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Z-source T-type inverter for renewable energy systems with proportional resonant controller

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ABSTRACT

In this study, a novel z-source T-type inverter for grid connected renewable energy system is proposed. The proposed system has ability of boosting voltage level without any additional DC–DC converter or transformer through the z-impedance network. The size of the system is reduced by eliminating DC–DC converter or step-up transformer requirement. Furthermore, an additional improvement in system efficiency is obtained by using T-type inverter structure which is more efficient than the conventional two-level inverter or three-level neutral point clamped inverter. Inverter output currents are controlled by the proportional resonant controller. MATLAB/Simulink simulations show that, fast dynamic response is obtained and steady state error is eliminated. In addition, the inverter output currents are in sinusoidal waveforms and synchronous with the grid frequency and phase. Besides, total harmonic distortion values of the inverter currents are measured as 2.41% which meets the international standards such as IEC61727 and IEEE1547.

Introduction

The world energy demand is increasing exponentially during last years. This increasing energy demand, the limited reserve of conventional energy sources and environmental effects of conventional sources, clean energy awareness, the principle of generating energy at where it is consumed increase the number of studies on renewable energy sources. As a result of the studies on renewable energy sources, the wind energy, the solar energy and the hydrogen energy becomes popular. The obtained energy from these renewable energy sources can be used locally, but exporting this energy to the grid is more common and effective. While, the photovoltaic (PV) modules and fuel cells (FCs) generate DC electrical energy, wind turbines can generate DC or AC. However, variable speed wind turbines which are commonly used generate variable frequency AC electrical energy. Thus, energy generated from renewable energy sources should be conditioned. This process is usually performed by grid interactive inverters. The studies on grid interactive inverters can be grouped into two categories: studies on control methods of the inverters and studies on inverter topologies. These inverters are structurally similar to conventional ones. The conventional current source inverters (CSIs) or voltage source inverters (VSIs) can be used as inverter power stage. While CSIs are less sensitivity to short circuits, VSIs are commonly used because of their ease of control and design [1]. Besides, these VSIs are usually operated as current controlled mode to decrease the sensitivity to the phase errors. A variety of control methods such as linear controllers, hysteresis control method, deatbeat control, fuzzy logic control etc. have been proposed to perform this current

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Nomenclature

CSI	Current Source Inverter
EMI	Electromagnetic Interference
FC	Fuel Cell
LST	Lower Shoot Through
NPC	Neutral Point Clamped
MB	Maximum Boost
MCB	Maximum Constant Boost
NST	Non-Shoot Through
PI	Proportional Integral
PID	Proportional Integral Derivative
PLL	Phase Locked Loop
PV	Photovoltaic
PR	Proportional Resonant
PWM	Pulse Width Modulation
REC	Reduced Element Count
SB	Simple Boost
ST	Shoot Through
THD	Total Harmonic Distortion
UST	Upper Shoot Through
VSI	Voltage Source Inverter
B	Boost Factor
C_f	Inverter Output Filter Capacitor
C_1, C_2	Voltage Divider Capacitor
C_3, C_4	Z-source Network Capacitor
I_{inv}	Inverter Output Current
K_p	Proportional Gain Term
K_i	Integral Gain Term
L_f	Inverter Output Filter Inductor
L_1, L_2	Z-source Network Inductor
M	Modulation Index
v_C	Capacitor Voltage
v_D	Down-Non-Shoot Through Voltage
v_{inv}	Inverter Input Voltage
v_L	Inductor Voltage
V_{PN}	Inverter Line-Neutral Voltage
V_{PP}	Inverter Line–Line Voltage
v_U	Upper Non-Shoot Through Voltage
T	Switching Period
T_0	Shoot-Through Time
T_1	Non-Shoot Through Time
U_g	Grid Voltage
ω	Resonant Frequency
ω_C	Cut-off Frequency

control action with fast transient response and no steady state error [2]. The linear controllers such as proportional integral (PI) and proportional integral derivative (PID) which have superior performance in DC systems cannot track the reference AC current without steady state error. So, it is used with grid voltage feedforward control [3]. Hysteresis control is fast and robust control techniques and it is easy to implement. However, it has some drawbacks depending on its variable switching frequency operation feature such as difficulties about filter design etc. [4]. The deadbeat control also has a good performance in grid interactive inverter. But control time delay and changing values of the passive elements affect its performance [5]. There are lots of fuzzy logic control scheme introduced in literature such as conventional fuzzy logic controller, type-2 fuzzy logic controller, fuzzy-PI controller etc. [5]. However, these techniques require great computational effort, and the performance of these control techniques mainly depends on the experiences of the designer. The proportional resonant (PR) control method provides acceptable dynamic performance and eliminates the steady state error [6]. Therefore, the PR control becomes popular in grid interactive inverter applications.

However, conventional voltage source inverters have some disadvantages in grid interactive inverter applications. The DC input voltage must be higher than the peak value of the load or AC grid voltage level in voltage source grid interactive inverter applications [7]. In PV and FC applications, generated DC voltage levels are usually low and also these systems have wide operation areas. Furthermore, their voltage level may be changeable with the load level. So, an additional DC–DC converter to step up the DC voltage is used to increasing inverter input voltage level. Another solution is using step-up transformer [8,9]. The transformer can be used in two ways. The first solution is using the DC–DC converter with high-frequency transformer before the inverter, which is called isolated DC–DC converter. Using the line frequency transformer at the inverter output is the second solution. The usage of the line frequency transformer prevents DC current injection, increases the system size and weight, and decreases the efficiency. Lower size and weight, and higher efficiency values can be obtained by using high-frequency transformer, but these transformers cannot prevent DC current injection.

In addition, the dead time must be used to prevent the short circuits and damaging switches because of the intersection of the switch on times in an inverter leg of the conventional VSI. However, this dead time reduces the output quality of the inverter [6]. Z-source inverters remove these disadvantages. The z-impedance network, connected between the DC supply and inverter, brings voltage boosting ability. Thus, both the additional DC–DC converter or step-up transformer requirement can be removed and short circuit sensitivity can be reduced by using z-source inverter [6]. In addition, waveform distortion as a result of the dead time is also removed. Z-source inverters have been started to use in grid applications, motor drives, electrical vehicle applications and etc. [10]. The basic z-source inverter circuit for grid interactive inverter application is given in Fig. 1. The system consists of DC power supply, z-source impedance network, three phase inverter, the L or LCL filter and the grid.

In the past literature, different circuit structures and control techniques for z-source inverters have been proposed. In these studies, generally conventional two-level voltage source inverter structure has been used. Today, inverter power level is increasing in parallel with increasing power demand. There are some design limitations at high power levels in conventional two level inverter structures such as difficulties of manufacturing high voltage semiconductor switches or their high prices, increase in size of the filter components, high electromagnetic interference and etc. These limitations can be overcome by using multilevel inverter structures [11]. These inverters make possible to work with standard power switches in high power levels. Although, multilevel inverters used only at high power levels, they become popular in a wide