



Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

A New Voltage Doubler Based DC-DC 2LCm-Y Power Converter Topologies for High-Voltage/Low- Current Renewable Energy Applications

Bhaskar, Mahajan Sagar; Padmanaban, Sanjeevikumar; Wheeler, Patrick; Blaabjerg, Frede; Siano, Pierluigi

Published in:

Proceedings of 2018 IEEE Transportation Electrification Conference and Expo (ITEC 2018)

DOI (link to publication from Publisher):

[10.1109/ITEC.2018.8450120](https://doi.org/10.1109/ITEC.2018.8450120)

Publication date:

2018

Document Version

Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Bhaskar, M. S., Padmanaban, S., Wheeler, P., Blaabjerg, F., & Siano, P. (2018). A New Voltage Doubler Based DC-DC 2LCm-Y Power Converter Topologies for High-Voltage/Low- Current Renewable Energy Applications. In *Proceedings of 2018 IEEE Transportation Electrification Conference and Expo (ITEC 2018)* (pp. 75-83). [8450120] IEEE. <https://doi.org/10.1109/ITEC.2018.8450120>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

A New Voltage Doubler Based DC-DC $2LC_m$ -Y Power Converter Topologies for High-Voltage/Low-Current Renewable Energy Applications

Mahajan Sagar Bhaskar
Dept. of Electrical Engg.,
Qatar University, Doha, Qatar
sagar25.mahajan@gmail.com

Sanjeevikumar Padmanaban
Dept. of Energy Technology,
Aalborg University, Denmark
san@et.aau.dk

Patrick Wheeler
Dept. of Electrical & Electronics Engg.,
Nottingham University, United Kingdom
pat.wheeler@nottingham.ac.uk

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

Pierluigi Siano
Dept. of Industrial Engg.,
University of Salerno, Campus of Fisciano, Salerno, Italy
psiano@unisa.it

Abstract— In this treatise, a new voltage doubler based DC-DC $2LC_m$ -Y power converter topologies are uttered for the high-voltage/low-current renewable energy applications. L-Y, 2L-Y, 2LC-Y and $2LC_m$ -Y power converter categories are recently proposed in the existing X-Y converter family. To provide an effective and viable solution to renewable energy system; four new voltage doubler based converters ($2LC_m$ -LVD, $2LC_m$ -2LVD, $2LC_m$ -2LCVD and $2LC_m$ -2LCmVD converters) are proposed in $2LC_m$ -Y converter category. The proposed converters are well suited for renewable energy applications which required high output voltage power converter such as a Photovoltaic Multilevel DC-AC converter system, renewable High Voltage Direct Current (HVDC) applications, Hybrid Electric Vehicles (HEV) etc. The perceptible characteristics of proposed $2LC_m$ -Y power converter topologies are presented in detail. Working of $2LC_m$ -Y proposed converters with the derivation of V_o/V_{in} is discussed in detail. Proposed converter topologies are simulated in the Numerical Computing Matrix Laboratory 9.0 (R2016a) software. The simulation results are discussed in details and it constantly showed the high-quality agreement with hypothetical analysis and validates the functionality and characteristics of the proposed $2LC_m$ -Y converter topologies of X-Y converter family.

Keywords— X-Y Converter Family; DC-DC Converter; Voltage Doubler; High-Voltage; Low-Current; Renewable Energy.

I. INTRODUCTION

Presently, looking forward for renewable energy it has become more popular day by day and it can be considered as prominent solution to fulfill energy demand of community. The renewable sources are reliable and plentiful in nature and can be harvested and consequently not defenseless against any sort of dangers. Thus, energy organization concentrates on unlimited of renewable power source assets for power era [1]-[2]. Massive energy era through a course of action of various little voltage producing units is getting mainstream like series and parallel association of solar cell or panels. Consequently, series and parallel association of solar module is not an appropriate way out for accomplish high voltage and high current because of necessity of extensive area and high cost is required. The fine case of such electric power framework is a photovoltaic power plant which contains various photovoltaic oriented boards/modules for generation of energy. Produced

voltage at each photovoltaic based boards/module is inadequate for feeding the electric energy directly to inverter for handy application or to insert it into the electric network or grid. Therefore, series connection of solar panels/module is not a suitable and practicable solution to achieve high voltage due to requirement of large area and high cost is needed [3]. Thus, DC-DC converter is requisite to lift the voltage with adequate high conversion ratio before feeding it into inverter. Along these lines, DC-DC converter is the most imperative constituent in the renewable power conversion stage. Conventional DC-DC converter because of various constrains is not a good technical solution to attain high voltage conversion ratio. These constrains includes excess voltage stress across switch, high rating of components and capability of conventional boost converter starts deteriorating with increase in duty cycle [4]-[5]. Major real restriction of traditional Buck-Boost Converter (BBC) is discontinuous input current which shows the negligible use of power source. Depends on the bountiful novel idea numerous isolated transformer and coupled inductor based power converters are proposed in the literature to achieve high V_o/V_{in} without using high duty cycle for the power switch [5]-[7]. However, magnitude and leakage reactance of converter is increased because of occupancy of transformer and coupled inductor. The converter usefulness, functionality and performance additionally degrade because of making of Electro-Magnetic-Interference (EMI) by such magnetic parts. The primary drawbacks of isolated converter topologies are extensive in size, weight and losses of power transformer. Size and leakage reactance of converter is increases due to tenancy of transformer and coupled inductor. To defeat the disadvantages of isolated DC-DC converter numerous Cascaded Boost Converters (CBCs) are proposed in literature for renewable energy applications [8]-[9]. The control circuit of CBCs is most complex part for real time application due to several controlled switches and reactive components. The major drawbacks of cascaded converter is high ripple current, several controlled switches, high energy loss to attain a high voltage gain and low efficiency. Quadratic Boost Converter (QBC) is proposed by utilizing less number of power controlled devices to defeat the disadvantage of CBC. But in QBC, the voltage appeared in OFF state across the power control device is

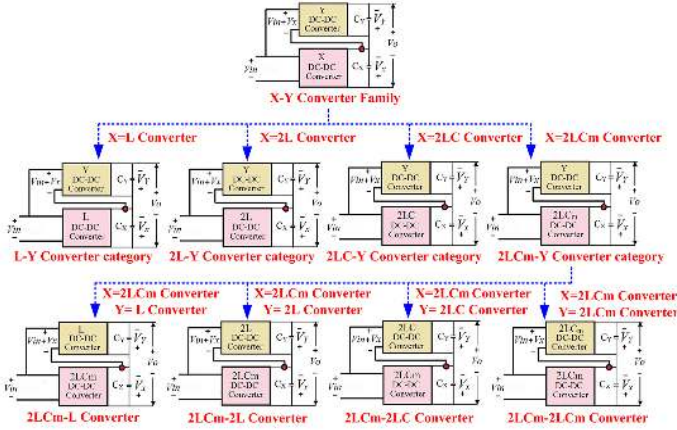


Fig. 1. X-Y converter family generalized structure and hierarchy of L-Y, 2L-Y, 2LC-Y, 2LC_m-Y, 2LC_m-L, 2LC_m-2L, 2LC_m-2LC and 2LC_m-2LC_m power converters.

complete output voltage (V_o) and that is very high. Thus, high rated capacitors and power controlled devices are required [9].

Nowadays, DC-DC Multilevel Boost Converters (MBC) is addressed in literature to overcome the drawback of above discussed converter using diode and capacitor networks [10]-[14]. In [11], inverted high voltage with conversion ratio 20 and 40 at duty cycle 75% is accomplished using N_x and $2N_x$ MBC. Reduce current/voltage ripple with high non-inverting voltage is attained by using N_x , $2N_x$ IMBC [12]-[13]. The multilevel DC-DC converter topology discussed above gives a suitable way to accomplish high voltage however, required substantial number of diode and capacitor. In [14], X-Y converter family is proposed to attain high voltage conversion ratio by utilizing least number of components. In view of the arrangement of inductor, total sixteen converter topologies are proposed in X-Y family. In [15], to achieve high conversion ratio (V_o/V_{in}) novel four L-Y converter topologies using voltage doubler (L-LVD, L-2LVD, L-2LCVD and L-2LC_mVD) are articulated.

A new voltage doubler based DC-DC 2LC_m-Y power converter topologies (2LC_m-LVD, 2LC_m-2LVD, 2LC_m-2LCVD and 2LC_m-2LC_mVD converters) are proposed in this treatise to provide an effective and viable solution to renewable energy system such as a Photovoltaic Multilevel DC-AC converter system, renewable High Voltage Direct Current (HVDC) applications, Hybrid Electric Vehicles (HEV) etc. The perceptible characteristics of proposed 2LC_m-Y power converter topologies are i) Single input source ii) Single controlled semiconductor device iii) High inverting V_o/V_{in} at average duty cycle iv) High-voltage and low-current at the output side of converter v) Minimum internal resistance vi) Transformer-less and coupled inductor-less power converter topologies. The concept of proposed converter is verified through Numerical Computing Matrix Laboratory 9.0 (R2016a) software.

II. REVIEW OF EXISTING 2LC_m-Y DC-DC CONVERTERS: A MEMBERS OF X-Y CONVERTER FAMILY

Fig. 1 depicts the X-Y power converter family generalized structure and hierarchy of L-Y, 2L-Y, 2LC-Y, 2LC_m-Y, 2LC_m-L, 2LC_m-2L, 2LC_m-2LC and 2LC_m-2LC_m converters. In X-Y

family two separate DC-DC converters named as X-converter and Y-converter are associated in particular way as depicted in Fig. 1. The contribution for X-converter is directly fed from the input source voltage (V_{in}) and for Y-converter contribution voltage is addition of input source voltage (V_{in}) and output of X-converter. The total output voltage of X-Y converter is easily measured by equation (1) in which V_X and V_Y is the output of converter X and Y. G_X and G_Y are the voltage conversion ratio of converter X and Y.

$$\left. \begin{aligned} V_o &= -(V_X + V_Y) \\ V_X &= G_X \times V_{in} \\ V_Y &= G_Y \times V_{in} \end{aligned} \right\} \quad (1)$$

The various combination of 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 are employed to designed X-Y converter family. Depending on X converter entire X-Y converter family (sixteen topologies) are categorized into four sub categories; L-Y, 2L-Y, 2LC-Y and 2LC_m-Y converter. The entire categorization is shown in Fig. 1. 2LC_m-L, 2LC_m-2L, 2LC_m-2LC and 2LC_m-2LC_m power converter topologies are existing four member of 2LC_m-Y power converter category of X-Y converter family. The power circuits of existing 2LC_m-Y converter are shown in Fig. 2(a)-(d). X-converter is 2LC_m (modified Voltage-Lift-Switched-Inductor BBC or mVLSI-BBC) in 2LC_m-Y power converter category of X-Y converter family. The supply for 2LC_m converter is directly fed from the input source voltage (V_{in}) and for Y converter supply voltage is addition of input source voltage (V_{in}) and output voltage of 2LC_m converter (X converter, V_{X2LCm}). As a result, the output voltage of 2LC_m-Y power converter is inverting summation of output voltage of 2LC_m converter (X converter) and Y converter as shown in equation (2).

$$\left. \begin{aligned} V_o &= V_{2LCm-Y} = -(V_{X2LCm} + V_Y) \\ V_o &= V_{2LCm-Y} = -(G_{X2LCm} + G_Y) \times V_{in} \text{ or} \\ V_o &= V_{2LCm-Y} = -(G_X + G_Y) \times V_{in} \end{aligned} \right\} \quad (2)$$

III. VOLTAGE DOUBLER BASED 2LC_m-Y DC-DC CONVERTER TOPOLOGIES (PROPOSED TOPOLOGIES)

Four voltage doubler based 2LC_m-Y power converter topologies in 2LC_m-Y category of X-Y family are proposed to accomplish higher (V_o/V_{in}) voltage conversion ratio compared to conventional 2LC_m-Y converter configurations. Y-converter of conventional 2LC_m-Y converter category is modified by employing voltage doubler stage to design proposed converter topologies. Four proposed voltage doubler based power converter topologies are i) 2LC_m-LVD power converter (where Y-converter is LVD converter which combines the features of L converter (conventional Buck Boost) and voltage doubler (VD) and X converter is 2LC_m converter) ii) 2LC_m-2LVD (where Y-converter is 2LVD converter which combines the features of 2L converter (Switched Inductor Buck Boost) and voltage doubler (VD) and X converter is 2LC_m converter)

iii) $2LC_m-2LCVD$ (where Y-converter is $2LCVD$ converter which combines the features of $2LC$ converter (Voltage Lift Switched Inductor Buck Boost) and voltage doubler (VD) and X converter is $2LC_m$ converter) iv) $2LC_m-2LC_mVD$ (where Y-converter is $2LC_mVD$ converter which combines the features of $2LC_m$ converter (modified Voltage Lift Switched Inductor Buck Boost) and voltage doubler (VD) and X converter is $2LC_m$ converter). The main power circuit of proposed four voltage doubler based converters is depicted in Fig. 3(a)-(d). The detail information of requirement of number component to design $2LC_m-Y$ converter is tabulated in table-I. The switching states of all $2LC_m-Y$ converter topologies are divided into two states- one when the control semiconductor device is in ON-state (short circuit) and second when the control semiconductor device is in OFF-state (open circuit). Among the four proposed voltage doubler based converter topologies; $2LC_m-2LC_mVD$ is considered to explain the switching states of proposed converters.

A. Voltage Doubler Based $2LC_m-2LC_mVD$ Power Converter

$2LC_m-Y$ category of X-Y converter family is extended and $2LC_m-2LC_mVD$ power converter is one new proposed member in $2LC_m-Y$ category. Modified VLSI BBC converter ($2LC_m$) is considering as an X-converter, whereas Y-converter is combination of $2LC_m$ and voltage doubler ($2LC_mVD$ or modified VLSI BBC with voltage doubler). Fig. 3(d) depicts the power circuit of voltage doubler based $2LC_m-2LC_mVD$ converter. Two capacitors (C_1 and C_X), two inductors (L_{X1} and L_{X2}) which are indistinguishable and equal in rating, four uncontrolled semiconductor devices (diodes D_{X1} to D_{X4}) are compulsory needed to design $2LC_m$ converter which is X converter of $2LC_m-2LC_mVD$ power converter. Four capacitors (C_2 and C_{Y1} to C_{Y3}), two inductors (L_{Y1} and L_{Y2}) which are indistinguishable and equal in rating, five uncontrolled semiconductor devices (diodes D_{Y1} to D_{Y5}) are compulsory needed to design $2LC_mVD$ converter which is Y-converter of $2LC_m-2LC_mVD$ power converter. Therefore, overall to design $2LC_m-2LC_mVD$ converter, four indistinguishable inductors which are equal in rating, nine uncontrolled semiconductor device (diodes) and six capacitors besides one semiconductor controlled device (Switch) are compulsory required.

When semiconductor controlled device S is in ON-state (short circuit), the slope of current flowing through inductors L_{X1} and L_{X2} are positive. Hence, L_{X1} inductor is magnetized by input supply (V_{in}) by way of uncontrolled devices D_{X1} , D_{X2} and controlled device S (charging path is $V_{in}-S-D_{X1}-L_{X1}-D_{X2}-V_{in}$) whereas L_{X2} inductor is magnetized by input supply (V_{in}) by

way of uncontrolled devices D_{X1} , D_{X3} and controlled device S (charging path is $V_{in}-S-D_{X1}-D_{X3}-L_{X2}-V_{in}$). By way of uncontrolled devices D_{X1} , D_{X3} , D_{X2} and controlled device S ; capacitor C_1 is get charged by input voltage (V_{in}) (charging path is $V_{in}-S-D_{X1}-D_{X3}-C_1-D_{X2}-V_{in}$). The slope of current flowing through L_{Y1} and L_{Y2} inductor is positive at the same time. Hence inductor L_{Y1} and L_{Y2} are magnetized. Thus, L_{Y1} inductor is magnetized by capacitor C_X voltage and input supply (V_{in}) by way of uncontrolled devices D_{Y1} and controlled device S (charging path is $V_{in}-S-L_{Y1}-D_{Y1}-C_X-V_{in}$) whereas inductor L_{Y2} are charged by capacitor C_X voltage and input supply (V_{in}) by way of uncontrolled devices D_{Y2} and controlled device S (charging path is $V_{in}-S-D_{Y2}-L_{Y2}-C_X-V_{in}$). By way of uncontrolled devices D_{Y1} , D_{Y2} and controlled device S ; capacitor C_2 is get charged by capacitor C_X voltage and input voltage (V_{in}) (charging path is $V_{in}-S-D_{Y2}-C_1-D_{Y1}-C_X-V_{in}$). By way of uncontrolled devices D_{Y4} and controlled device S , capacitor C_{Y2} is charged by input voltage (V_{in}), capacitor C_{Y1} and C_X voltage (charging path is $V_{in}-S-C_{Y2}-D_{Y4}-C_{Y1}-C_X-V_{in}$). Thus, inverting addition of capacitor C_X and C_Y ($C_Y=C_{Y1}+C_{Y3}$) voltages is output voltage of $2LC_m-2LC_mVD$ power converter.

Main input supply is isolated from the power circuit of $2LC_m$ converter when semiconductor control device S is in OFF-state (open circuit). The slope of current flowing through inductor L_{X1} , L_{X2} is negative. Hence L_{X1} , L_{X2} inductors demagnetized in series with capacitor C_1 by way of uncontrolled device D_{X4} to transfer the stored energy to capacitor C_X (charging path is $L_{X1}-C_1-L_{X2}-C_X-D_{X4}$). The slope of current flowing through inductor L_{Y1} , L_{Y2} is negative. Hence, at the same time L_{Y1} , L_{Y2} inductor demagnetized in series with capacitor C_2 by way of uncontrolled device D_{Y3} to transfer the stored energy to charge the capacitor C_{Y1} (charging path is $L_{Y1}-C_2-L_{Y2}-C_{Y1}-D_{Y3}$). C_{Y2} capacitor transferred its energy to charge C_{Y3} capacitor by way of uncontrolled device D_{Y5} . Thus, inverting addition of capacitor C_X and C_Y ($C_Y=C_{Y1}+C_{Y3}$) voltages is output voltage of $2LC_m-2LC_mVD$ power converter. Inductor current slope is analyzed for the $2LC_m-2LC_mVD$ power converter and the nature of inductor current is shown in Fig. 4. It is observed that that all the inductors available in proposed $2LC_m-2LC_mVD$ converter are magnetized when the semiconductor controlled device is in ON-state and demagnetized when semiconductor controlled device is in OFF-state.

IV. DERIVATION OF VOLTAGE CONVERSION RATIO FOR PROPOSED $2LC_m-Y$ CONVERTER

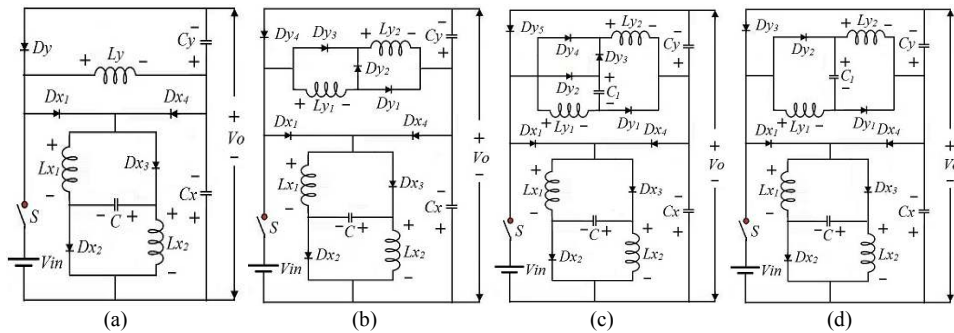


Fig.2. Existing $2LC_m-Y$ converters of X-Y family (a) $2LC_m-L$ (b) $2LC_m-2L$ (c) $2LC_m-2LC$ (d) $2LC_m-2LC_m$.

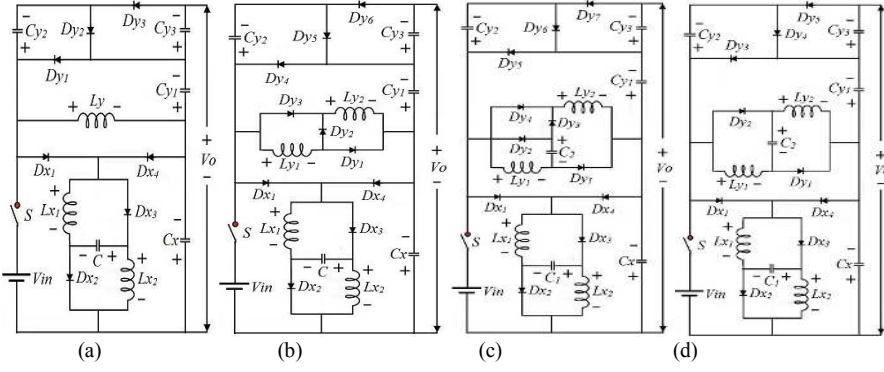


Fig. 3. Voltage Doubler (VD) based proposed converters power circuit (a) 2LC_m-LVD (b) 2LC_m-2LVD (c) 2LC_m-2LCVD (d) 2LC_m-2LC_mVD.

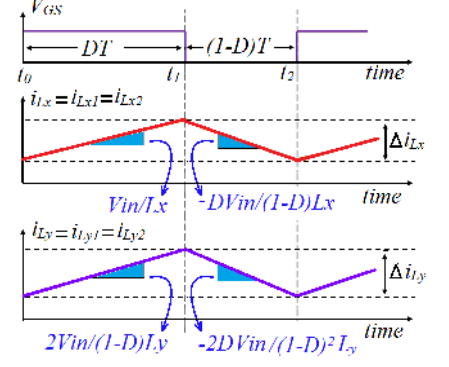


Fig. 4. Waveform of inductor current of 2LC_m-2LC_mVD converters

TABLE-I. NUMBER OF COMPONENTS DETAILS

No. of Component	2LC _m -Y Converter							
	2LC _m -L	2LC _m -2L	2LC _m -2LC	2LC _m -2LC _m	2LC _m -LVD	2LC _m -2LVD	2LC _m -2LCVD	2LC _m -2LC _m VD
switches	1	1	1	1	1	1	1	1
inductors	3	4	4	4	3	4	4	4
capacitors	3	3	4	4	5	5	6	6
diodes	5	8	9	7	7	10	11	9

Proposed voltage doubler based 2LC_m-Y converter voltage conversion ratio is derived by considering following assumption i) Constant ripple free pure DC input supply (V_{in}) ii) Voltage V_d is the ON-state voltage drop of all semiconductor devices, hence if $V_d = 0$ all the semiconductor devices are ideal (100% efficient) iii) for simplicity assume drop at inductor due to internal resistance of inductor is V_d iv) assume very small ripple at capacitors. Consider K is the duty cycle.

A. Voltage Doubler Based 2LC_m-LVD Converter

Fig. 3(a) depicts the power circuit of voltage doubler based 2LC_m-LVD Converter.

$$\left. \begin{aligned} G_{X2LCm} &= G_X = \\ \frac{V_{CX}}{V_{in}} &= \left(\frac{1+K}{1-K} - \left(\frac{7V_d}{(1-K)V_{in}} + \frac{KV_d}{(1-K)V_{in}} \right) \right) \end{aligned} \right\} \quad (3)$$

$$G_{Y1} = \frac{V_{CY1}}{V_{in}} = \left(\frac{K(G_{X2LCm} + 1)}{1-K} - \frac{2V_d}{(1-K)V_{in}} \right) \quad (4)$$

$$\left. \begin{aligned} G_{Y2} &= \frac{V_{CY2}}{V_{in}} = \left(P_{YL} - \frac{2V_d}{V_{in}} \right) \\ P_{YL} &= 1 + G_{X2LCm} + G_{Y1} \end{aligned} \right\} \quad (5)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = \left(P_{YL} - \frac{4V_d}{V_{in}} \right) \quad (6)$$

$$G_{YLVD} = G_Y = G_{Y1} + G_{Y3} \quad (7)$$

Thus, overall voltage conversion ratio of 2LC_m-LVD converter is $G_{2LCm-LVD}$ or G_{XY} and provided in equation (8).

$$\left. \begin{aligned} G_{2LCm-LVD} &= G_{XY} = \\ \frac{V_O}{V_{in}} &= -(G_{X2LCm} + G_{YLVD}) = -(G_X + G_Y) \end{aligned} \right\} \quad (8)$$

B. Voltage Doubler Based 2LC_m-2LVD Converter

Fig. 3(b) depicts the power circuit of voltage doubler based 2LC_m-2LVD Converter.

$$\left. \begin{aligned} G_{X2LCm} &= G_X = \\ \frac{V_{CX}}{V_{in}} &= \left(\frac{1+K}{1-K} - \left(\frac{7V_d}{(1-K)V_{in}} + \frac{KV_d}{(1-K)V_{in}} \right) \right) \end{aligned} \right\} \quad (9)$$

$$G_{Y1} = \frac{V_{CY1}}{V_{in}} = \left(\frac{2K(G_{X2LCm} + 1)}{1-K} - \frac{2(K+2)V_d}{(1-K)V_{in}} \right) \quad (10)$$

$$\left. \begin{aligned} G_{Y2} &= \frac{V_{CY2}}{V_{in}} = \left(P_{Y2L} - \frac{2V_d}{V_{in}} \right) \\ P_{Y2L} &= 1 + G_{X2LCm} + G_{Y1} \end{aligned} \right\} \quad (11)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = \left(P_{Y2L} - \frac{6V_d}{V_{in}} \right) \quad (12)$$

$$G_{Y2LVD} = G_Y = G_{Y1} + G_{Y3} \quad (13)$$

Thus, overall voltage conversion ratio of 2LC_m-2LVD converter is $G_{2LCm-2LVD}$ or G_{XY} and provided in equation (14).

$$\left. \begin{aligned} G_{2LCm-2LVD} &= G_{XY} = \\ \frac{V_O}{V_{in}} &= -(G_{X2LCm} + G_{Y2LVD}) = -(G_X + G_Y) \end{aligned} \right\} \quad (14)$$

C. Voltage Doubler Based $2LC_m$ - $2LCVD$ Converter

Fig. 3(c) depicts the power circuit of voltage doubler based $2LC_m$ - $2LCVD$ Converter.

$$\left. \begin{aligned} G_{X2LCm} &= G_X = \\ \frac{V_{CX}}{V_{in}} &= \left(\frac{1+K}{1-K} - \left(\frac{7V_d}{(1-K)V_{in}} + \frac{KV_d}{(1-K)V_{in}} \right) \right) \end{aligned} \right\} \quad (15)$$

$$G_{Y1} = \frac{V_{CY1}}{V_{in}} = \left(\frac{(1+K)(G_{X2LCm} + 1)}{1-K} + \frac{(K-7)V_d}{(1-K)V_{in}} \right) \quad (16)$$

$$\left. \begin{aligned} G_{Y2} &= \frac{V_{CY2}}{V_{in}} = \left(P_{Y2LC} - \frac{2V_d}{V_{in}} \right) \\ P_{Y2LC} &= 1 + G_{X2LC} + G_{Y1} \end{aligned} \right\} \quad (17)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = \left(P_{Y2LC} - \frac{6V_d}{V_{in}} \right) \quad (18)$$

$$G_{Y2LCVD} = G_Y = G_{Y1} + G_{Y3} \quad (19)$$

Thus, overall voltage conversion ratio of $2LC_m$ - $2LCVD$ converter is $G_{2LCm-2LCVD}$ or G_{XY} and provided in equation (20).

$$\left. \begin{aligned} G_{2LCm-2LCVD} &= G_{XY} = \frac{V_O}{V_{in}} \\ &= -(G_{X2LCm} + G_{Y2LCVD}) = -(G_X + G_Y) \end{aligned} \right\} \quad (20)$$

D. Voltage Doubler Based $2LC_m$ - $2LCmVD$ Converter

Fig. 3(d) depicts the power circuit of voltage doubler based $2LC_m$ - $2LCmVD$ Converter.

$$\left. \begin{aligned} G_{X2LCm} &= G_X = \\ \frac{V_{CX}}{V_{in}} &= \left(\frac{1+K}{1-K} - \left(\frac{7V_d}{(1-K)V_{in}} + \frac{KV_d}{(1-K)V_{in}} \right) \right) \end{aligned} \right\} \quad (21)$$

$$G_{Y1} = \frac{V_{YC1}}{V_{in}} = \left(\frac{(1+K)(G_{X2LCm} + 1)}{1-K} - \frac{6V_d}{(1-K)V_{in}} \right) \quad (22)$$

$$\left. \begin{aligned} G_{Y2} &= \frac{V_{CY2}}{V_{in}} = \left(P_{2LCm} - \frac{2V_d}{V_{in}} \right) \\ P_{2LCm} &= 1 + G_{X2LCm} + G_{Y1} \end{aligned} \right\} \quad (23)$$

$$G_{Y3} = \frac{V_{CY3}}{V_{in}} = \left(P_{2LCm} - \frac{5V_d}{V_{in}} \right) \quad (24)$$

$$G_{Y2LCmVD} = G_Y = G_{Y1} + G_{Y3} \quad (25)$$

Thus, overall gain of $2LC_m$ - $2LCmVD$ converter is $G_{2LCm-2LCmVD}$ or G_{XY} and provided in equation (26).

$$\left. \begin{aligned} G_{2LCm-2LCmVD} &= G_{XY} = \frac{V_O}{V_{in}} \\ &= -(G_{X2LCm} + G_{Y2LCmVD}) = -(G_X + G_Y) \end{aligned} \right\} \quad (26)$$

The relation between voltage conversion ratio versus duty for proposed voltage doubler $2LC_m$ -Y converters with considering maximum $V_d=I$ is shown graphically in Fig. 5. It is investigated that all the slope of voltage conversion plot is very high after 75% duty cycle. Hence quasi linear region to

operate $2LC_m$ -Y converter is 0 to 75% duty cycle. The effect of internal resistance of proposed $2LC_m$ -Y power converter topologies of X-Y family is minimal as compared to $2LC$ -Y member of X-Y family.

V. NUMERICAL COMPUTING MATRIX LABORATORY 9.0 (R2016A) SIMULATION RESULTS AND DISCUSSION

The simulation of proposed $2LC_m$ -Y converter is workout in Numerical Computing Matrix Laboratory 9.0 (R2016a) software with the parameters: 10V input voltage, 240W power and 60% duty cycle. The Pulse Modulation technique with 50kHz switching frequency is employed to control the switch. Fig. 6 depicts the V_o (output voltage) and I_o (output current) waveform of voltage doubler based $2LC_m$ -LVD converter. It is investigated that the achieve voltage and current is -239.6V and -0.997A respectively. Thus, -24 voltage conversion ratio (V_o/V_{in}) is noticed at 60% duty cycle. Fig. 7(a) depicts the V_o (output voltage) and I_o (output current) waveform of voltage doubler based $2LC_m$ - $2LVD$ converter. It is investigated that the achieve voltage and current is -389.4V and -0.63A respectively. Thus, -39 voltage conversion ratio (V_o/V_{in}) is noticed at 60% duty cycle. Fig. 7(b) depicts the V_o (output voltage) and I_o (output current) waveform of voltage doubler based $2LC_m$ - $2LCVD$ converter. It is investigated that the achieve voltage and current is -489.3V and -0.48A respectively. Thus, -49 voltage conversion ratio (V_o/V_{in}) is noticed at 60% duty cycle. Fig. 7(c) depicts the V_o (output voltage) and I_o (output current) waveform of voltage doubler based $2LC_m$ - $2LCmVD$ converter. It is investigated that the achieve voltage and current is -489.5V and -0.495A respectively. Thus, -49 voltage conversion ratio (V_o/V_{in}) is noticed at 60% duty cycle. From the discussion done up till now, first it is clear that $2LC_m$ -Y converter topologies have high inverting output voltage. Second, it is investigated that the voltage conversion ratio of $2LC_m$ - $2LVD$ converter is greater than voltage conversion ratio of $2LC_m$ -LVD converter ($G_{2LCm-LVD} < G_{2LCm-2LVD}$). Third, it is investigated that the voltage conversion ratio of converter $2LC_m$ - $2LCVD$ and $2LC_m$ - $2LCmVD$ converters is greater than the voltage conversion ratio of $2LC_m$ - $2LVD$ converter ($G_{2LCm-2LCVD}$ or $G_{2LCm-2LCmVD} > G_{2LCm-2LVD}$). Fourth it is investigated that the proposed voltage doubler based $2LC_m$ -Y converter topologies have greater voltage conversion ratio compared to existing $2LC_m$ -Y (without doubler) category of X-Y converter family. Fifth, among the four voltage doubler based $2LC_m$ -Y power converters topologies, $2LC_m$ - $2LCmVD$ provides a maximum conversion ratio with minimal internal resistance effect.

VI. CONCLUSION

Four new voltage doubler based $2LC_m$ -Y ($2LC_m$ -LVD, $2LC_m$ - $2LVD$, $2LC_m$ - $2LCVD$ and $2LC_m$ - $2LCmVD$) power converter topologies are proposed which provides a acceptable and effective solution for renewable energy applications which required high-voltage/low-current power converter such as a Photovoltaic Multilevel DC-AC converter system (PV-MLI system), renewable High Voltage Direct Current (HVDC) applications, Hybrid Electric Vehicles (HEV) etc. The perceptible characteristics of proposed $2LC_m$ -Y converters are i) Single input source ii) Single controlled semiconductor device iii) High inverting V_o/V_{in} at moderate duty cycle v)

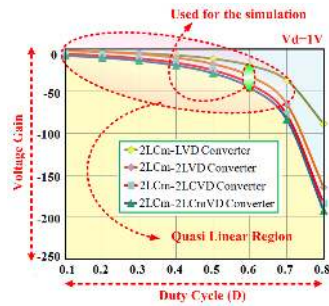


Fig. 5. Voltage conversion ratio versus duty cycle plot of $2LC_m$ -Y converter

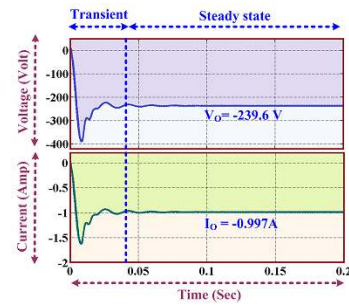
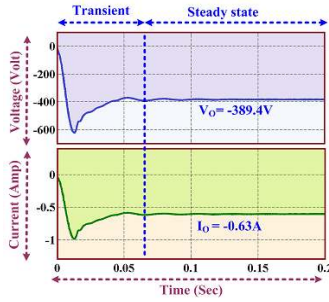
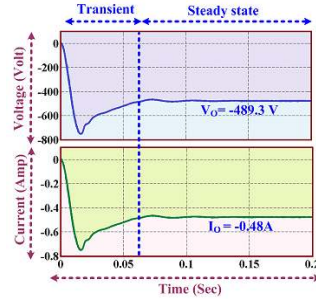


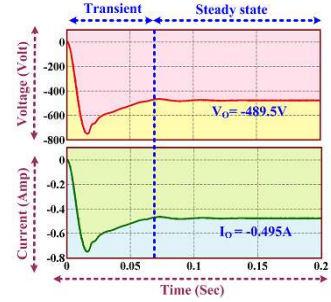
Fig. 6. Numerical Computing Matrix Laboratory 9.0 (R2016a) Simulation Result, $2LC_m$ -LVD converter output current and voltage.



(a)



(b)



(c)

Fig. 7. Numerical Computing Matrix Laboratory 9.0 (R2016a) Simulation Result of proposed $2LC_m$ -Y converter with 10V, 240W, 0.60 duty cycle with 50kHz switching Frequency (a) $2LC_m$ -2LVD converter output current and voltage (b) $2LC_m$ -2LCVD converter output current and voltage (c) $2LC_m$ -2LC_mVD converter output current and voltage.

High-voltage and low-current at the output side of converter v) Minimum internal resistance vi) Transformer-less and coupled inductor-less converter topologies. Numerical software simulation results of proposed converters constantly shows high-quality agreement with hypothetical analysis.

REFERENCES

- [1] F. Blaabjerg, Y. Yang, K. Ma, X. Wang, "Power electronics - the key technology for renewable energy system integration," *Conf. Proc., Intl. Conf. on Renewable Energy Research and Applications, IEEE-ICRERA'15*, pp. 1618–1626, Palermo (Italy), 22-25 Nov. 2015.
- [2] D. Vipin, P. Sanjeevikumar P., V. Karthikeyan, S. Rajasekar, F. Blaabjerg, S. Pierluigi "Recent advances and challenges of fuel cell based power system architectures and control – A review" *Renewable and Sustainable Energy Reviews*, vol. 73, pp. 10–18, Jun. 2017.
- [3] M. S. Bhaskar, S. Padmanaban, F. Blaabjerg, "A Multistage DC-DC Step-Up Self-Balanced and Magnetic Component-Free Converter for Photovoltaic Applications: Hardware Implementation," *Energies*, vol. 10, no. 5, pp. 719, May 2017.
- [4] P. Sanjeevikumar, G. Grandi, P. W. Wheeler, F. Blaabjerg, and J. Lencarski, "A simple MPPT algorithm for novel PV power generation system by high output voltage DC-DC boost converter," *Conf. Proc., 24th IEEE Intl. Symposium on Industrial Electronics, IEEE-ISIE'15*, pp. 214–220, Rio de Janeiro (Brazil), 3–5 Jun. 2015.
- [5] M. Forouzesh, Y. P. Siwakoti, S. A. Gorji, F. Blaabjerg, and B. Lehman, "Step-Up DC-DC Converters: A Comprehensive Review of Voltage-Boosting Techniques, Topologies, and Applications," *IEEE Trans. on Power Electronics*, vol. 32, no. 12, pp. 9143–9178, Dec. 2017.
- [6] S. K. Changchien, T. J. Liang, J. F. Chen, and L. S. Yang, "Step-up DC-DC converter by coupled inductor and voltage-lift technique," *IET Power Electronics*, vol. 3, no. 3, pp. 369–378, May 2010.
- [7] M.-H. Keum, Y. Choi, S.-K. Han, and J.-I. Kang, "High efficiency voltage-clamped coupled-inductor boost converter," *Conf. Proc., 39th Annual Conf. of the IEEE Industrial Electronics Society, IEEE-IECON'13*, pp. 828–833, Vienna (Austria), 10-13 Nov. 2013.
- [8] A. I. Bratu, I. Munteanu, S. Bacha, D. Picault, and B. Raison, "Cascaded DC-DC Converter Photovoltaic Systems: Power Optimization Issues," *IEEE Trans. on Industrial Electronics*, vol. 58, no. 2, pp. 403–411, Feb. 2011.
- [9] F. L. Tofoli, D. d. C. Pereira, W. J. de Paula, and D. d. S. O. Júnior, "Survey on non-isolated high-voltage step-up dc-dc topologies based on the boost converter," *IET Power Electronics*, vol. 8, no. 10, pp. 2044–2057, 2015.
- [10] 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.
- [11] M. S. Bhaskar, S. Padmanaban, F. Blaabjerg, O. Ojo, S. Seshagiri, and R. Kulkarni, "Inverting Nx and 2Nx non-isolated multilevel boost converter for renewable energy applications," *Conf. Proc., 4th IET Clean Energy and Technology Conference, IET-CEAT'16*, 2016, pp. 1–8, Kuala Lumpur (Malaysia), 14-15 Nov. 2016.
- [12] M. S. Bhaskar, R. M. Kulkarni, S. Padmanaban, P. Siano, and F. Blaabjerg, "Hybrid non-isolated and non inverting Nx interleaved DC-DC multilevel boost converter for renewable energy applications," *Conf. Proc., IEEE 16th Intl. Conf. on Environment and Electrical Engg., IEEE-EEEIC'16*, pp. 1–6, Florence (Italy), 7-10 June 2016.
- [13] M. S. Bhaskar, P. Sanjeevikumar, F. Blaabjerg, V. Fedák, M. Cernat, and R. M. Kulkarni, "Non isolated and non-invertingCockcroft-Walton multiplier based hybrid 2Nx interleaved boost converterfor renewable energy applications," *Conf. Proc., IEEE Intl. Power Electronics and Motion Control Conference, IEEE-PEMC'16*, pp. 146–151, Varna (Bulgaria), 25-28 Sept. 2016.
- [14] S. B. Mahajan, P. Sanjeevikumar, P. Wheeler, F. Blaabjerg, M. Rivera, and R. Kulkarni, "X-Y converter family: A new breed of buck boost converter for high step-up renewable energy applications," *Conf. Proc., IEEE Intl. Conference on Automatica, IEEE-ICA-ACCA'16*, pp. 1–8, Curico (Chile), 19-21 Oct. 2016.
- [15] M. S. Bhaskar, S. Padmanaban, R. Kulkarni, F. Blaabjerg, S. Seshagiri, and A. Hajizadeh, "Novel LY converter topologies for high gain transfer ratio: A new breed of XY family," *Conf. Proc., 4th IET Clean Energy and Technology Conference , IET-CEAT'16*, pp. 1–8, Kuala Lumpur (Malaysia), 14-15 Nov. 2016.