High Step-up Voltage High Efficiency Boost Converter – a review

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Abstract - The renewable energy sources such as fuel cells, PV cells or energy storage devices such as super capacitors or batteries deliver output voltage at the range of around 12V to 70V DC. In order to connect them to the grid or to use for three phase load, the voltage level should be adjusted according to the electrical network standards. First of all the voltage should be stepped up to sufficient level at which the DC/AC conversion can be performed to AC mains voltage requirements. Overall performance of the renewable energy system is then affected by the efficiency of step-up DC/DC converters (especially boost converter), which are the key parts in the system power chain. This review is focused on high step-up voltage and high efficiency DC/DC converters with high voltage gain boost converter. A comparison and discussion of different DC/DC step-up topologies will be performed across number of parameters and presented in this paper.

Index Terms - High step-up, high efficiency, DC/DC converter, renewable energy, MPPT

I. INTRODUCTION

Energy consumption tends to grow continuously now a day in many countries. To satisfy the demand for electric power against a background of the depletion of conventional, fossil resources the renewable energy sources are becoming more popular [1, 2]. According to the researches [3, 4] despite its fluctuating nature and weather dependency the capacity of renewable resources can satisfy overall global demand for energy. The international investments and R&D efforts are focused on reduction of renewable energy production cost. Thanks to these activities the contribution of renewable energy continuously increases in overall energy consumption budgets [2].

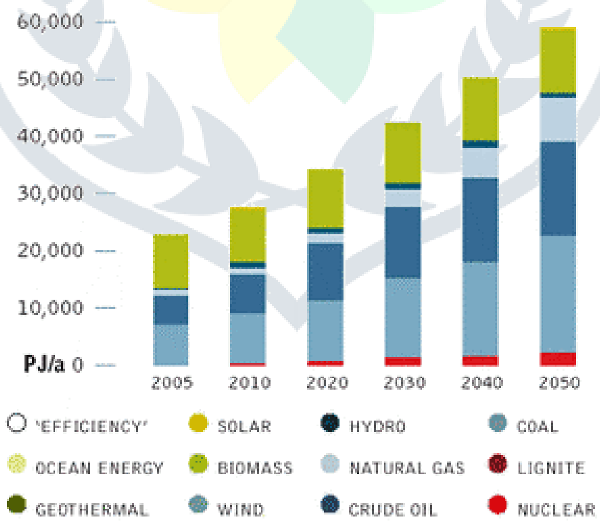

Fig. 1 India Energy Consumption Scenario

High gain Boost converters are the key part of renewable energy systems (Figs. 2, 3). The designing of high gain Boost converter is imposed by severe demands. Designers face contradictory constraints such as low cost and high reliability.

First of all the inverters must be safe in terms of further maintenance as well as in relation to the environment. Since the renewable sources can be utilized for many years the converter designers cope with long time reliability issues [3-5]. The main problem for the operator is to maximize the energy yield and to minimize the maintenance. For these reasons the converters must be distinguished by high efficiency over wide input power and voltage range. High voltage gain is required to produce sufficient

DC bus voltage level. Such demands create severe constraints for DC/DC boost converter designing which are key parts in terms of efficiency of overall renewable energy systems [6–32].

The majority of commonly used renewable energy sources deliver electric power at the output voltage range of 12 VDC to 70 VDC.

To adjust it to the electric grid standards that voltage should be boosted to the system DC Bus voltage of around 200V DC or 400V DC depending on the grid requirements (Fig.3). Power conditioning can be accomplished by high efficiency high voltage gain step-up DC/DC converters.

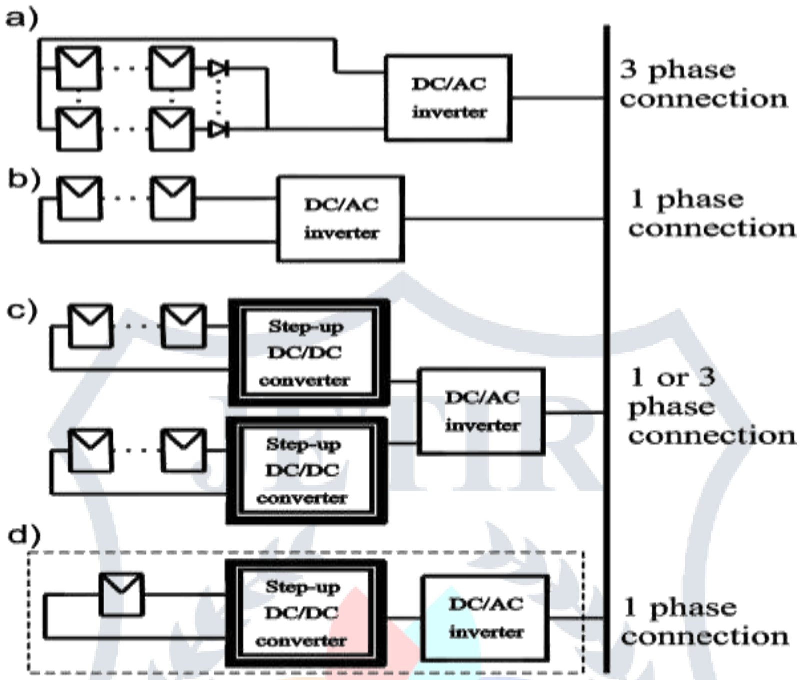

Fig. 2 Historical overview of PV inverters after Ref.28

In the past one centralized inverter was responsible for connecting several modules or other renewable energy sources into the grid. The PV modules were divided into series connections, so called strings. Each module was generating high voltage sufficient to avoid further amplification Fig. 2a.

At the moment, string technology is dominating. Centralized technology has been replaced and two standards are currently used. The first technology comprises separate strings attached to one DC/AC inverter connected directly to the grid Fig. 2b. The sub-type of string technology is called multistring technology Fig. 2c with separate DC/DC converter that supports a panel or panel structure. Then DC/DC converter is attached to the DC/AC inverter which is coupled to the grid (1-or 3-phase).

The string inverter is nothing but the reduced version of the technology seen on (Fig. 2a) – one string corresponds to a single inverter. While technologies (2b), (2c) and (2d) are currently used, a better choice seems to be a multi-string (2c). Since every string can be controlled individually thus the solar panels can be utilized more efficiently. This provides greater flexibility and facilitates the control and occasional replacement of individual panels. On Fig. 2d we can see the synthesis of the inverter and PV module into one electrical device. This technology has only one PV module so individual Maximum Power Point Tracking (MPPT) system for each inverter is needed [14]. Expandability of the system and opportunity to become a "plug-and-play" device is undoubtedly part of the benefits. There are no bypass or string diodes necessary. Each panel in this structure has its own MPPT controller which maximizes the power production. Module structure Fig. 2d. has one major disadvantage which is low efficiency due to high voltage amplification, so the price per watt is the largest of the four topologies discussed. This review therefore highlights the highest efficiency step-up converter topologies. Evolution of PV inverters is described in detail in the literature [28].

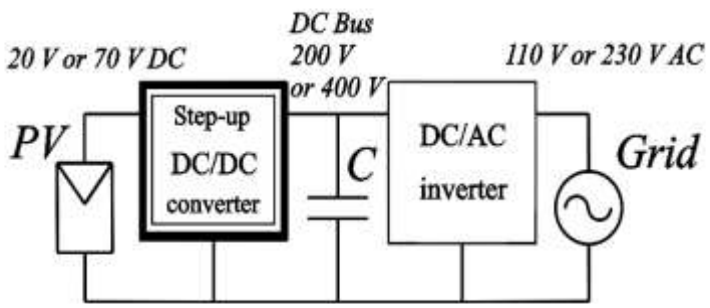

Fig. 3 The example of PV inverter with integrated DC/DC step-up converter

II. COMPARISION OF DC-DC BOOST CONVERTER

III. In order to satisfy the requirements with performance in renewable energy applications, many researchers concentrate on high voltage gain step-up, low cost and high efficiency single-stage converters [12]. They provide the voltage gain up to 20 using coupled inductors or switched capacitor technique. Usually the efficiencies of high voltage gain step-up converters are at the levels over 90% at sub kilowatt or single kilowatt powers. To increase the overall efficiency of converter soft switching technique [8] as well as active clamped circuit [12] introduction may be considered.

Boost converter. The single phase single switch boost converter is a basic step-up topology [32] (Fig. 4). The voltage gain theoretically is infinite when duty cycle reaches 1. But switch turn on period becomes long as the duty cycle (D) increases causing conduction losses to increase. The power rating of single switch boost converter is limited to switch rating. In order to obtain higher gain several boost converters can be cascaded at the expense of efficiency decrease. Interleaved parallel topology is the solution to increase the power and reduce input current ripple allowing lower power rated switches to be used.

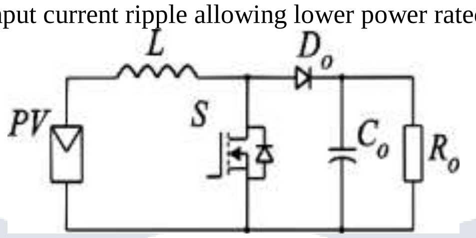

Fig. 4 Single cell boost converter

Interleaved boost converters. The simplicity is major advantage of that topology (Fig. 5) [6]. Since interleaved boost converter cells share the input current the input current ripples are small which increases the life of PV modules. Moreover single cell feeds only the fraction of total input current and the duty cycle of a single switch does not exceed 0.25. Smaller inductors can be used along with the power rating of switches and diodes decrease. When driving sequentially switches are switched on and off one by one enabling low output voltage ripples. The diode reverse recovery current flow when the diodes are switched off causes electromagnetic noise (EMI). To overcome that problem discontinuous inductor current driving mode should be used. In the other hand continuous inductor current mode demonstrates lower input current ripples as well as lower switching losses. The main disadvantage of that topology is relatively low voltage gain, usually not higher than 2. To improve voltage gain interleaved structures can be mixed with transformers [27] or the inductors can be coupled [10, 11, 16].

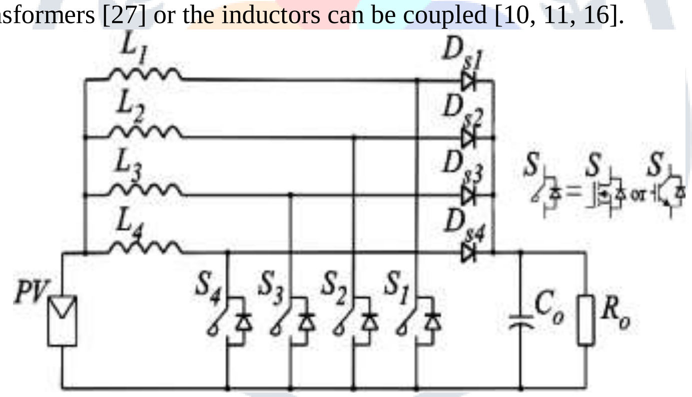

Fig. 5 Four cell interleaved boost converter

Soft switching boost converters. This high performance converter (Fig. 6), [7] has slightly improved voltage gain in comparison to single switch boost converter. It operates in ZVS (Zero Voltage Switching) mode dramatically reducing switching losses thus achieving better efficiency. The driving sequence is bit more complex, but both switches operate at the same ground potential thus additional separation at driver side is needless. The disadvantage of that topology is the complexity of the circuit, because of 5 more components addition including a switch and an extra inductor.

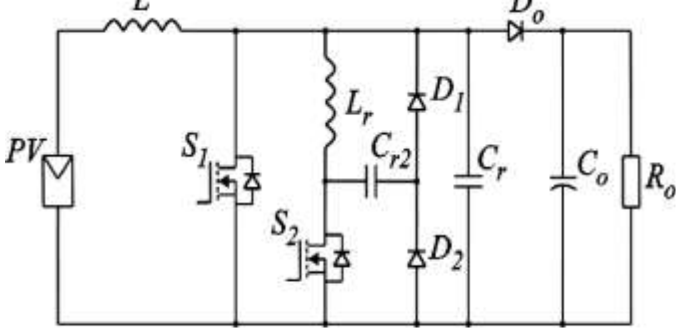

Fig. 6 Soft switching boost converter

Coupled inductor structures. Coupled inductor can serve as a transformer to enlarge the voltage gain in non-isolated DC/DC converters in proportion to winding turns ratio (Fig. 7). These converters can easily achieve high voltage gain using low RDS−on switches working at relatively low level of voltage. The switch driving scheme is simple as the converter usually utilizes single switch. Common mode conducted EMI is reduced due to balanced switching. To reduce passive component size coupled inductors can be integrated into single magnetic core [12].

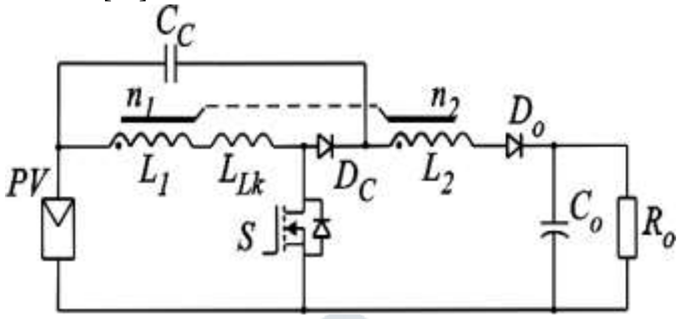

Fig. 7 Coupled inductor step-up converter

Boost, fly back or charge-pump topologies or the combinations of any of them (Fig. 8) can be utilized achieving the efficiency better than 95% [9, 10, 15]. However, the voltage gain can be easily achieved by turns-ratio of coupled inductors the leakage energy induces high voltage stress and switching losses. Thanks to the active clamp circuit used the leakage energy can be recycled. The other benefits of presented circuit are wide input voltage range, high voltage gain and low cost simultaneously.

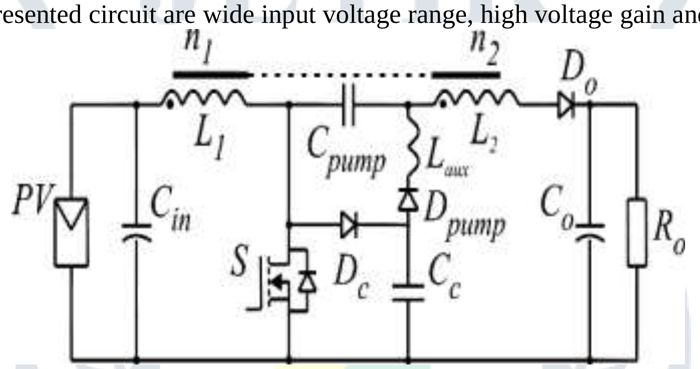

Fig. 8 Coupled Inductor Step-up Converter with Charge Pump

At kilowatt power level the power dissipation within the components becomes an important issue especially in case of inductive components. Interleaved solutions can tackle that problem as the input current is shared between the cells.

Interleaved Step-up Converter with Voltage Multiplier Cell. In presented topology (Fig. 9) high voltage gain can be achieved without extreme duty cycles adjusting the turn's ratio of two same coupled inductors [11]. That straightforward topology utilizes current sharing technique at the input allowing the use of smaller inductors and lower power rated switches. The voltage multiplier cell composed of two diodes, capacitor and secondary windings of coupled inductors is inserted in conventional interleaved boost converter structure. Low RDS−on switches can be used to improve the converter performance. Presented circuit works in turn-on ZCS (Zero Current Switching) mode which reduces switch losses as well as EMI noise.

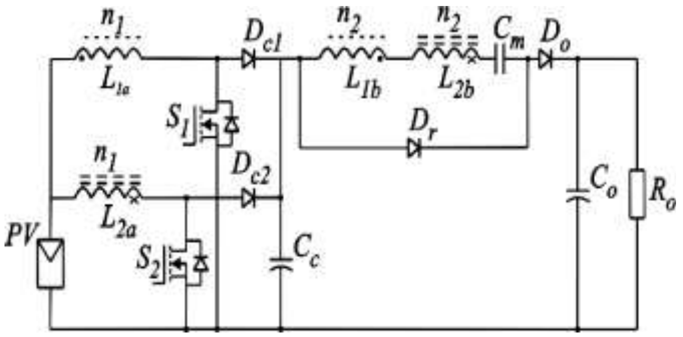

Fig. 9 Interleaved step-up converter with voltage multiplier cell

Isolated boost converter with coupled inductors. Proposed topology satisfies high efficiency and high voltage gain in combination with isolation requirements (Fig. 10). In order to share large input current and conduction losses parallel circuit is adopted. Output inductors are connected in series to double an output voltage gain.

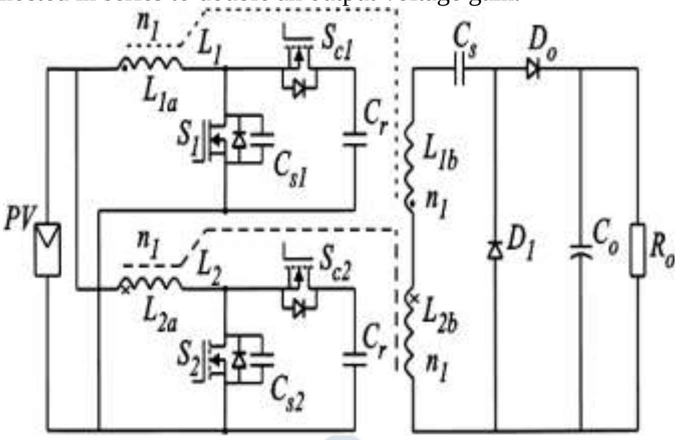

Fig. 10 Coupled inductors isolated boost converter

The switching losses are reduced and efficiency improved by applying active clamp technique. ZVS soft switching mode is implemented leveraging the efficiency [16]. Because of the inductor used in the other hand there is the limitation as to the maximum operating temperature above which the magnetic core loses its magnetic features.

Table 1

Topology	Figure	Efficiency (%)	P_{MAX} [kW]	Gain [V/V]	f_S [kHz]	V_I [VDC]	V_{BUS} [VDC]	No of Switches	No. of Diodes
[6]	(5)	97.3	2.50	1.3	25	250	320	4	4
[7]	(6)	96.2	0.60	3.0	30	130 to 170	400	2	3
[8]	-	95.4	0.50	2.5	300	80	200	1	4
[9]	(8)	97.0	0.80	8.0	100	24 to 38	200	1	3
[10]	(6)	97.4	0.22	10.0	85	20 to 70	200	1	3
[11]	(9)	94.7	1.00	9.5	100	40 to 56	380	4	2
[13]	(11)	94.0	0.45	5.6	100	12	68	12	0
[15]	(7)	92.3	1.00	8.0	100	48 to 75	380	1	2
[16]	(10)	94.7	1.00	9.5	100	40 to 56	380	4	2

Non inductive solutions. Avoiding the transformers brings obvious benefits of size, cost and weight reduction thus the reduction of overall complexity of the converter. The other advantage is the possibility to work at higher temperatures than inductor based counterparts. Recently there has been a new converter developed [13] which meets the requirements of high efficiency and ability to work in high temperatures (Fig. 11). The voltage gain is accomplished by voltage multiplier cells that operate basing on switching capacitor principle. The penalty is relatively big number of switches, which is in this case 12. Moreover, due to capacitive load the switches are exposed to high current stress.

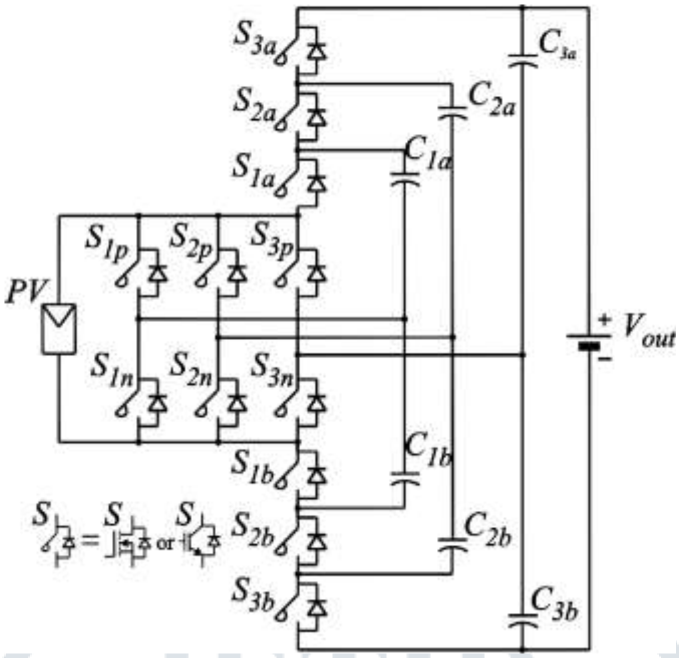

Fig. 11 Multilevel switched capacitor DC/DC Converter

The possibility to use low voltage rated switches and the lack of inductors make it possible to achieve the compact and cost effective solution. Comparison of different boost converter prototype is given in below Table 1.

III. Acknowledgment

This work is done for getting idea and usefulness of high step-up voltage, high efficiency with low losses in power electronics switches for the use of renewable energy source and to get interest to small industries that they can use this type of technique to save long time energy cost with small initial cost and to increase use of renewable energy. Also this work indicates use of soft switching technique for various purpose in different switching equipment also.

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