A Soft Switching Scheme for DC-DC Converter by Employing Single Phase Multi-level Inverters for Photovoltaic Systems

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Abstract - In order to increase the conversion efficiency of a PV system, a high-efficiency PV power inverter with simple control methodology is required. To satisfy this requirement, an improved single-phase inverter using soft-switching technique is proposed. The proposed power inverter circuit is composed of a ZVT-PWM boost dc-dc converter and a LLCC resonant inverter. The dc-link voltage amplitude is controlled by ZVT-PWM boost dc-dc converter with soft-switching transition. The stable sinusoid ac output voltage is inverted from dc-link voltage via a LLCC resonant inverter. The effectiveness of the proposed inverter for small PV system is verified by simulation results.

I. INTRODUCTION

Due to the Kyoto agreement on global reduction of greenhouse gas emissions that generated by the burning process from the primary fossil fuels such as coal, oil, natural gas etc. Many renewable energy sources are developed such as solar, wind, biomass and fuel cell [1]. The solar energy is clean and viable source of electricity. It has been used as the main source for electrical loads in rural areas away from the grid or grid-connected in distributed energy production. In recent years, the conventional buck-boost PWM inverters shown in figure 1 have been widely used for small PV system [2-3] due to the individual operation and simple control. These systems compose of a PV array, a dc-dc converter and a dc-ac inverter. The dc-dc converter is used to boost the PV voltage to a level higher than the peak of the voltage utility and also responsible for tracking the maximum point of the PV array to fully utilize the PV power. The excessive power from the PV module to the load can be fed to the load. The balance of power flow is controlled through the inverter. The dc-ac inverter is usually a pulse-width-modulation (PWM) voltage source inverter, which shapes and inverts the output current. The inverter is also used to act as a high-frequency filter to eliminate the high-frequency component at the inverter output to achieve the low output harmonic distortion and high output power factor. To minimize the size and weight of overall system, high switching frequency operations are required for inverters. However, high switching operation causes switching power losses and high switching stresses in the semiconductor devices as shown in figure 2. In order to solve these problems, resonant converters using zero voltage switching (ZVS) and zero current switching (ZCS) techniques [4] can be used to greatly reduce the switching losses at the expenses of high voltage or current stresses on power switches.

Fig. 1 : The conventional buck-boost PWM inverter for small PV system

Fig. 2 : Hard-switching waveform of semiconductor switching devices (a) switching power losses (b) voltage and current stresses
For the inverter without reactive energy feedback paths, the parasitic reactive energy due to the possible leakage of inductors also imposes transient high voltage, dv/dt or di/dt stresses on switch devices that causes high electromagnetic interference (EMI). Therefore, soft-transition switching techniques such as zero voltage transition (ZVT) [5] and zero current transition (ZCT) [6] have been developed to minimize or eliminate both switching losses and stresses, and thus improving converter efficiency. In this paper, a soft-switching single-phase inverter for small PV system is proposed. This inverter is composed of a ZVT-PWM boost dc-dc converter and a LLCC resonant inverter [7]. An auxiliary circuit is used to provide the active switches in a boost converter operate at soft-switching without additional voltage and current stresses. The stable ac output voltage is generated from the LLCC resonant inverter with low total harmonic distortion (THD). In the following, the operating principles of the proposed PV-system will be thoroughly discussed. Simulation results will be given to validate the effectiveness of the fulfilled functions. The proposed single-phase inverter for small PV-system is shown in figure 3. The inverter circuit is composed of a ZVTPWM boost dc-dc converter that uses PWM control and a dc-ac LLCC resonant inverter. According to the PV array characteristic, the output voltage of PV array varies with light intensity. The boost dc-dc converter with dc voltage feedback control is utilized to provide the constant dc voltage $V_{dc}$ for the inverter. The dc-link voltage amplitude is controlled by the boost dc-dc converter.

### A. ZVT-PWM Boost DC-DC Converter

Fig. 4. shows the key waveforms of the ZVT-PWM boost dc-dc converter. By adding the resonant network with a conventional PWM boost dc-dc converter, the converter achieves zero-voltage switching for both the active and passive switches without increasing the voltage and current stresses. The additional resonant network is composed of a resonant inductor ($L_r$), resonant capacitor ($C_r$), an auxiliary switch (SZVT) and diode ($D1$).

\[
T_{ZVT} \geq t_{01} + t_{12} = \frac{L_r I_{in}}{V_0} + \frac{\pi}{2} \sqrt{L_r C_r}.
\]

\[
C_r = \left( \frac{\pi}{2} + \frac{1}{(a - 1)} \right) \frac{V_0}{T_{ZVT}}.
\]

\[
L_r = \frac{V_{dc} T_{ZVT}}{(a - 1) \left( \frac{\pi}{2} + 1 \right) I_{in, max}}.
\]

### B. LLCC-Resonant Inverter

The LLCC-resonant inverter has full-bridge switches ($S_{inv1}$, $S_{inv2}$, $S_{inv3}$ and $S_{inv4}$) that transfer the dc-link voltage to a square wave with amplitude $V_{dc}$. The inverter is operated at a geometric mean frequency to provide stable sinusoid ac voltage ($v_O$) output. The input voltage of the resonant circuit is a square wave of the following form.

\[
v_{AB} = \begin{cases} 
V_{dc}, & \text{for } 0 < \omega t < \pi \\
-V_{dc}, & \text{for } 0 < \omega t < 2\pi
\end{cases}
\]

The fundamental component of the square wave is

\[
v_i = V_m \sin(\omega_s t).
\]

\[
\omega_s = 2\pi f_S
\]

in which $f_S$ is the switching frequency, and

\[
V_m = \left( \frac{4}{\pi} \right) V_{dc}.
\]

The output voltage of the resonant tank is

\[
v_O = V_O \sin(\omega_s t + \theta).
\]

Where $VO$ and $\theta$ represent the amplitude and phase of the output voltage $v_O$. The input impedance of the LLCC-resonant tank can be represented as

\[
Z_{in} = j \omega S L_s + \frac{1}{j \omega S C_s} + \frac{1}{Y_p}.
\]

Where the admittance of the parallel-resonant tank is
The voltage gain of the LLCC-resonant tank $G_{LLCC}$ is defined as the ratio of the ac output voltage and the fundamental of square input voltage:

$$ G_{LLCC} = \frac{V_o}{V_i} = \frac{1}{Z_p Y_p}.$$  

When the resonant condition occurs, the real part of the denominator of $G_{LLCC}$ is equal to zero, that is:

$$1 + \frac{C_p}{C_s} + \frac{L_s}{L_p} - \frac{1}{\omega_0^2 L_p C_s} - \omega_0^2 L_p C_p = 0.$$  

The two resonant frequencies in radian ($\omega_{01}$, $\omega_{02}$) of the LLC Resonant circuit can be obtained as:

$$\omega_{01} = \sqrt{\frac{K}{2} \left( \frac{1}{2} \sqrt{K^2 - 4} \left( \frac{1}{L_p L_p C_s C_p} \right) \right)}$$  

$$\omega_{02} = \sqrt{\frac{K}{2} + \frac{1}{2} \sqrt{K^2 - 4} \left( \frac{1}{L_s L_p C_s C_p} \right)}.$$  

Where $K=(1/(LSCP))(1+(CP/CS)+(LS/LP))$. Define the ratio $Lp/LS=CS/CP$, then the geometric mean frequency in radian can be obtained as:

$$\omega_g = 2\pi f_g = \sqrt{\omega_{01} \omega_{02}} = \frac{1}{\sqrt{L_s C_s}} = \frac{1}{\sqrt{L_p C_p}}.$$  

When the switching frequency is operated at the geometric mean frequency, the real and imaginary part of the voltage gain are equal to one and zero, respectively. Therefore, the amplitude of the voltage gain is not influenced by the variation of the quality factor, and the amplitude of the output voltage, $V_o$, is equal to $4Vdc/\pi$. The amplitude and phase of $G_{LLCC}$ as the function of $f_S$ at different values of $Q$ are shown in figure 5.

### III. SIMULATION RESULTS

To evaluate the performance of the proposed system, the prototype circuit is designed and simulated with OrcadPSpice as shown in figure 6. A 40kHz ZVT-PWM boost converter is utilized to provide constant dc voltage $V_{dc} = 245Vdc$ for the LLCC resonant inverter.
\[ L_S = L_P = 63.3 \text{mH}, \quad C_S = C_P = 160 \mu \text{F} \]

The main switch current \( i_S \) and the voltage across the main switch \( v_Cr \) of the boost converter are shown in figure 7. The waveforms confirm the zero-voltage-switching of the main switch of the boost converter. The simulation input and output voltage waveform results from the LLCC resonant inverter are depicted in figure 8. It can be observed that the input and output voltages of the LLCC resonant tank are in phase when the switching frequency of the inverter is operated at the geometric mean frequency. The THD of output voltage is also shown in figure 8.

IV. CONCLUSION

An improved single-phase inverter for small PV-system using resonant-technique has been proposed to overcome the drawbacks of the conventional single-phase PV power inverter. This inverter comprises of a ZVT-PWM boost dc-dc converter and a LLCC-resonant inverter. The active switches in a ZVT-PWM boost dc-dc converter operate in soft-switching condition and without voltage and current stresses. This reduces switching losses, thereby increasing the efficiency of the converter. The LLCC resonant inverter incorporates series and parallel combinations of inductors and capacitors otherwise know as a series-resonant tank and parallel-resonant tank to provide a stable ac output voltage with low THD. The simulation results show that the ZVT-PWM boost dc-dc converter and the LLCC-resonant inverter can be applied to the small scale PV system with high performance.

VI. REFERENCES