X2</sub> and D<sub>X3</sub> respectively. At the same time, series connection of input voltage and voltage across capacitor C<sub>X</sub> charges inductor L<sub>Y1</sub> and L<sub>Y2</sub> through diode D<sub>Y1</sub> and D<sub>Y2</sub>. Capacitor of X, C<sub>1</sub> is charged by input voltage through diode D<sub>X2</sub> and D<sub>X3</sub>. Similarly capacitor of Y, C<sub>2</sub> is charged by series connection of input voltage and voltage across C<sub>X</sub>. The output voltage of the 2LC<sub>m</sub>-2LC<sub>m</sub> converter is equal to the negative sum of

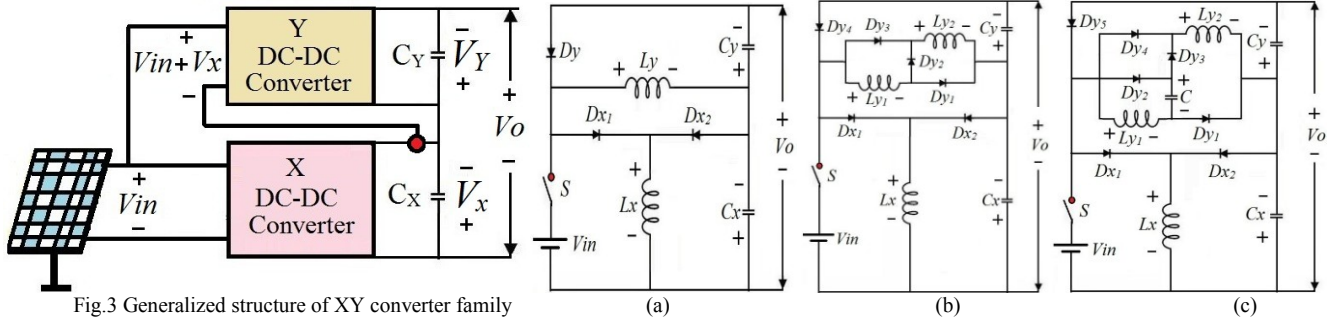


Fig.3 Generalized structure of XY converter family

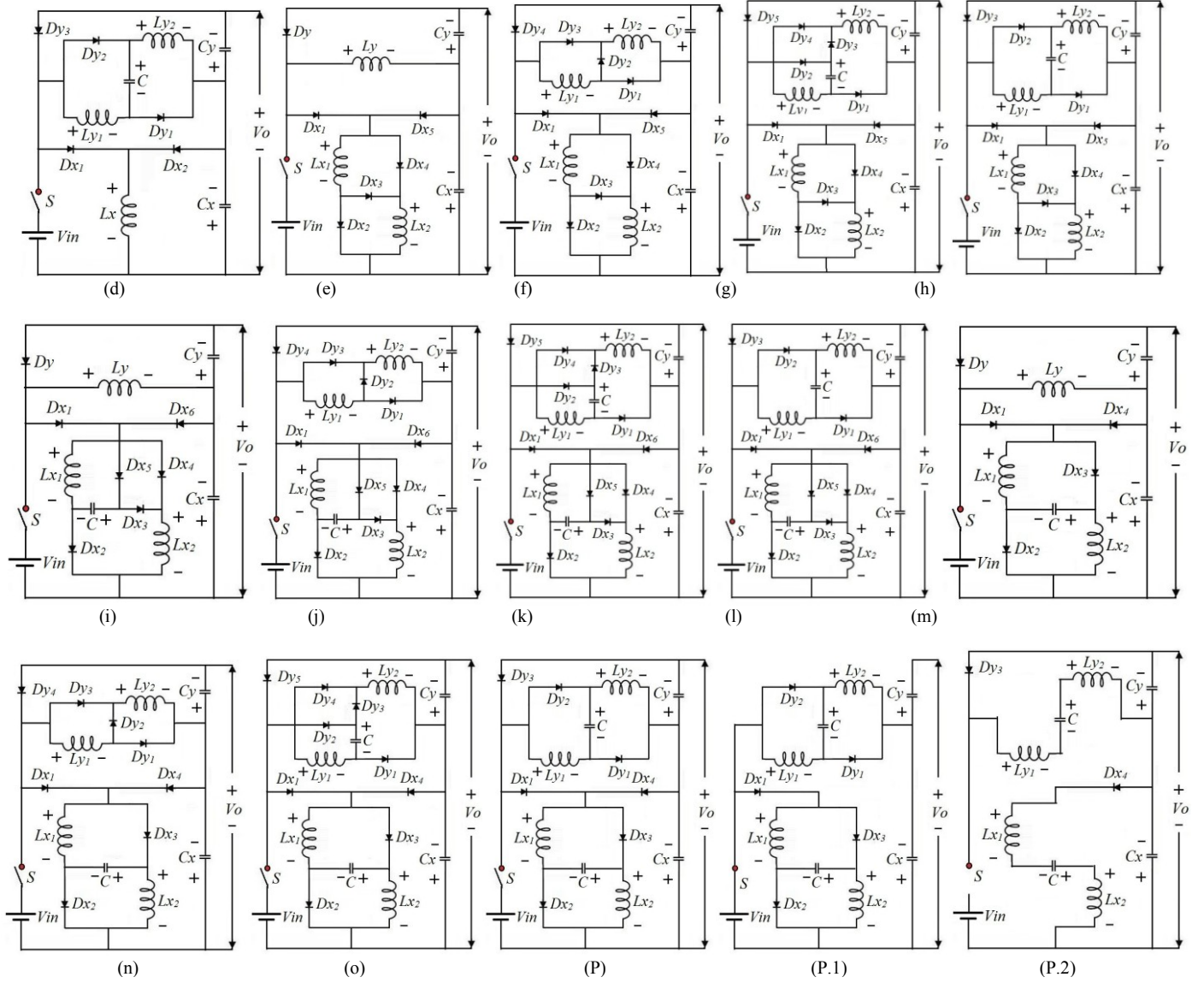


Fig.4 XY Converter Topologies (a) L-L Converter (b) L-2L Converter (c) L-2LC Converter (d) L-2LC<sub>m</sub> Converter (e) 2L-L Converter (f) 2L-2L Converter (g) 2L-2LC Converter (h) 2L-2LC<sub>m</sub> Converter (i) 2LC-L Converter (j) 2LC-2L Converter (k) 2LC-2LC Converter (l) 2LC-2LC<sub>m</sub> Converter (m) 2LC<sub>m</sub>-L Converter (n) 2LC<sub>m</sub>-2L Converter (o) 2LC<sub>m</sub>-2LC Converter (p) 2LC<sub>m</sub>-2LC<sub>m</sub> Converter (P.1) ON state equivalent circuit of 2LC<sub>m</sub>-2LC<sub>m</sub> converter (P.2) OFF state equivalent circuit of 2LC<sub>m</sub>-2LC<sub>m</sub> converter.

voltage across  $C_X$  and  $C_Y$ . Fig.4 (p. 1) shows ON state equivalent circuit of the 2LC<sub>m</sub>-2LC<sub>m</sub> converter.

$$\begin{aligned}
 V_{L_{X1}} &= V_{L_{X2}} = V_{in} \\
 V_{L_{Y1}} &= V_{L_{Y2}} = V_{in} + V_{C_X}; V_{C_1} = V_{in} \\
 V_{C_2} &= V_{in} + V_{C_X} \\
 V_O &= -(V_{C_X} + V_{C_Y}) \quad \text{ON-State}
 \end{aligned}
 \tag{2}$$

When Switch S is not conducting, input supply is disconnected from the power circuit. Both inductor  $L_{X1}$  and  $L_{X2}$  discharges in series with a capacitor of X,  $C_1$  through load and simultaneously charges the capacitor  $C_X$ . Similarly inductor  $L_{Y1}$  and  $L_{Y2}$  discharges in series with capacitor of Y,  $C_2$  to charge the capacitor  $C_Y$ . Fig.4 (p. 2) shows the OFF state equivalent circuit of the 2LC<sub>m</sub>-2LC<sub>m</sub> converter.

$$\begin{aligned}
 2V_{L_{X1}} &= 2V_{L_{X2}} = V_{C_1} - V_{C_X} \\
 2V_{L_{Y1}} &= 2V_{L_{Y2}} = V_{C_2} - V_{C_Y}
 \end{aligned}$$

$$\begin{aligned}
V_{C_1} &= (1+D)V_{in}/(1-D) \\
V_{C_2} &= 2V_{in}/(1-D) \quad \text{OFF-State} \\
V_O &= -(V_{C_x} + V_{C_y})
\end{aligned} \quad (3)$$

From (2) and (3) the input to output voltage conversion ratio of the 2LC<sub>m</sub>-2LC<sub>m</sub> converter can be determined as

$$\left. \begin{aligned}
V_{C_x} &= (1+D)/(1-D)V_{in} \\
V_{C_y} &= 2(1+D)/(1-D)^2V_{in} \\
V_O &= -(3-D)(1+D)/(1-D)^2V_{in}
\end{aligned} \right\} \quad (4)$$

The input to output voltage conversion ratio of XY converter family and recent converter topologies is determined and is also given in Table-III. The current waveform of inductors present in all XY Converter topologies is analyzed and shown in Fig.5 (a) -(p). It is observed that inductors present in XY converter are charged when the switch is conducting and discharged when the switch is not conducting.

### III. SIMULATION RESULTS

All the proposed XY Converter topologies are simulated for 10V input supply, 100W and 60% duty cycle and 50 kHz switching frequency in MATLAB. Output voltage waveforms of all the XY converter topologies are provided in Fig.6 (a)-(p). It is observed that all the XY converter topologies give negative output voltage and the conversion ratio is higher than the existing recent converters. It is investigated that 2LC-2LC Converter, 2LC-2LC<sub>m</sub> Converter, 2LC<sub>m</sub>-2LC Converter and 2LC<sub>m</sub>-2LC<sub>m</sub>

TABLE III. VOLTAGE CONVERSION RATIO OF XY CONVERTER FAMILY AND RECENT TOPOLOGY.

No.	Converter Topology	Conversion Ratio
1. XY Converter Family	L-L Converter	$(D^2-2D)/(1-D)^2$
	L-2L Converter	$(D^2-3D)/(1-D)^2$
	L-2LC Converter	$(D^2-2D-1)/(1-D)^2$
	L-2LC <sub>m</sub> Converter	$(D^2-2D-1)/(1-D)^2$
	2L-L Converter	$(D^2-3D)/(1-D)^2$
	2L-2L Converter	$-4D/(1-D)^2$
	2L-2LC Converter	$(D^2-4D-1)/(1-D)^2$
	2L-2LC <sub>m</sub> Converter	$(D^2-4D-1)/(1-D)^2$
	2LC-L Converter	$(D^2-2D-1)/(1-D)^2$
	2LC-2L Converter	$(D^2-4D-1)/(1-D)^2$
	2LC-2LC Converter	$(D^2-2D-3)/(1-D)^2$
	2LC-2LC <sub>m</sub> Converter	$(D^2-2D-3)/(1-D)^2$
	2LC <sub>m</sub> -L Converter	$(D^2-2D-1)/(1-D)^2$
	2LC <sub>m</sub> -2L Converter	$(D^2-4D-1)/(1-D)^2$
2LC <sub>m</sub> -2LC Converter	$(D^2-2D-3)/(1-D)^2$	
2LC <sub>m</sub> -2LC <sub>m</sub> Converter	$(D^2-2D-3)/(1-D)^2$	
2	Conventional Boost Converter	$1/(1-D)$
3	Switched Inductor (SI) Boost Converter	$1+D/(1-D)$
4	Single switch Quadratic Boost Converter	$1/(1-D)^2$
5	Conventional Three Level Boost Converter	$2/(1-D)$
6	Quadratic Three Level Boost Converter	$1/(1-D)^2$
7	Converters using bootstrap capacitors and boost inductors	$3+D/1-D$
8	Switched Capacitor Based Boost Converter	$1+D/1-D$
9	Two-phase quadrupled interleaved boost converter	$4/(1-D)$
9	High-voltage gain two-phase interleaved boost converter using one VMC	$((VMC+1)/1-D)$
10	Extra high voltage (HV) dc-dc converter	$4/(1-D)$

Converter have a maximum conversion ratio in XY converter family and it convert the input, voltage output voltage with a conversion ratio 24 at 60% duty cycle.

### IV. CONCLUSIONS

A new breed of buck Boost converter named as XY converter family is proposed for high step-up renewable applications. All the XY converter topologies have negative conversion ratio and have ability to provide a higher output voltage by using less number of power devices and reactive components. Other distinct features of the XY converter family are i) Single control switch ii) Provide negative output voltage iii) Non-isolated topologies iv) High conversion ratio without making the use of high duty cycle and v) modular structure. Detailed analysis of the conversion ratio of XY family is discussed. The simulation results are provided and it confirms the feasibility, functionality and validity of the concepts of the proposed XY converter family.

### REFERENCES

- [1] Tomaszuk and A. Krupa, "High efficiency and high stepup DC/DC converters- A review", Bullentin of polish academy of sciences, Technical sciences, Vol. 59, No. 4, pp.475-483, 2011.
- [2] J. Dawidziuk, "Review and comparison of high efficiency high power boost DC/DC converter for photovoltaic applications", Bullentin of polish academy of sciences, Technical sciences, Vol. 59, No. 4, pp.475-483, 2011.
- [3] W. Li, X. He, "Review of non-isolated high step-up dc/dc converters in photovoltaic grid-connected applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1239-1250, Apr. 2011.
- [4] F.L.Tofoli, P.Denis de Castro, W.Josias de Paula, O.J.Demercil de Sousa, "Survey on non-isolated high-voltage step-up dc-dc topologies based on the boost converter", *IET Power Electron.*, pp. 1-14, July 2015.
- [5] Mahajan Sagar Bhaskar Ranjana, Pandav Kiran Maroti, B Revathi "A Novel Single Phase Multilevel Inverter with Single Photovoltaic Source and Less Number of switches" *IEEE International Conference on Devices, Circuits and Systems (IEEE-ICDCS) 2014, Coimbatore (India)*.
- [6] Mahajan Sagar Bhaskar Ranjana, Nandyala Sreeramula Reddy, Repalle Kusala Pavan Kumar "A Novel single phase Advanced Multilevel Inverter with Adjustable Amplitude of voltage Levels" *IEEE International Conference on Circuit, Power and Computing Technologies (IEEE- ICCPCT) 2014, Nagarcoll (India)*.
- [7] J. C. Rosas-Caro, J. M. Ramirez, F. Z. Peng, and A. Valderrabano, "A DC-DC multilevel boost converter," *IET Power Electron.*, vol. 3, no. 1, pp. 129-137, Jan. 2010.
- [8] L. H. S. C. Barreto, P. P. Praça, D. S. Oliveira, and R. P. T. Bascope, "Single-stage topologies integrating charging, high voltage stepup and photovoltaic energy extraction capabilities," *Electron. Lett.*, vol. 47, no. 1, pp. 49-50, Jan. 2011.
- [9] Z. Dongyan, A. Pietkiewicz, and S. Cuk, "A three-switch high-voltage converter," *IEEE Trans. Power Electron.*, vol. 14, no. 1, pp. 177-183, Jan. 1999.
- [10] L. H. S. C. Barreto, P. P. Praça, D. S. Oliveira, and R. P. T. Bascope, "Single-stage topologies integrating charging, high voltage stepup and photovoltaic energy extraction capabilities," *Electron. Lett.*, vol. 47, no. 1, pp. 49-50, Jan. 2011.
- [11] Y.P. Hsieh, J.F. Chen, T.J. Liang, and L.S. Yang, "Novel High Step-Up DC-DC Converter for Distributed Generation System," *IEEE Trans. on Industrial Electronics*, vol.60, no.4, pp.1473,1482, April 2013.
- [12] S. M. Chen, T. J. Liang, L. S. Yang, and J. F. Chen, "A cascaded high step-up DC-DC converter with single switch for microsource applications," *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1146-1153, Apr. 2011.
- [13] C. S. Leu, P. Y. Huang, and M. H. Li, "A novel dual-inductor boost converter with ripple cancellation for high-voltage-gain applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1268-1273, Apr. 2011.

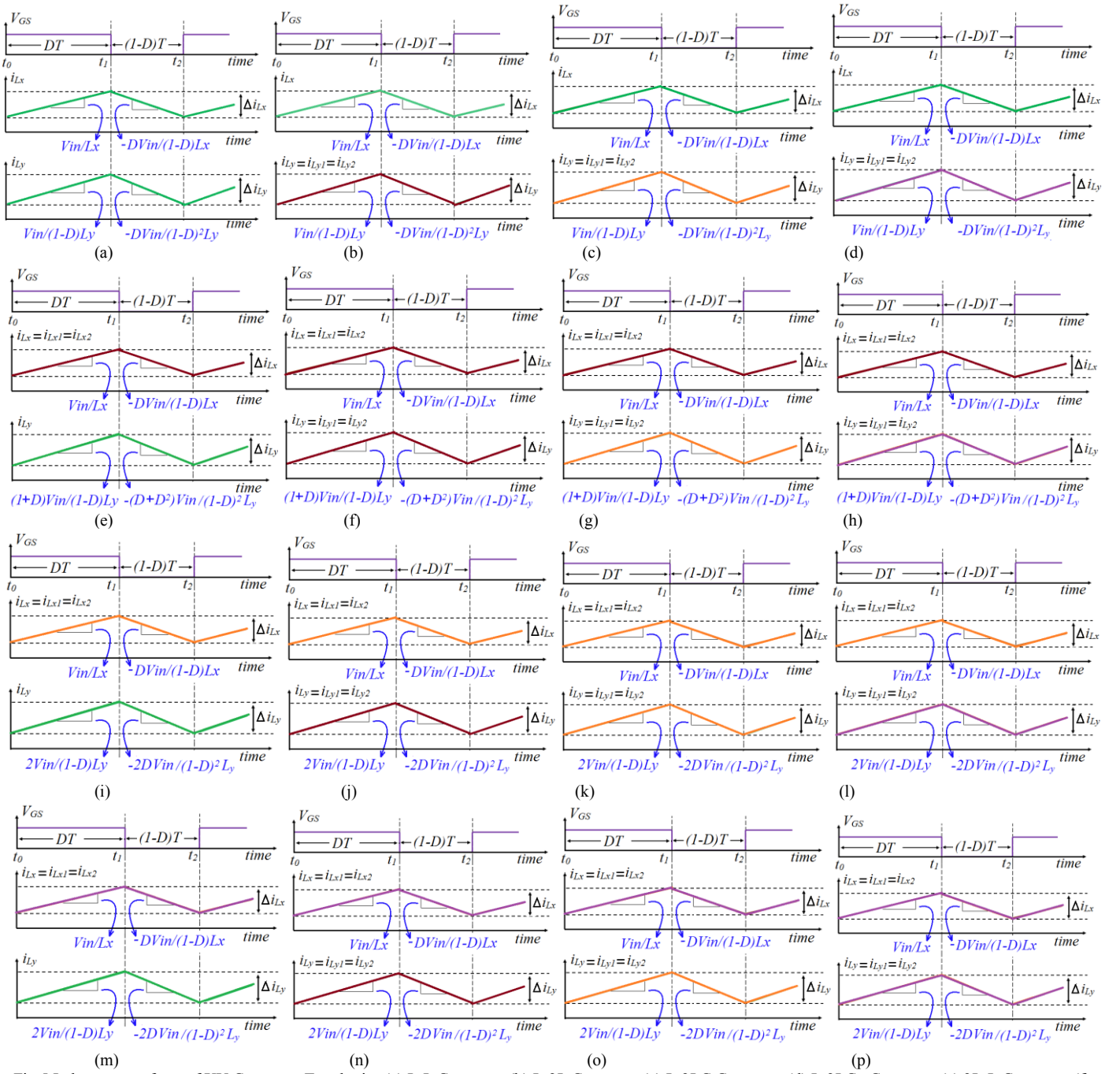


Fig.5 Inductor waveform of XY Converter Topologies (a) L-L Converter (b) L-2L Converter (c) L-2LC Converter (d) L-2LC<sub>m</sub> Converter (e) 2L-L Converter (f) 2L-2L Converter (g) 2L-2LC Converter (h) 2L-2LC<sub>m</sub> Converter (i) 2LC-L Converter (j) 2LC-2L Converter (k) 2LC-2LC Converter (l) 2LC-2LC<sub>m</sub> Converter (m) 2LC<sub>m</sub>-L Converter (n) 2LC<sub>m</sub>-2L Converter (o) 2LC<sub>m</sub>-2LC Converter (p) 2LC<sub>m</sub>-2LC<sub>m</sub> Converter. [Colour indication Green: Inductor waveform of L converter, Brown: Inductor waveform 2L Converter, Orange: Inductor waveform 2LC Converter, Violet: Inductor waveform 2LC<sub>m</sub> Converter].

- [14] T. J. Changchien, S. K. Liang, J. F. Chen, and L. S. Yang, "Step-up DC-DC converter by coupled inductor and voltage-lift technique," *IET Power Electron.*, vol. 3, no. 3, pp. 369-378, May 2010.
- [15] Y. Berkovich, and B. Axelrod, "Switched-coupled inductor cell for dc/dc converters with very large conversion ratio," *IET Power Electronics*, vol. 4, no. 3, pp. 309-315, March 2011.
- [16] R. J. Wai and R.-Y. Duan, "High step-up converter with coupled-inductor" *IEEE Trans. Power Electron.*, vol.20, no.5, pp.1025-1035, Sep.2005.
- [17] Zhao Q., Lee F. C. "High efficiency, high step-up DC-DC converter," *IEEE Trans. power Electron*, 2003, 18, pp 65-73.
- [18] Keum M. H., Choi Y., Han S. K. "High efficiency voltage clamped coupled inductor boost converter", *proc. Thirty Nine IEEE Industrial Electronics Society*, 2013, pp. 828-833.
- [19] K. W. ma and Y. S. Lee, "An integrated flyback converter for dc uninterruptible power supply," *IEEE Trans. Power Electron*, vol. 11, no. 2, pp. 318-327. Mar. 199
- [20] F. L. Tofoli, D. de C. Perrira, W. J. de. Paulo, D. de S. O. Junior, "Survey on non isolated high voltage step-up dc-dc topologies based on the boost converter" *IET power Electronics*, ISSN:1755-4535, pp. 1-14, 2015.
- [21] E. H. Ismail, M. A. Alsaffar, A. J. Sabzali, "High conversion ratio DC-DC converters with reduced switch stress", *IEEE Trans. On circuit and system-I*, vol. 55, no. 7,2008.
- [22] Mahajan Sagar Bhaskar Ranjana, Nandyala Sreeramula Reddy, Repalle Kusala Pavan Kumar "A Novel Non Isolated Switched Inductor Floating Output DC-DC Multilevel Boost Converter For Fuelcell Applications" *IEEE Students' Conference on Electrical, Electronics and Computer Sciences (IEEE-SCEECS) 2014*, Bhopal, (India).
- [23] Axelrod B., Berkovich Y., ioinovici A.: 'Switched-capacitor/switched-inductor structures for getting transformerless hybrid DC-DC PWM converters', *IEEE Trans. Circuits Syst. I*, 2008, 55, (2), pp. 687-696
- [24] Mahajan Sagar Bhaskar Ranjana, Nandyala Sreeramula Reddy, Repalle Kusala Pavan Kumar "A Novel Non-Isolated High Step-Up

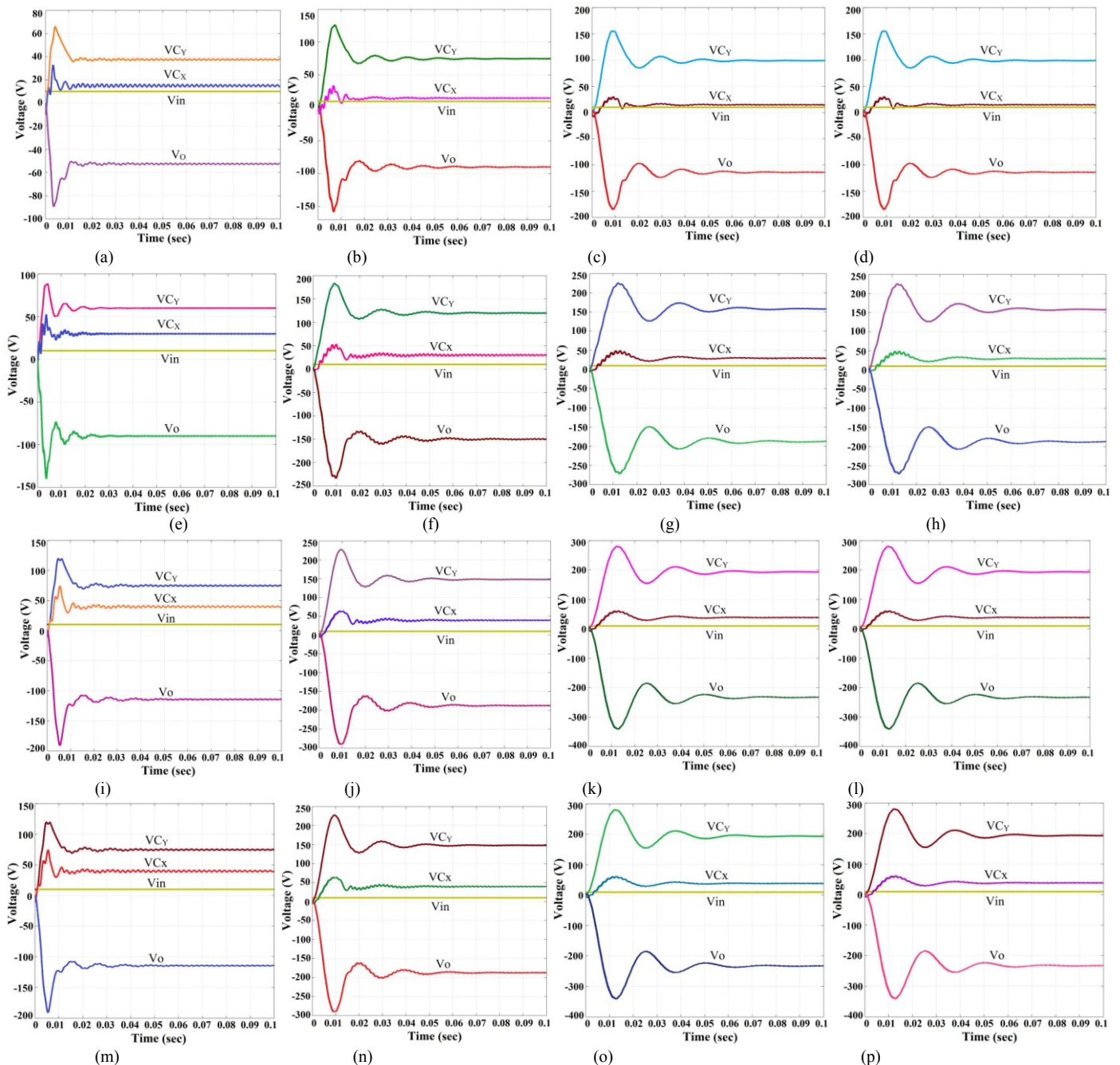


Fig.6 Simulation result of XY converter family: input voltage, output voltage of XY converter, output of X converter and output voltage Y Converter (a) L-L Converter (b) L-2L Converter (c) L-2LC Converter (d) L-2LC<sub>m</sub> Converter (e) 2L-L Converter (f) 2L-2L Converter (g) 2L-2LC Converter (h) 2L-2LC<sub>m</sub> Converter (i) 2LC-L Converter (j) 2LC-2L Converter (k) 2LC-2LC Converter (l) 2LC-2LC<sub>m</sub> Converter (m) 2LC<sub>m</sub>-L Converter (n) 2LC<sub>m</sub>-2L Converter (o) 2LC<sub>m</sub>-2LC Converter (p) 2LC<sub>m</sub>-2LC<sub>m</sub> Converter.

DC-DC Converters for Photovoltaic Applications” *IEEE International Conference on Circuit, Power and Computing Technologies (IEEE- ICCPCT) 2014*, Nagargoil (India).

- [25] Abutbul O., Gherlitz A., Berkovich Y., Ioinovici A.: ‘Step-up switching-mode converter with high voltage gain using a switched-capacitor circuit’, *IEEE Trans. Circuits Syst. I: Fundam. Theory Appl.*, 2003, 50, (8), pp. 1098–1102
- [26] Dongyan Z., Pietkiewicz A., Cuk S.: ‘A three-switch high-voltage converter’, *IEEE Trans. Power Electron.*, 1999, 14, (1), pp. 177–183
- [27] Shih-Ming Chen, Tsong-Juu Liang, Lung-Sheng Yang, Jiann-Fuh Chen. A Cascaded High Step-Up DC-DC Converter With Single Switch for Microsource Applications. *IEEE Trans. Power Electron.*, 2011; 26(4): 1146-1153.
- [28] M. Prudente, Luciano. L. Pfischer, Gustavo. E. E. F. Romaneli, R. Gules "Voltage Multiplier Cells Applied to Non-Isolated DC-DC Converters" *IEEE Transactions on Power Electronics*, vol.23, no.2, pp.871-887, March 2008.
- [29] C.T.Chuang, C.F. Chu, “A novel transformer-less adaptable voltage quadrupler dc converter with low switch voltage stress”, *IEEE Trans. Power Electron.*, vol. 29, no. 9, pp. 4787–4796, 2014.

- [30] P.Sanjeevikumar, A.Iqbal, H.Abu-Rub, “Implementation and control of extra high voltage dc-dc boost converter,” *The 7th IET Intl. Conf. on Sustainable Energy and Intelligent System, IET-SEISCON'14*, Chennai (India). 12–14 Dec. 2013.
- [31] J.C.Rosas-Caro, J.C.Mayo-Maldonado, R.S.Cabrera, A.G.Rodriguez, S.C.Eduardo Nacu, R.Castillo-Ibarra “A Family of DC-DC Multiplier Converters”, *Advance online publication: 10 Feb. 2011*.
- [32] P.Sanjeevikumar, K.Rajambal, “Extra high voltage DC-DC boost converters with simplified control strategy,” *Intl. J. of Modeling and Simulation, Hindawi Pub. Corp., US*, vol. 2008, Article ID 593042, 8 pages, Jan. 2008.
- [33] P.Sanjeevikumar, G.Grandi, P.WWheeler, F.Blaabjerg, J.Loncarski, "A Simple MPPT Algorithm for Novel PV Power Generation system by High Output Voltage DC-DC Boost Converter," *Conf. Proc., 24th IEEE International Symposium on Industrial Electronics, IEEE-ISIE'15*, Rio de Janeiro (Brazil), pp. 214–220, 3–5 Jun. 2015.
- [34] P.Sanjeevikumar, E.Kabalci, A.Iqbal, H.Abu-Rub, O.Ojo, “Control Strategy and Hardware Implementation for DC-DC Boost Power Conversion Based on Proportional-Integral Compensator for High Voltage Application,” *Engg. Science and Tech.: An Intl. J.*

- [35] Mahajan Sagar Bhaskar Ranjana, Rishi Kulkarni, Sanjeevikumar Padmanaban, Pierluigi Siano, Frede Blaabjerg “Hybrid Non-Isolated And Non Inverting Nx Interleaved DC-DC Multilevel Boost Converter For Renewable Energy Applications” *The 16th IEEE International Conference on Environment and Electrical Engineering, (IEEE-EEEIC'16)*, Florence (Italy).

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