

Design of Auxiliary Resonant Boost Converter for Flywheel based Photovoltaic Fed Microgrid

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Abstract

Background/Objectives: To have a sustainable and low carbon living, efficient use of renewable energy is necessary hence, a power converter with less switching loss is proposed for the improvement of efficiency of proposed system. **Methods/Statistical Analysis:** In this work a dc boost converter is considered using an auxiliary resonant circuit for implementation of soft switching technology to reduce switching loss in the converter. The proposed dc resonant boost converter is designed for a required dc output based on the gate duty cycle. The soft switching is made possible by suitably designing the values of the inductor and capacitor of the dc resonant circuit. This circuit is simulated with MATLAB software. **Findings:** The resonant dc boost converter was simulated using MATLAB software with hard switching, the results of the simulation is discussed with waveforms and numerical values. The soft switched converter was able to provide an improved output voltage of 2Volts, current of 0.4 A, compared to the conventionally designed converter. Suitable design of the resonant components namely the inductor and capacitor, the efficiency of the soft-switched resonant boost converter improved by 2% compared to hard switched converter. Both the hard switching and soft-switched converters were simulated in open loop. It is evident from the output voltage and current waveforms, the settling time taken by the soft-switched converter is more compared to hard switched converter, but the improvement in voltage profile, current profile and efficiency overcomes the drawback of increased settling time. The resonant soft-switched converter when compared with the other converters reported provides an improved performance hence very much suitable for solar photovoltaic application. **Applications/Improvements:** The performance of the soft-switched converter can be improved further through closed loop control with simple controllers or using fuzzy logic controllers. This converter can also be used for other sources in any distributed generation.

Keywords: Auxiliary Resonance, dc-dc Converter, Resonant Converter, Soft Switching, Solar Photovoltaic

1. Introduction

The demand for electrical energy, environmental constraints has resulted in the need for generation of electrical power using non-conventional energy resources. Centralized power generation, transmission and distribution have several negative feedbacks which include poor quality, unreliability, economic losses and so on¹. To overcome these factors power generation at

community level has become essential. Microgrid is a new way to integrate non-conventional energy resources at the smaller level which also facilitates the participation of consumers in the electricity system of generation and distribution. The advantage of the micro grid is its capability to supply reliable and sustainable electricity in areas not covered by the conventional power grid². Microgrid incorporating distributed energy resources (DERs) along with suitable energy storage systems

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(ESS) provides a quality, stiff, green power. The power converter which links the DERs and load plays a vital role in the microgrid. This paper focuses on the choice of boost converters since the microgrid is chosen to be solar fed and battery less. A detailed comparison of hard-switched conventional boost converter with soft-switched resonant dc boost converter has been done by simulating these converters in MATLAB-Simulink. The different parameters namely the voltage stress, switching losses, and converter efficiency were analyzed.

2. Microgrid

Microgrid is a modern, small-scale version of the conventional electrical grid or a centralized electricity system. A microgrid with the application of modernized digital processors for automated distribution is called smart microgrid. Like the conventional power grid, smart microgrid locally generates, distributes and regulates the flow of electricity to consumers. Thus it provides power to a small community²⁻³ with high reliability and better power quality. The consumers connected in a renewable energy fed microgrid not only save money³ but can also generate revenue if they feed power to the microgrid through renewable energy sources. The major components of a smart microgrid are distributed energy resources, power converters, energy storage systems, control systems.

The block diagram of the flywheel based photovoltaic fed microgrid is presented in Figure 1 and the system is designed for 3.2 kW electric loads.

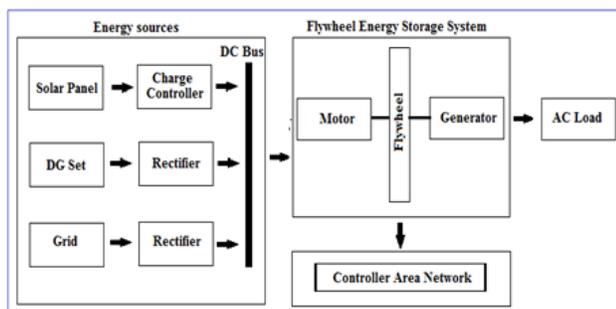


Figure 1. Block diagram of photovoltaic based microgrid.

The system is operated with flywheel energy storage system replacing the conventional electrochemical batteries. A dc bus bar is connected with photovoltaic system through charge controller, diesel generator and an electrical grid through rectifiers. The flywheel

energy storage system gets its input from the dc bus bar. Whenever there is a good solar insolation, the power from the PV panels will be harvested and fed to the dc bus. For any short time variations in the solar input the charge controller as well as the motor connected with the fly wheel will assist in maintaining an uninterrupted power to the load. If there is poor insolation the load will be connected to the electrical grid and when the grid fails, the load will be connected to a diesel generator. The transfer time between the connection of various sources is compensated by the kinetic energy stored in the flywheel, thereby the need for batteries is totally overcome. The entire operation of this system will be controlled by a controller area network (CAN) bus protocol and suitably monitored through announcements and actuations. The aim is to reach the suitable dc voltage at the common dc bus bar to meet the necessary rated conditions of the motor in the flywheel power conditioning system and thereby a reliable, stabilized power is obtained at the load side. This work describes the choice of suitable dc resonant converter for the photovoltaic system.

3. Proposed Boost Converter

The dc resonant boost converters form an important part of a distributed generation system where a common dc bus voltage is converted to different voltages according to the load requirements. The dc-dc boost converters can be utilized for making constant photovoltaic (PV) panel's output voltage by operating the solar PV panels at maximum power point (MPP)⁴. The dc-dc boost converters can be used to match the output of a PV system to a varying load. The dc-dc boost converters can be divided into two main types:

- hard-switching pulse width modulated (PWM) converters
- resonant and soft-switching converters

In this work, a soft-switching method is proposed in order to reduce switching losses, by means of an additional circuit, instead of a conventional switching circuit to build a converter as shown in Figure 2. This dc boost converter circuit contains a resonant circuit comprising an additional switch, a diode, an inductor, and a capacitor. In the proposed configuration, the switches in the circuit undergo zero-current/zero current switching (ZCS) due to the resonant inductor as well as by the resonant capacitor at turn ON and OFF respectively. This switching technology reduces the losses incurred in the switches

and also voltage as well as the current stress of the switching devices⁵⁻⁶. This converter is also configured in closed-loop control mode with PI-controller. This additional circuit added as an auxiliary circuit brings in complexity in control and increased cost. In spite of the claim that this converter can improve efficiency actually, this dc converter cannot improve the efficiency of the whole system considering the switching loss of additional auxiliary switch. Whereas during hard switching in dc converters, the high frequency gating results in increase in switching loss hence considering the above the proposed dc converter is found to have good efficiency compared to the hard switched boost converter. As discussed earlier the proposed dc boost converter with additional auxiliary circuit is the one where the switches turn ON/OFF at zero-voltage and zero-current conditions. Hence, the loss generated at turn ON/OFF is considerably decreased. This simple auxiliary resonant dc boost converter is easily controllable by applying same control signal at the same instant to both the switches. This proposed dc boost converter is found suitable for a stand-alone as well as for a grid-connected PV system based power conditioning system⁷⁻⁹.

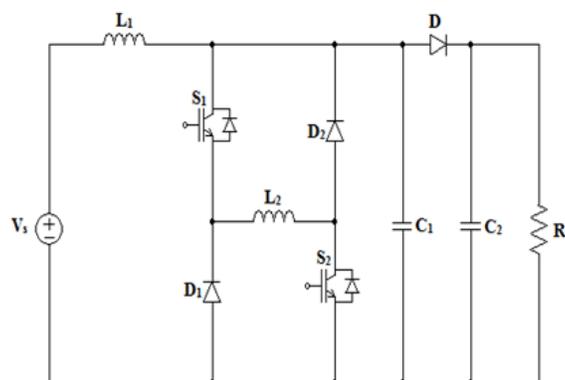


Figure 2. Soft switched resonant boost converter.

The advantages of this converter includes high efficiency, reduced switching loss, and low voltage stress. However, it is suitable for limited range of input voltage or load variations.

4. Operation of the Boost Converter

The working of the proposed converter is explained in this section through the state of the Switches S_1 and S_2 . When they are in the OFF state, the current through the

switches S_1 and S_2 , is zero also the stored energy of the main inductor is fed to the load. Hence, the current in the main inductor decreases linearly. During this time, the current flowing through the resonant inductor is zero with the resonant capacitor has charged to the value of output voltage. When the switches S_1 and S_2 are turned on, then a current starts to flow through the resonant inductor in the auxiliary circuit thus the switches are made ON through zero-current condition. Due to the fact that the main as well as the auxiliary switches use ZCS, this dc boost converter results with lower switch loss compared to the hard switching dc converter. With the linear rise of the resonant current, there is a decrease in the load current value. Hence the current in the main inductor is same as the current through the resonant inductor also the output diode current value is zero. Whenever the voltage across the resonant capacitor is of V_o , then the output diode gets turned-off. During this condition resonant capacitor C_1 as well as the resonant inductor L_2 starts resonating. It should be noted that at this instant the resonant inductor current is the sum of the current in the main inductor and resonant capacitor. During this period, the capacitor C_1 gets discharged from a value V_o to zero. The flywheel diodes namely D_1 and D_2 are turned-ON at the maximum value of current through the resonant inductor. Hence the path for the flow of the resonant inductor current is through S_1 - L_2 - D_2 and S_2 - L_2 - D_1 which is along the freewheeling path. At this time, the voltage across the main inductor is same as the input voltage and results in linear rise of the current. So in this situation the switches in the converter circuit are turned-OFF with the zero voltage condition by the action of the resonant capacitor as it is charged to the value of output voltage. The output diode will be in off state till the resonant capacitor is charged to V_o . The resonant capacitor is same as the output voltage as well as the output diode is turned-ON by the zero voltage condition. Hence at this interval, the current in the main inductor i_1 and the current through the resonant inductor current i_{L2} flow is taken by the diode D to the output. At the same time, there is a linear decrease in two of the inductor currents as well as the energy transfer to the load is achieved.

5. Design Procedure

The design procedure discussed in this section is based on the turn-ON and turn-OFF requirements of the main switch, the main diode and the auxiliary switch¹⁰⁻¹¹ by

means of ZVS and ZCS

Duty cycle ratio is defined by

$$D = \frac{T_{on}}{T} \tag{1}$$

and the output voltage can be changed from 0 to ∞ when the duty cycle varies from 0 to 1. The voltage output is found to be more than the input voltage [2].

$$V_o = \frac{1}{1-D} * V_s \tag{2}$$

The converter operates in the mode where continuous conduction is achieved hence the inductor and capacitor values were obtained by

$$L = \frac{1-D^2 * DR}{2f} \tag{3}$$

$$C = \frac{DV_o}{V_r R_f} \tag{4}$$

Where voltage ripple (V_r) is 0.01 times of output voltage V_o . The role of the resonant capacitor (C_1) is perform the ZVS of the main switch in the converter. Hence the resonant capacitor (C_1) has to be charged for a longer duration for applying zero voltage switching of the main switch in the converter. This in turn results in the value of the resonant capacitor (C_1) being ten times more than the output capacitor of the circuit. The capacitor is charged by the resonant current by the inductor (L_2). It is to be noted that the voltage stress across the capacitor increases with the increase in the charging voltage hence the charging voltage must be under the value of the output voltage.

6. Simulation Results

The comparative analysis of the dc boost converter is simulated under hard switching without the resonant tank circuit elements. The circuits were simulated with MatLab software. The output voltage and the output current of the hard switching are depicted in Figure 3 and Figure 4. The voltage across and the current through the switch is shown in Figure 5. The parameters used in the simulation is shown in Table 1.

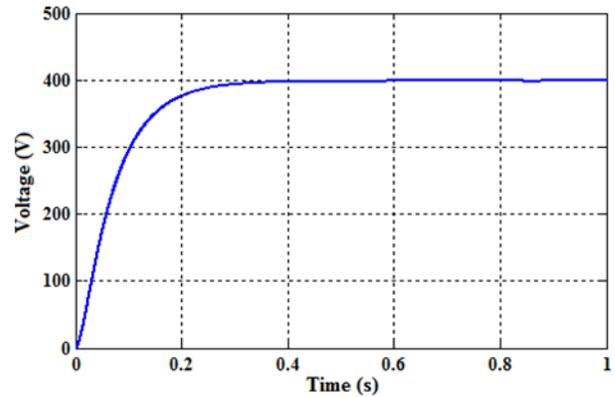


Figure 3. Output voltage of the hard switched converter.

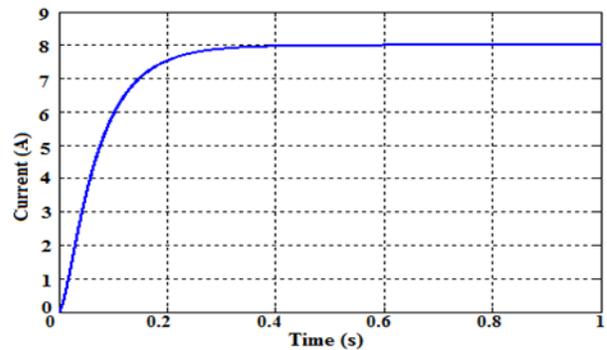


Figure 4.

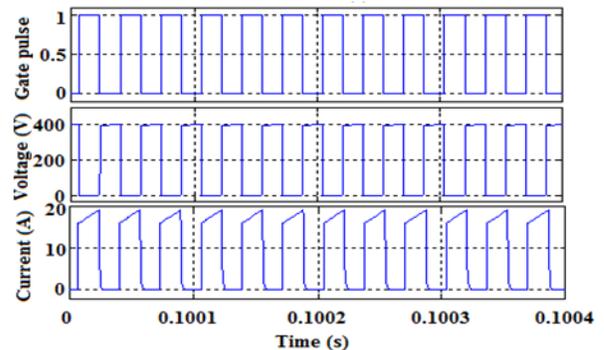


Figure 5. Voltage and current of main switch under hard switching.

Table 1. Simulation parameters of MMC

Parameters	Values
Input Voltage, V_i Inductor, L_1	200 V 560 mH
Output capacitor, C_2	1000 μ F
Switching frequency, f_s	30 kHz
Resonant inductor, L_2	40 μ H
Resonant capacitor, C_1	20 nF

Under hard switching technique the voltage stress is found to be 200V on average. For better performance the proposed converter employs resonant tank circuit with auxiliary switch for applying soft switching technique in the main switch. The output voltage as well as the current waveforms related to the soft switched converter is presented in Figure 6 and Figure 7 respectively.

PI controller is tuned by trial and error method, hence by proper tuning, the soft switching waveforms showed in Figure 6 and Figure 7, will further improve. The tank circuit elements and the auxiliary switch reduce much of the stress across the main switch as shown in Figure 8.

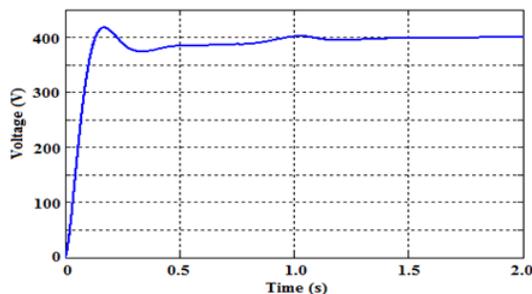


Figure 6. Output voltage under soft switching.

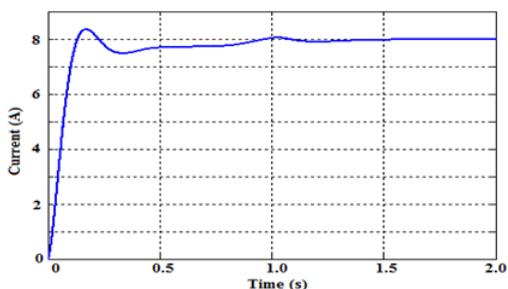


Figure 7. Output current under soft switching.

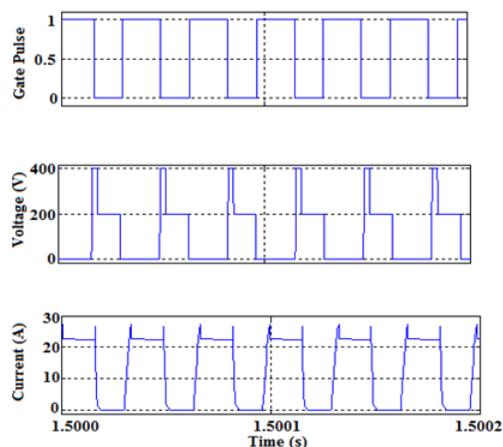


Figure 8. Voltage and current of main switch under soft switching.

7. Comparative Study of Parameters

The key parameters under hard and soft switching are presented in this section.

1.1. Switching Losses

Power semiconductor devices may fail to operate or even get damaged when they dissipate power more than certain level. This condition may become dangerous as it may result in damage to other components. The converter should be designed that how to minimize the power dissipation in the devices.

1.2. Efficiency

The parameters needed to calculate the power output are the range of the input voltage, output voltage at nominal value as well as the maximum output current and finally the overall losses.

$$\eta = \frac{P_o}{P_{in}} \tag{5}$$

The use of soft-switching technology results not only in reduction of switching loss, it also permits high frequency operation as well as the snubberless operation of the converter. Thus improvement in the performance as well as efficiency is achieved. The comparison of the output between conventional and the proposed resonant boost converter is shown in Table 2.

Table 2. Comparison of the conventional converter and resonant boost converter

Parameters	Conventional boost Converter	Resonant boost converter
Output voltage	398V	401V
Output current	8 A	8.4A
Efficiency	93%	95%

Hence, the two techniques of switching are discussed, compared and found that the proposed converter under soft switching performs better than the conventional hard switching technique¹³.

8. Scope for Future Developments

The latest developments includes improvement in usage of various algorithms for control in the converters based on soft-switching technique in order to reduce switching loss as well as the conduction loss¹⁴. Boost converters of high quality at high switching frequency operation resulting in enhanced dynamic response and reduction in size of components used mainly the reactive components including the high-frequency transformers¹⁵ is currently researched. The latest development includes the single-stage conversion resulting in increase of efficiency, reduction in size, highly reliable, and the compactness for quality improvement of boost converters. The latest developments in solid-state electronics and technology leading to devices with low conduction loss, high switching frequency, simple gating, as well as low voltage drop and reduced switching loss. Considering the above in future boost converters with improved quality is possible.

9. Conclusion

This paper has attempted to give a comparative analysis of conventional boost converter with soft switched auxiliary resonant boost converter. The conventional boost converter and soft switched resonant boost have been simulated using MATLAB-Simulink. Using these results, the comparison has been done and the efficiency improvement was discussed. The resonant boost converter has high-power efficiency with reduced voltage stress on switches and much less switching loss. So the resonant boost converter is an attractive topology for application of medium power levels. The improved quality of soft switched boost converters are gaining popularity in a variety of applications ranging from low to high power levels due to their improved power quality both at the input as well as the output terminals.

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