Design and analysis of grid connected photovoltaic system for Step-up Resonant Converter

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Abstract—In the grid connected photovoltaic system for Step-up Resonant Converter, processes of multiple dc-ac-dc or ac-dc-ac conversions are reduced in an individual ac or dc grid. The grid consists of ac and connected together by multi directional converters. In this micro grid network, it is especially difficult to support the critical load without incessant power supply. The generated power can be extracted under varying wind speed, solar irradiation level and can be stored in batteries at low power demands. In this paper, AC-DC micro grid with solar energy, energy storage, and a pulse load is proposed. This micro grid can be viewed as a PEV parking garage power system or a ship's power system that utilizes sustainable energy and is influenced by a pulse load. The battery banks inject or absorb energy on the DC bus to regulate the DC side voltage. The frequency and voltage of the AC side are regulated by a bidirectional AC-DC inverter. The power flow control of these devices serves to increase the system's stability and robustness. The system is simulated in Matlab/Simulink.

Index Terms—Renewable energy, resonant converter, soft switching, voltage step-up, voltage stress.

I. INTRODUCTION

In general, manufacturers provide 5 second and ½ an hour surge figures which give an indication of how much power is supplied by the inverter. Solar inverters require a high efficiency rating. Since use of solar cells remains relatively costly, it is paramount to adopt high efficiency inverter to optimize the performance of solar energy system. High reliability helps keep maintenance cost low. Since most solar power stations are built in rural areas without any monitoring manpower, it requires that inverters have competent circuit structure, strict selection of components and protective functions such as internal short circuit protection, overheating protection and overcharge protection. Wider tolerance to DC input current plays an important role, since the terminal voltage varies depending on the load and sunlight [1-4]. Though energy storage batteries are significant in providing consistent power supply, variation in voltage increases as the battery’s remaining capacity and internal resistance condition changes especially when the battery is ageing, widening its terminal voltage variation range. In mid-to-large capacity solar energy systems, inverters’ power output should be in the form of sine waves which attain less distortion in energy transmission. Many solar energy power stations are equipped with gadgets that require higher quality of electricity grid, when connected to the solar systems, requires sine waves to avoid electric harmonic pollution from the public power supply.[5] How Inverters Work: There are three major functions an inverter provides to ensure the operation of a solar system One of the most efficient and promising way to solve this problem is the use of pumping and water treatment systems supplied by photovoltaic (PV) solar energy. Such systems aren’t new, and are already used for more than three decades [6-8]. But until recently the majority of the available commercial converters are based on an intermediate storage system performed with the use of batteries or DC motors to drive the water pump. The batteries allow the system to always operate at its rated power even in temporary conditions of low solar radiation [9-10]. This facilitates the coupling of the electric dynamics of the solar panel and the motor used for pumping. Generally, batteries used in this type of system have a low life span, only two years on average, which is extremely low compared to useful life of 15 years of a photovoltaic module. Also, they

Available online:https://edupediapublications.org/journals/index.php/IJR/
make the cost of installation and maintenance of such systems substantially high. These systems are directly coupled to the electric distribution network and do not require battery storage. Figure 1 describes the basic system configuration. Electric energy is either sold or bought from the local electric utility depending on the local energy load patterns and the solar resource variation during the day, this operation mode requires an inverter to convert DC currents to AC currents. There are many benefits that could be obtained from using grid-tied PV systems instead of the traditional stand-alone schemes [11-12]. The benefits are:

- Smaller PV arrays can supply the same load reliably.
- Less balance of system components are needed.
- Comparable emission reduction potential taking advantage of existing infrastructure.
- Eliminates the need for energy storage and the costs associated to substituting and recycling batteries for individual clients. Storage can be included if desired to enhance reliability for the client.
- Takes advantage of the existing electrical infrastructure.
- Efficient use of available energy. Contributes to the required electrical grid generation while the client’s demand is below PV output.

II. CONVERTER STRUCTURE AND OPERATION PRINCIPLE

Fig. 1. Grid-Tied Photovoltaic System.

Hybrid systems may be possible were battery storage or a generator (or both) can be combined with a grid connection for additional reliability and scheduling flexibility (at additional cost). [13] Most of the installed residential, commercial and central scale systems use prefabricated flat plate solar modules, because they are widely available. Most 5-7 available reports on PV system costs are therefore related to this kind of technology and shall be our focus in this chapter. Other specialized technologies are available (e.g., concentrating PV systems), but not as commercially available as the traditional PV module.

The converter is composed of an FB switch network, which comprises Q1 through Q4, an LC parallel resonant tank, a voltage doubler rectifier, and two input blocking diodes, Db1 and Db2. The steady-state operating waveforms are shown in Fig. 3 and detailed operation modes of the proposed converter are shown in Fig. 4. For the proposed converter, Q2 and Q3 are tuned on and off simultaneously; Q1 and Q4 are tuned on and off simultaneously. In order to simplify the analysis of the converter, the following assumptions are made:

1) All switches, diodes, inductor, and capacitor are ideal components;
2) Output filter capacitors C1 and C2 are equal and large enough so that the output voltage \( V_o \) is considered constant in a switching period \( T_s \).

A. Mode 1 \([t_0, t_1]\) [See Fig. 4(a)]

During this mode, Q1 and Q4 are turned on resulting in the positive input voltage \( V_{in} \) across the LC parallel resonant tank, i.e., \( V_{Lr} = V_{Cr} = V_{in} \). The converter operates similar to a conventional boost converter and the resonant inductor \( L_r \) acts as the boost inductor with the current through it increasing linearly from \( I_0 \). The load is powered by \( C_1 \) and \( C_2 \). At \( t_1 \), the resonant inductor current \( i_{Lr} \) reaches \( I_1 \).
Fig. 3. Operating waveforms of the proposed converter.

\[ I_1 = I_0 + \frac{V_{\text{in}} T_1}{L_r} \]  

(1)

Where \( T_1 \) is the time interval of \( t_0 \) to \( t_1 \).

Fig. 4. Equivalent circuits of each operation stage. (a) \([t_0, t_1]\). (b) \([t_1, t_3]\). (c) \([t_3, t_4]\). (d) \([t_4, t_5]\). (e) \([t_5, t_6]\). (f) \([t_6, t_8]\). (g) \([t_8, t_9]\). (h) \([t_9, t_{10}]\).

In this mode, the energy delivered from \( V_{\text{in}} \) to \( L_r \) is

\[ E_{\text{in}} = \frac{1}{2} L_r \left( I_1^2 - I_0^2 \right) \]  

(2)

**B. Mode 2 \([t_1, t_3]\) [See Fig. 4(b)]**

At \( t_1 \), \( Q_1 \) and \( Q_2 \) are turned off and after that \( L_r \) resonates with \( C_r \), \( V_{C_r} \) decreases from \( V_{\text{in}} \) and \( i_{L_r} \) increases from \( I_1 \) in resonant form. Taking into account the parasitic output
Capacitors of Q1 through Q3 and junction capacitor of Db2, the equivalent circuit of the converter after $t_1$ is shown in Fig. 5(a), in which $C_{D2}$, $C_{Q1}$, and $C_{Q3}$ are charged, $C_{Q2}$ and $C_{Q4}$ are discharged. In order to realize zero-voltage switching (ZVS) for Q2 and Q3, an additional capacitor, whose magnitude is about ten times with respect to $C_{Q2}$, is connected in parallel with Db2. Hence, the voltage across Db2 is considered unchanged during the charging/discharging process and Db2 is equivalent to be shorted. Due to $C_r$ is much larger than the parasitic capacitances, the voltages across Q1 and Q4 increase slowly.

As a result, Q1 and Q4 are turned off at almost zero voltage in this mode. When $V_{C1}$ drops to zero, $i_{L1}$ reaches its maximum magnitude. After that, $V_{C1}$ increases in negative direction and $i_{L1}$ declines in resonant form. At $t_2$, $V_{C1} = -V_{in}$, the voltages across Q1 and Q4 reach $V_{in}$ the voltages across Q2 and Q3 fall to zero and the two switches can be turned on under zero-voltage condition. It should be noted that although Q2 and Q3 could be turned on after $t_2$, there are no currents flowing through them. After $t_2$, $L_r$ continues to resonate with $C_r$, $V_{C1}$ increases in negative direction from $-V_{in}$, $i_{L1}$ declines in resonant form. Db2 will hold reversed-bias voltage and the voltage across Q4 continues to increase from $V_{in}$. The voltage across Q1 is kept at $V_{in}$. The equivalent circuit of the converter after $t_2$ is shown in Fig. 5(b), in which D2 and D3 are the antiparallel diodes of Q2 and Q3, respectively. This mode runs until $V_{C1}$ increases to $-V_{o/2}$ and $i_{L1}$ reduces to $I_2$, at $t_3$, the voltage across Q4 reaches $V_{o/2}$ and the voltage across Db2 reaches $V_{o/2} - V_{in}$. It can be seen that during $t_2$ to $t_3$, no power is transferred from the input source or to the load, and the whole energy stored in the LC resonant tank is unchanged, i.e.,

$$\frac{1}{2} L_r I_1^2 + \frac{1}{2} C_r V_{in}^2 = \frac{1}{2} L_r I_2^2 + \frac{1}{2} C_r \left(\frac{V_o}{2}\right)^2$$  \hspace{1cm} (3)

We have

$$i_{Lr}(t) = \frac{V_{in}}{Z_r} \sin[\omega_r(t-t_1)] + I_1 \cos[\omega_r(t-t_1)]$$  \hspace{1cm} (4)

$$v_{C1}(t) = V_{in} \cos[\omega_r(t-t_1)] - I_1 Z_r \sin[\omega_r(t-t_1)]$$  \hspace{1cm} (5)

$$T_2 = \frac{1}{\omega_r} \left[ \arcsin \left( \frac{V_{in}}{\sqrt{V_{in}^2 + \frac{L_r I_1^2}{C_r}}} \right) 
\right. 
+ \left. \arcsin \left( \frac{V_o}{2 \sqrt{\frac{V_{in}^2}{V_o^2} + \frac{L_r I_1^2}{C_r}}} \right) \right]$$  \hspace{1cm} (6)

Where $\omega_r = 1/\sqrt{L_r C_r}$, $Z_r = \sqrt{L_r/C_r}$, and $T_2$ is the time interval of $t_1$ to $t_3$.

C. Mode 3 [$t_3$, $t_4$] [See Fig. 4(c)]

At $t_3$, $V_{C1} = -V_{o/2}$, DR1 conducts naturally, $C_1$ is charged by $i_{L1}$ through DR1. $V_{C1}$ keeps unchanged, and $i_{Lr}$ decreases linearly. At $t_4$, $i_{Lr} = 0$. The time interval of $t_3$ to $t_4$ is

$$T_3 = \frac{2 I_2 L_r}{V_o}$$  \hspace{1cm} (7)

The energy delivered to load side in this mode is

$$E_{out} = \frac{V_o I_2 T_3}{4}$$  \hspace{1cm} (8)

The energy consumed by the load in half-switching period is

$$E_R = \frac{V_o I_0 T_s}{2}$$  \hspace{1cm} (9)

Assuming 100% conversion efficiency of the converter and according to the energy conversation rule, in half-switching period

$$E_{in} = E_{out} = E_R$$  \hspace{1cm} (10)

Combining (7), (8), (9), and (10), we have

$$I_2 = V_o \sqrt{\frac{I_0 T_s}{V_o L_r}}$$  \hspace{1cm} (11)

$$T_3 = 2 \sqrt{\frac{T_s I_0 L_r}{V_o}}$$  \hspace{1cm} (12)

D. Mode 4 [$t_4$, $t_5$] [See Fig. 4(d)]

At $t_4$, $i_{Lr}$ decreases to zero and the current flowing through DR1 also decreases to zero, and DR1 is turned off with
zero current switching (ZCS), therefore, there is no reverse recovery. After $t_4$, $L_r$ resonates with $C_r$, $C_r$ is discharged through $L_r$, $V_{Ct}$ increases from $-V_o/2$ in positive direction, and $i_{Lr}$ increases from zero in negative direction. Meanwhile, the voltage across $Q_1$ declines from $V_o/2$. At $t_5$, $V_{Ct} = -V_{in}$, and $i_{Lr} = -I_3$. In this mode, the whole energy stored in the LC resonant tank is unchanged, i.e., where $T_4$ is the time interval of $t_4$ to $t_5$.

$$\frac{1}{2}C_r \left( \frac{V_o}{2} \right)^2 = \frac{1}{2}L_r I_3^2 + \frac{1}{2}C_r V_{in}^2$$ (13)

We have

$$I_0 = I_3 = \frac{1}{2} \sqrt{\frac{C_r(V_o^2 - 4V_{in}^2)}{L_r}}$$ (14)

$$i_{Lr}(t) = -\frac{V_o}{2\omega_r L_r} \sin[\omega_r (t - t_5)]$$ (15)

$$v_{Ct}(t) = -\frac{V_o \cos[\omega_r (t - t_5)]}{2}$$ (16)

$$T_4 = \frac{1}{\omega_r} \arccos \left( \frac{2V_{in}}{V_o} \right)$$ (17)

E. Mode 5 [$t_5$, $t_6$] [See Fig. 4(e)]

If $Q_2$ and $Q_3$ are turned on before $t_5$, then after $t_5$, $L_r$ is charged by $V_{in}$ through $Q_2$ and $Q_3$, $i_{Lr}$ increases in negative direction, and the mode is similar to Mode 1. If $Q_2$ and $Q_3$ are not turned on before $t_5$, then after $t_5$, $L_r$ will resonate with $C_r$, the voltage of node A $V_A$ will increase from zero and the voltage of node B $V_B$ will decay from $V_{in}$, zero-voltage condition will be lost if $Q_2$ and $Q_3$ are turned on at the moment. Therefore, $Q_2$ and $Q_3$ must be turned on before $t_5$ to reduce switching loss. The operation modes during [$t_6$, $t_{10}$] are similar to Modes 2–4, and the detailed equivalent circuits are shown in Fig. 4(f)–(h). During [$t_6$, $t_{10}$], $Q_2$ and $Q_3$ are turned off at almost zero voltage, $Q_1$ and $Q_4$ are turned on with ZVS, and $D_R2$ is turned off with ZCS.

### III. A PHOTOVOLTAIC SYSTEM

The photovoltaic system converts sunlight directly to electricity without having any disastrous effect on our environment. The basic segment of PV array is PV cell, which is just a simple p-n junction device. The Fig.6 manifests the equivalent circuit of PV cell. Equivalent circuit has a current source (photocurrent), a diode parallel to it, a resistor in series describing an internal resistance to the flow of current and a shunt resistance which expresses a leakage current. The current supplied to the load can be given as.

$$I = I_{PV} - I_0 \left[ \exp \left( \frac{V + IR_S}{aV_T} \right) - 1 \right] - \left( \frac{V + IR_S}{R_p} \right)$$

Where

$I_{PV}$–Photo current,
$I_0$–diode’s Reverse saturation current,
$V$–Voltage across the diode,
$a$–Ideality factor
$V_T$–Thermal voltage
$R_s$–Series resistance
$R_p$–Shunt resistance

This paper presents a single-phase inverter topology for grid-connected PV systems with a novel pulse width-modulated (PWM) control scheme. Two reference signals identical to each other with an offset equivalent to the amplitude of the triangular carrier signal were used to generate PWM signals for the switches. A digital proportional-integral current control to keep the current injected into the grid sinusoidal and to have high dynamic performance with rapidly changing atmospheric conditions. The proposed system is verified through simulation.
IV. MATLAB/SIMULATION RESULTS

Fig. 7. Matlab/Simulation circuit of the proposed resonant step-up converter.

Fig. 8. Simulation waveform of the switching pulses (Q₁, Q₂, Q₃, and Q₄) for 5MW.

Fig. 9. Simulation waveform of resonant inductor current iₐ, capacitor voltage Vₓ, and capacitor Current iₓ for 5MW.

Fig. 10. Simulation waveform of the switch voltages (VQ₁ and VQ₂) for 5MW.

Fig. 11. Simulation waveform of the output filter Capacitor Voltages (VC₁ and VC₂) for 5 MW.

Fig. 12. Simulation waveform of the input blocking diodes Voltages (VDb₁ and VDb₂) for 5MW.

Fig. 13. Simulation waveform of the switching pulses (Q₁, Q₂, Q₃, and Q₄) for 1MW.

Fig. 14. Simulation waveform of resonant inductor current iₐ, capacitor voltage Vₓ, and capacitor Current iₓ for 1MW.

Fig. 15. Simulation waveform of the switch voltages (VQ₁ and VQ₂) for 1MW.

Fig. 16. Simulation waveform of the output filter Capacitor Voltages (VC₁ and VC₂) for 1MW.

Fig. 17. Simulation waveform of the input blocking diodes Voltages (VDb₁ and VDb₂) for 1MW.
Fig. 18. Simulation circuit for input voltage step.

Fig. 19. Input Voltage.

Fig. 20. Output Voltage.

Fig. 21. Simulation waveform of resonant inductor current $i_{Lr}$.

Fig. 22. Simulation circuit for step load.

Fig. 23. Output Current.

Fig. 24. Output Voltage.

Fig. 25. Simulation waveform of resonant inductor current $i_{Lr}$.

Fig. 26. Simulation circuit for grid connected PV cell fed Step-up Resonant Converter.

Fig. 27. Simulation waveforms of $v_c$, $i_{Lr}$, $i_L$ with grid connected system.
V. CONCLUSIONS
A step-up resonant converter is proposed in this paper, which can achieve very high step-up voltage gain and it is suitable for high-power high-voltage applications. The converter utilizes the resonant inductor to deliver power by charging from the input and discharging at the output. The resonant capacitor is employed to achieve zero-voltage turn-on and turn-off for the active switches and ZCS for the rectifier diodes. In this paper, the converter was designed to grid connected PV solar energy and was conceived to be a commercially viable high efficiency, and high robustness. Depending on the reactive management in real conditions, the power fluctuation of the PV production is balanced to the power exchanged with the grid or with the batteries. In this context, next and future works will deal with reactive management for real condition operations. The management developed helps integration of PV power into the grid as peak loads are shaved. Depending on the reactive management in real conditions, the power fluctuation of the PV production is balanced to the power exchanged with the grid or with the batteries.

REFERENCES


