New 2LC-Y DC-DC Converter Topologies for High-Voltage/Low-Current Renewable Applications: New Members of X-Y Converter Family

Mahajan Sagar Bhaskar
Dept. of Electrical and Electronics Engg.
University of Johannesburg,
South Africa
sagar25.mahajan@gmail.com

Sanjeevikumar Padmanaban
Dept. of Electrical and Electronics Engg.
University of Johannesburg,
South Africa
sanjeevi_12@yahoo.co.in

Pandav Kiran Maroti
Dept. of Electrical and Electronics Engg.
University of Johannesburg,
South Africa
kiranpandav88@yahoo.co.in

Viliam Fedák
Dept. of Electrical Engineering and Mechatronics, Technical University of Kosice,
Kosice, Slovak Republic
viliam.fedak@tuke.sk

Frede Blaabjerg
Center for Reliable Power Electronics (CORPE), Dept. of Energy Technology,
Aalborg University, Denmark
fbl@et.aau.dk

Vigna K. Ramachandaramurthy
Power Quality Research Group,
Department of Electrical Power Engineering, Universiti Tenaga Nasional,
Malaysia. Vigna@uniten.edu.my

***Abstract*—New members of XY converter family topologies are proposed in this treatise for a high-voltage/low-current renewable application. Based on the X Converter, the whole existing X-Y Converter family is categorized into four categories; L-Y, 2L-Y, 2LC-Y and 2LC$_m$-Y converter. Four new 2LC-Y topologies (2LC-LVD, 2LC-2LVD, 2LC-2LCVD and 2LC-2LC$_m$VD) converters are presented in this treatise which offer an effective solution for renewable applications requiring a very high voltage conversion ratio such as a Photovoltaic Multilevel Inverter (PV-MLI) system, hybrid electrical drives and automotive applications. The noticeable features of the proposed 2LC-Y converter topologies are: i) Only one power control switch and input source; ii) High negative output voltage with moderate duty ratio; iii) Low output current and minimal internal resistance; iv) Transformer-less converter topologies; v) High voltage conversion ratio; vi) Minimal number of power devices and components. Working and output voltage analysis of the proposed 2LC-Y converter topologies are discussed in details. The MATLAB simulation results are provided and good agreement with theoretical analysis is shown. Simulation results also validate the performance and functionality of the proposed 2LC-Y converter topologies of the XY converter family.**

Keywords—DC-DC converter; X-Y Family; high voltage; low current; renewable energy; minimal internal resistnace.

I. INTRODUCTION

At the present time renewable energy sources are well-liked and getting more popular with day-by-day increasing demands for energy and fuel cost. Renewable energy sources are consistent and bountiful in nature. They can be locally produced and therefore are not vulnerable to any kind of risks [1]-[2]. Hence energy management focuses on the boundless use of renewable energy resources for power generation. Enormous energy generation through an arrangement of many small voltage generating units is getting popular like series and parallel connection of solar cell or panels. The fine example of such electric power system is a photovoltaic power plant which contains a number of solar panels/modules for production of energy. Generated voltage at each solar panels/module is insufficient for feeding the electric power to inverter for practical application or to insert it into the electric grid. Therefore, series connection of solar panels/module does not present a suitable solution to achieve high voltage due to requirement of large area and high needed cost [3]. As a result a DC-DC converter is required to increase the voltage level with sufficient high conversion ratio before supplying it to inverter. Thus, the DC-DC converter is the most important constituent in the renewable power conversion stage. Also the traditional DC-DC Converter is not a practical solution to achieve high voltage due to high voltage stress across switch, high rating of components, the leakage resistance of the inductor and the capability of a traditional boost converter is deteriorating at high duty cycle [4]-[5]. Major limitation of traditional Buck-Boost Converter (BBC) consists in discontinuous input current which proves the minimal utilization of input source.

Based on the several novel concepts various transformer and coupled inductor based isolated converters are addressed in the literature to achieve high output voltage without using high duty cycles to control switch [6]-[8]. But size and leakage reactance of converter is increased due to tenancy of transformer and coupled inductor. The converter functionality, efficiency and performance also degrade due to creation of Electro-Magnetic Interference (EMI) by such magnetic components. The main drawbacks of isolated converter topologies are large in size, weight and losses of power transformer.

To overcome the drawbacks of isolated DC-DC converter various Cascaded Boost Converters (CBCs) are addressed in literature for renewable applications [9]-[10]. The control circuit of CBCs is the most complex part for real time application due to several controlled switches and reactive components. The major drawbacks of cascaded converter are high ripple current, more controlled switches and a high energy loss to attain a high voltage gain and low efficiency. Quadratic Boost Converter (QBC) is proposed by using less

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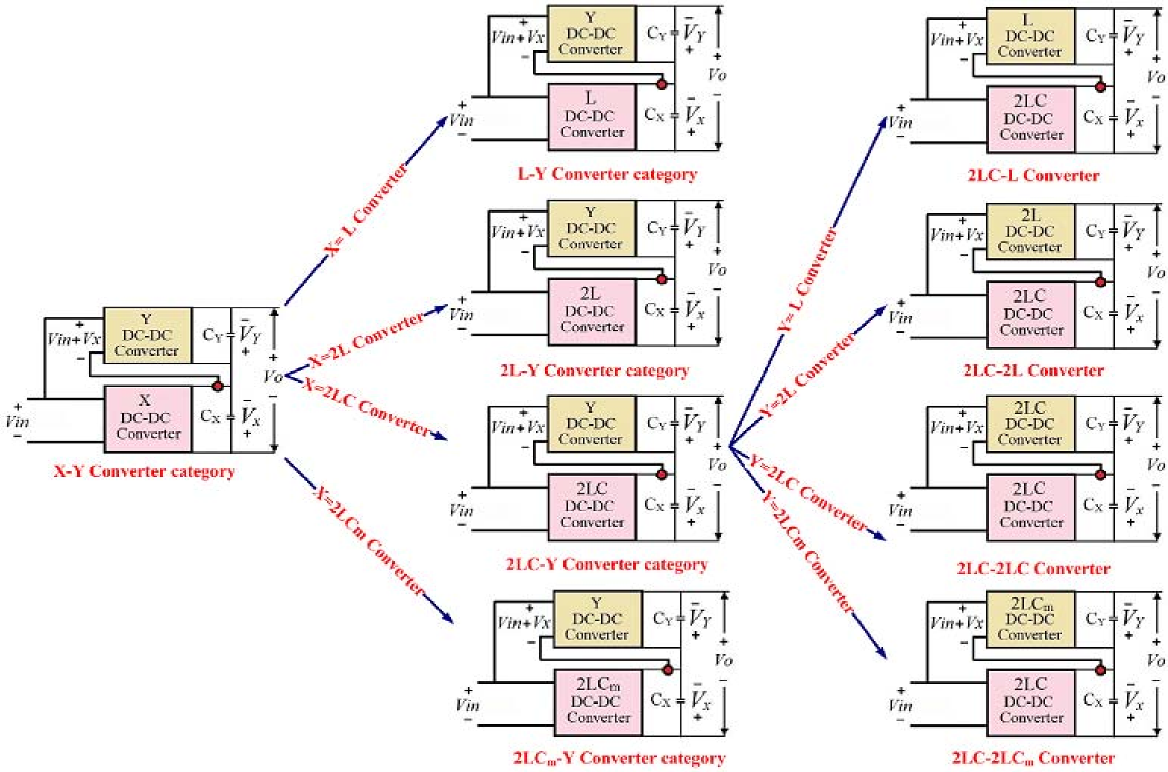


Fig. 1 Generalized structure of XY converter family and family tree of L-Y, 2L-Y, 2LC-Y, $2LC_m$-Y, 2LC-L, 2LC-2L, 2LC-2LC and 2LC-$2LC_m$ converters

TABLE I. CATEGORIZATION OF X-Y DC-DC CONVERTER

X-Y Converter		Y DC-DC Converter				CATERGORIES
		BBC (L)	**SI (2L)**	**VLSI BBC (2LC)**	**Modified VLSI BBC ($2LC_m$)**	
X DC-DC Converter	**BBC (L)**	L-L Converter	L-2L Converter	L-2LC Converter	L-$2LC_m$ Converter	L-Y Converter
	SI BBC (2L)	2L-L Converter	2L-2L Converter	2L-2LC Converter	2L-$2LC_m$ Converter	2L-Y Converter
	VLSI BBC (2LC)	2LC-L Converter	2LC-2L Converter	2LC-2LC Converter	2LC-$2LC_m$ Converter	2LC-Y converter
	Modified VLSI BBC ($2LC_m$)	$2LC_m$-L Converter	$2LC_m$-2L Converter	$2LC_m$-2LC Converter	$2LC_m$-$2LC_m$ Converter	$2LC_m$-Y Converters

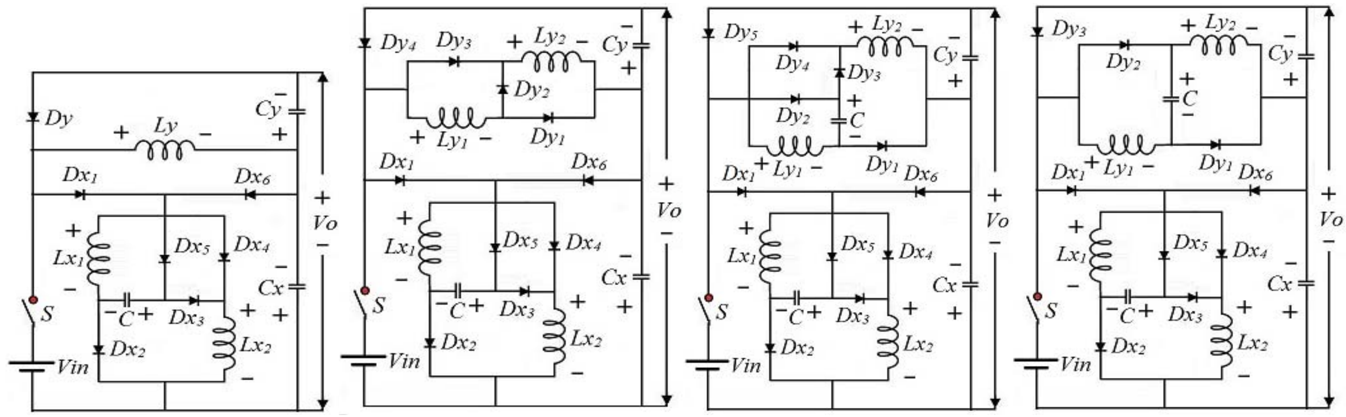
number of switches to overcome the drawback of CBC [10]-[11]. But in QBC very high voltage (nearly equal to output voltage) appears across the switch in OFF state. This requires high rating of controlled switch and capacitor to design QBC.

Nowadays based on diode and capacitor circuitry several DC-DC multilevel converters are proposed to overcome the drawback of above discussed converters [12]-[16]. In [13], Nx and 2Nx multilevel converter is proposed to achieve inverting high voltage with conversion 20 and 40 at duty cycle 75 %. In [14]-[16] non–inverting Nx, 2Nx, 4Nx interleaved converter is proposed to reduce current/voltage ripple and to achieve high non-inverting output voltage. Above multilevel DC-DC converter topology is provides a viable solution to achieve high voltage but required large number of diode and capacitor. In [17], X-Y converter family is propose to achieve high voltage conversion ratio using minimum number of devices. Based on the arrangement of inductor, total sixteen converter topologies are proposed in X-Y family. In [18], novel LY converter topologies (L-LVD, L-2LVD, L-2LCVD and L-$2LC_m$VD) are addressed to attain high voltage conversion ratio. In this treatise a new members in 2LC-Y converter category of XY family are proposed which offers an effective solution for high-voltage/low-current renewable applications such as a Photovoltaic Multilevel Inverter (PV-MLI) system, hybrid electrical drives and automotive applications. The noticeable features of proposed 2LC-Y converter topologies are: i) Only one power control switch and input source; ii) High negative output voltage with moderate duty ratio; iii) Low output current and minimal internal resistance; iv) Transformer-less converter topologies; v) High voltage conversion ratio; vi) Minimal number of power devices and components.

II. X-Y CONVERTER FAMILY AND ITS CATEGORIZATION

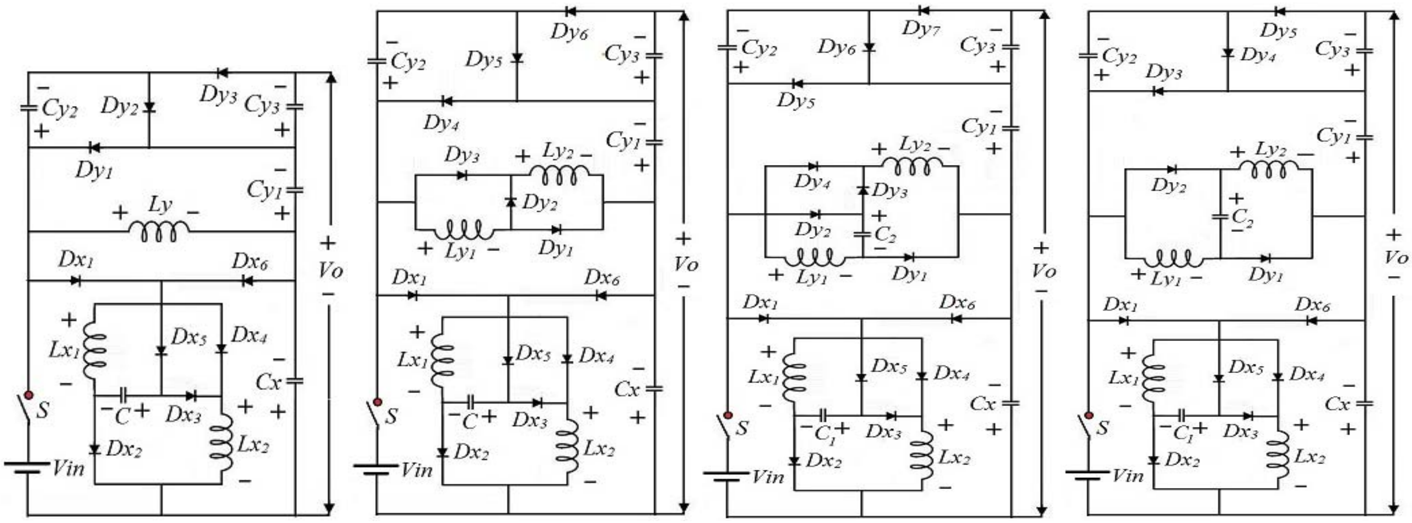
A. Generalized Structure of X-Y ConverterFamily

The X-Y converter family generalized structure and tree of L-Y, 2L-Y, 2LC-Y, 2LCm-Y, 2LC-L, 2LC-2L, 2LC-2LC and 2LC-$2LC_m$ converters is depicted in Fig. 1. In X-Y family two separate DC-DC converters named as X converter and Y converter are connected in specific manner as shown in Fig. 1.



(a) (b) (c) (d)

Fig. 2 Power circuit of existing converters: (a) 2LC-L; (b) 2LC-2L; (c) 2LC-2LC; (d) 2LC-2LCm



(a) (b) (c) (d)

Fig. 3 Power circuit of proposed converters: (a) 2LC-LVD; (b) 2LC-2LVD; (c) 2LC-2LCVD; (d) 2LC-2LCmVD

The input for X converter is directly fed from the input voltage source and for Y converter the input voltage is addition of input source voltage and output of X converter. The inverting sum of output voltages of X converter and Y converter appear at the output port of X-Y converter as shown in equation (1).

$$V_o = -\left(V_X + V_Y\right) \tag{1}$$

B. Categorization of X-Y Family

X and Y converters of X-Y converter family is designed by using single Inductor (L), Switch-Inductor (SI or 2L), Voltage-lift-Switched-Inductor (VLSI or 2LC) and modified-Voltage-lift-Switched-Inductor (mVLSI or $2LC_m$) reactive network in power circuit. Based on the X converter whole X-Y converter topologies (16 topologies) are categorized into four sub categories; L-Y, 2L-Y, 2LC-Y and $2LC_m$-Y converter. The details of categorization is shown in Fig. 1 and also tabulated in Table I.

III. Outline of Existing 2LC-Y Converters

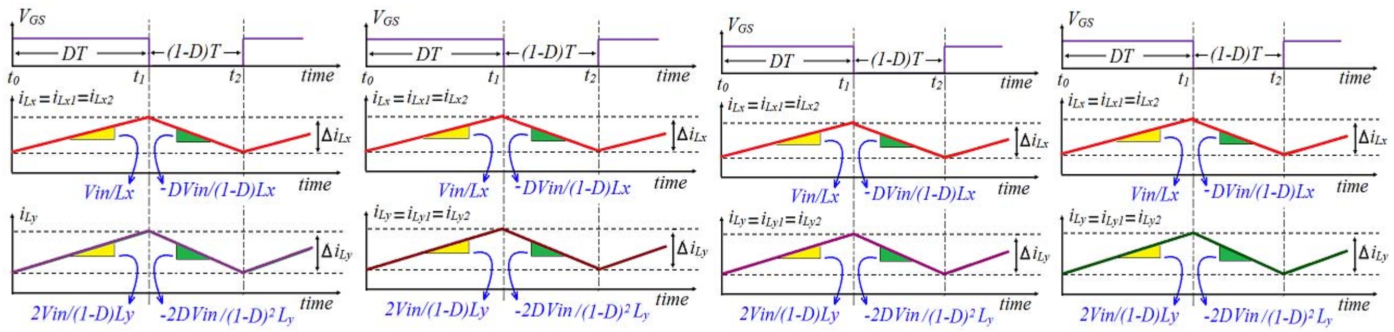
Power circuit of existing 2LC-Y converter category of X-Y converter family consists of the 2LC-L, 2LC-2L, 2LC-2LC and $2LC_m$ converters as shown in Fig. 2(a)-(d). Thus, 2LC-Y converter is a category of the X-Y converter family in which X converter is VLSI-BBC or 2LC Converter (Voltage-Lift-Switch-Inductor Buck-Boost Converter). 2LC-Y converter category of X-Y converter family consisting of two separate converters is named as 2LC converter and Y converter.

The input voltage (V_{in}) is directly fed to the 2LC converter. The input voltage for Y converter is addition of input voltage (V_{in}) and output voltage of X converter (here 2LC converter, V_{X2LC}). Hence total voltage at the output port of 2LC-Y converter (V_{2LC-Y}) is equal to the negative addition of output voltage of 2LC converter and Y converter as in (2).

$$V_o = V_{2LC-Y} = -\left(V_{X2LC} + V_Y\right) \tag{2}$$

IV. Proposed 2LC-Y Converters: Next Members of X-Y Family

Four new members in 2LC-Y converter category of X-Y family are proposed to attain higher voltage conversion ratio compared to existing 2LC-Y converter category. Y converter of existing 2LC-Y converter category is modified to design new members. For new members are: i) 2LC-LVD converter



(a) (b) (c) (d)

Fig. 4. Inductor waveforms of proposed converter: (a) 2LC-LVD; (b) 2LC-2LVD; (c) 2LC-2LCVD; (d) 2LC-2LC$_m$VD

(where X converter is 2LC and Y converter is LVD (L or Buck-Boost converter with voltage doubler)); ii) 2LC-2LVD (where X converter is 2LC and Y converter is 2LVD (Switched-Inductor-Buck-Boost or 2L converter with voltage doubler)); iii) 2LC-2LCVD (where X converter is 2LC and Y converter is 2LCVD (2LC or VLSI Buck-Boost converter with voltage doubler)); iv) 2LC-2LC$_m$VD (where X converter is 2LC and Y converter is 2LC$_m$VD (2LC$_m$ or modified VLSI Buck-Boost converter with voltage doubler)). The power circuit of proposed four members is depicted in Fig. 3(a)-(d). The mode of operation of 2LC-Y converter topologies is split into two modes- one when the power switch is turned-ON (switch act as short circuit) and other when power switch is turned-OFF (switch act an open circuit). To explain the operation modes of new proposed 2LC-Y converter category, 2LC-2LC$_m$VD converter is considered.

A. 2LC-2LC$_m$VD converter topology

2LC-2LC$_m$VD is a new member in 2LC-Y category of X-Y converter family. 2LC-2LC$_m$VD converter is designed by considering that X converter is 2LC converter (VLSI BBC) and Y converter is 2LC$_m$VD (modified VLSI BBC).

The power circuit of 2LC-2LC$_m$VD is shown in Fig. 3(d). To design 2LC converter (X converter of 2LC-2LC$_m$VD) two similar and equal rating inductors (L_{X1} and L_{X2}), six diodes (D_{X1} to D_{X6}) and two capacitors (C_1 and C_X) are required. To design 2LC$_m$VD converter (Y converter of 2LC-2LC$_m$VD) two similar and equal rating inductors (L_{Y1} and L_{Y2}), five diodes (D_{Y1} to D_{Y5}) and four capacitors (C_2 and C_{Y1} to C_{Y3}) are required. Hence in total to design 2LC-2LC$_m$VD converter four inductors, eleven diodes and six capacitors along with one controlled switch are required. When the power switch S is turned-ON (acting as a short circuit), the current through inductors L_{X1} and L_{X2} are increased. Thus, the inductor L_{X1} id charged by input supply (V_{in}) through diode D_{X1}, D_{X2} and switch S whereas the inductor L_{X2} is charged by input supply (V_{in}) through the diodes D_{X1}, D_{X4} and switch S. Capacitor C_1 is charged by input voltage through the diodes D_{X1}, D_{X2}, D_{X5} and switch S. At the same time currents through inductor L_{Y1} and L_{Y2} are increased. Thus, the inductor L_{Y1} is charged by voltage across capacitor C_X and input supply (V_{in}) through the diode D_{Y1} and switch S whereas the inductor L_{Y2} is charged by voltage across capacitor C_X and input supply (V_{in}) through diode D_{Y2} and switch S. The capacitor C_2 is charged by voltage across the capacitor C_X and input supply (V_{in}) through the diodes D_{Y2}, D_{Y1} and switch S. The capacitor C_{Y2} is charged by voltage across capacitors C_{Y1}, C_X and input voltage (V_{in}) through th e diode D_{Y4} and switch S. The total output voltage of the 2LC-2LC$_m$VD converter is negative and equal to the addition of the voltage across capacitors C_X and C_Y where ($C_Y = C_{Y1}+C_{Y3}$). When the power switch S is turned-OFF (acting as an open circuit), main power supply is disconnected from the 2LC converter. The inductor L_{X1}, L_{X2} and capacitor C_1 are discharged in series through the diodes D_{X3}, D_{X6} to charge the capacitor C_X. Similarly, the inductor L_{Y1}, L_{Y2} and capacitor C_2 are discharged in series through the diode D_{Y3} to charge the C_{Y1}. At the same time the capacitor C_{Y2} delivers its energy to the capacitor C_{Y3} through the diode D_{Y5}. The total output voltage of the 2LC-2LC$_m$VD converter is negative and equal to the addition of voltage across capacitor C_X and C_Y where ($C_Y = C_{Y1}+C_{Y3}$). The slope of inductor current of all proposed converters (2LC-L, 2LC-2L, 2LC-2LC and 2LC-2LCm converter) is analyzed and shown in Fig. 4 (a)-(d). It is noticed that all the inductors present in proposed converters are charged when the switch is turned-ON and discharged when the switch is turned-OFF.

V. Voltage Conversion Ratio Analysis of Existing and Proposed 2LC-Y Converter

In order to analyze the proposed 2LC-Y converter, it is consider that the all the converter is working in steady state and the following hypothesis are considered throughout the switching: i) Input supply (V_{in}) is pure DC (Vin); ii) voltage drop across all power devices while conducting is V_d, (efficiency of devices are 100% if $V_d = 0$); iii) Let's consider for simplicity that V_d is also voltage drop across inductor due to internal resistance; iv) The ripple across capacitor at switching frequency f_s is very small.

A. 2LC-L Converter

Power circuit of 2LC-L Converter is shown in Fig. 2(a).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = \left(\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}\right) \tag{3}$$

$$G_Y = G_{YL} = \frac{V_{CY}}{V_{in}} = \left(\frac{D(G_{X2LC}+1)}{1-D} - \frac{2V_d}{(1-D)V_{in}}\right) \tag{4}$$

where G_{X2LC} or G_X is gain of X converter (2LC converter) and Where G_{YL} or G_Y is gain of Y Converter (L converter)

$$G_{XY} = G_{2LC-L} = \frac{V_O}{V_{in}} = -(G_{X2LC} + G_{YL}) = -(G_X + G_Y) \tag{5}$$

where G_{XY} or $G_{2LC\text{-}L}$ is voltage gain of 2LC-L converter.

B. 2LC-2L Converter

Power circuit of 2LC-2L Converter is shown in Fig. 2(b).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = (\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}) \quad (6)$$

$$G_Y = G_{Y2L} = \frac{V_{CY}}{V_{in}} = (\frac{2D(G_{X2LC}+1)}{1-D} - \frac{2(D+2)V_d}{(1-D)V_{in}}) \quad (7)$$

where G_{X2LC} or G_X is gain of X converter (2LC converter) and G_{Y2L} or G_Y is gain of Y Converter (2L converter)

$$G_{XY} = G_{2LC-2L} = \frac{V_O}{V_{in}} = -(G_{X2LC} + G_{Y2L}) = -(G_X + G_Y) \quad (8)$$

where G_{XY} or $G_{2LC\text{-}2L}$ is voltage gain of 2LC-2L converter.

C. 2LC-2LC Converter

Power circuit of 2LC-2LC converter is shown in Fig. 2(c).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = (\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}) \quad (9)$$

$$G_Y = G_{Y2LC} = \frac{V_{CY}}{V_{in}} = (\frac{(1+D)(G_{X2LC}+1)}{1-D} + \frac{(D\text{ - }7)V_d}{(1-D)V_{in}}) \quad (10)$$

where G_{X2LC} or G_X is gain of X converter (2LC converter) and G_{Y2LC} or G_Y is gain of Y Converter (2LC converter).

$$G_{XY} = G_{2LC-2LC} = \frac{V_O}{V_{in}} = -(G_{X2LC} + G_{Y2LC}) = -(G_X + G_Y) \quad (11)$$

where G_{XY} or $G_{2LC\text{-}2LC}$ is voltage gain of 2LC-2LC converter.

D. 2LC-2LCm Converter

Power circuit of 2LC-2LC Converter is shown in Fig. 2(d).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = (\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}) \quad (12)$$

$$G_Y = G_{Y2LCm} = \frac{V_{CY}}{V_{in}} = (\frac{(1+D)(G_{X2LC}+1)}{1-D} - \frac{6V_d}{(1-D)V_{in}}) \quad (13)$$

where G_{X2LC} of G_X is gain of X converter (2LC converter), G_{Y2LCm} or G_Y is gain of Y Converter (2LCm converter).

$$G_{XY} = G_{2LC-2LCm} = \frac{V_O}{V_{in}} = -(G_{X2LC} + G_{Y2LCm}) = -(G_X + G_Y) \quad (14)$$

where G_{XY} or $G_{2LC\text{-}2LCm}$ is voltage gain of 2LC-2LC$_m$ converter

E. 2LC-LVD Converter

Power circuit of 2LC-LVD converter is shown in Fig. 3(a).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = (\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}) \quad (15)$$

$$G_{Y1} = \frac{V_{CY1}}{V_{in}} = (\frac{D(G_{X2LC}+1)}{1-D} - \frac{2V_d}{(1-D)V_{in}}) \quad (16)$$

where G_{Y1} is ratio of (voltage across C_{Y1} and input voltage) V_{CY1}/Vin.

$$G_{Y2} = \frac{V_{CY2}}{V_{in}} = (1 + G_{X2LC} + G_{Y1} - \frac{2V_d}{V_{in}}) \quad (17)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = (1 + G_{X2LC} + G_{Y1} - \frac{4V_d}{V_{in}}) \quad (18)$$

where G_{Y2} and G_{Y3} are (ratio of voltage across C_{Y2} and input voltage) V_{CY2}/V_{in} and (ratio of voltage across C_{Y3} and input voltage) V_{CY3}/V_{in} respectively.

$$G_Y = G_{YLVD} = G_{Y1} + G_{Y3} \quad (19)$$

$$G_{XY} = G_{2LC-LVD} = \frac{V_O}{V_{in}} = -(G_{X2LC} + G_{YLVD}) = -(G_X + G_Y) \quad (20)$$

where G_{XY} or $G_{2LC\text{-}LVD}$ is voltage gain of 2LC-LVD converter.

F. 2LC-2LVD Converter

Power circuit of 2LC-2LVD Converter is shown in Fig. 3(b).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = (\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}) \quad (21)$$

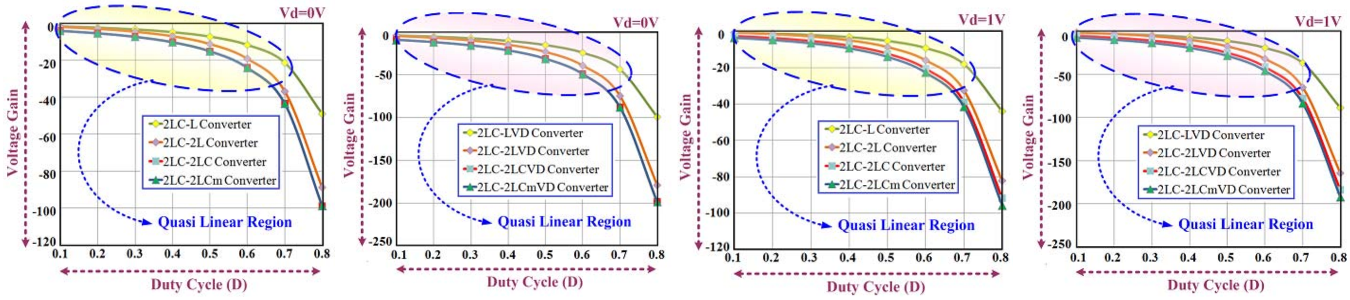
$$G_{Y1} = \frac{V_{CY1}}{V_{in}} = (\frac{2D(G_{X2LC}+1)}{1-D} - \frac{2(D+2)V_d}{(1-D)V_{in}}) \quad (22)$$

where G_{Y1} is ratio of (voltage across C_{Y1} and input voltage V_{CY1}/V_{in}).

$$G_{Y2} = \frac{V_{CY2}}{V_{in}} = (1 + G_{X2LC} + G_{Y1} - \frac{2V_d}{V_{in}}) \quad (23)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = (1 + G_{X2LC} + G_{Y1} - \frac{6V_d}{V_{in}}) \quad (24)$$

where G_{Y2} and G_{Y3} are (ratio of voltage across C_{Y2} and input voltage) V_{CY2}/V_{in} and (ratio of voltage across C_{Y3} and input



(a) (b) (c) (d)

Fig. 5 Plot of Voltage Conversion Ratio: (a) 2LC-Y when $V_d = 0$; (b) 2LC-YVD when $V_d = 0$; (c) 2LC-Y when $V_d = 1$; (d) 2LC-YVD when $V_d = 1$

voltage) V_{CY3}/V_{in}, respectively.

$$G_Y = G_{Y2LVD} = G_{Y1} + G_{Y3} \quad (25)$$

$$G_{XY} = G_{2LC-2LVD} = \frac{V_O}{V_{in}} = -(G_{X2LC} + G_{Y2LVD}) = -(G_X + G_Y) \quad (26)$$

Where G_{XY} or $G_{2LC\text{-}2LVD}$ is voltage gain of 2LC-2LVD converter.

G. 2LC-2LCVD Converter

Power circuit of 2LC-2LCVD Converter is shown in Fig. 3(c).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = \left(\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}\right) \quad (27)$$

$$G_{Y1} = \frac{V_{CY1}}{V_{in}} = \left(\frac{(1+D)(G_{X2LC}+1)}{1-D} + \frac{(D\text{-}7)V_d}{(1-D)V_{in}}\right) \quad (28)$$

where G_{Y1} is ratio of (voltage across the capacitor C_{Y1} and input voltage) V_{CY1}/V_{in}.

$$G_{Y2} = \frac{V_{CY2}}{V_{in}} = \left(1 + G_{X2LC} + G_{Y1} - \frac{2V_d}{V_{in}}\right) \quad (29)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = \left(1 + G_{X2LC} + G_{Y1} - \frac{6V_d}{V_{in}}\right) \quad (30)$$

where G_{Y2} and G_{Y3} are (ratio of voltage across C_{Y2} and input voltage) V_{CY2}/V_{in} and (ratio of voltage across C_{Y3} and input voltage) V_{CY3}/V_{in} respectively.

$$G_Y = G_{Y2LCVD} = G_{Y1} + G_{Y3} \quad (31)$$

$$\left.\begin{aligned} G_{XY} &= G_{2LC-2LCVD} = \frac{V_O}{V_{in}} \\ &= -(G_{X2LC} + G_{Y2LCVD}) = -(G_X + G_Y) \end{aligned}\right\} \quad (32)$$

where G_{XY} or $G_{2LC\text{-}2LCVD}$ is voltage gain of 2LC-2LCVD converter.

H. 2LC-2LC$_m$VD Converter

Power circuit of 2LC-2LC$_m$VD Converter is shown in Fig. 3(d).

$$G_X = G_{X2LC} = \frac{V_{CX}}{V_{in}} = \left(\frac{1+D}{1-D} - \frac{8V_d}{(1-D)V_{in}}\right) \quad (33)$$

$$G_{Y1} = \frac{V_{YC1}}{V_{in}} = \left(\frac{(1+D)(G_{X2LC}+1)}{1-D} - \frac{6V_d}{(1-D)V_{in}}\right) \quad (34)$$

where G_{Y1} is ratio of (voltage across the capacitor C_{Y1} and input voltage) V_{CY1}/V_{in}.

$$G_{Y2} = \frac{V_{CY2}}{V_{in}} = \left(1 + G_{X2LC} + G_{Y1} - \frac{2V_d}{V_{in}}\right) \quad (35)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = \left(1 + G_{X2LC} + G_{Y1} - \frac{5V_d}{V_{in}}\right) \quad (36)$$

where G_{Y2} and G_{Y3} are (ratio of voltage across C_{Y2} and input voltage) V_{CY2}/V_{in} and (ratio of voltage across C_{Y3} and input voltage) V_{CY3}/V_{in} respectively.

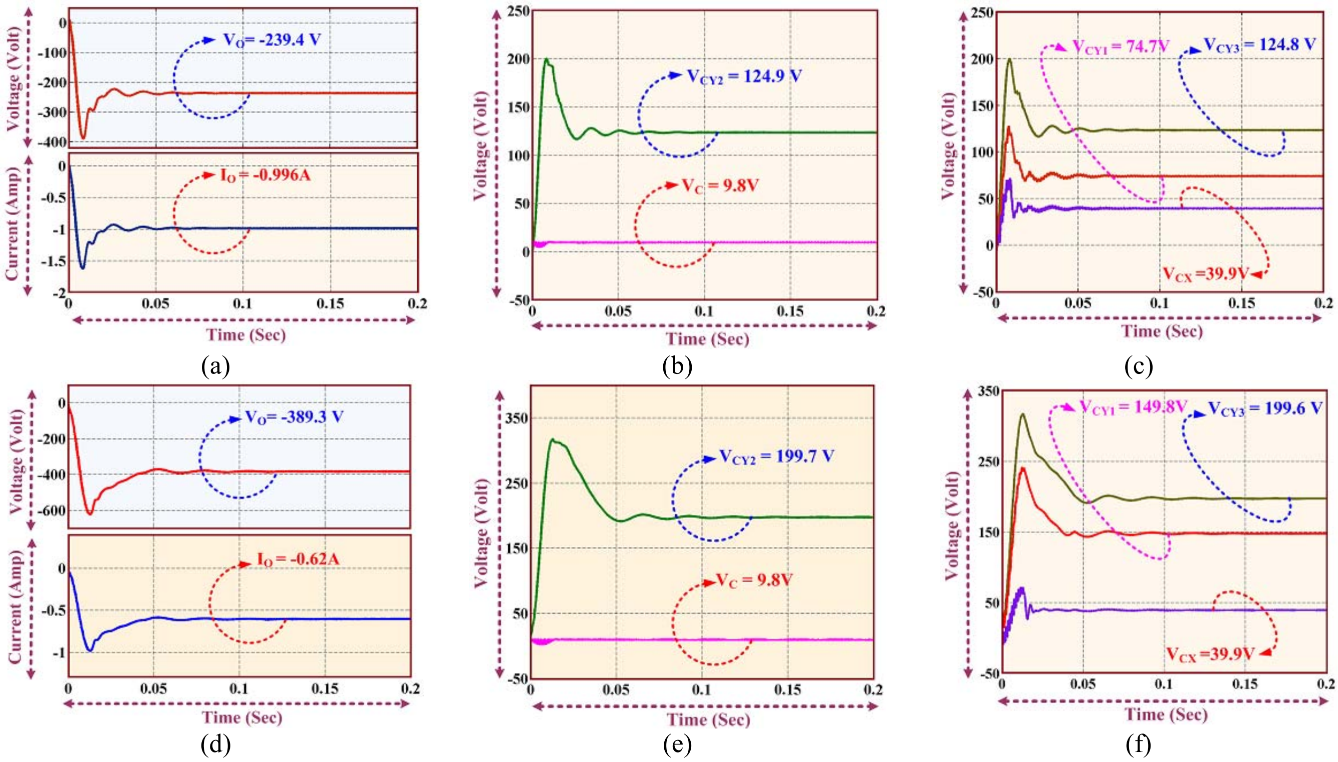


Fig. 6. Simulation results of the proposed 2LC-Y converter with 240 W, 60 % duty cycle: (a) Output voltage and current of 2LC-LVD converter: (b) Voltage across V_C, V_{CY2} of 2LC-LVD converter; (c) Voltage across V_{CX}, V_{CY1} and V_{CY3} of 2LC-LVD converter; (d) Output voltage and current of 2LC-2LVD converter; (e) Voltage across V_C, V_{CY2} of 2LC-2LVD converter; (f) Voltage across V_{CX}, V_{CY1} and V_{CY3} of 2LC-2LVD converter

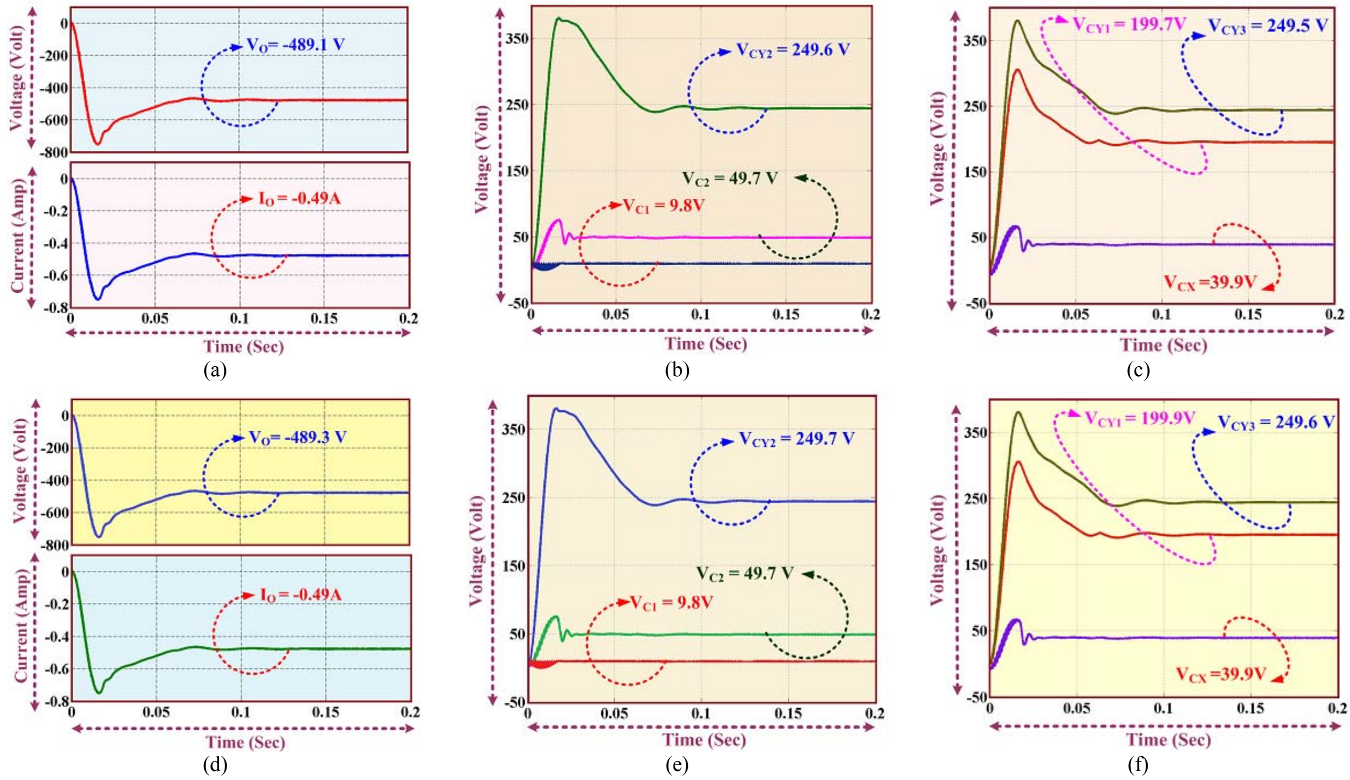


Fig. 7 Simulation results of the proposed 2LC-Y converter with 240 W, 60 % duty cycle: (a) Output voltage and current of 2LC-2LCVD converter; (b) Voltage across V_{C1}, V_{C2}, V_{CY2} of 2LC-2LCVD converter; (c) Voltages V_{CX}, V_{CY1} and V_{CY3} of 2LC-2LCVD converter; (d) Output voltage and current of 2LC-2LC$_m$VD converter; (e) Voltages V_{C1}, V_{C2}, V_{CY2} of 2LC-2LC$_m$VD converter; (f) Voltage across V_{CX}, V_{CY1} and V_{CY3} of 2LC-2LC$_m$VD converter

$$G_Y = G_{Y2LCmVD} = G_{Y1} + G_{Y3} \tag{37}$$

$$\left.\begin{aligned} G_{XY} &= G_{2LC-2LCmVD} = \frac{V_O}{V_{in}} \\ &= -(G_{X2LC} + G_{Y2LCmVD}) = -(G_X + G_Y) \end{aligned}\right\} \tag{38}$$

where G_{XY} or $G_{2LC\text{-}2LCmVD}$ is voltage gain of 2LC-2LC$_m$VD converter.

Each converter voltage conversion ratio is calculated by considering $V_d = 0$ and 1. The plot of voltage gain versus duty is shown in Fig. 5 and it is observed that from 0 to 0.7 duty cycle all the 2LC-Y converter operates in quasi linear region. The slope of all the converter voltage conversion ratio plot is very high after the 0.7 duty cycle. The effect of internal resistance on proposed X-Y family members is minimal as compared to existing member.

VI. Simulation Results and Discussion

All the proposed 2LC-Y members of X-Y are simulated in MATLAB with input voltage 10 V, 240 W and 60% duty cycle. The control switch is operating at 50 kHz switching frequency.

The output voltage and output current waveform of 2LC-LVD is shown in Fig. 6(a). It is observed that output voltage and current is -239.4 V and -0.996 A respectively. Thus, it is observed that at 60 % duty cycle the voltage conversion ratio of 2LC-LVD is -24. The capacitor C_1 and C_{Y2} voltage is shown in Fig. 6(b). It is observed that the voltage across C_1 and C_{Y2} is 9.8 V (nearly equal to input voltage) and 124.9 V respectively. The capacitor C_X, C_{Y1} and C_{Y3} voltage is shown in Fig. 6(c). It is observed that the voltage across C_X, C_{Y1} and C_{Y3} is 39.9 V, 74.7 V and 124.8 V.

The output voltage and current waveform of 2LC-2LVD is shown in Fig. 6(d). It is observed that output voltage and current is -389.3 V and -0.62 A respectively. Thus, it is observed that at 60 % duty cycle the voltage conversion ratio of 2LC-LVD is -39. The capacitor C_1 and C_{Y2} voltage is shown in Fig. 6(e). It is observed that the voltage across C_1 and C_{Y2} is 9.8 V (nearly equal to input voltage) and 199.7 V respectively. The voltage across the capacitors C_X, C_{Y1} and C_{Y3} are shown in Fig. 6(f). It is observed that the voltage across C_X, C_{Y1} *and* C_{Y3} is 39.9 V, 149.8 V and 199.6 V.

The output voltage and current waveform of 2LC-2LCVD is shown in Fig. 7(a). It is observed that output voltage and current is -489.1 V and -0.49 A, respectively. Thus, it is observed that at 60 % duty cycle the voltage conversion ratio of 2LC-LVD is -49 V. The capacitor C_1 and C_{Y2} voltage is shown in Fig. 7(b). It is observed that the voltage across C_1, C_2 and C_{Y2} is 9.8 V (nearly equal to input voltage), 49.7 V and 49.6 V, respectively. The capacitor C_X, C_{Y1} and C_{Y3} voltage is shown in Fig. 7(c). It is observed that the voltage across C_X, C_{Y1} and C_{Y3} is 39.9 V, 199.6 V and 249.5 V.

The output voltage and current waveform of 2LC-2LC$_m$VD is shown in Fig. 7(d). It is observed that output voltage and current is -489.3 V and -0.49 A respectively. Thus, it is observed that at 60 % duty cycle the voltage conversion ratio of 2LC-2LCmVD is -49 V. The capacitor C_1,

C_2 and C_{Y2} voltage is shown in Fig. 7(e). It is observed that the voltage across C_1, C_2 and C_{Y2} is 9.8 V (nearly equal to input voltage), 49.7 V and 249.7 V respectively. The capacitor C_X, C_{Y1} and C_{Y3} voltage is shown in Fig. 7(f). It is observed that the voltage across C_X, C_{Y1} and C_{Y3} is 39.9 V, 199.9 V and 249.6 V.

From the above discussion, first it is observed that all the 2LC-Y converter topologies have high negative output voltage. Second, it is investigated that 2LC-2LVD converter have greater voltage conversion ratio compared to the 2LC-LVD converter ($G_{2LC\text{-}2LVD} > G_{2LC\text{-}LVD}$). Third, it is investigated that 2LC-2LCVD and 2LC-2LCmVD converters have greater voltage conversion ratio compared to the 2LC-2LVD converter ($G_{2LC\text{-}2LCVD}$ or $G_{2LC\text{-}2LCmVD} > G_{2LC\text{-}2LVD}$). Fourth it is observed that proposed 2LC-Y members have greater voltage conversion ratio compared to the existing 2LC-Y member of X-Y converter family. Fifth, it is also investigated that 2LC-2LCmVD converter provides a maximum conversion ratio with minimal internal resistance effect.

VII. Conclusion

Four new 2LC-Y converter topologies (2LC-LVD, 2LC-2LVD, 2LC-2LCVD and 2LC-2LCmVD converters) of X-Y Family are presented for high-voltage/low-current renewable application. Proposed 2LC-Y offers an effective solution for renewable applications which requires a very high voltage conversion ratio such as a photovoltaic Multilevel Inverter (PV-MLI) system, hybrid renewable electrical drives and automotive applications. The noticeable features of proposed 2LC-Y converter topologies are: i) Only one power control switch and input source; ii) High Negative output voltage with moderate duty ratio; iii) Low output current; iv) Transformer-less topologies; v) High voltage conversion ratio; vi) Minimal number of power devices and components. Voltage analysis of 2LC-Y converter topologies with considering diode voltage drop is discussed in details. The MATLAB simulation results are provided and it incessantly showed the good agreement with theoretical analysis. Simulation results also validate the performance and functionality of the four proposed 2LC-Y converter topologies of the XY converter family.

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