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TOPOLOGICAL REVIEW AND ANALYSIS OF DC-DC BOOST CONVERTERS

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Abstract

DC voltage boost up is essential in numerous applications; especially considering Photovoltaic (PV) based renewable power generation system. The conventional DC-DC boost converter is the most admired configuration for this scheme, even if the converter efficiency is restricted at duty cycle near to maximum value. In order to find solution to the problem and improve its conversion capability, many converter configurations have been implemented so far. With this circumstance, this research work proposes to give overview of a few most imperative research works related to DC-DC boost converters. Some configurations are covered and classified basically based on the application. The major benefits and disadvantages related to the available techniques are also briefly conveyed. At last, a proper evaluation is recognized among the important types of DC-DC boost converters in terms of efficiency, number of components, and stability.

Keywords: Boost converter, Interleaved converter, Two-port converter, Multiport DC-DC converter.

1. Introduction

The PV cell is considered as one of the major renewable energy source which produces DC output. Similarly, Fuel cell (FC) is used in energy generation as a backup source which produces DC output. Battery plays an important role in the storage of an electric power in terms of DC. By considering the above renewable energy sources with DC, it is necessary to analyse about the DC-DC converters.

In the power electronics field, purpose of interleaving method can be traced back to extremely early days, particularly in high power applications. In high power applications, the voltage and current stress on the power devices may rise

Nomenclatures

D	Duty ratio of the switch
N	Turns ratio of transformer
T_s	Switching time period, s
V_{cs}	Voltage across capacitor *CS*, V
V_o	Output voltage, V
V_t	Voltage across transformer primary, V

Greek Symbols

ΔI	Change in input current , *A*
ω_{r1}	Angular resonant frequency 1 in rad/s
ω_{r2}	Angular resonant frequency 2in rad/s

Abbreviations

EMI	Electro Magnetic Interference
HSBC	Hard Switching Boost Converter
MIMO	Multi-Input Multi-Output
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulation
SMPS	Switched Mode Power Supply
SSBC	Soft Switching Boost Converter
SVM	Space Vector Modulation
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching
ZVT	Zero Voltage Transition

beyond its withstanding capability. Coupling many power devices in parallel or series could be one result to meet the above problem. However, voltage division and current distribution are still the concerns. Instead of power devices paralleling, power converters paralleling is another solution which could be more helpful. Moreover, with the power converter architecture paralleling, interleaving technique comes logically. Advantages like harmonic deletion, improved efficiency, superior thermal performance and high power density can be gained [1].

In previous days, for high power applications, in order to gather certain system necessity, interleaving multi-port converter could be a better solution particularly in view of the existing power devices with constricted performance at that instant [2].

Interleaving method is also examined in the early days for the small power aircraft, satellite applications, and launched as unconventional Switched Mode Power Supply (SMPS) power stage design. In such cases, one main concern is the input side and output side filters due to the maximum accessible power storage to size ratio problem in that time. Interleaving converters can considerably decrease the amount of switching pulsed current go through the output side filter capacitor [2-3]. By properly selecting the duty cycle, the input ripple content in current may be decreased to zero. Moreover, interleaving raises the ripple frequency to be N-times the switching frequency. Interleaving method can successfully shrink the capacitor filter dimension and weight. One more concern of this method is covering. Because of thermal management problems, non-interleaved converter power loss goes beyond the classic dissipation capacity. Interleaving method can split the power transmit into many modules, lighter and lesser parts can be accumulating on the printed circuit card. The third advantage of the converter lies in the redesign to higher power levels are necessary than originally operating arrange at the time of start of the design. With the interleaving construction, enlarged power output may be supplied by adding further similar sections. The interleaved converter is planned and developed which can demonstrate the advantages on modularity, filter design and packaging.

Two-port converters using the working principle of power flow such as the dual active bridge DC-DC converter and series resonant boost converter are available in literature [4-5] . These converter circuits are used in high-power level DC-DC converters and high output voltage DC-DC boost converters. These converter circuits are mostly used only for power flow from source to load. Hence the active switches in the load side are changed by a diode bridge. In applications like telecommunication and aerospace high frequency AC voltage based schemes are investigated. They have several converters powered from the single source or various sources, used mostly for paralleling and AC distribution.

Converters in power electronics are required to interface many renewable power sources with the load along with storage element in stand-alone or grid-connected housing, commercial and vehicle applications. Newly, multi-port DC-DC converters have fascinated concentration for many applications since they utilize one-stage high frequency AC-link conversion as compared to many conversion stages in conventional DC-link systems. Two high frequency AC-link method, series resonant and current-fed three-port DC-DC converters already exist. In this a renewable source such as FC or PV is connected to one-port, energy storage elements such as batteries in another port and the load is used as a third port. Batteries are only utilized as storage elements.

2. Research Motivation

Investigation carried out on multi-port DC-DC boost converters has been very narrow and presents an integrated approach in contrast to separate working of individual DC-DC converters. All of the existing schemes have the problems like absence of bi-directional port, maximum number of components, asymmetrical converter structure, complexity in power management, difficulty in an individual and simultaneous power transfer and problem of isolation.

The main objective of this paper is to build up a novel multi-port DC-DC boost converter with unified structure for hybrid renewable power generation system. This converter interfaces multiple number of input power sources. These input power sources transfer the power bi-directionally with the help of battery. Individual and simultaneous power transfer is also done by proper control of duty cycle.

In the traditional converters operating on hard switching, the current and voltage pulses either goes from high to low value or from low to high value. During the transition period, switching loss occurs and generates a substantial amount of electromagnetic interference. To overcome this difficulty, in this proposed converter soft switching technique is adopted and switching losses are reduced. Soft switching for all power MOSFET switches is attainable without adding any auxiliary resonant components such as capacitor and inductor. It improves the converter efficiency by reducing the switching losses.

The multi-port boost converter is a nonlinear Multi-Input Multi-Output (MIMO) system that includes a number of interacting variables. All the output variables are having an effect on two or more control variables. Because of many interactions between control loops, the design of controllers like Proportional-Integral-Derivative (PID) is complicated. Decoupling network is a suitable method of control that permits designing a controller for this multi-port boost converter and hence the development of this is the main objective of this work.

3. Review of Existing Methodologies

A feasible categorization for DC-DC boost converters is presented as shown in Fig. 1, while this review is related with the talk of several configurations existing in literature. Special attention is paid to the available structures based on the applications. Starting from basic conventional DC-DC converter, numerous boost converter configurations have been implemented by many authors mainly to increase the major issues related to converter efficiency, boost up gain, and power handling capacity of the converter. Several significant structures normally boost the voltage up without the necessity of maximum duty cycles and may use paralleling of multiple converter structures to raise the output side power levels.

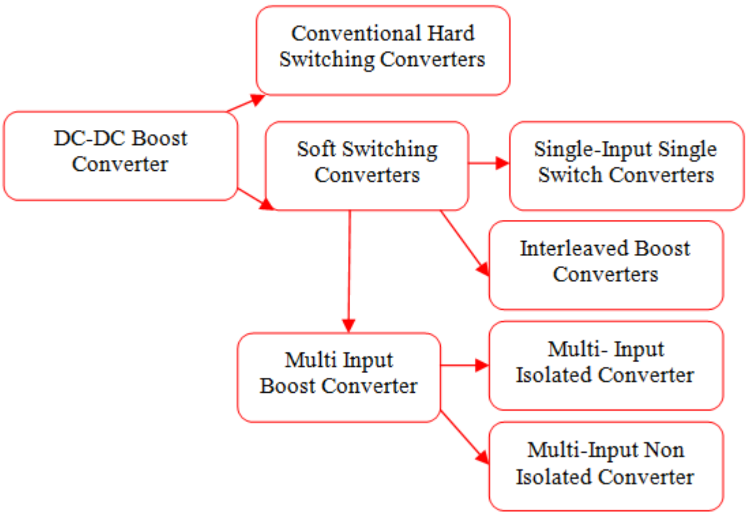

Fig. 1. Boost converters-Feasible classification.

3.1. Interleaved soft switching boost converter

The converters are operated in the hard switching, resulting in large switching losses and the serious Electro Magnetic Interference (EMI) problem. A new active soft switching circuit based on interleaving two boost converters and adding two simple auxiliary commutation circuits is proposed in [6]. The added auxiliary switches do not cause extra voltage on the main switches and the auxiliary switches are under Zero Voltage Transition (ZVT) during the whole switching transition.

Silva et al. [7] analyzed an interleaved boost converter with soft-switching and high voltage gain. The converter with high voltage gain is the right choice for applications where a high boost-up voltage is necessary, as in some renewable energy sources, which use like PV cells and FC. Besides, in order to promise less switching losses and a high efficiency, a non dissipative soft-switching cell with supplementary commutation circuit is utilized. Thus, a high boost-up voltage, minimum switching stress, less switching losses, and maximum efficiency are anticipated from this topology. The efficiency improvement is proved by comparing the experimental results obtained from the high voltage gain hard-switching converter and soft-switching converter.

Yao et al. [8] suggested an interleaved soft switching boost converter consists of two shunted basic boost converter units and a supplementary inductor. This converter is capable to turn ON both the active power switching devices at zero voltage to minimize their switching losses and obviously increase the conversion efficiency. Since the two paralleled elementary boost converter units are the same, operating principle, design and analysis for the converter becomes easier.

Mahdi et al. [9] proposed a new Zero Current Switching (ZCS) Pulse Width Modulation (PWM) circuit for an interleaved DC-DC boost converter which is established to employ one supporting switch to give soft-switching condition. They proposed interleaved converter with soft switching is attained for all the semiconductor switches. Under zero current condition the main and secondary switches are turned OFF and ON. The reverse-recovery losses of boost converter diodes are minimized and also, maximum efficiency is attained because of minimum switching losses. Moreover, the circuit is controlled by PWM method.

Sungsik et al. [10] proposed a general scheme of novel interleaved boost converters with soft switching that is more appropriate for high boost-up and high power applications. The proposed converter configuration is designed with accurate numbers of parallel and series connected cells to accomplish the necessary power and voltage levels, respectively. This directs to flexibility in switching device collection results in maximum component accessibility and simple thermal distribution. Design of determination of the best circuit for given power and voltage level is depicted. The major advantages of this scheme are 1) Reduced voltage stresses on switches and diodes, 2) Zero Voltage Switching (ZVS) turn ON of the switches and ZCS turn OFF of the diodes, 3) Low input current ripple due to the interleaved structure, 4) Reduced energy volumes of most passive components, and 5) Extendibility to desired voltage gain and power.

3.2. Isolated DC-DC converter with multi-winding transformer

Multi-input converters are used to integrate different power sources where each one of them has different power rating. These converters accommodate a range of sources and pools in their advantage such that the energy source is diversified to enhance utilization and reliability of the renewable source. Some of the advantages of the multi-input converter are reduction in size, parts count and cost, in addition to increasing the efficiency of the system [11].

Survey of literature reveals that in the past decade, several multiple-input power electronic converter topologies have been recommended to interface traction drive needs with on-board energy sources. Most of these methods are based on PWM, flux summation concept, DC-DC converter for high or low voltage sources, and converters for energy storage units including batteries and ultra-capacitors [12].

The principle of flux summation can be used to drive multi-input converters, where the sources are interconnected through a multi winding transformer. The principle helps to interconnect multiple converters which have different voltage levels [13]. Chen et al. [14] proposed a novel multi-input DC-DC converter based on the transformer flux summation concept. Several advantages were observed through the circuit topology proposed by them. Some of the advantages are the magnitude of the DC voltage need not be the same, soft switching method is available, DC sources can deliver power both individually and concurrently and the electrical isolation is naturally achieved.

The literature reports the development of several front-end DC-DC converters that could interface the sources. These are current-fed push-pull converter [15], the interleaved boost converter [16], the three-phase converter, and the phase shifted full-bridge converter [17]. Subsequently, some researchers have proposed design for bi-directional converters to connect to the storage [18]. Nevertheless, these models have been found to be highly complex with a high cost attributed to it because of the several conversion stages and devices which were used between the individual converters [19].

Chen et al. [20] proposed a multi-input, current-fed full-bridge DC-DC converter. This converter adds up the produced magnetic flux in the magnetic core of the coupled transformer and converts it into a magnetic form in the DC input sources. The model proposed by them includes a common output-stage circuit, two current-source input stage circuits, and a three-winding coupled transformer. To meet the specification of multi-input DC sources, the input stage circuit number may be increased, while the other two components cannot be modified. The main advantage of this transformer less method is that it attains a higher efficiency while the size and weight are maintained small, in comparison with the other power generation systems. This method is considered to have higher efficiency than the transformer method, which is usually bulky, heavy and also not suitable for PV panel installations.

Zhang et al. [21] investigated and designed a new two-input isolated DC-DC converter based on a distributed multi-transformer arrangement, which is an appropriate model for hybrid energy systems. A new transformer winding-connection approach, the dual-inputs are decoupled totally, so that the converter can get the power from both DC sources, which have little output voltage, and shift it to the DC bus, which has maximum voltage, independently or concurrently. They analyzed a detailed operating principles of the converter in the two-input mode and the one-input mode, correspondingly. The main benefit of this topology is that all the transformers and the converters are completely operated for both operating modes. Even though the four transformers are worked, the powers of each transformer and converter are four times reduced. Moreover, some particular issues on design of converter, such as rising number of ports, the magnetic integration and the decoupling are conversed.

3.3. Non isolated two-input converters

Several reports are published on the tremendous advancement of the traditional power converter topologies. The development has started with single phase interleaving which later moved to multiphase interleaving and from single level to several levels. The recent trend has been found to use single-input DC-DC converters and single output converters. Besides these changes, research also focuses on multi-port DC-DC converters. These are, especially, used for generating energy where varied sources and storage elements are combined and used for high power application.

The three-port converter is found to be better than conventional converters which use multiple converters. They are superior system efficiency, faster response, fewer components, compact packaging, and unified power management [22]. A dual active bridge topology is found to be commonly popular among the bi-directional DC-DC converters that uses two half bridges or two full bridges in the high frequency transformer that has phase shift control ensuing in ZVS and flexible power flow control.

Kumaran and Lakshmi [23] investigated a high efficiency ZVS multi-input converter, which directly utilized the current-source type applying for both input power sources. This method proposes a reduction in conduction loss of switches in the dual-power-supply state depending on the designed PWM signals and series-connected input circuits. In order to achieve turn-ON ZVS of the switches, an auxiliary circuit with small inductor functioning in Discontinuous Conduction Mode (DCM) was used. It is possible to remove the huge reverse-recovery current of the output diode through auxiliary inductor which connected to Schottky diode [24].

Zhang et al. [25] proposed an interleaved method that can alleviate the output voltage ripple of two-input inductor currents. Thus, this converter was beneficial to convert two power sources of different voltages to a single DC-bus voltage. This converter can be used both in the single and dual power supply states. Nejabatkhah et al. [26] proposed a two-input power converter that has a ZVS for a hybrid FC and battery power system. However, this converter could neither deliver a bi-directional functionality nor could boost the input voltage, despite having well developed circuit efficiency.

Ravichandrudu et al. [27] proposed a novel three-input DC-DC boost converter be used for hybrid power system applications. The proposed method was able to produce current-source type in the input power ports that could control the input voltages. This method was successfully used to control the power flow between the input sources and the load using duty ratios. The advantage of this converter is that it can deliver the input power sources to the load either individually or simultaneously. In comparison with the multi-source hybrid power systems, the proposed method was better in that it had simple structure, bi-directional power flow, low power components, transformer less, centralized control, high stability working point, light weight, high level of boosting and independent operation of input power sources. The latest technologies have given rise to multi-input DC-DC converters for hybrid power system. In these converters, the boosting level was low without bi-directional operation.

Hosseini et al. [28] proposed three-input DC-DC converter for grid-connected hybrid power system fed from full bridge inverter with bi-directional flow. In this model, the presence of transistors resulted in THD and switching losses. Four-port DC-DC converter is also introduced with decoupling and small signal modelling. In this work soft switching multi-port DC-DC boost converter designed for hybrid power generation.

3.4. Non isolated multi-port DC-DC converter

Tao et al. [29] presented a novel multi-input bi-directional DC-DC boost converter which connects a FC, storage and load by a mixture of a DC linkage and magnetic-coupling. A boost two half-bridge and bi-directional direct-connected switching cells are utilized. The topology is uncomplicated and requires only minimum number of power switching devices. Moreover, this converter derives or feeds current from the FC and the super capacitor. The scheme is correct choice for medium-power applications where easy topology, independent operation, compacted, and minimum cost are necessary. Various control methods to handle power flow are projected and evaluated. Further, they showed that the proposal of combining the DC-link and magnetic-coupling is developed to multi-port bi-directional DC-DC converters.

Al-Atrash et al. [30] proposed an integrated single-stage DC-DC converter. The converter connects two bi-directional ports and storage port, and an output loading port. The topology is based on the integration of a two-phase boost pre-regulator into a phase shift controlled converter. The four bridge power switches participate in the shared role of understanding boost conversion, and the transformer operation. The technique is temporarily capable to achieve ZVS of all switching devices. This technique improves the cost related with initiate a switching leg for boost conversion, and saves the loss during switching. A stable frequency switching design is implemented that avoids two of freedom essential for suitable control. The duty ratio of the two phase legs of the bridge is different to control power flow in the boost conversion, while the phase-shift between the legs is used to control the power output port.

Qian et al. [31] presented the design and analysis of a satellite power system, which make use of three-port converters to interface a range of autonomous PV panels, one battery to a regulated bus. The features of converter are minimum component and compact configuration. The interleaved three-port converters boost the power and offer redundancy. The output port “hybrid” current distribution technique displays good transients while necessitate no internal current sharing bus, in the meantime, the passive current sharing scheme is well appropriate to both the Maximum Power Point Tracking (MPPT) and the battery charge control. The analysis and design of the control strategy, the method current sharing for three ports, the MPPT and battery charging are demonstrated.

Al-Atrash and Batarseh [32] suggested a converter to full fill many modern systems that need energy harvesting from numerous sources and the supervision of power storage. The implementation of converter schemes purposely modified for such applications suggest great development potential over conventional methods. Investigation of operating modes and component strain is offered, leading to a talk of proper design procedure. A comparative study is made on the proposed schemes and a conventional converter system. This study created the restrictions under which each of the three design option is most gainful. It demonstrated the ability of the converters to achieve considerable investments in losses and expenses for a variety of multi-port applications.

Zhang et al. [33] designed a new isolated current-fed DC-DC converter with two-input power sources based on multi-transformer, which is appropriate for FC and super-capacitors hybrid system. With particular transformer windings connection approach, the converter can derive power from two different DC sources with minimum voltage and feed it to the higher voltage DC bus or load independently and simultaneously. The detailed operation principle of the proposed converter has been analyzed in dual-input mode and single-input mode, respectively.

Zeng et al. [34] proposed a novel isolated multi-port DC-DC boost converter for concurrent power management of various renewable sources, which can be of dissimilar models and ratings. This DC-DC converter uses one switching device in single-port to which a renewable source is coupled. Consequently, it has the merits of uncomplicated topology and least number of power switching devices. The DC-DC converter is applied for simultaneous MPPT control of a wind and PV hybrid generation system contains one wind energy source and two different PV sources.

4. Analysis of Conventional Boost Converter

Chopper is used to convert fixed DC voltage into variable DC voltage. This chopper can be used to step up or step down the DC input voltage. The boost converters are widely used in renewable power generation such as PV and FC based system for conversion. Moreover, these converters are used in applications such as automobiles, hoists, trolley cars and mine haulers. The existing converters such as basic boost converter topology, single switch soft switching boost converter, isolated boost converter, two-input DC-DC converter and three-input boost converter are dealt in this chapter. At last the problems associated with these converters are presented.

Boost converters are used for the conversion of lower DC input voltage into higher DC output voltage. Conventional DC-DC boost converter using a single power switch as shown in Fig. 2, in which the MOSFET is used as the power switch. There are two operating modes in the converter. During the first operating mode, the switch is turned ON and current completes its path via inductor as shown in Fig. 3. At this mode, inductor stores the energy and load current is maintained by the load capacitor. During the time t1, inductor current increases from minimum to maximum. During the time t2, inductor current falls from the maximum value to minimum value. Δi is change in input current. The *t1* and *t2* are derived as follows [35]:

$$V_{in} = L\frac{\Delta I}{t_1} \tag{1}$$

$$t_1 = L\,\frac{\Delta I}{V_{in}} \tag{2}$$

$$V_{in} - V_0 = -L\,\frac{\Delta I}{t_2} \tag{3}$$

$$t_2 = -L\,\frac{\Delta I}{V_{in}-V_0} \tag{4}$$

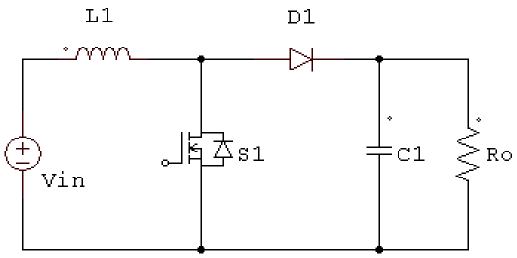

Fig. 2. Boost converter.

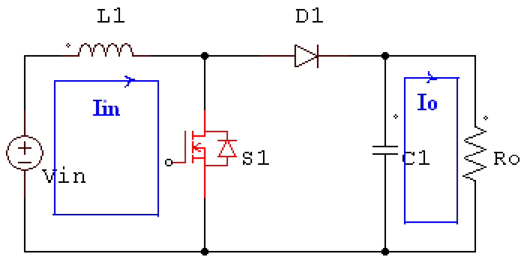

Fig. 3. Boost converter-MOSFET ON.

During the second operating mode, the power switch is turned OFF, and current completes its path via inductor as shown in Fig. 4. At this mode, inductor releases the stored energy, and the load receives the load current. The diode and MOSFET switch is operating in a complementary manner. The current flows through the inductor, diode, capacitor and load. The output side capacitor across the load used as a filter in the converter circuit [35]. For high switching frequencies the switching device can be replaced by IGBT.

The mean value of output voltage can be estimated by replacing time period *t1*=*DT* and *t2*= (1-*D*) *T* in Eqs. (1) and (3) [35]. Similarly, average current in the output is calculated by assuming *VinIin* = *Vo Io*. The output voltage *Vo* is calculated as follows and it shows that *Vo* is the function of duty cycle.

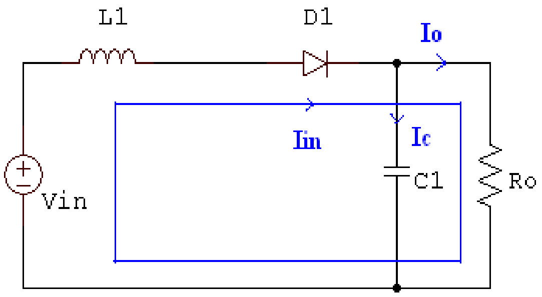

Fig. 4. Boost converter - MOSFET OFF.

$$V_0 = V_{in}\frac{T}{t_2} \tag{5}$$

$$V_0 = \frac{V_{in}}{(1-D)} \tag{6}$$

$$I_{in} = \frac{I_o}{(1-D)} \tag{7}$$

The switching time period is calculated by summing up both the time periods *t1*and *t2* from Equations (3.2) and (3.4) [35]. The frequency is obtained by taking inverse of this switching time period *Ts*.

$$T_s = t_1 + t_2 \tag{8}$$

$$T_s = L\, V_0 \frac{\Delta I}{V_{in}(V_o - V_{in})} \tag{9}$$

Peak to Peak value of ripple current and ripple voltage in this boost converter is calculated given in Eqs. (10) and (12) [35]. The ripple current mainly depends on the value of inductance connected to input side, while the ripple voltage mainly depends on the capacitance connected in the load side [35].

$$\Delta I = \frac{V_{in}(V_o - V_{in})}{L\, V_0 f} \tag{10}$$

$$\Delta V_c = \frac{1}{C}\int_0^{t_1} I_c \, dt \tag{11}$$

$$\Delta V_c = \frac{I_0\,(V_o - V_{in})}{f\, V_o C} \tag{12}$$

Parameters designed for this conventional boost converter is shown in Table 1. The variation of input current ripple for change input inductor is shown in Fig. 5. It clearly shows that, current ripple in the input increases for small value of inductor. The current through an inductor is shown in Fig. 6. The DC input voltage is boosted as shown in Fig. 7. These waveforms clearly show that the load voltage is present when an inductor current decreases from maximum to minimum and vice versa [1]. The boosted output voltage is equal to 200 V.

Table 1. Conventional boost converter parameters.

Input Voltage	100V
Output Voltage	200V
Duty cycle	60%
Frequency	5kHz
Inductor	1mH
Capacitor	100µF
Load Resistance	100 Ω

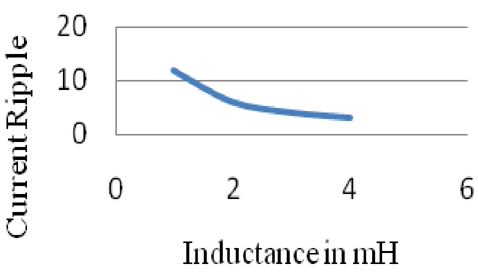

Fig. 5. Inductor vs. current ripple.

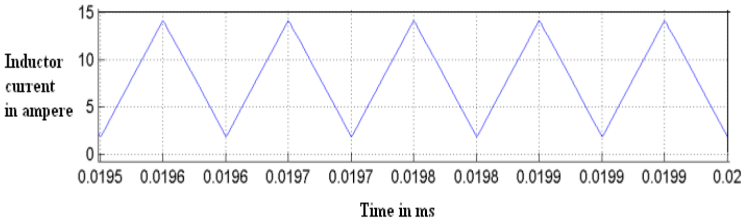

Fig. 6. Inductor current of boost converter.

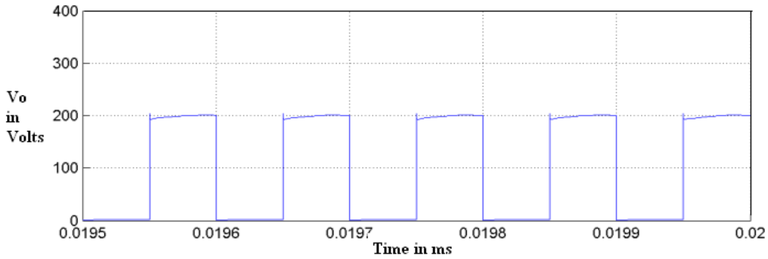

Fig. 7. Output DC voltage of boost converter.

The boost converter operation is continuous and the efficiency of the converter is good due to the presence of single switch. The output voltage depends on the duty cycle value of the switch. The output voltage can be stabilized by applying appropriate design of input side inductor and output side capacitor.

5. Analysis of Soft Switching Boost Converter

The above hard switching DC-DC converters are replaced gradually by soft switching converters in many applications due to the associated switching losses and large number of components [36]. The soft switching boost converter circuit is obtained by including, an inductor, two diodes and two capacitors in the conventional boost converter circuit. Switching ON/OFF is controlled by one switch while the switching loss is decreased by switching at zero-current and zero-voltage controlled resonance of *L2* and *C2*. Fig. 8 illustrates the single-switch soft switching boost converter.

In Fig. 8 the switch is kept in the OFF position during the first switching stage and the DC output of PV cell is directly transferred to the load via *L1* and *D3*. The inductor current reduces linearly, because at this point, the main inductor voltage reaches *Vin-Vo*. The second switching will start in case the switch becomes ON in ZCS condition. The output voltage is then given to the resonant inductor *L2* increasing the current linearly. When the inductor current *L1* and *L2* becomes equal, the output side diode *D3* current reaches zero. When the *Dout*, i.e., output side diode, current reaches zero, the switch turns OFF leading to the beginning of switching period. At this point, the auxiliary capacitor *C1* and the auxiliary resonant inductor *L2* resonate resulting in fall of *C2* voltage to zero at the output voltage. During this time, the main inductor *L1* current passes through *L2* and the switch.

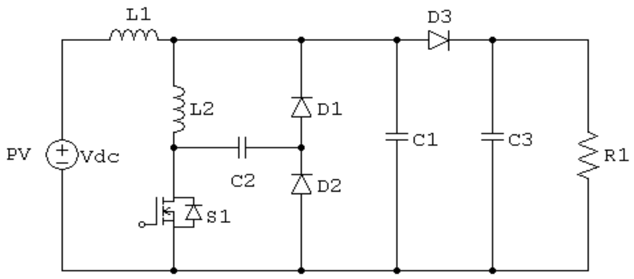

Fig. 8. Single switch soft switching boost converter.

During the fourth switching period, this mode starts. The result of auxiliary resonant capacitor voltage becomes zero and turning ON of the two auxiliary diodes *D1* and *D2* occurs. The splitting of auxiliary resonant inductor current into two occurs at this stage: (1) Main inductor *L1* current and (2) The current turning through two auxiliary diodes. The current of the main inductor increases linearly and the entire current is supplied to the boost converter.

Two current loops occur during the fifth switching period. One of them is the *LI-C1-Vin* loop and auxiliary resonant capacitor *C2* increases linearly from zero to the output voltage *Vout*. The second resonance occurs at the other loop *L2-C2-D1*. The energy stored at *L2* moves to *C2*. On complete storing of the energy, the current of *L2* reaches zero while the voltage of *C2* reaches the maximum value.

During the sixth switching period, the voltage of *C2* reduces continuously resonates on the loop of *D2-C2-L2-D3-C3* and moves the energy of *C2* to *L2*. On *C2* voltage becoming zero, there will be a reverse flow of *L2* current from the existing direction in mode 5. At the same time, when the *C3* voltage becomes zero, the anti-parallel diode of the switch becomes ON moving to the next mode.

The seventh switching period also has two current paths. The main inductor *L1* current transfers the current to the output via *Dout* and the current decreases linearly. The current of the auxiliary resonant inductor *L2* transmits the energy to the load through *Dout* and flows through the anti-parallel diode of the switch. If the current of the auxiliary resonant inductor *L2* becomes zero, mode ends.

Table 2 depicts the parameters of the boost converter. For the tabulated parameters the converter can produce the maximum power of 1 kW. The resonant inductor and capacitor are selected such that to operate the converter with soft switching.

Table 2. Soft switching converter parameters.

Parameters	Values
Rated Power	1kW
Input Voltage	200V
Output Voltage	360V
Inductor L_1	1.5mH
Switching frequency	10kHz
Capacitor C_1, C_3	10nF
Inductor L_2	50μH
Capacitor C_2	100nF

The following equations are used to calculate the resonant frequency and the impedance at resonant condition.

$$\omega_{r1} = \frac{1}{\sqrt{L_1 C_3}} \tag{13}$$

$$\omega_{r2} = \frac{1}{\sqrt{L_2 C_2}} \tag{14}$$

$$Z_{r1} = \sqrt{\frac{L_1}{C_3}} \tag{15}$$

$$Z_{r2} = \sqrt{\frac{L_2}{C_2}} \tag{16}$$

The soft switching DC-DC converter efficiency is calculated by increasing the load gradually, which is shown in Table 3. The efficiency is calculated for both hard switching boost converter and soft switching boost converter. In Fig. 9, the change in efficiency is clearly shown for different values of input voltage. It shows that the efficiency in the Soft Switching Boost Converter (SSBC) is higher than the Hard Switching Boost Converter (HSBC) [37].

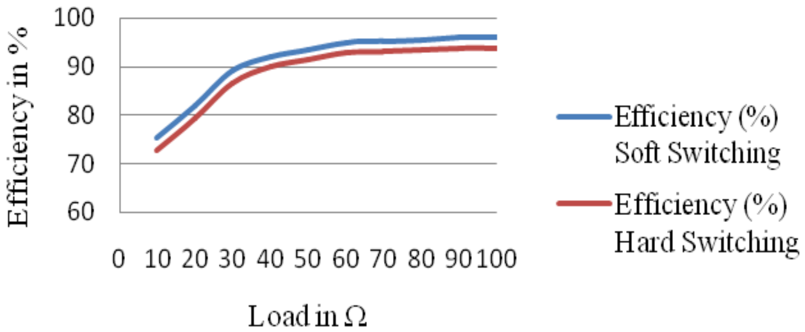

Fig. 9. Efficiency comparisons - HSBC and SSBC.

6. Analysis of Interleaved Boost Converter

In case of normal boost converter, if the duty cycle is more than 50%, the capacitor, stores the output current for a greater section of every time period than the storage inductor. Consequently, to sustain tolerably less output side ripple in voltages, a big capacitance is need to make sure that the *Vo* does not drop as the stored energy is provided by capacitor during the operating period. Both DC and AC currents are sourced via a storage inductor, this must be considered such that the inductor core should not soak at high power applications. In addition, elevated temperatures typically lower the saturation flux threshold of the inductor core material, making this requirement a more significant design consideration. To overcome these problems, an interleaved converter configuration involving two conventional boost converters, was calculated to minimize reduce the trouble on the C_0 as well as the inductor. Further profits of interleaving contain good power handling capacity, and reliability. An interleaved converter configuration, however, increases the cost of extra inductors, power devices, and output side converters. Coupled inductor schemes also offer more merits such as minimized core loss and winding loss as well as reduced current ripple (Fig. 10).

The increase in size of an inductor reduces the current ripple. It reduces the voltage stress on the power MOSFET switches considerably and improves the lifecycle of the switches. Comparison with voltage stress on conventional type converter switch and interleaved converter switch depicted in Fig. 11. Thus, it can reduce the current rating of the switch and the maximum voltage across the switch. The voltage stress on the switches is calculated in terms of output voltage 1V= *Vo* of the converter. These inductors also used to reduce the input side current ripples considerably. The stress on the switching device is less when duty cycle is 30%.

7. Analysis of Isolated Multi-Port Converters

Now a day, multi-port converters propose a promising solution for the replacement of many power conversion steps used in conventional hybrid systems, which joins various renewable sources in its structure. Power electronic interfacing methods are categorized into two types one is DC-link interfacing in which the converter directly combines different power sources through a common DC-link and second one is magnetic interfacing in which converter combines different power sources by means of magnetic coupling. In both the methods current fed and voltage fed interfacing is possible.

Table 3. Efficiency with change in load.

Load in Ω	Efficiency (%) Soft Switching	Efficiency (%) Hard Switching
10	75.2	72.8
20	81.8	79.2
30	89.1	86.6
40	92	89.9
50	93.4	91.4
60	95	92.8
70	95.2	93
80	95.4	93.4
90	96	93.8
100	96	93.8

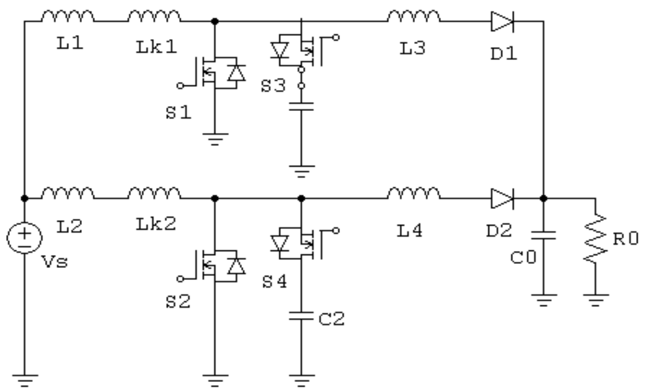

Fig. 10. Interleaved soft switching boost converter.

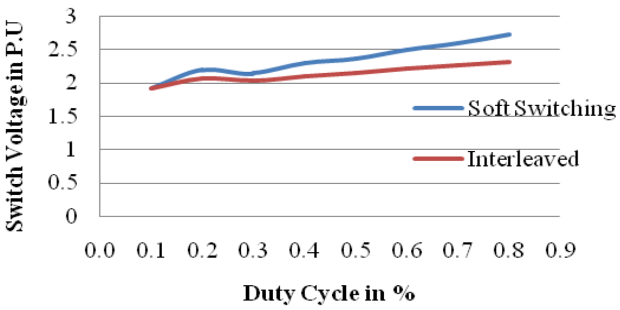

Fig. 11. Voltage stress in switching devices.

7.1. Analysis of three-port converter with transformer

At first multi-input converter was initiated by Matsuo et al. [38]. Figure 12 shows the basic structure of multi-input converter, which is fundamentally composed of two fly-back converters with magnetic coupling. Any one of source can transfer power at moment because of the fact that switching devices *S1* and *S2* are operated on time sharing concept due to the clamped voltage on the transformer winding.

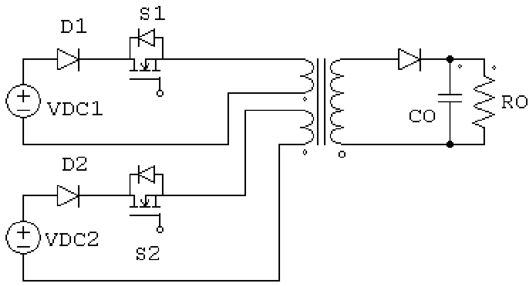

Fig. 12. Basic two-input DC-DC converter.

Moreover, working based on fly-back technique is not practically applicable for applications with high power due to its more leakage inductance current. Another drawback is that there is no bi-directional power flow in this converter. Another current fed multi-input converter used for renewable source applications, is implemented by Chen et al. [39] as shown in Fig. 13. In this topology there are two current-fed input circuits, a three-winding transformer, and a common diode output side circuit. In this current-fed multi-input converter type switches are connected in series with a reverse-blocking diode. It is used to regulate the current path direction and avoid the reverse flow of power from other DC sources. The circuit topology has many merits such as simultaneous power transfer capability, soft switching facility and proper electric isolation [40-41]. However one disadvantage due to the existence of block diodes is that, it permits the power transfer from sources to the load and this prevents the DC-DC converter from applications with energy storage elements which usually require bi-directional power flow. In this method, current ripple present in the input is more due to its voltage fed input. Tao et al proposed three-port dual half bridge DC-DC boost converters in which the component count is reduced much than the previous topologies. But this asymmetrical structure leads to the complicated design of controller.

7.2. Analysis of multi-port converter with transformer

A single switch isolated DC-DC boost converter has minimum number of switches than the existing isolated techniques and hence it reduces the cost of the converter [42-44]. The energy in this technique is moved in an entire switching period instead of only during the switch ON time interval of switch, which decreases the maximum current and improves the efficiency of the converter.

The circuit topology of the single-switch isolated DC-DC converter is shown in Fig. 14, which contains of a low voltage side and a high voltage side connected using high frequency transformer. The low voltage side contains of an inductor *L1*, a switch *S1*, an energy storage capacitor, and the transformer primary winding. The high voltage side contains of the transformer secondary winding, it is joined to a bridge rectifier consists of four diodes *D1 - D4* and a *LC* filter. The high frequency transformer's turn ratio is *N = N1 / N2*, where *N1* and *N2* represents the number of turns in the primary winding and secondary windings, respectively. This converter achieves two major functions: regulation of low varying input DC voltage of PV to a high fixed output voltage *Vo* and tracking the PV panel maximum power point. The converter operation is controlled by a switch *S1* and capacitors are enough to reduce the voltage ripples.

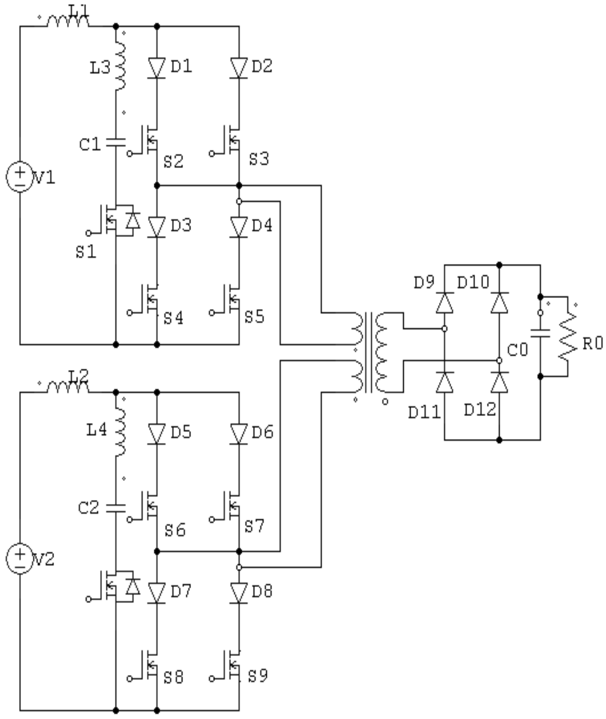

Fig. 13. Two-Input current fed full bridge DC-DC converter.

The primary side voltage across primary winding, current in the switch during its ON and OFF period and duty cycle of the switch for the single-switch isolated DC-DC converter is shown in Fig. 15. In Fig. 13, first key waveform shows the duty cycle of the switch *S1*. When *S1* is in ON condition the, inductor *L1* starts to store the energy which is shown in the second key waveform. Inductor discharges the energy stored in it when the switch is in OFF condition. Simultaneously, the primary side DC voltage is also captured to show the negligible voltage during turn OFF period.

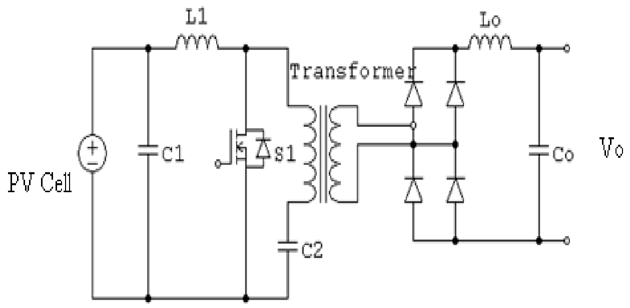

Fig. 14. Single switch isolated DC-DC converter.

The relationship between input and output voltage of the converter is depends on the transformer turns ratio and duty cycle of the switch. This converter operate as a boost converter for duty ratio more than 0.5 with *N*=1.The relation given as follows.

$$\frac{V_{out}}{V_{in}} = 2\,ND \qquad (17)$$

where *N* is Turns ratio of transformer and *D* is Duty ratio of the switch.

This single switch circuit is extended for multiple inputs as shown in Fig. 16. It consists of a low voltage input side and a boosted voltage output side circuit connected using high frequency transformer. Parallel connected input side ports and energy storage capacitor linked with the primary winding of the high frequency transformer [45-46]. Single-port contains a controllable MOSFET switch, inductor and a power diode. In the secondary side of the high frequency transformer consists of a diode rectifier, and a *LC* filter.

The transformer's turn ratio is defined as *N*= *N1* /*N2*, where *N1* and *N2* are the numbers of turns of the transformer primary winding and secondary windings, respectively. This isolated boost converter has three operating modes: 1) All three switches are ON condition 2) Switch *S1* is OFF while at least any other switches is ON and 3) All the switches are in OFF condition.

In the above topology the stress on the switch is more and usage of transformer increases the cost and losses too. The switch *S1* should be turned OFF before the switch *S2*, otherwise *L2* will continue to charge through *S1* even *S2* is in OFF. Moreover, the size of the transformer is bulky which maximizes the size. The steady state equations for multi-input isolated DC-DC converter is derived as follows

When the switch 1 conducts,

$$L_1 \frac{di_1}{dt} = V_1 - (i_1.r_1 - V_{cs} - V_t)(1 - d_1) \qquad (18)$$

$$C_s \frac{dV_{cs}}{dt} = i_{cs}d_1 + i_1(1 - d_1) \qquad (19)$$

$$\frac{di_L}{dt}\frac{L_0}{N} = Ni_{cs}d_1 + NV_t(1 - d_1) - V_{dc} \qquad (20)$$

where d_1=duty cycle of switch1, V_t=Voltage across transformer primary V_{cs}=Voltage across capacitor *CS*, i_1r_1= Parasitic resistive drop in L_1, V_{dc} =Output voltage. When the switch 2 conducts,

$$L_2\frac{di_2}{dt} = V_2 - (i_2.r_2 - V_{cs} - V_t)(1 - d_2) \tag{21}$$

$$C_s\frac{dV_{cs}}{dt} = i_{cs}d_2 + i_2(1 - d_2) \tag{22}$$

$$\frac{di_L}{dt}\frac{L_0}{N} = Ni_{cs}d_2 + NV_t(1 - d_2) - V_{dc} \tag{23}$$

where *d2*=duty cycle of switch 2, *i2r2*= Parasitic resistive drop in *L2*.

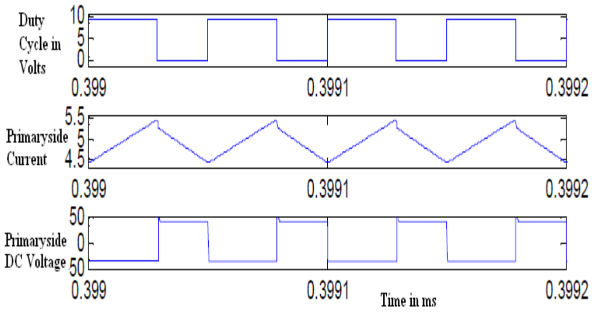

Fig. 15. Single switch isolated converter waveforms.

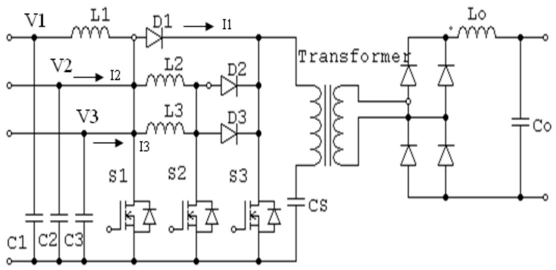

Fig. 16. Multi-input isolated DC-DC converter.

When the switch 3 conducts,

$$L_3\frac{di_3}{dt} = V_3 - (i_3.r_3 - V_{cs} - V_t)(1 - d_3) \tag{24}$$

$$C_s\frac{dV_{cs}}{dt} = i_{cs}d_3 + i_3(1 - d_3) \tag{25}$$

$$\frac{di_L}{dt}\frac{L_0}{N} = Ni_{cs}d_3 + NV_t(1 - d_3) - V_{dc} \tag{26}$$

where *d3*=duty cycle of switch 3, *i3r3*= Parasitic resistive drop in *L3*. The output DC voltage in the multi-input DC-DC converter is shown in Fig. 17. The steady state is reached at 142.5V. The figure presents that the conversion ratio of the isolated converter is poor than the integrated converter. The *PWM1*, *PWM2* and *PWM3* are the signals applied to gate of the switches *S1*, *S2*, and *S3* respectively (Fig. 18). All the sources are effectively working in this converter configuration, for which the switch *S3* must not be turned off before *S2* is switched off.

Similarly switch *S2* must not be turned off before *S1* is switched off, if not, *L3* will constantly store up energy through *S1* even *S3* is in off condition, which is not preferred operation.

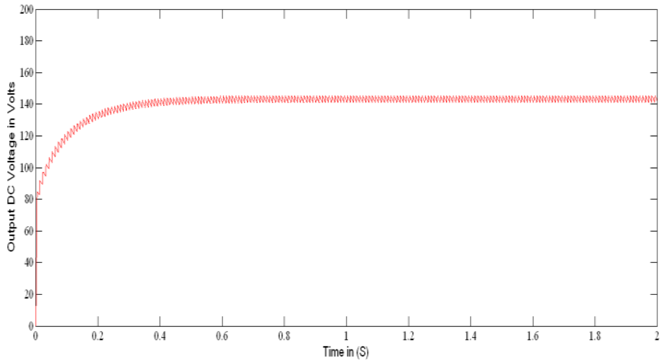

Fig. 17. Isolated converter output DC voltage.

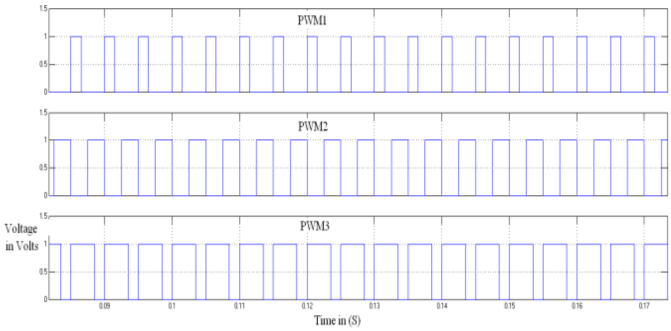

Fig. 18. Isolated converter PWM signals.

All the above reported DC-DC boost converter topologies have one or more of the difficulties given below:

- There is no facility for bi-directional port for energy storage application.
- The powers from renewable sources are not transferred individually and simultaneously.
- Electric isolation is poor. So that it is not suitable for high power application.
- Soft switching technique is not accomplished for all the switches present in the circuit.
- More number of components is present in the circuit and related gate driver circuits are complicated.
- Asymmetrical design structure will lead to complicated power flow control.

8. Analysis of Non Isolated Multi-Port Converters

In this research study, a DC-DC boost converter that uses the wind, PV, FC and battery input ports for hybrid power generation system is proposed. The proposed converter with unified structure consists of three unidirectional input ports, which act as the input power sources; a bi-directional input-port for storage, and an output load-port as shown in Fig. 19. PV and FC input ports function as constant current source type as well as build up the input voltages [47-48]. This is a unique arrangement availing just five power MOSFET switches; each of the switches uses different duty ratio and hence controlled individually. The duty ratios also control the power flow between the input sources. The excess power generated through the PV and FC cells are directed to the battery for storage. Depending on how the energy is utilized by the storage element, four different power operation modes of the converter are defined.

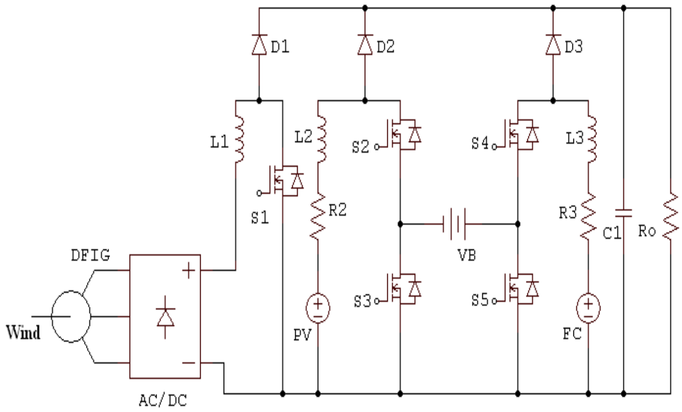

Fig. 19. Non-isolated boost converter topology.

The boosted voltage from DC-DC converter is 337.8V when the generation is contributed by PV and Wind alone (Fig. 20) and the corresponding mode gate pulses are shown in Fig. 21. In this mode of operation duty ratio of switch 3 is kept in maximum. When generated power is more than the power demand, the voltage regulation is performed. The efficiency of the both isolated and non isolated converters is calculated in the different power levels as shown in Fig. 22. The figure shows the non isolated converters performance improvement in terms of efficiency.

All the power electronics converters for hybrid system are recognized by connecting many DC-DC converters. The advantages of using integrated DC-DC converters with multiple ports, defined as multi-port converter, in its place of employing individual DC-DC boost converters are as follows: (1) Minimum cost because of minimum component and related circuits, (2) Superior power density, (3) Good thermal management, (4) Better reliability (5) Simple implementation and centralized structure of control. Therefore it is significant to build up integrated power converters with multiple ports able to control power flow among several input power sources to attain optimum power sharing, and reliability.

Table 4 shows the overall deficiency on the existing type DC-DC boost converters used for hybrid power generation [49-50]. This table also depicts advantages of proposed multi-port converter over conventional type converter and interleaved boost converter. It proves that the performance of proposed converter is the best suitable converter for hybrid power conversion in all the aspects with a simple compromise on the complex controller design structure.

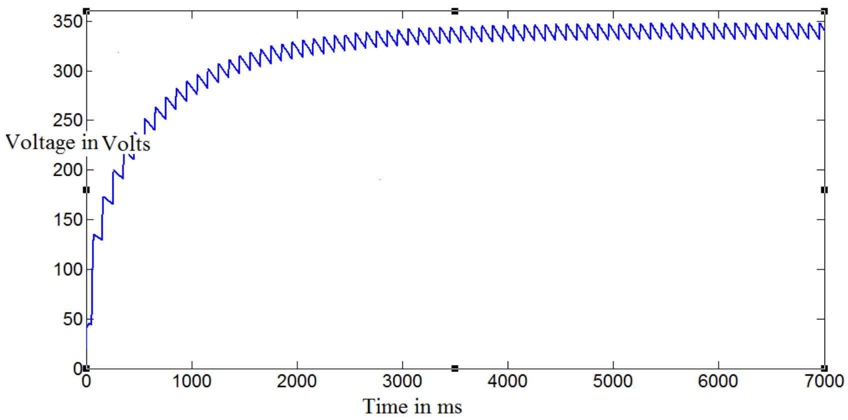

Fig. 20. DC link voltage.

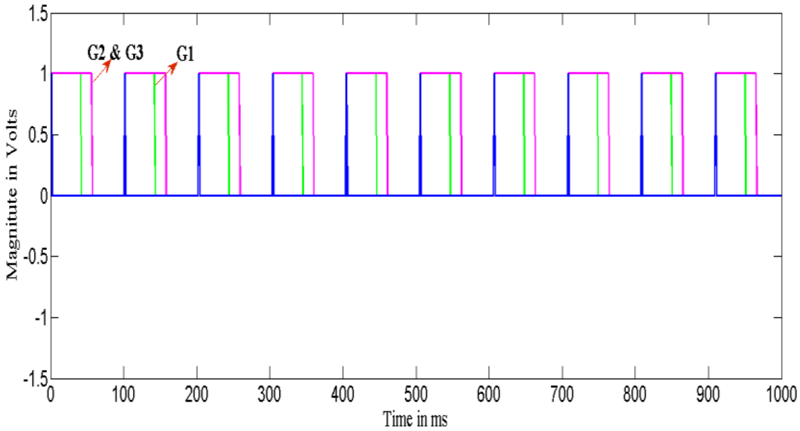

Fig. 21. Gate pulses G1, G2, G3.

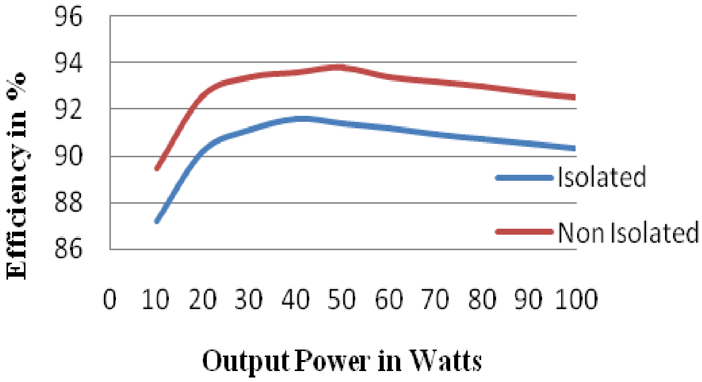

Fig. 22. Efficiency comparison -isolated and non-isolated converters.

Table 4. Overall comparative analysis.

Parameters	Conventional Converter	Interleaved Converter	Proposed Multi-Port Converter
Switching	Hard switching	Soft switching	Soft switching
No of devices	Less	More	Less than Interleaved
Switching Losses	High	Less	Less than Interleaved
Efficiency	Low	1% Higher than conventional	Higher than interleaved
Input Sources	Individual converters are joined for hybrid operation	Single-input	Multiple input, More Efficient for hybrid
Stress on the Switches	More	Normal	Less
Ripple Content	High	Less than Conventional	Less
Controller design	Simple	Easier than Multi-port	Difficult
Stability	Not stable in all operating points	Not stable in all operating points	stable in all operating points
Circuit Topology	Easiest Topology, No bi-directional port and backup	Easier Topology, No bi-directional port and backup	Difficult topology, Bi-directional port and backup is available

9. Conclusion

This literature review presents number of configurations where the output voltage is boosted up by DC-DC converter. This review paper has presented a widespread overview of DC-DC boost converter configurations based on its switching technique. It was found that the review recommends the usage of soft switching technique in the boost converters to achieve good efficiency. An interleaved boost converter configurations are also discussed in this paper which is extensively used in high step-up applications, interleaving principle is repeatedly utilized to recover better performance and shrink the size of filters. This review paper has offered a widespread analysis on isolated and non-isolated boost converter configurations. Also the significance to build up integrated power converters with multiple ports are also reviewed which is able to control power flow among several input power sources to attain optimum power sharing, and reliability. In comparison to the multi-source hybrid power systems, it was found that multi-port converters are better in that it had simple structure, bi-directional power flow, low power components, transformer less, centralized control.

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