High Efficient Converters: A Backbone of Efficient Renewable Energy Systems in an Indian Electricity Network

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Continuously growing population and industrial revolution in India demands affordable, reliable, uninterrupted and quality power supply. Thermal power generation has major share of current electricity demand in India, which leads to emission of carbon pollutants and causes global warming. In order to overcome the energy crises and avoid hazardous effects of global warming, hybrid DC/AC micro-grids equipped with renewable energy sources such as solar photovoltaic, wind energy systems, fuel cells, micro-hydro power generation units, etc. are gaining more popularity. These sources are low voltage sources; therefore, design of high efficient, high step-up, soft-switched converters plays a prominent role in efficient utilization and conversion of available energy; particularly, DC-DC converters for DC micro-grids and DC-AC converters for AC micro-grids. High-speed wide band-gap (WBG) semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN) both, having ability to withstand higher voltages with reduced switching and conduction losses are used to further increase the converter efficiency. Use of high-speed semiconductor devices allows converter to operate at high switching frequency, which reduces size of the magnetic components, hence increases power density of the converters and overall power conversion efficiency with reduced size and cost. This letter aims to focus the researcher's concentration towards the necessity and practical implementation of renewable energy based hybrid DC/AC micro-grid systems. Necessity of high efficient converters using high-speed wide band-gap (WBG) semiconductor switches for further efficiency improvement is narrated in subsequent sections. An improvement in the converter efficiency compared to conventional converter efficiency is demonstrated graphically.

I. Necessity of DC micro-grid

At the beginning, invention of electricity distribution was started with DC power distribution electricity grids in 18th century. Due to lack of technology and availability of resources for energy transformation, instead of developing DC power grids, researchers have concentrated on generation, transmission and distribution of AC power networks in 19th century. In last century, most of the residential lighting loads and industrial motor loads demand AC power only. Hence, installation of AC power grids became necessity for energy utilization. In addition, it is very easy to step-up and step-down AC voltage levels in order to transmit generated power over a long distance for efficient utilization. These advantages made AC power network a main choice.

Today's continuously growing population and industrialization in India demands affordable, reliable, uninterrupted and quality power supply. Fossil fuel based thermal AC power generation has major share of current electricity demand in India. Due to scarcity and the soaring prices of fossil fuels, installation of new thermal AC power plants is becoming expensive day by day. In addition, fossil fuel based thermal power generation leads to emission of carbon pollutants and causes global warming. These generating stations are remotely located, hence increases the long distance transmission losses so decreases the overall power conversion efficiency. In order to overcome the energy crises and avoid hazardous effects of global warming, locally distributed DC micro-grids equipped with renewable energy sources such as solar photovoltaic, wind energy systems, fuel cells, mini-hydro power generation units, etc. are gaining more popularity.

From last few decades, inventions of new solid-state devices and advancements in the power electronics technology have evolved an advanced DC-DC converters and different types of residential and industrial DC power loads. Today's most of the residential and industrial loads demand DC power supply such as: Electric vehicles, international space station (ISS), spacecrafts, modern aircrafts, telecommunications, off-grid buildings loads, LED lighting loads, charging phones, laptops, LCD TVs, modern variable speed industrial drives, electronics loads, heating, ventilation and energy efficient air conditioning equipments, etc. Air conditioning equipments have variable speed DC motor drives. Incorporation of high efficient DC micro-grid with appropriate voltage levels is the only economical solution for such loads where conversion of AC to DC is not necessary that leads to tremendous amount of conversion losses. Therefore, it is more economical and efficient way to power such loads directly from a local DC micro-grid. Fig. 1 shows typical structure of an efficient DC micro-grid incorporated with renewable energy sources, energy storage systems and high efficient power electronics converters. As it is very difficult to replace strong AC grid entirely with DC micro-grid, interconnection of DC/AC grid is feasible and economical solution. Therefore, in order to overcome global energy crises and the effects of global warming, incorporation of hybrid DC/AC micro-grid systems should be India's future contribution to globalization.

II. Necessity of high efficient converters design and development

Keeping in mind today's energy scenario and electricity consumers demand, it is necessary to build a power supply system with low energy conversion losses, high conversion efficiency and pollution free. With these goals, researchers should focus towards development of renewable energy systems based hybrid DC/AC micro-grids.

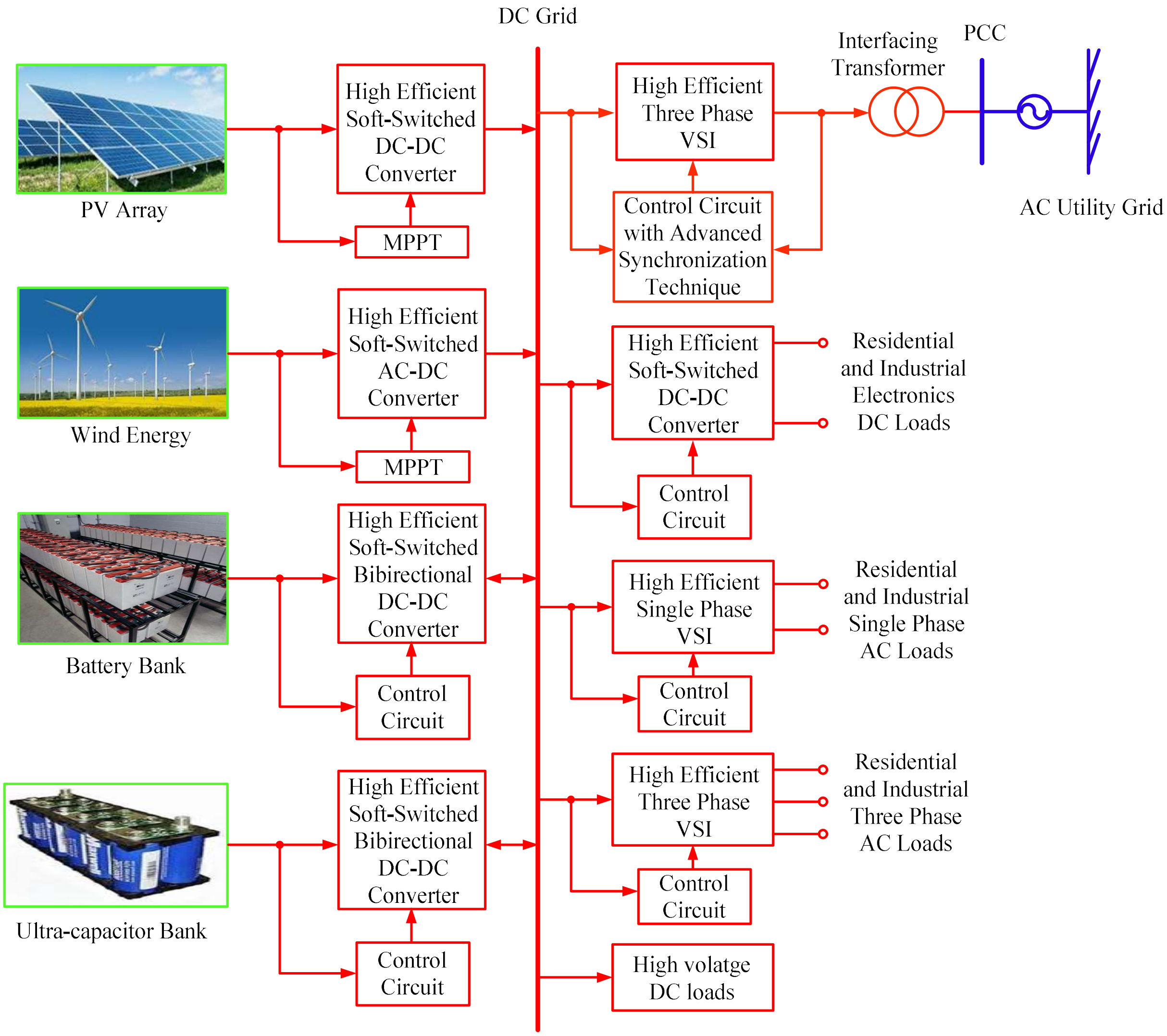

Fig. 1 Typical structure of an efficient DC micro-grid incorporated with high efficient converters.

Due to easily available solar energy, solar photovoltaic panels based locally distributed DC micro-grids are gaining more popularity. The only drawback of solar photovoltaic generation unit is its energy conversion efficiency is very less. Maximum efficiency of the solar PV cell is 16%. Due to this reason, solar PV systems installed for residential and industrial applications are preferred to operate at low output voltage (generally less than 50V). This voltage is not sufficient to drive most of the loads and cannot be integrated to the utility grid. In order to boost this voltage to utility voltage level, conventional boost converters are used. However, conventional boost converters have limitation of high voltage gain as its efficiency decreases due to high conduction losses, large voltage stress on the switches and diode's reverse recovery losses.

To avoid these problems, in the past few decades, extensive research has made revolutionary changes to conventional boost converters. Various researchers have proposed different types of high step-up DC-DC converters, which incorporate different features such as high frequency transformers, coupled inductors, interleaved coupled inductors, active and passive clamp circuits, etc. Isolated converters can also be used to achieve high voltage gain, but non-isolated converters are preferably used because of their higher efficiency, lower cost and higher power density. Among the various non-isolated high step-up DC-DC converters, the coupled inductor boost converters are considered as best solution for high-step-up applications, because it has facility to increase the voltage conversion gain by simply changing the turn's ratio. The main drawback of these converters is that the leakage energy in the coupled inductor increases voltage spike on the switches, which is further reduced by using lossless active and passive clamp circuits.

The integrated boost converter is also used as high step-up converter, in which boost converter is acting as a passive clamp circuit but experiences high voltage stress on the output diodes. In order to reduce this voltage stress and improve the voltage gain, voltage multipliers are introduced at the secondary side of the coupled inductor. In this type of converters, the leakage inductance of the coupled inductor reduces the reverse recovery losses of the diodes and hence increases converter efficiency. However, these converters are all hard-switched converters, which have limited conversion efficiency up to 80%. Hence, overall solar PV based generation system conversion efficiency is very less as indicated in Table I.

TABLE I: Overall system conversion efficiency with hard switching converters.

Sr. No.	Renewable Energy System Component	Efficiency
1	DC-DC Converter	Less than 80%
2	DC-AC Converter	Less than 80%
3	Magnetic components: Transformers, Inductors, Switching devices, Gate driver circuits, Digital signal processor, Power supply	Less than 95%
4	Solar Cell	Less than 16%
Overall system efficiency (1 to 3) = 0.8*0.8*0.95		Less than 60.8%
Overall system efficiency including solar cell (1 to 4)= 0.8*0.8*0.95*0.16		**Less than 9.73%**

A. Why not hard switching converters?

1) Switching frequency of the hard switching converters can be increased to reduce the size of the converter reactive components like inductors, capacitors, high frequency transformers etc.
2) However, such high switching frequency operation significantly affects power conversion efficiency because of increased switching power losses caused due to the overlap of switch voltage and switch current during a switching transition.

Efficiency of all these high gain hard-switched converters is further improved by reducing the switching losses. This is achieved by incorporating soft switching techniques such as zero voltage switching (ZVS) and zero current switching (ZCS). In integrated boost converter, ZVS of the main switch depends only on the stored energy of the leakage inductance. In non-isolated, soft switched integrated boost converter, a resonant voltage quadrupler cell is integrated at the secondary terminals of the coupled inductor to obtain high voltage gain. In addition, ZVS turn on of main MOSFET and the ZCS turn off of all the diodes reduces the high frequency switching losses and reverse recovery losses. Hence improves overall power density and converter efficiency as shown in Table II.

TABLE II: Overall system conversion efficiency with soft switching converters.

Sr. No.	Renewable Energy System Component	Efficiency
1	DC-DC Converter	Greater than 95%
2	DC-AC Converter	Greater than 95%
3	Magnetic components: Transformers, Inductors, Switching devices, Gate driver circuits, Digital signal processor, Power supply	Less than 95%
4	Solar Cell	Less than 16%
Overall system efficiency (1 to 3) = 0.95*0.95*0.95		Greater than 85.74%
Overall system efficiency including solar cell (1 to 4) = 0.95*0.95*0.95*0.16		**Greater than 45.6%**
% Rise in the overall system efficiency (1 to 3)		**41.02%**
% Rise in the overall system efficiency including solar cell (1 to 4)		**368.65%**

B. Why soft switching converters?

1) The soft-switching techniques like zero-voltage switching (ZVS) and zero-current switching (ZCS) will reduce switching power losses.
2) Soft switching converters are operated at high switching frequencies hence reduction in size of reactive components.
3) Switching converters have higher conversion efficiency and power density.
4) Soft switching feature is favorable to reduce noise and electromagnetic interference (EMI) effects.
5) Reduced stresses on the switching devices due to ZVS & ZCS.

6) Can be operated in variable frequency control, variable duty ratio control or combined variable frequency and duty ratio control.
7) Reduces filter size.
8) Hence, improves overall system efficiency.

All these aforementioned converters are developed by using silicon based power semiconductor switching devices. Silicon material properties have some limitations such as, low band-gap energy, low operating switching frequency and low thermal conductivity. In addition, the on-state resistance of silicon switches is also high. These limitations do not allow the converter to operate at high switching frequency because it increases losses and the size of magnetic components required. This affects the converter efficiency and power density.

However, new invention of wide band-gap semiconductor devices such as silicon carbide (SiC) and gallium nitride (GaN) have wider band-gaps, higher thermal conductivity and high breakdown electric field. Such devices are able to block higher voltages, operate at higher switching frequencies than silicon devices. In addition, the on state resistance of these switches is also low. Therefore, converters developed using such switches are operated at high switching frequencies. Hence, it drastically reduces the size and cost of the magnetic components required. In addition, the switching and conduction losses are very less. As these switches are able to block higher voltages, such converters can be used for high power application. Hence, using such devices, it is possible to achieve highest conversion efficiency and highest power density. As it is very difficult to improve efficiency of the solar cell, it became mandatory to develop high efficient soft switched converters using high-speed wide band-gap (WBG) semiconductor switches, such as silicon carbide (SiC) and gallium nitride (GaN) in order to improve overall system efficiency. These advantages make such high power, high step-up, high efficient soft-switched converters as perfect solution to integrate low voltage renewable energy resources with the DC micro-grid. The graph shows comparison of efficiencies of the hard-switched and soft-switched converters having conventional devices and soft-switched converters having WBG devices with respect to power output.

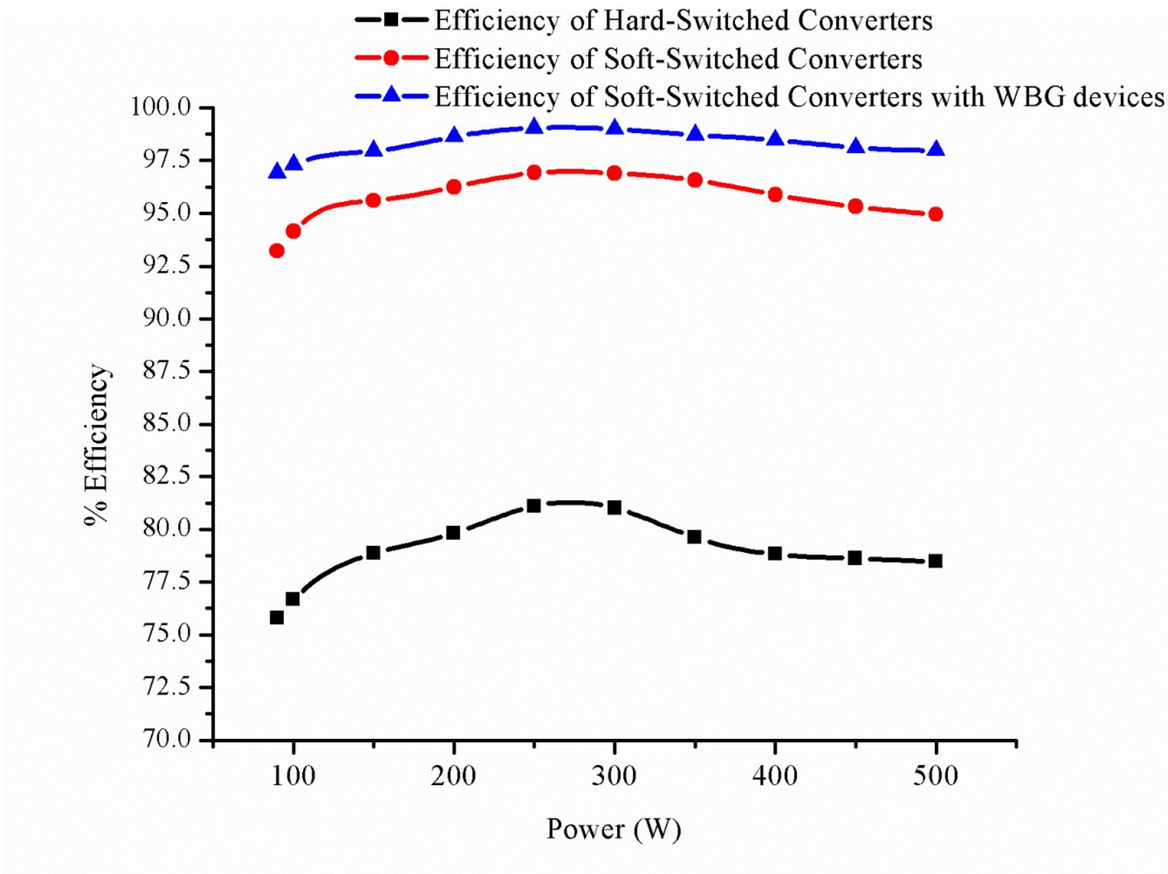

Fig. 2 Comparison of efficiencies of the hard-switched and soft-switched converters having conventional devices and soft-switched converters having WBG devices.

III. Conclusion

Keeping in mind today's electricity demand and the hazardous effects of global warming, development of high efficient hybrid DC/AC micro-grids equipped with renewable energy sources should be the ultimate goal of all researchers. In order to reduce the installation cost of renewable energy sources; high step-up, high efficient, soft-switched converters plays an important role in efficient conversion and utilization of available energy. High-speed wide band-gap (WBG) semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN) both increases power density of the converters and overall power conversion efficiency with reduced size and cost. Because of excellent properties of WBG devices, high step-up, high efficient soft-switched converters developed using such devices is the good solution for integration of low voltage renewable energy resources to the hybrid DC/AC micro-grid.