Electrical Power and Energy Systems 82 (2016) 49–57

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Double input Z-source inverter applicable in dual-star PMSG based wind turbine

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ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form 25 January 2016
Accepted 19 February 2016
Available online 18 March 2016

Keywords:
Permanent magnet synchronous generator
Dual-star
Double-input Z-source inverter

ABSTRACT

This paper proposes a new double-input Z-network for application in wind energy conversion system (WECS) which is composed of two same DC voltage sources as input sources, two inductors and one capacitor. As a result, the presented structure requires less capacitor number compared to traditional Z-network and it will be able to deliverer energy of both DC sources to local load or grid. The proposed inverter is applicable in dual-star PMSG based WECS, since it requires two DC voltage sources in same value. Besides, dynamic modeling of dual-star PMSG is presented to analyze proposed WECS connected to grid which employs dual-star PMSG and double-input Z-source inverter. The proposed dual-input Z-source inverter controls maximum power point tracking (MPPT) and delivering power to the grid. Therefore, other DC–DC chopper is not required to control two sets of rectified output voltage of generator in view of MPPT. As a result, the proposed topology requires less power electronic switches and the suggested system is more reliable against short circuit. The ability of proposed WECS with dual-star PMSG and double-input Z-source inverter is validated with simulation results and experimental tests using PCI-1716 data acquisition system.

Introduction

Recently, Permanent magnetic synchronous generators (PMSG) have achieved more attention due to development of permanent magnet (PM) materials, especially in wind energy conversion system (WECS) applications. The PMSG structure typically has large number of poles and is makes elimination of gearbox between turbine blades and generator. As a result, the PMSG is proper generator for WECS. The WECS based PMSG compared to doubly fed induction generator (DFIG) decreases system fault rate because of gearbox elimination. In addition, low rotor losses make it possible to obtain high efficiency in PMSGs [1–5].

The PMSG structure is categorized in two groups of one and dual-star forms in view of winding design style. The dual star PMSGs are composed of two groups of three phase windings that located with displacement of 30 electrical degrees. Some good favorable characteristics are achieved in the dual-star PMSG as compared to conventional PMSG such as: quality improvement of DC link current and voltage and reduction of torque pulsation. Moreover, two independent sets of rectified outputs can be proper choice for WECS application due to capability of series or parallel connection of the outputs [6–9].

Papers study endorses that there are few research [6–9] about description and modeling of dual-star PMSGs. Ref. [5] deals with modeling and simulation about dual-star PMSG. Ref. [7] deals with determining of machine inductance parameters based finite element modeling (FEM) and simulation of dual-star PMSG model. Refs. [8,9] describe the application of dual-star PMSG for wind turbine based diode rectifiers. The mentioned references study the design and performance of dual-star PMSG without paying to grid connection of the generator based advanced power electronic converters. The ac-dc-ac converter structure is a well-known topology for variable speed wind turbines based PMSG to attract maximum power under various wind speeds [10–14]. In the wind turbine based dual-star PMSG, the ac-dc-ac converter consists of two sets of diode rectifier, a kind of DC–DC converter and three-phase inverter, which inverter and DC–DC converter are controlled to send high-quality power to the gird and absorb maximum power from the wind turbine respectively [10–14].

In view of power electronic components reduction, the multi port converters are proper choice for application in grid connection of dual-star PMSG, because the dual-star PMSG has two sets of stator windings. This paper proposes the novel dual-input Z-source inverter for wind turbines based dual-star PMSG.

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http://dx.doi.org/10.1016/j.ijepes.2016.02.017
0142-0615/

The Z-source inverter has been proposed recently as a one stage controlled DC–AC converter with many advantages [15–19]. This inverter makes it possible to boost voltage and improves reliability of system due to short circuit possibility across any legs of inverter. Also, presence of Z-network causes to reduce distortion of output voltage due to no request of dead-time in switching algorithm [15–19]. In this study, new inverter structure based on dual input Z-source network is proposed that consists of two power sources, two inductors, one capacitor and switching circuits. In this structure, it will be necessary that the voltages of both two power sources are similar. So, this topology is very applicable in coupling of systems with two similar outputs to load or grid as a dual-star PMSG. The suggested structure requires less passive components as compared to traditional Z-network and achieves the advantages of traditional Z-network.

The paper is organized as follows: in Section "Proposed dual-input Z-source inverter", the proposed dual input Z-source inverter is explained and then dynamic model of the considered generator is developed in Section "Dual-star PMSG dynamic modeling". The proposed wind turbine and its control scheme are presented in Section "Proposed WECS". The simulation results of dynamic model of suggested wind turbine energy conversion system are shown and discussed in Section "Simulation results". Section "Experimental results" presents the experimental tests which were conducted in laboratory on the suggested inverter for validating its performance. Finally, conclusion will be given in last section.

Proposed dual-input Z-source inverter

To extend the Z-source structures, dual-input Z-source is proposed in this paper. The proposed structure consists of two power sources, two inductors and one capacitor as shown in Fig. 1(a). In this inverter, voltages of power sources are similar and it makes this inverter to be very applicable in connection of dual-star PMSG to grid which has two similar outputs in view of voltage amplitude. Such an inverter has all advantages of Z-source families and as compared to traditional Z-source inverters requires less passive components.

It operates in two modes: shoot-through and non shoot-through states. In shoot-through mode, the output of dual input Z-source inverter becomes short circuit across any leg of inverter. But, in non shoot-through state, the dual input Z-source inverter operates such a traditional inverter. Assuming the inductors and voltage of power sources have the same value as L and V_{dc}, respectively, the proposed Z-network becomes symmetric. Fig. 1(b) and Fig. 1(c) show the equivalent circuit of shoot-trough state and non shoot-through state, respectively.

The Eqs. (1) and (2) can be expressed with analyze of proposed equivalent circuit during shoot-through state as follows:

$$V_l = V_{dc1} = V_{dc} \tag{1}$$

$$V_i = 0 \tag{2}$$

With analysis of non shoot-through state, the maximum output voltage of z impedance network and voltage across inductors can be written as:

$$V_l = V_c - V_{dc} \tag{3}$$

$$V_i = V_{dc} - V_l \tag{4}$$

$$V_i = 2V_{dc} - V_c \tag{5}$$

It is known that the steady state average voltage of the inductors is zero in one switching cycle. Then, it can be obtained:

$$V_C = \frac{T_{ns} - T_{sh}}{T_{ns}} V_{dc} = \frac{1 - 2\left(\frac{T_{sh}}{T}\right)}{1 - \left(\frac{T_{sh}}{T}\right)} V_{dc} \tag{6}$$

where T_{sh} and T_{ns} show total shoot-through state period and total non shoot-through state period during switching period, respectively. V_i and boost factor of dual input Z-source inverter are achieved as (7) and (8) with substituting (6) into (5), when the system is in the non shoot-through mode.

$$V_i = \left(\frac{1}{1 - \frac{T_{sh}}{T}}\right) V_{dc} \tag{7}$$

$$B = \frac{1}{1 - \frac{T_{sh}}{T}} \tag{8}$$

where T and B are period switching and boost factor, respectively. It is obvious that $B \geqslant 1$.

In shoot-through state, the inductor voltage equals input DC voltage and inductor current increases linearly. Inductor value is obtained as:

$$L = \frac{V_{dc} T_{sh}}{\Delta I} \tag{9}$$

where ΔI is the assumed current ripple of the inductor.

During the shoot-through state, capacitor is disconnected from Z-network and its current is equal to zero. As a result, the capacitor voltage remains constant. In non shoot-through state, the capacitor current is obtained as:

$$i_c = 2I_L - i_i \tag{10}$$

where I_L is current of inductor and i_i is output current of double-input Z-network. Therefore, the capacitor voltage ripple occurs during in non shoot-through state. The capacitor voltage follows both increasing and decreasing modes in non shoot-through state. Because the average of capacitor current in steady state is zero, times of both modes are equal, approximately.

It is necessary that maximum value of i_c is applied to calculate the capacitor value, where it occurs in minimum i_i, Then maximum value of i_c equals $2I_L$.

Based represented description, and assuming linear variation of capacitor current, its value is obtained as:

$$C = \frac{2I_L \frac{T_{ns}}{2}}{2\Delta V_C} = \frac{I_L T_{ns}}{2\Delta V_C} \tag{11}$$

where, ΔV_C is the assumed voltage ripple of capacitor.

In this structure, it will be necessary that the voltages of both two power sources are similar. In state of $V_{dc1} \neq V_{dc2}$, average voltage of inductors are calculated as (12) and (13) with assuming that steady state average voltage of the inductors is zero in one switching cycle.

$$\text{For } L_1: \quad V_{dc1} T_{sh} + (V_c - V_{dc2}) T_{ns} = 0 \tag{12}$$

$$\text{For } L_2: \quad V_{dc2} T_{sh} + (V_c - V_{dc1}) T_{ns} = 0 \tag{13}$$

V_c is achieved from (13) as follow:

$$V_c = \frac{V_{dc1} T_{nsh} - V_{dc2} T_{sh}}{T_{ns}} \tag{14}$$

Then, the (14) is substituted in (12) to obtain (15) as:

$$V_{dc1}(T_{sh} + T_{ns}) = V_{dc2}(T_{sh} + T_{ns}) \tag{15}$$

Eq. (15) shows that V_{dc1} must be equal with V_{dc2} to achieve stable V_c.

Dual-star PMSG dynamic modeling

The dual-star PMSG structure is like to the common PMSGs except for the windings arrangement in the stator. The stator of dual-star PMSG consists of double groups of three phase windings (stator1 and stator2) which there are 30 electrical degrees as a