

High efficiency high step-up DC/DC converters – a review

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Abstract. The renewable energy sources such as PV modules, fuel cells or energy storage devices such as super capacitors or batteries deliver output voltage at the range of around 12 to 70 VDC. In order to connect them to the grid the voltage level should be adjusted according to the electrical network standards in the countries. 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, which are the key parts in the system power chain. This review is focused on high efficiency step-up DC/DC converters with high voltage gain. The differentiation is based on the presence or lack of galvanic isolation. A comparison and discussion of different DC/DC step-up topologies will be performed across number of parameters and presented in this paper.

Key words: high efficiency, high step-up, DC/DC converter, renewable energy.

1. Introduction

Global energy consumption tends to grow continuously. 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 (Fig. 1), [2].

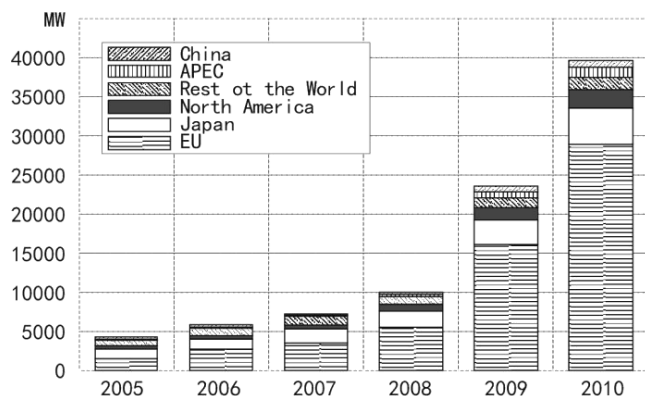


Fig. 1. Cumulative PV installed capacity 2005 to 2010 (source: EPIA: www.epia.org)

High gain DC/DC converters are the key part of renewable energy systems (Figs. 2, 3). The designing of high gain DC/DC converters 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 (usually ten-fold) is required to produce sufficient DC bus voltage level. Additionally they should operate at wide temperature range expressing low EMC emission and be immune to environmental conditions. 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].

Although the European standard EN 61000-3-2 discusses mainly the power quality issues, it influences designing of all power supply equipment [1]. Since single phase converter can be connected to low-voltage AC public mains distribution system (grid) it should be complied with that standard. The EN 61000-3-2 gives the constraints as to the maximum power which can be drawn from (or delivered to) the grid. According to that standard the electric and electronic equipment can draw up to 16 A of current from the mains thus its maximum rated power is at the level of 3.7 kW (i.e. 230 V of AC line voltage times 16 A). That is why this investigation will be focused on the area of DC/DC boost converters with the maximum power of 3.7 kW. To complete the standard discussion it has to be mentioned that IEEE 1547 [3], IEC 61727 and NEC 690 summarize all interconnection related issues, such as power quality, operation, safety considerations, testing, and maintenance of the grid to renewable energy system connection.

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

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around 200 VDC or 400 VDC depending on the grid requirements (Fig. 3). Power conditioning can be accomplished by high efficiency high voltage gain step-up DC/DC converters. In this article two major topology types of step-up converters will be reviewed. However topologies presented in this paper can work with all low voltage renewable energy sources the review will cover the converters working with PV (photovoltaic) systems.

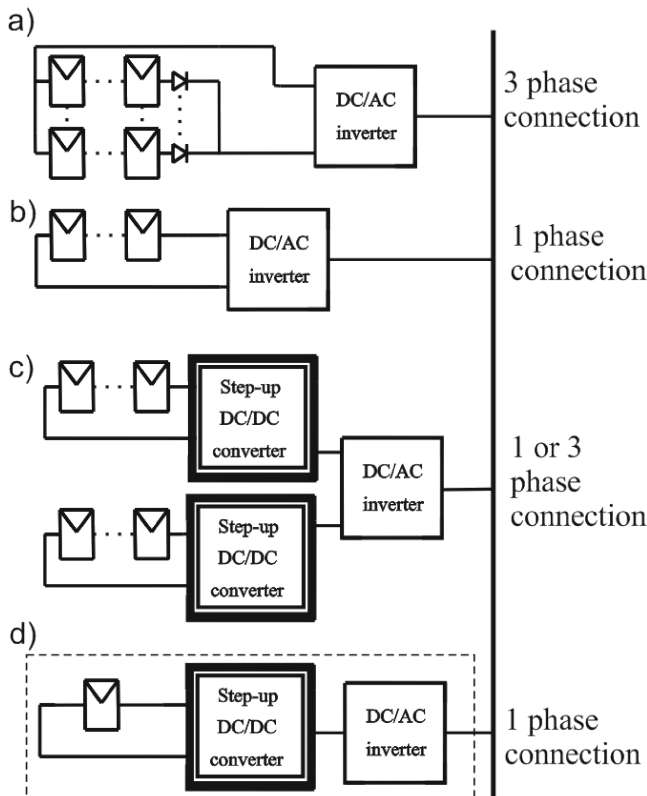


Fig. 2. Historical overview of PV inverters after Ref.28

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 multi-string 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 pro-

vides 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.

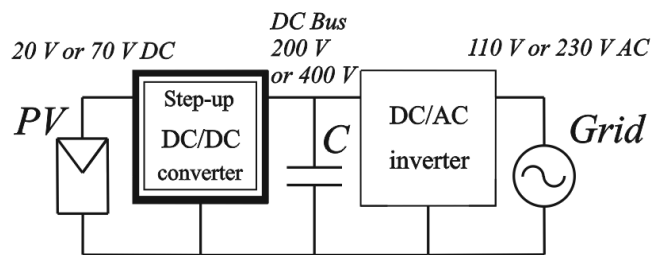


Fig. 3. The example of PV inverter with integrated DC/DC step-up converter

Evolution of PV inverters is described in detail in the literature [28].

2. Comparison of DC-DC boost converters

2.1. Transformerless solutions. In order to satisfy the stringent requirements with performance in renewable energy grid-connected power applications, many researchers concentrate on how to realize high voltage gain step-up, low cost and high efficiency single-stage converters [12]. The brief comparison of available single-stage transformerless converters will be presented below. 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.

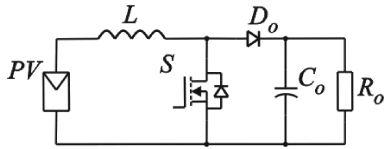


Fig. 4. Single cell boost converter

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].

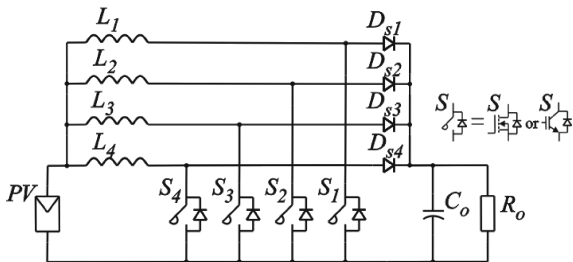


Fig. 5. Four cell interleaved boost converter

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.

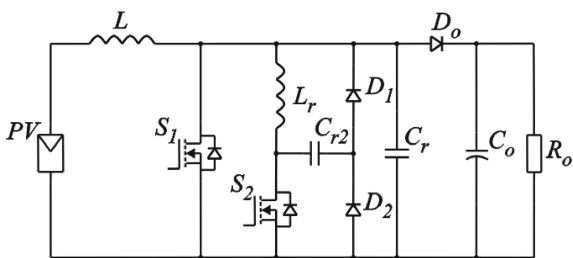


Fig. 6. Soft switching boost converter

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 R_{DS-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].

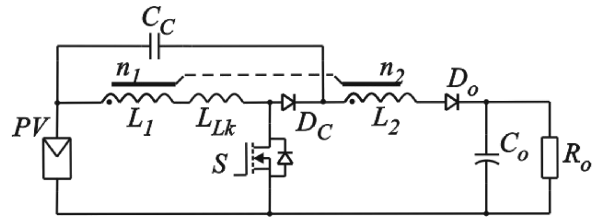


Fig. 7. Coupled inductor step-up converter

Boost, flyback 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.

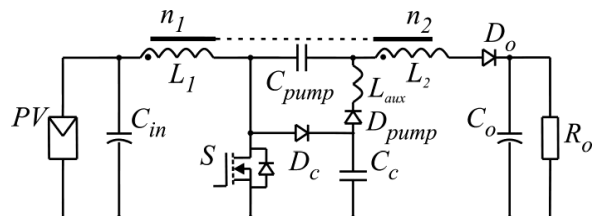


Fig. 8. Coupled Inductor Step-up Converter with Charge Pump

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 turns-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 R_{DS-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.

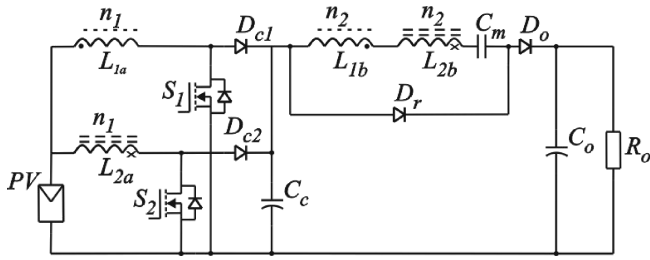


Fig. 9. Interleaved step-up converter with voltage multiplier cell

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.

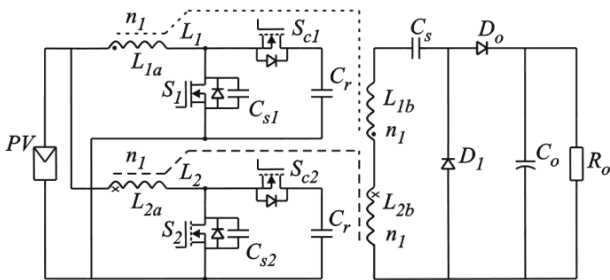


Fig. 10. Coupled inductors isolated boost converter

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.

Noninductive 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.

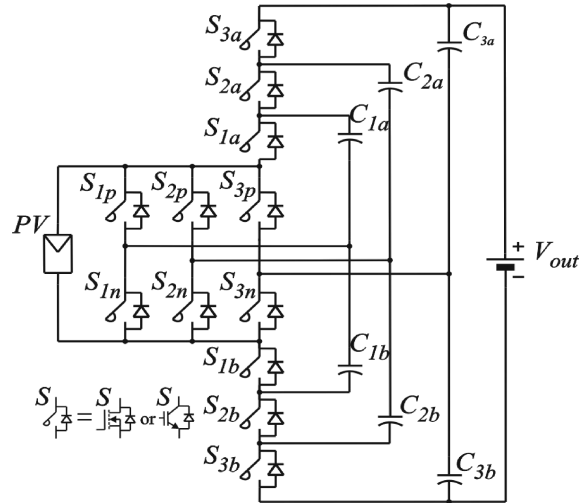


Fig. 11. Multilevel switched capacitor DC/DC Converter

The possibility to use low voltage rated switches and the lack of inductors make it possible to achieve the compact and cost effective solution.

Transformerless converter comparison. Table 1 presents the brief comparison of chosen transformerless solutions with performance proven in hardware prototype. Highlighted are the best efficiencies and voltage gains reported there.

Table 1
Comparison of transformerless converter hardware prototypes

Topology	Figure	η [%]	P_{MAX} [kW]	Gain [V/V]	f_S [kHz]	V_I [VDC]	V_{BUS} [VDC]	Voltage Gain Formula	No of Switches	No of Diodes
[6]	(5)	97.3	2.50	1.3	25	250	320	$\frac{1}{1-n \cdot D}$	4	4
[7]	(6)	96.2	0.60	3.0	30	130 to 170	400	$\frac{1}{1-(D_1+D_2)}$	2	3
[8]	-	95.4	0.50	2.5	300	80	200	$\frac{1}{1-D+\alpha(f_r, I_T, V_O)}$	1	4
[9]	(8)	97.0	0.80	8.0	100	24 to 38	200	$\frac{1-D}{1+(n+1) \cdot D}$	1	3
[10]	(6)	97.4	0.22	10.0	85	20 to 70	200	$\frac{1-D}{2+n \cdot D}$	1	3
[11]	(9)	94.7	1.00	9.5	100	40 to 56	380	$\frac{1-D}{2n+1}$	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	$\frac{4 \cdot n}{\sqrt{(1-D^2)+32 \cdot n^2 \cdot \alpha(f_S, I_O)}+(1-D)}$	4	2

2.2. DC/DC boost converters with transformer isolation.

Transformers have significant influence on efficiency of whole energy conditioning system and hence on the quality of energy supplied to the network. The absence of transformer in the system may result in injecting DC currents into AC current, which may disturb the operation of electric grid distribution transformers due to saturation of magnetic cores [17]. Moreover the absence of active elimination of unwanted DC currents injected to the grid can lead to distribution transformers damage and whole electric grid failure.

According to the electrical regulations and standards which are in place in some countries the galvanic isolation of the PV system may be necessary or not. It is performed by the transformers of high or low frequency.

Galvanic isolation can be accomplished by either line frequency transformer or a high frequency one. Both are shown in Fig. 12. The grid frequency transformer (50/60 Hz) is not often used because of high price, and low power efficiency.

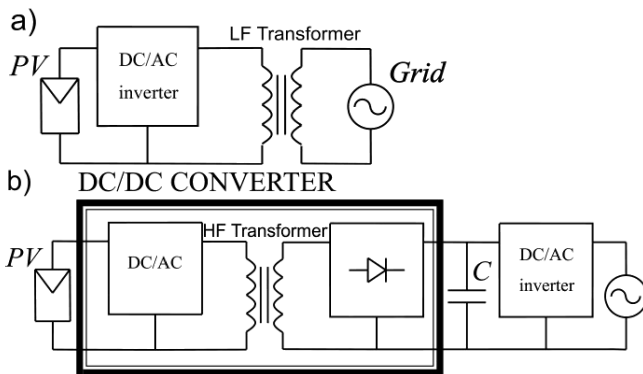


Fig. 12. Types of transformer isolation

The comparison of transformer isolated step-up converters is presented below. For the reasons listed above it is focused on the topologies with high frequency transformers.

Basic isolated step-up converter topologies. Among power electronics converters with galvanic isolation there are several topologies, which are the starting point for further investigations and designing more advanced systems. Topologies such as flyback, forward or push-pull, and their variants have been described in detail in the literature [18]. The voltage step-up obtained in these systems is high, unfortunately, does not go hand in hand with efficiency. Only by applying ZVS, ZCS soft switching techniques, these systems can achieve a satisfactory efficiency.

The active clamp step-up DC/DC converter [19], (Fig. 13) has the advantages of both flyback and forward converters. It regulates the DC link voltage providing high voltage conversion ratio. The active clamp high step-up DC/DC converter unlike the conventional flyback and forward DC/DC converters uses the active-clamp circuit both in ON-state and OFF-state so the input power is delivered to the output in both these states.

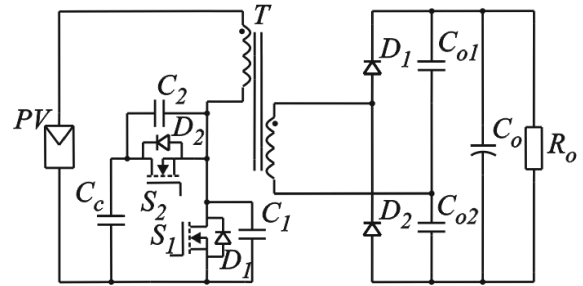


Fig. 13. Active clamp step-up converter

Both positive and negative input voltages are injected to the resonant tank and thanks to the voltage doubler the transformer's winding ratio can be decreased. This feature allows providing only half of the distribution line voltage on the transformer's secondary winding.

Thanks to the resonance of leakage inductance of the transformer and capacitors paralleled with the rectifier diodes the reverse-recovery loss of these diodes can be eliminated which, combined with an active-clamp circuit for soft switching of the MOSFET transistors ensures high system efficiency.

The high step-up resonant push-pull converter [32] depicted in Fig. 14 has advantages of a conventional current-fed push-pull converter such as low input current stress, high-voltage conversion ratio and low conduction loss of switches. The voltage doubler rectifier doubles conversion ratio and the voltage stress on rectifying diodes is reduced to half of voltage on transformer secondary winding. Thanks to LC resonance output diodes can commute softly without the reverse recovery problem. Mentioned features together with high efficiency and low current ripples of the inductor make that converter appropriate to use in photovoltaic systems.

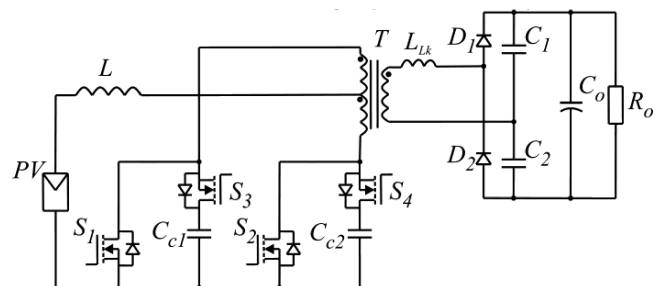


Fig. 14. Resonant push-pull converter

Although the efficiency of the system seems to be the most important parameter distinguishing the converter in many cases, the designers also strive to simplify the control system. Example of this is high step-up ZVS current-fed DC/DC converter [20] shown in Fig. 15. Apart from ZVS condition of the main and auxiliary active switches (snubber) only one PWM control signal is connected to the pair of transistor gates. The pairs consisting of a main transistor in bridge leg and the auxiliary one from other leg are alternated in conduction during one switching period.

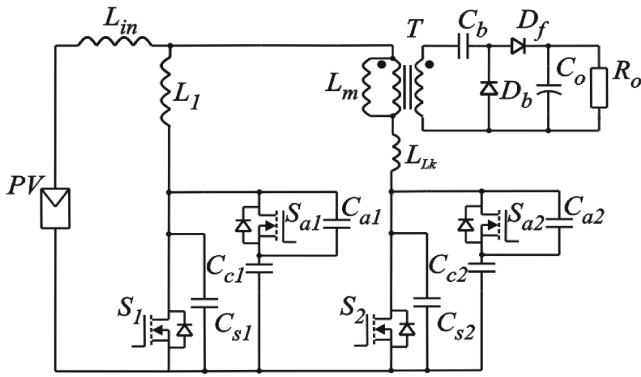


Fig. 15. High step-up zero-voltage switching current-fed converter

Bridge and half-bridge resonant converters. Another part of the review focuses on half-bridge and full-bridge isolated converter topologies. These systems are characterized with high efficiency associated with the resonant soft-switching techniques.

ZCS condition in half-bridge resonant converter [21] seen in Fig. 16 is achieved by connecting capacitor C_r , in series with transformer leakage inductance forming a resonant tank which can be tuned to the switching frequency by choosing appropriate capacitance. Apart from that high efficiency is achieved by the use of capacitive snubbers connected in parallel with the MOSFET switches, so they can be switched in zero voltage and nearly zero current. The diodes of the rectifier are switched at zero current. As the switching losses are negligible only the conduction losses dominate.

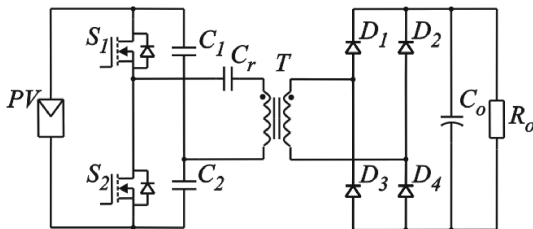


Fig. 16. Resonant half-bridge converter

Figure 17 shows ZVS two-inductor boost converter [22] for low voltage, high current DC to DC conversion. During turn off of the transistor the parallel capacitor C_1 , C_2 resonates with inductor L_r thus ZV turn off is achieved. Consequently turning on of the transistor occurs when voltage of the capacitor equals zero.

Interesting is the fact that the resonant inductance L_r and capacitors C_1 , C_2 may be physical or they can be replaced by the transformer leakage inductance and the MOSFET switch parasitic capacitances.

The resonant half bridge dual converter can work in continuous and discontinuous mode depending on whether the current of boost circuit is continuous or not.

Despite the high voltage gain, system efficiency is still high. Consequence of this topology is its multi-resonance variant with voltage doubler.

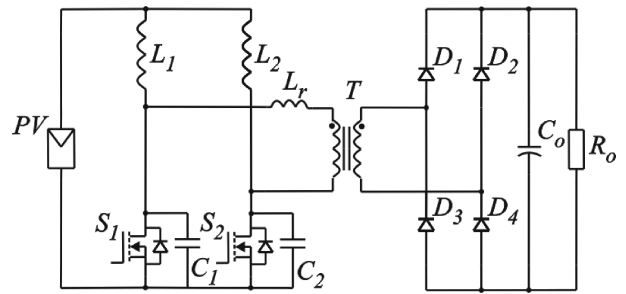


Fig. 17. Resonant half-bridge dual converter

Current fed multi-resonant converter (CFMRC) [24] consists of a current fed two inductor half-bridge structure followed by transformer with multi resonant tank and an output full bridge rectifier. However the secondary winding losses of the transformer which go together with high turns-ratio may limit the efficiency.

Even though that converter demonstrates the number of advantages such as high voltage gain, low input ripple current and ZCS of bridge diodes the improved CFMRC topology was further developed [23]. In CFMRC seen in Fig. 18 voltage doubler was implemented to reduce the turns-ratio of transformer. Therefore the cost of the transformer can be reduced.

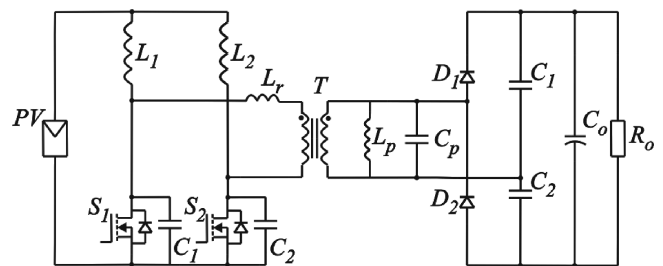


Fig. 18. Current fed multi-resonant converter

During switching period the overlapping of the signals driving two main switches is present resulting in resonance between leakage inductor L_r and resonant capacitor C_p . The ZCS condition of the half bridge transistors is achieved and voltage spikes within converter are reduced. The power losses in semiconductor components are reduced also by ZCS of voltage doubler diodes. They are turned off at zero current in full load condition and during lighter load the primary current is limited. The common ground gate driving is also undoubted advantage of half-bridge current-fed converters.

The LLC Series-Parallel Resonant Converter (SPRC) [26] is depicted in Fig. 19. In this topology square wave generator (full bridge inverter) is linked with half bridge rectifier by high step-up high-frequency transformer.

Due to resonance bridge MOSFET transistors are zero-voltage-switched and voltage doubler diodes are turned off at zero current. Mentioned features as well as half-bridge diode snubbers contribute to high efficiency of the system. There is a possibility to use series-parallel resonance feature both in single as well as in the three-phase converters through variable number of inverter and rectifier legs.

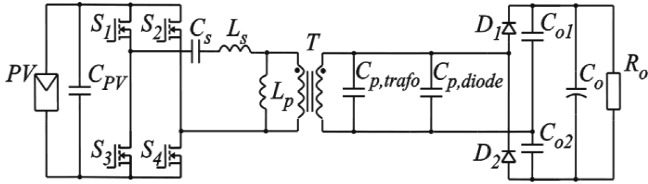


Fig. 19. Series-Parallel Resonant Converter

Reaching high efficiency half-bridge and full-bridge converter topologies seem to merge two desirable characteristics: high voltage gain and high efficiency at a relatively small number of semiconductor components.

Two transformer converter. In topologies presented so far the isolation was provided by one transformer, which simultaneously ensures the voltage gain. In high step-up bridge converter seen in Fig. 20 two transformers are utilized to double the voltage conversion ratio [26]. Distributed magnetic components not only lower the power losses and thermal stresses of the converter but also reduce transformer turns-ratio. Resonance of the leakage inductances of the transformers and series connected capacitors in the voltage doubler makes the output diodes to be turned off at zero-current. This two series-resonant circuits and active clamping of the switching transistor ensure high efficiency.

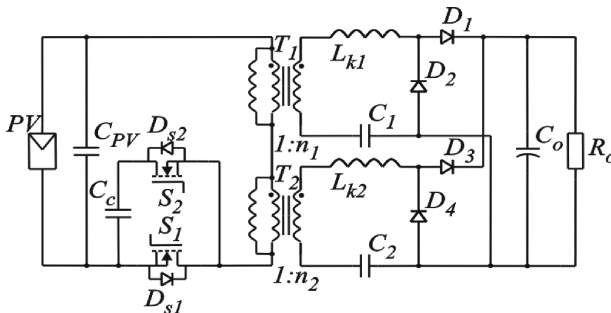


Fig. 20. High step-up two transformer converter

Non-isolated high step-up converter with built in transformer. A non-isolated high step-up converter with built-in transformer topology is derived from the isolated interleaved boost converter with full-bridge rectifier [27]. Despite the

presence of the transformer this converter has no galvanic isolation (Fig. 21).

As it was outlined earlier most of the transformerless topologies should work with a very high duty cycle to achieve high voltage conversion ratio. The isolation-to-nonisolation transformation method proposed here results in wide voltage regulation and thus the high voltage output ratings can be achieved without extreme duty cycle. The leakage of the transformer reduces reverse recovery current of the bridge diodes which together with energy recycling of an active clamp and MOSFET soft switching performance effect in high efficiency and high voltage gain.

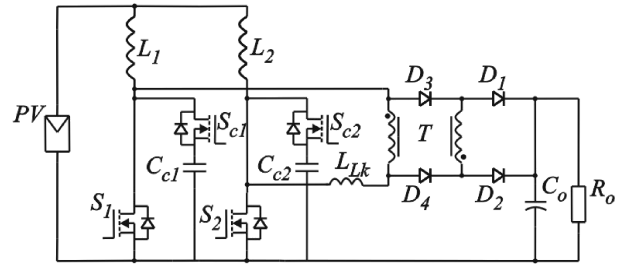


Fig. 21. Non-isolated high step-up converter

Comparison of transformer converters. Table 2 presents the comparison of chosen transformer based step-up converters.

3. Summary

Different step-up DC/DC topologies have been presented in Table 1 and Table 2. However the solution chosen by the designer depends on particular design constraints there is a need to determine the most robust and best performance topology. High efficiency of step-up DC/DC converters can be achieved by decreasing duty cycle (lower conduction losses) and reducing voltage stress on switches (cheaper and lower R_{DS-on} switches) applying soft switching technique (minimizing switching losses) and utilizing active clamp circuits (recycling the energy stored in parasitic inductances). Below there are a few distinguishing solutions presented.

Table 2
Comparison of DC/DC converters with transformer isolation hardware prototypes

Topology	Figure	0 [%]	P_{MAX} [kW]	Gain [V/V]	f_S [kHz]	V_I [VDC]	V_{BUS} [VDC]	Voltage Gain Formula	No of Switches	No of Diodes
[19]	(13)	94.0	0.10	11.6	20	30 to 60	350	$\frac{n}{1-D}$	2	2
[32]	(14)	95.5	1.5	10	70	35 to 60	350	$\frac{2n}{1-D}$	4	2
[20]	(15)	92.0	0.4	4.4	100	45	200	$\frac{n}{D(1-D)}$	4	2
[21]	(16)	–	0.25	11.9	100	36	430	–	2	4
[22]	(17)	90.0	0.1	18.0	1000	20	360	–	2	4
[23]	(18)	96.0	0.15	15.2	255	23	350	–	2	2
[25]	(19)	97.0	0.19	35.0	215	20 to 35	700	–	4	2
[26]	(20)	97.0	0.26	–	–	36	–	$\frac{2n}{1-D}$	2	4
[27]	(21)	94.7	1.0	9.5	100	40 to 56	380	$\frac{n+1}{1-D}$	2	4

Half-bridge and full-bridge step-up topologies based on low R_{DS-on} MOSFET transistors with soft switching technique implemented demonstrate the highest efficiency. LLCC converter [25] is a good example of converters that merges the requirements of high efficiency and voltage gain.

CFMRC is another distinguishing high performance topology [23] and (Fig. 18) where a multi-resonant circuit eliminates parasitic parameters of transformer assuring high voltage gain. The presence of voltage doubler allows using lower turns-ratio transformers thus reduces overall cost of the system. Other advantage of that topology is that both switches work on low-side.

In [26] even though two transformers are in use the voltage gain and efficiency are still excellent.

Topology [27] however is not isolated presents interesting utilization of transformer which ensures high voltage gain but the interleaved driving scheme gives the possibility for the switches to work with low duty cycle.

Basic topology such as push-pull converter with additional snubbers and voltage doubler [32] can be competitive solution among the other more advanced topologies.

It's worth mentioning of topology presented in [20] which is distinguished by simple driving scheme as it utilizes only one switch.

From presented in Table 1 topologies two types of them [4, 10, 11] are competitive candidates for high voltage gain and high efficiency applications.

Coupled inductor topology [9] and [10] provides compact design with the features rarely to be found in other topologies. First of all the energy stored in parasitic leakage inductance of coupled inductors is recycled there. Avoiding the use of electrolytic capacitors improves the reliability of that solution. Active clamp circuit decreases voltage stress on the switch. And finally only one switch at a low-side is needed so driving scheme is simple.

Topology [11] is compact and robust solution. The leakage energy is recycled utilizing passive clamp. Due to the voltage multiplier cell switch voltage stress is reduced and voltage gain extended. Input current ripples are low and input current sharing is obtained due to interleaved input structure allowing lower duty cycle to be used. 1 kW experimental example [11] proves the performance of that topology.

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Appendix A. Symbols

n	– transformer or coupled inductor turns-ratio,
D	– duty cycle,
α	– function followed by its parameters in brackets,
f_r	– resonant frequency,
f_s	– switching frequency,
V_o	– output voltage DC,
I_o	– output current,

V_I	– input voltage DC,
I_I	– input current,
η	– efficiency,
P_{MAX}	– DC/DC converted rated power,
V_{BUS}	– stepped-up DC bus system voltage.

REFERENCES

- [1] F. Blaabjerg, F. Iov, T. Kerekes, and R. Teodorescu, "Trends in power electronics and control of renewable energy systems", *14th Int. Power Electronics and Motion Control Conf. (EPE/PEMC)* 1, K-1–K-19 (2010).
- [2] EPIA, "Global market outlook for photovoltaics until 2013", *Eur. Photovoltaic Industry Association* 1, CD-ROM (2010).
- [3] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, IEEE Std 1547, CD-ROM (2003).
- [4] J.H.R. Enslin, "The role of power electronics and storage to increase penetration levels of renewable power", *Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century*, IEEE 1–2, CD-ROM (2008).
- [5] M. Calais and V.G. Agelidis, "Multilevel converters for single-phase grid connected photovoltaic systems-an overview", *Int. Sympos. on Indust. Electronics (ISIE)* IEEE 1, 224–229 (1996).
- [6] C. Chunliu, W. Chenghua, and H. Feng, "Research of an interleaved boost converter with four interleaved boost convert cells", *Asia Pacific Conf. on Postgraduate Research in Microelectronics & Electronics (PrimeAsia)* IEEE 1, 396–399 (2009).
- [7] S.-H. Park, S.-R. Park, J.-S. Yu, Y.-C. Jung, and C.-Y. Won, "Analysis and design of a soft-switching boost converter with an hi-bridge auxiliary resonant circuit", *Trans. on Power Electronics* IEEE 1, 2142–2149 (2010).
- [8] E.S. da Silva, L. dos Reis Barbosa, J.B. Vieira Jr., L.C. de Freitas, and V.J. Farias, "An improved boost PWM soft-single-switched converter with low voltage and current stresses", *Trans. on Indust. Electronics* IEEE 1, 1174–1179 (2001).
- [9] R.J. Wai and R.Y. Duan, "High-efficiency DC/DC converter with high voltage gain", *IEEE Proc. Electric Power Applications* IEEE 1, 793–802 (2005).
- [10] W. Yu, C. Hutchens, J.-S. Lai, J. Zhang, G. Lisi, A. Djabbari, G. Smith, and T. Hegarty, "High efficiency converter with charge pump and coupled inductor for wide input photovoltaic AC module applications", *Energy Conversion Congress and Exposition (ECCE)* IEEE 1, 3895–3900 (2009).
- [11] W. Li, Y. Zhao, Y. Deng, and X. He, "Interleaved converter with voltage multiplier cell for high step-up and high-efficiency conversion", *Trans. on Power Electronics* IEEE 1, 2397–2408 (2010).
- [12] W. Li, X. Li, Y. Deng, J. Liu, and X. He, "A review of non-isolated high step-up dc/dc converters in renewable energy applications", *24th Annual Applied Power Electronics Conf. and Exposition (APEC)* IEEE 1, 364–369 (2009).
- [13] W. Qian, J.G. Cintroñ-Rivera, F.Z. Peng, and D. Cao, "A multilevel DC/DC converter with high voltage gain and reduced component rating and count", *26 Th Annual Applied Power Electronics Conf. and Exposition (Apec)*, IEEE 1, 1146–1152 (2011).
- [14] T. Esum and P.L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques", *Trans. on Energy Conversion* IEEE 1, 439–449 (2007).

- [15] Q. Zhao and F.C. Lee, "High-efficiency, high step-up DC-DC converters", *Trans. on Power Electronics IEEE* 1, 65–73 (2003).
- [16] Y. Zhao, W. Li, Y. Deng, and X. He, "Analysis, design, and experimentation of an isolated ZVT boost converter with coupled inductors", *Trans. on Power Electronics IEEE* 1, 541–550 (2011).
- [17] L. Gertmar P. Karlsson, and O. Samuelsson, "On DC Injection to AC grids from distributed generation", *Eur. Conf. on Power Electronics and Applications (EPE) IEEE* 1, CD-ROM (2005).
- [18] Q. Li and P. Wolfs, "A review of the single phase photovoltaic module integrated converter topologies with three different DC link configurations", *Trans. on Power Electronics IEEE* 1, 1320–1333 (2008).
- [19] J.-M. Kwon B.-H. Kwon, and K.-H. Nam, "High-efficiency module-integrated photovoltaic power conditioning system", *IET J. IEEE* 1, 410–420 (2009).
- [20] M. Delshad and H. Farzanehfar, "High step-up zero-voltage switching current-fed isolated pulse width modulation DC–DC converter", *IET J. IEEE* 1, 316–322 (2008).
- [21] A. Itoher, T. Meyer, and A. Nagel, "A new panel-integratable inverter concept for grid-connected photovoltaic systems", *Int. Symp. on Indust. Electronics (ISIE) IEEE* 1, 827–831 (1996).
- [22] Q. Li and P. Wolfs, "An analysis of a resonant half bridge dual converter operating in continuous and discontinuous modes", *33rd Annual Power Electronics Specialists Conf. (PESC) IEEE* 1, 1313–1318 (2002).
- [23] D. Li, B. Liu, B. Yuan, X. Yang, J. Duan, and J. Zhai, "A high step-up current fed multi-resonant converter with output voltage doubler", *26th Applied Power Electronics Conf. and Exposition (APEC) IEEE* 1, CD-ROM (2011).
- [24] B. Yuan, X. Yang, and D. Li, "A high efficiency current fed multi-resonant converter for high step-up power conversion in renewable energy harvesting", *Energy Conversion Congress and Exposition (ECCE) IEEE* 1, 2637–2641 (2010).
- [25] C. P. Dick, F. K. Titiz, and R.W.De Doncker, "A high-efficient llcc series-parallel resonant converter", *25th Annual Applied Power Electronics Conf. and Exposition (APEC) IEEE* 1, 696–7-01 (2010).
- [26] W. Choi, S. Kim, S. Park, K. Kim, and Y. Lim, "High step-up dc/dc converter with high efficiency for photovoltaic module integrated converter systems", *31st Int. Telecomm. Energy Conf. (INTELEC) IEEE* 1, CD-ROM (2009).
- [27] W. Li, W. Li, M. Ma, Y. Deng, and X. He, "A non-isolated high step-up converter with built-in transformer derived from its isolated counterpart", *36th Annual Conf. on IEEE Indust. Electronics Society (IECON) IEEE* 1, 3173–3178 (2010).
- [28] F. Blaabjerg, S.B. Kjaer, and J.K. Pedersen, "A review of single-phase grid-connected inverters for photovoltaic modules", *Trans. on Indus. Applications IEEE* 1, 1292–1306 (2005).
- [29] R. Smolenski, "Selected conducted electromagnetic interference issues in distributed power systems", *Bull. Pol. Ac.: Tech.* 57 (4), 383–394 (2009).
- [30] S. Pirog, R. Stala, and L. Stawiarski, "Power electronic converter for photovoltaic systems with the use of FPGA-based real-time modeling of single phase grid-connected systems" *Bull. Pol. Ac.: Tech.* 57 (4), 345–354 (2009).
- [31] K. Kazimierczuk, *Pulse-Width Modulated DC-DC Power Converters*, John Wiley & Sons, London, 2008.
- [32] E.-H. Kim and B.-H. Kwon, "High step-up resonant push–pull converter with high efficiency", *IET J, IEEE* 1, 79–89 (2009).