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Topologies of DC-DC Converter in Solar PV Applications

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Abstract

Solar energy plays an important role in renewable energy generation systems since it is clean, pollution-free sustainable energy as well as the increasing cost-of-electricity which causes high-growth demands amongst utility customers. This paper presents various circuit topologies of DC-DC converters in solar photovoltaic (PV) applications. There are three types of DC-DC converter presented in this paper that can be integrated with solar PV system which are buck, boost and buck-boost converter in various applications. This paper also presents the application on DC-DC converter in solar PV system for maximum power point tracking (MPPT) feature. The advantages and disadvantages of each topology will be discussed further in term of cost, components, efficiency and limitations.

***Keywords**: DC-DC converter, PV module, MPPT, buck, boost, buck-boost*

1. Introduction

Renewable energy systems offer economic and environmental benefits in providing clean and sustainable energy rather than conventional fossil fuels [1]. Renewable energy sources such as solar energy has received tremendous demands since it is pollution-free from any poisonous byproducts that can pollute the environment [2]. DC-DC converters are widely used in renewable energy generation systems such as solar photovoltaic (PV) system, wind power system and fuel cell for correct energy conversions [3-5]. The solar photovoltaic (PV) power generation system is extensively used in grid-connected and off-grid applications [6]. Due the nature of grid-connected solar PV generation systems such as solar farms and residential solar PV installers that can only operate during the daytime when the sun shines brightly, thus it will affect equipments' utilization and power system stability. Instead of producing clean and sustainable energy for utility consumers, the solar PV generation system may also optimize its equipements' utilization by providing the function of power quality management such as harmonic suppression, reactive power compensation and power outage avoidance [7-10].

A combination of PV cells will form a PV module and a combination of PV modules will form a PV array to supply the specified loads. Normally, these solar PV modules will be connected in series to increase the PV output voltage due to the nature of solar PV energy that can only generate low DC output voltage in the range between 12V to 75V [6]. Thus, the power electronic interfaces or power converter such as DC-DC converter is a compulsory interface to convert the low DC output voltage from solar PV system to the required voltage rating needed by the utility grid or any suitable utilization voltage [11]. The low DC output voltage from the solar PV system can be used locally through indirect connection before supplying the excessive energy to the utility grid. These PV modules or arrays can charge the rechargeable batteries by using PV battery charger for various applications such as the solar PV off-grid systems, satellites, solar vehicles, street-lightings, base transceiver stations as well as building interated PV systems where the solar energy can be stored for winter or rainy seasons, during nighttime and others. However, direct charging from solar PV modules or arrays will damage the batteries and reduce its lifespan due to the unregulated charging voltage and current. So, the DC-DC converter will regulate the charging voltage/current from the solar PV modules or arrays

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according to the batteries' specifications. These issues have triggered a severe demand for highly efficient DC-DC converters [12, 13].

Besides, the low DC output voltages generated by PV array are also varied widely according to the solar irradiation, abrupt change due to the shadowing effects, ambient temperature, the cleanliness degree of the PV module surface, mismatch of PV modules and others [9], [14, 15]. Thus, it is a critical need to design a DC-DC boost converter to regulate the low and inconsistent DC output voltage from the PV arrays. Instead of stepping-up or stepping-down the DC output voltage from the PV array, the DC-DC converter are also implementing a crucial task to extract the maximum power point (MPP) output power from the PV arrays at various conditions throughout the day based on the PV I-V charateristics by using Maximum Power Point Tracking (MPPT) algorithms [16-20]. Furthermore, the selection of suitable DC-DC converter topology for integration with solar PV system or other renewable energy sources has not been investigated explicitly even though its integration to solar PV system will increase its optimum utilization effectively [21]. Thus, this paper presents topologies of DC-DC converter in various solar PV application systems.

2. Topologies of DC-DC Converter

The topologies of DC-DC converter are designed to meet specific demand of DC loads. There are several types of DC-DC converter that can be functioned as switching mode regulators that can regulate the unregulated DC voltage with conversion to suitable utilization voltage through increase or decrease the value of DC output voltage by using power switching devices for PWM switching at a fixed frequency which are buck, boost, buck-boost, cuk, Single Ended Primary Inductor Converter (SEPIC) and flyback–boost converter [1], [15], [22]. Each converter requires the power switching devices for turn-on and turn-off when it is needed. The power switching devices such as MOSFETs, IGBTs, BJTs and thyristors are used depending upon the applications and parameters of designing the circuit. In order to trigger the power switching devices, appropriate gate drive signals by using gate driver circuit should be considered [22]. The DC-DC converters are driven by Pulse Width Modulation (PWM) switching to control the converter voltage, frequency and phase delay [2], [23].

2.1 DC-DC Boost Converter

Figure 1 shows basic circuit topology of a DC-DC boost converter circuit consists of power switch (M), diode (D), inductor (L), capacitor (C), switching controller and load (R). This topology can be used for interface connection between low PV array voltage to a high battery bank input voltage or any DC load [25]. The DC-DC boost converter will boost up or step up the output voltage to be greater than input voltage [5], [26]. Controller will control the switch for turn-on and turn-off to boost the input voltage to the needed value of output voltage. When the switch is turn-on, the diode will be in reversed bias and electrical energy will be stored in the inductor. Thus, the capacitor will supply current to the load. When the switch is turn-off, the stored electrical energy in the inductor will be transferred to the capacitor and load. The DC-DC boost converters have two type of operation which is continuous-conduction mode (CCM) and discontinuous-conduction mode (DCM). When the DC-DC boost converter operates in CCM, the inductor current will be greater than zero at all time whereas during DCM, the inductor current will drop to zero after each switching cycle [1], [24], [27]. Current research trends for DC-DC boost converter with PV based power quality management are reported for harmonic elimination, power factor correction, zero voltage regulation and load balancing [28-30].

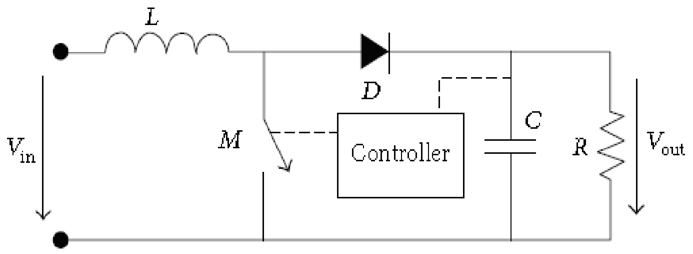


Figure 1. Circuit topology of DC boost converter [1], [24]

2.2 DC-DC Buck Converter

Similar to DC-DC boost converter, basic circuit topology of DC-DC buck converter also consists of power switch (M), diode (D), inductor (L), capacitor (C), switching controller and load as depicted in Figure 2. DC-DC buck converter operates as a step down system that will step down the high input voltage to the low output voltage which the magnitude of output voltage is always lower than the input voltage. The objective of this circuit is to produce a purely DC output by adding the LC low pass filter to the basic circuit of this converter. This DC-DC buck converter can be connected to low voltage DC load or battery bank from a high PV array voltage. DC-DC buck converters are commonly used in very high range step down converters and low power range regulators because of its simple topology with low control difficulty, less number of components and no isolation. Most of the DC-DC buck converters are used in battery charging by modulating the high input voltage through PWM to generate the low output voltage required by the batteries as well as MPP tracking in order to maximize the output power obtained from the PV arrays [1], [25]. Several solar PV applications with DC-DC buck converter are standalone solar PV pumping system for water supply in rural areas [33], solar battery charger [34, 35], MPPT tracking for grid-connected [36] and off-grid PV system [37].

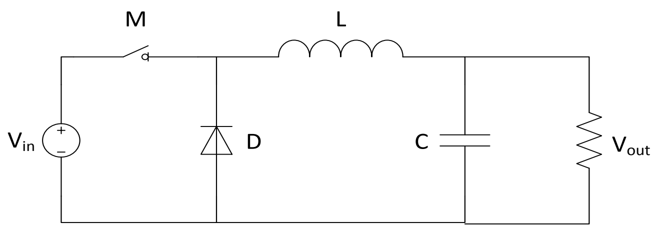


Figure 2. Circuit topology of DC-DC buck converter [31], [32]

2.3 DC-DC Buck-Boost Converter

The circuit topology for DC-DC buck-boost converter is very much similar to DC-DC boost converter except for the placement of switching element before the inductor (L) as shown in Figure 3. The DC-DC buck-boost converter or namely as step-up/down and bidirectional converter can generate either lower or higher output voltage from its input voltage by in order to connect with suitable PV array voltage, DC load or battery input voltage [25]. DC-DC buck-boost converter is a cascaded connection of two basic converters which are DC-DC buck and boost converters. The output of this converter can be controlled by changing its duty cycle, D. If the duty cycle is lower than 50%, the converter will be operated in buck mode and the output voltage will be less than the input voltage. When the duty cycle is higher than 50%, the converter will be functioned in boost mode and the output voltage will be greater than input voltage [1]. The design parameters that should be considered in designing this converter are the operating frequency of the inductor, the maximum current and voltage that the inductor can withstand as well as the gate driver circuit to generate the PWM switching signals for triggering the power switch.

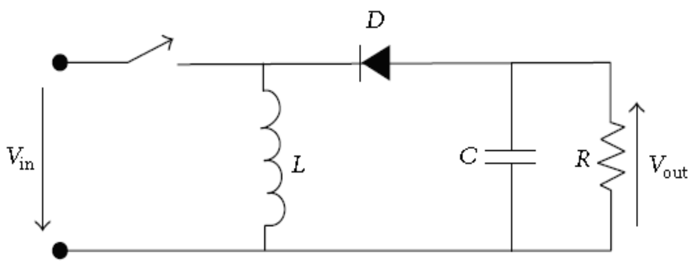


Figure 3. Circuit topology of DC-DC buck-boost converter [1]

2.4 Comparison between DC-DC Buck, Boost and Buck-Boost Converter

The similarities amongst DC-DC buck, boost and buck-boost converter are using the same components in their circuits but different in individual characteristics and operational purposes. Several parameters such as inductors, capacitors and power switches with gate drivers can be considered in comparing the performances between buck and boost converter. The DC-DC boost converter needs higher inductance than DC-DC buck converter whereas the DC-DC buck converter requires larger and costlier capacitor to smooth the discontinuous PV module input current than the DC-DC boost converter. Furthermore, the DC-DC boost converter has lower current rating for power switches and gate drivers but the DC-DC buck converter requires high-side power switches driver which is more difficult and expensive than the DC-DC boost converter. Besides, the existing free-wheeling diode of the DC-DC boost converter can avoid reverse current which the DC-DC buck converter requires extra blocking diode in DC-DC buck converter to conduct PV maximum current. Thus, the DC-DC boost converter has more advantages due to its better dynamic performance and inexpensive implementation [25], [38].

However, the DC-DC boost converter also has some limitations which may lead to less efficiency and losses due to too high output power, excessive input current and large voltage drop across the diode during voltage collapse point. For low voltage application, the efficiency of the DC-DC boost converter can be improved by replacing the diode with a power switch device which creates a synchronous DC-DC boost converter topology as shown in Figure 4 [24]. Besides, the DC-DC boost converter also suffers power losses due to conduction loss and switching loss under different load conditions as well as high switching noise that will reduce the quality of the output voltage [1]. On the other hand, the DC-DC buck-boost converter is reported to be the most effective solution in tracking maximum power point (MPP) of the PV array irrespective of ambient temperature, solar irradiance, and load condition. Its integration with solar PV sytem is the best practice to improve solar PV system performance. However, the drawbacks of this topology are less efficient and costlier than other topologies [21], [39].

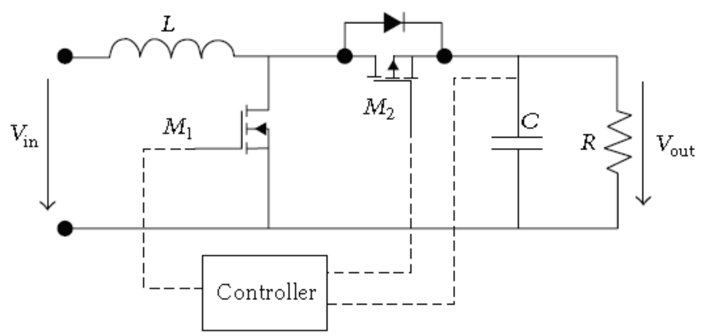


Figure 4. Circuit topology for synchronous DC-DC boost converter [1]

3. Application of DC-DC converter in PV system

Figure 5 shows an example of solar PV system integrated with DC-DC boost converter for Distribution Static Synchronous Compensator (DSTATCOM) in order to mitigate power quality issues such as harmonic elimination, load balancing, power factor correction and zero voltage regulation at the distribution network. By using the DC-DC boost converter with MPPT algorithm, the solar PV system can be fully utilized for generating clean electricity and improving power quality simultaneously. However, tracking solar PV power is complicated because of the non-linear characteristic of PV current-voltage (I-V) curve with distinctive maximum power points (MPP) at different operating conditions. Solar power generated by the PV panels and its MPPs are depending on atmospheric conditions such as cell temperature and solar irradiation. In order to optimize the generated solar PV power, the PV panels must be operated at a voltage that is consistent with the MPP to extract maximum power. Thus, the converter regulated with MPPT controller is used to achieve load matching, extract the most extreme power as well as improve the PV module efficiency [40], [41]. The DC-DC converter alongside with MPPT controller is embedded amidst the load and the PV module to ensure that the PV system will be operating close to MPP. Then, the DC-DC converter will transfer the DC voltage with suitable voltage level to the load. Normally, the maximum power point tracking with power management circuit (PM-MPPT) is used to achieve the high efficiency of the solar PV system [9], [42].

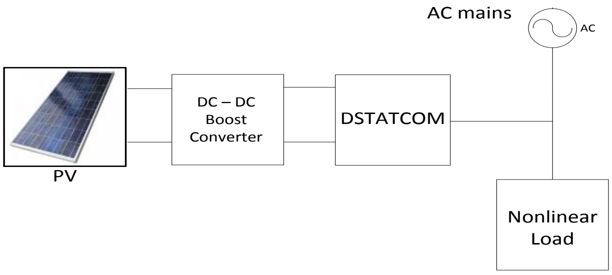
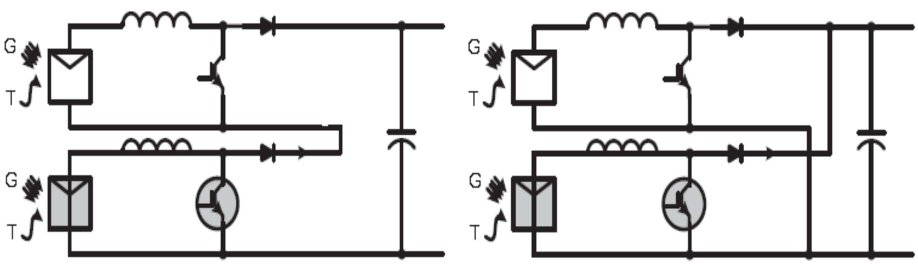


Figure 5. Solar PV system with DC-DC boost converter for DSTATCOM

The selection of DC-DC converter depends on the PV arrays arrangement whether in series or parallel connection. The DC-DC buck converter is more suitable for PV arrays connected in series whereas the DC-DC boost converter works satisfactorily with PV arrays in parallel connection. Figure 6 presents the multi-level cascaded DC-DC boost converter connected to PV array in different connections with faulty PV module in gray shading. The faulty PV module may be caused by shadowing effect that will reduce the output power generated by solar PV system. Thus, the selection of DC-DC converter is necessary to optimize the solar PV output power in partial shading condition due to the shadowing effect. In series connection, the output current is equal while in boost topology, the input current is greater than the output current that becomes the operational constraint. Thus, the current drops significantly as well as the PV output power. Besides, the PV array output current in parallel connection is the summation current of the individual PV current. If partial shading occurs in any PV module which caused its current drops, the remaining PV modules will operate normally and the partial shading will not affect significantly the total PV array output power. On the other hand, PV arrays in series connection with DC-DC buck converter has free-wheeling diode that will avoid the faulty PV module to reduce the effect of partial shading and increase the total PV output power [43].



(a) (b)

Figure 6. DC-DC boost converter with PV module in (a) Series (b) Parallel connection [43].

6. Conclusion

The DC-DC converters play an important role in renewable energy applications particularly solar PV system. This paper presented various topologies of DC-DC converters such as buck, boost and buck-boost integrated with solar PV system that are capable to supply effectively suitable utilization DC voltage with respect to the specified load. The limitations of the unstable, unregulated and low voltage generated from solar PV array have been resolved successfully with the converters. The DC-DC converters with MPPT algorithms are also addressed the limitation of solar PV generation system optimum utilization to generate maximum output power from the PV arrays in various conditions. The benefits and drawbacks of each topology have been discussed in term of cost, components, efficiency and its limitations. The DC-DC buck-boost converter integrated with solar PV system is found to be the most effective solution in producing maximum PV output power at any circumstances. Further improvement of these topologies will improve its efficiency with a reduced cost to support the demanding growth of solar PV power generation for a greener future.

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