Implementation of High-Gain Medium-Voltage DC- DC Converters for High-Power PV Applications

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Abstract: Medium-Voltage (MV) DC grids for collecting and integrating Photovoltaic (PV) systems offer an effective solution to overcome the problems introduced due to AC grid. The directcon version of the PV power to MV DC grid increases the efficiency and reduces the cost when compared to MV AC grid. In MV DCgrid connected PV systems, a high gain DC-DC converter isrequired to convert the unregulated PV DC voltage to a regulated MV DC voltage. In this paper, voltage Re-Lift and Super Re-LiftLuo converters, are used as high-gain DC-DC converters to integrate the solar energy into the MV DC grid. Design, modelling and analysis of the operation of these converters at MV high power levels are presented. Also, performance assessment for thetwo different DC-DC converter topologies is conducted. Both the voltage Re-Lift and the Super Re-Lift Luo converters have high output voltage transfer gain, high power density, high efficiency,and high output voltage with small ripples. However, the Voltage-Lift Luo converter increases the output voltage in arithmetic progression, while the Super Lift Luo converter increases the output voltage in geometric progression. Digital simulations arecarried out to validate the analysis and the comparison of the two converters performance using Matlab/Simulink platform for10kV DC grid and 1MW PV power plant.

Keywords—PV; MV; DC grid; DC-DC converters; Voltage-Lift;Voltage Re-Lift; Voltage Super Re-Lift, Maximum Power-Point Tracking (MPPT).

I. INTRODUCTION

During the previous years, Photovoltaic (PV) power age framework has extended fundamentally around the world, particularly in lattice associated applications, giving high force that is relied upon to reach up to 100 GW [1]. Inferable from the cost decrease in PV frameworks, they are assuming a significant part in power market. In expansion, the establishment of enormous scope PV plants is altogether developing, which are commonly associated with AC matrices. In AC framework, concentrated inverters and low recurrence voltage venture up transformers are utilized to coordinate PV frameworks into AC lattice [2],[3]. In reconciliation of enormous scope PV frameworks to AC matrix, a single DC-AC change stage plan might be utilized since it lessens power misfortunes, framework cost, and the framework size. Notwithstanding, the general effectiveness might be diminished because of fractional concealing. As needs be, in the event of halfway concealing, the two transformation stages have higher effectiveness extraordinarily with utilizing Greatest Power Point Tracking (MPPT) calculation. Be that as it may, because of the significant expense and force quality unsettling influences, this plan is normally utilized in little and medium scale PV frameworks.

Besides, in AC network associated PV frameworks, receptive force pay, significant distance transmission, and thunderous issues speak to the principle challenges influencing the matrix unwavering quality and security [2],[4]. As a compelling answer for defeat the AC lattice associated PV framework inadequacies, Medium-Voltage (MV) DC matrix associated PV framework has been proposed [5]. To further outline, the immediate change of PV capacity to MV DC matrix with straightforward structure will expand the effectiveness and decrease the expense when contrasted with MV AC network associated framework in utility scale PV plant applications. What's more, expanded power age and consistent activity are additionally given. Like MV AC frameworks, a couple of change plans can be utilized for DC-DC voltage transformation. In MV DC matrix associated PV frameworks, a significant part is the high increase, high recurrence DC-DC transformation framework that is utilized to change over factor and unregulated PV DC voltage to a directed MV DC voltage [2]. Right now, broad examinations are being directed on DC-DC converters for MV DC lattices with the turn of events and organization of sustainable power sources, for example, wind turbines furthermore, PV plants [6]-[9]. Numerous geographies have been examined for this application, and can be isolated into two primary sorts, separated and non-secluded DC-DC converters. The disconnected sort requires low voltage semiconductor gadgets at the info side, with the benefit of galvanic separation arrangement. Regardless, the plan of transformer at MV and high-power levels may be complex [10]. However, non-secluded DC-DC converter gives a voltage venture up without the necessity of transformer. In [11], non-detached DC-DC converter geography was presented, which depends on the notable lift converter geography, where silicon carbide gadgets are utilized to help the converter productivity what's more, to support MV levels. In spite of the fact that the aftereffects of the lift converter with silicon carbide MOSFETs indicated a productivity of 98.5% with 30kW force rating converter, yet the voltage and current constraints of the exchanging gadgets are as yet an issue. The utilized gadget has voltage and current rating of 10kV and 10A, which would restrict the chance of interfacing PV strings in equal for bigger current. Another geography was presented in [12], which depends on half and half mix of lift and buck/support converter for accomplishing high advance up voltage increase, through arrangement association between them for seaward wind ranch application. High voltage gain is accomplished utilizing numerous modules of singleswitch single-inductor converter, with the end goal that if a solitary module comes up short, the converter would keep working with less force level. In [13], the thunderous advance up (RS) was presented, thataccomplishes the progression up proportion utilizing an inductor and a capacitor. This converter geography diminishes the misfortunes by accomplishing delicate exchanging, along these lines taking out the side road and opposite recuperation misfortunes. In [10], Resonant Switched-Capacitor (RSC) was proposed as a DC-DC step converter, which diminishes the misfortunes through delicate exchanging for all the switches and diodes by Zero Current Switching (ZCS). The exchanging recurrence is made equivalent to the resounding recurrence. The zero current exchanging is accomplished by having all the flows in the resounding inductors arriving at zero, subsequently getting delicate exchanging. Accordingly, exchanging misfortunes are diminished and higher exchanging recurrence activity is conceivable. Because of the parasitic components impact, the DC-DC converters' yield voltage and force move effectiveness are limited. Consequently, the Voltage-Lift (VL) strategy is broadly used to improve the attributes of the DC-DC converters by expanding their yield voltage [13]. The VL is a straightforward methodology that can be utilized to plan converters with high voltage gain by expanding the voltage stage by stage in number-crunching movement. It tends to be applied to Luo-converters which are a progression of DC-DC converters [14]. These converters make change with DC-DC voltage boosting at high force thickness, high productivity, and high yield voltage with little waves in a modest and basic structure. They are grouped dependent on the quantity of their capacity stages; for instance, the rudimentary circuit (one force stage), Re-Lift circuit (two force stages), triple-lift circuit (three force stages), and so forth. There is likewise the Super Lift (SL) strategy which is more incredible when contrasted with the VL procedure. The SL strategy can likewise be applied to the Luo-converters to deliver the SL Luo converters that have a few merits, for example, high voltage move increase, expanding the yield voltage in mathematical movement, high effectiveness, high force thickness, and diminished swells for voltage and current [13].

In this paper, the two geographies utilizing Luo converters (voltage Re-Lift and Super Re-Lift) will be planned, demonstrated what's more, examined to interface enormous scope PV age framework to MV DC network, where execution appraisal is directed centering on non-separated unidirectional DC-DC converters. The converter ventures up the voltage from 1kV to 10 kV, with a force rating of 1MW. Hypothetical investigation, reproduction and examination of the achievability of the two converters for the reconciliation of the PV energy to MV DC framework are introduced in this paper. The association of this paper is as per the following: Section I presents the presentation, while segment II examines the DC-DC converters geographies and their displaying. Reproduction results for the two geographies are introduced in segment III. At last, area IV finishes up the paper.

II. DC-DC CONVERTERS TOPOLOGIES

In this section, the mathematical analysis of Re-Lift andSuper Re-Lift Luo converters is carried out assuming steadystate and Continuous Conduction Mode (CCM) operation of the converters, where is the conduction k duty cycle, fs is theswitching frequency, T is the switching period, R is the resistiveload, Vin and Iin are the input voltage and current, respectively,and Vo and Io are the output voltage and current, respectively. Inaddition, the analysis is carried out assuming no power losseswhere; $VinIin = VoIo$. Fig. 1 shows the general structure of thesystem with PV operating at the Maximum Power Point (MPP).

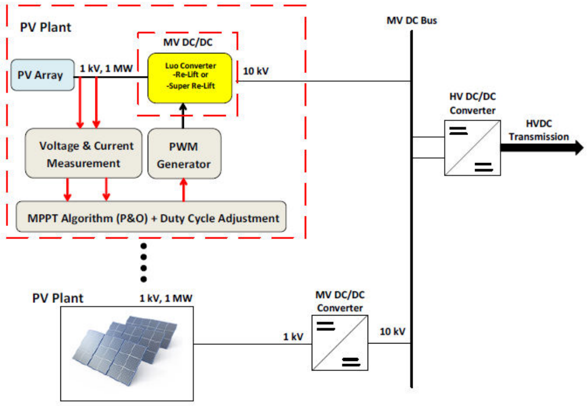

Fig. 1. General block diagram of the addressed MV DC network (1kV isassumed the voltage of the MPP of the installed PV).

A. Positive Output Re-Lift Luo Converter TopologyVoltage-Lift strategy, specifically the Re-Lift geography, is planned here for MV DC-DC converter. The Voltage-Lift strategy approach builds the yield voltage while surviving the parasitic components impacts. This strategy offers basic structure DC-DC converter of high-voltage gain with high productivity and high force thickness [15]. The Voltage-Lift approach activity depends on charging a capacitor during the switch-on period by the source voltage. While during the switchoffthis charged voltage is organized on top-up to the yield voltage, driving the yield voltage to be supported, and this activity is called self-lift. The Re-Lift circuit included extra capacitor charging by a specific voltage or the source voltage, and afterward the charged voltage is orchestrated on top-up to the yield voltage. The Voltage-Lift geographies are utilized in numerous kinds of Luo-converters, which offer high yield voltage with diminished waves. Positive yield Luo-converter of Re-Lift innovation will be utilized as a possibility for medium voltage DC-DC plan. The circuit graph for Re-Lift geography is appeared in Fig. 2, where the switches are driven by Pulse Width Modulation (PWM) sign of recurrence fs .

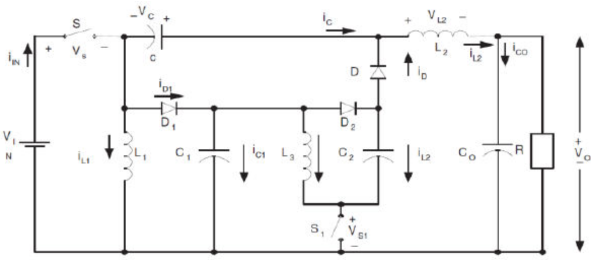

Fig. 2. Re-Lift circuit diagram.

The equivalent switch-on and off for the Re-Lift circuit isshown in Fig. 3 and Fig. 4. The lift elements in the circuit consistof D1, C1, L3, D2, S1, and C2. The capacitors C1 and C2 lift thecapacitor voltage Vc twice the source voltage. The inductor L3acts as a ladder joint for connecting C1 and C2 and lifting thecapacitor voltage Vc.

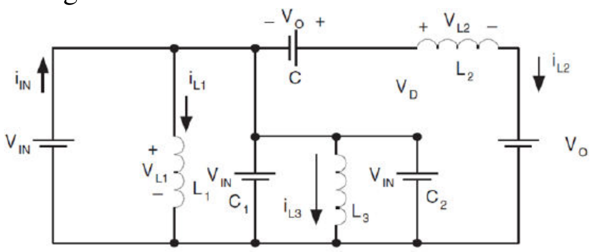

Fig. 3. Re-Lift circuit diagram during switch on period.

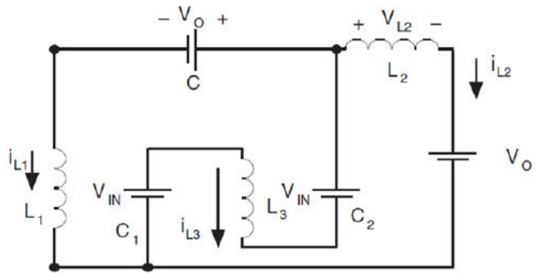

Fig. 4. Re-Lift circuit diagram during switch off period.

The voltage gain in terms of input/output voltage, $Vi_n$and Vo, is as follows [16]:

$$V_o = \frac{2}{1-k} V_{in} \quad (1)$$

This relationship is obtained by finding the relation betweenVL3,off and Vin as shown below through finding Δi3 during the onand off period.

$$V_{L3,off} = \frac{K}{1-k} V_{in} \quad (2)$$

Then finding the relation between Vc and Vin shown belowby solving KVL for VL1during on and off period.

$$V_c = \frac{2}{1-k} V_{in} \quad (3)$$

Finally, applying KVL for solving with respect to VL2 during
the on and off period, while using (2) and (3) to find directrelation between Vo and Vin as shown in (1) [16].
The average inductor currents can be expressed as shown in(4) and (5), while the capacitance *Co* is expressed as shown inTable I.

$$I_{L1} = I_{L2} = \frac{2}{k} I_{in}$$

$$I_{L3} = \frac{1}{1-k} I_o \quad (5)$$

The design equations for the Re-Lift circuit is listed below,while assuming $fs = 1\ kHz$, $G = 10$,$k = 0.8$, $Vin = 1kV$, Vo= $10kV$, $Po = 1\ MW$.

TABLE I. DESIGN EQUATIONS FOR RE-LIFT CIRCUIT

Design Equations	
$Gain\ = G = \frac{2}{1-k}$	
$L_n = \frac{V_{in} k T}{\Delta i_{Ln}}, n = 1,2,3\ , C_n = \frac{G V_{cn}}{Rf\ \Delta V_o}, n = 1,2$	
$\Delta i_L = \frac{V_{in} D T_s}{L_{design}}; \Delta i_L = 20\% I_{Ln}$	
$C_n = \frac{G V_{cn}}{Rf\ \Delta V_o}, n = 1,2$	
$C = \frac{k V_c}{Rf\ \Delta V_o}$	
$C_o = \frac{2k V_o}{8 \times G f^2 L_2 \Delta V_o}$	
$\frac{\Delta v_o}{V_o} = \frac{\Delta V_{cn}}{V_{cn}} \leq 0.5\%, n = 1,2$	
Design Calculations	
I_{in}	$1\ kA$
I_o	$100\ A$
L_1	$20\ mH$
L_2	$80\ mH$
L_3	$16\ mH$
Δi_{L1}	$40\ A$
Δi_{L2}	$10\ A$
Δi_{L3}	$50\ A$
$C_1 = C_2$	$4\ mF$
C	$0.2\ mF$
C_o	$0.8\ mF$
$\Delta v_{C1} = \Delta v_{C2}$	$25\ V$
Δv_o	$125\ V$

B. Positive Output Super Re-Lift Luo Converter Topology

Super Re-Lift (SL) technique is more powerful whencompared to the VL technique since it provides high voltagetransfer gain. The output voltage in SL technique increases ingeometric progression, however, the output voltage in VLtechnique increases in arithmetic progression.

The following figures show the Super Re-Lift circuitdiagram, in addition to the equivalent circuit during switch onand switch off respectively.

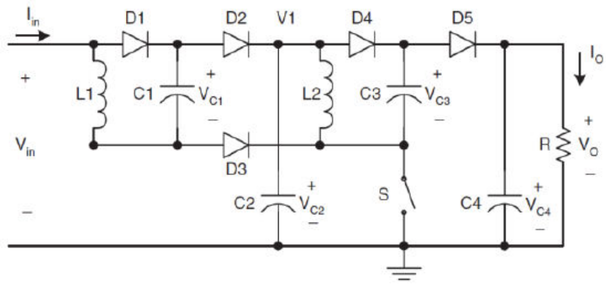

Fig. 5. Super Re-Lift circuit diagram.

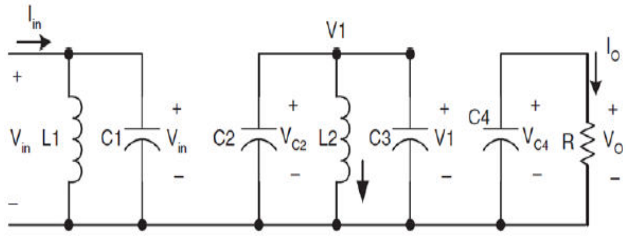

Fig. 6. Super Re-Lift circuit diagram during switch on period.

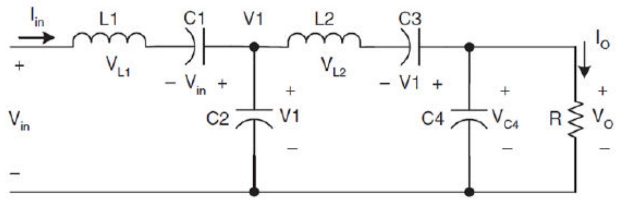

Fig. 7. Super Re-Lift circuit diagram during switch off period.

III. SIMULATION AND RESULTS

In this section the Re-Lift and Super Re-lift simulationresults are presented assuming the PV operates at the MPP anddelivering 1 MW.

A. Positive Output Re-Lift and Super Re-Lift Luo ConverterSimulation

The Re-Lift and Super Re-Lift converters design are testedwith an output power of 1MW and output voltage of 10kV forthe Medium-Voltage design, with the design equationspresented in the proposed system section. The PV MPP isassumed to be obtained at 1kV. Therefore the maximumrequired achievable step-up ration is assumed 1:10. Thecapacitors voltage waveform and inductors current waveformsare shown in Fig. 8 for the Re-Lift converter and in Fig. 9 for theSuper Re-Lift converter.

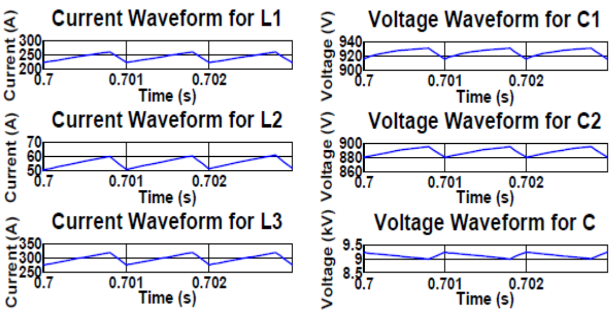

Fig. 8. Re-Lift inductor currents and capacitor voltages waveform with designcriteria of input 1 kV and output 10 kV, at 1MW.

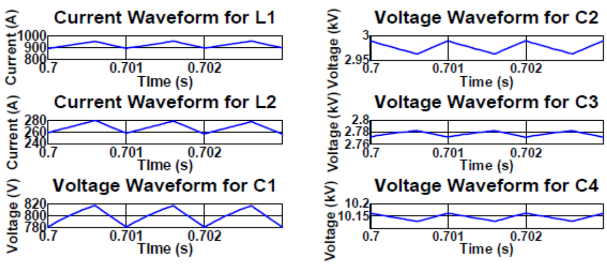

Fig. 9. Super Re-Lift inductor currents and capacitor voltages waveformwith design criteria of input 1 kV and output 10 kV, at 1MW.

TABLE II. SIMULATION RESULTS

Parameters	Re-Lift		Super Re-Lift	
Switches Voltage Rating	V_{s1}, V_{s2}	4.5 kV	V_s	7.2 kV
Diodes Voltage Rating	V_{D1}, V_{D2}		V_{D1}, V_{D2}	2.03 kV
			V_{D3}	5 kV
	V_{D3}	9 kV	V_{D4}, V_{D5}	7.04 kV
Capacitor Voltage Ripple	$\Delta V_{C1}, \Delta V_{C2}$	14.8 V	ΔV_{C1}	37 V
			ΔV_{C2}	27 V
	ΔV_C	235V	ΔV_{C3}	10 V
			ΔV_{C4}	35 V
Inductor Current Ripple	Δi_{L1}	37.5 A	Δi_{L1}	60 A
	Δi_{L2}	9.24 A	Δi_{L2}	20 A
	Δi_{L3}	44.4 A		

The simulation results for the two converters presented inTABLE II. illustrates the voltage stress across the switches andin the Re-Lift converter are imposed to less voltage stress. Incontrast, the diodes in the Super Re-lift converter are subjectedto lower voltage stress. Moreover, the current ripple content forthe inductors and the capacitors voltage ripple at the input sideof the Re-Lift converter are less compared to the Super Re-Liftconsidering the same design constraints. However, the outputside capacitor voltage ripples are less for the Super Re-Lift.

IV. CONCLUSION

This paper tends to the association of 1MW PV framework to a 10kV MV DC matrix through high-power DC-DC converters. The framework is mimicked utilizing two distinctive circuit arrangements for Luo converters which are the voltage Re-Lift also, the Super-Lift converters. The framework is recreated expecting that the PV clusters are conveying a most extreme intensity of 1 MW, also, the converters in both contextual investigations fill in as step up converters to help the voltage from 1 kV (voltage of PV MPP) to 10 kV. Hypothetical examination, reenactment and correlation of the possibility of the two converters for the incorporation of the PV energy to MV DC matrix are introduced. The switches in the Re-Lift converter are forced to less voltage stress. Conversely, the diodes in the Super Re-lift converter are exposed to lower voltage stress. Additionally, the current wave content for the inductors and the capacitors voltage swell at the information side of the Re-Lift converter are less contrasted with the Super Re-Lift. Nonetheless, the yield side capacitor voltage swells are less for the Super Re-Lift.

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