Electrical Power and Energy Systems 95 (2018) 601–616

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Small-signal stability analysis, and predictive control of Z-Source Matrix Converter feeding a PMSG-WECS

Mojtaba Alizadeh *, Shokrollah Shokri Kojori

Electrical Engineering Faculty, K.N. Toosi University of Technology, Shariatei Street, Seyed Khandan Bridge, P.O. Box 16315-1355, Tehran, Iran

A R T I C L E I N F O

Article history:
Received 7 March 2017
Received in revised form 25 July 2017
Accepted 10 September 2017

Keywords:
Small-signal stability analysis
Small-signal model
Quasi-Z-Source Matrix Converter (qZSMC)
Wind Energy Conversion System (WECS)
Predictive control

A B S T R A C T

The modeling, small-signal stability analysis, and control of quasi-Z-Source Matrix Converter (qZSMC), and also its application in Wind Energy Conversion System (WECS) are discussed. First, the small-signal model of the qZSMC, composed of an input filter, a Three-Phase Quasi-Z-Source Network (TPQZSN), and a Matrix Converter (MC), is derived. Then, a comprehensive stability study is carried out and it is shown that, unlike the conventional MC, the qZSMC does not have problem working stable for its entire range of operation. The small-signal model is used to obtain system transfer functions and perform a frequency domain analysis. A guide to choose proper passive components of qZSMC is also presented. The qZSMC is further employed as grid interface by a Permanent Magnet Synchronous Generator (PMSG) based WECS (PMSG-WECS). A modified predictive control (MPC) is developed, allowing shoot-through states to be inserted within the deliberately made sequences of zero switching states in MC switching pulses. The proposed MPC is then compared to its conventional version, showing that by the MPC, the grid-current ripples are reduced considerably. Simulation study is used to assess the effectiveness of proposed WECS and MPC, and to highlight the promising features of the proposed WECS in comparison to Conventional MC-based PMSG-WECS (CMC-WECS).

1. Introduction

THE IMPORTANCE of power electronics' role in what is called renewable energy revolution cannot be overemphasized. It is particularly true of wind energy conversion area, where wind energy is converted to electrical power while different power electronic configurations are used as a conditioning interface between the generator and the grid. The whole configuration can generally be classified as either fixed- or variable-speed Wind Energy Conversion System (WECS) [1]. Such appealing features as ability to extract maximum power from the wind, low mechanical stress, ability to operate at low wind speed, and reduction of output power and torque oscillations give the variable-speed WECS a distinct edge over the fixed-speed WECS [2].

Both synchronous and induction generators are used in variable-speed WECS. However, synchronous generator, which can be either a wound rotor synchronous generator or a permanent-magnet synchronous generator (PMSG), makes it possible to get rid of gearbox by means of multiple-pole design [3]. By employing the PMSG, a WECS can benefit from other advantages like high power factor, low losses, and high torque density owing to the fact that the PMSG does not need to additional power supply and rotor winding [1,3].

Various power electronic configurations have been proposed in literature as a bridge between the PMSG and the grid [4–14]. In [4] a simple low-cost configuration integrating a diode rectifier, a DC chopper, and a voltage source inverter (VSI) was proposed for low power levels (LPLs). Two-level back-to-back VSIs are also proposed in [5,6] for LPLs. In [7], a diode rectifier followed by a Z-source inverter was proposed. Three-switch PWM rectifier cascaded by a Z-source inverter was introduced in [8]. Back-to-back three-level neutral-point clamped (NPC) converter was discussed in [9–11] for high power levels (HPLs). A grid interface integrating

Abbreviations: WECS, Wind Energy Conversion System; TPQZSN, Three-Phase Quasi-Z-Source Network; MC, Matrix Converter; qZSMC, quasi-Z-Source Matrix Converter; PMSG, Permanent Magnet Synchronous Generator; PMSG-WECS, PMSG-based WECS; MPC, Modified Predictive Control; CMC-WECS, Conventional MC-based PMSG-WECS; VSI, Voltage Source Inverter; LPL, Low Power Level; HPL, High Power Level; NPC, Neutral-Point Clamped; NST, Non-Shoot Through; ST, Shoot-Through; AFRO, Allowed Frequency Range of Operation; qZSMC-WECS, quasi-Z-Source Matrix Converter based PMSG WECS; TPC, Traditional Predictive Control; SVD, Singular Value Decomposition; MPPT, Maximum Power Point Tracking; TSR, Tip-Speed-Ratio; MCVV, Magnitude of Capacitor Voltage Vector; THD, Total Harmonic Distortion; STD, Shoot-Through Duration; RRS, Reference Rotor Speed; RHP, Right-Half Plane.

* Corresponding author.
E-mail address: Mjt.alizadeh@gmail.com (M. Alizadeh).

https://doi.org/10.1016/j.ijepes.2017.09.018
0142-0615/

diode rectifier, three-level boost converter, and NPC inverter for HPLs is addressed by [12]. Matrix converter (MC) has also received increasing attention in recent years, as the grid interface of a PMSG-based WECS in low-power micro-grids and local applications [13,14].

Matrix converter provides a direct ac/ac frequency conversion with sinusoidal input current and output voltage, and does not need to any energy storage component [15]. If it is used as a grid interface in a PMSG-based WECS (PMSG_WECS), the MC allows us to get rid of rectifying stage, resulting in a gearless, compact and reliable single-stage configuration which is a good choice for low-power micro grids and local applications [14].

The system, however, suffers from disadvantages as well. Due to lack of energy storage element, both grid and the generator quantities are controlled at the same time. Accordingly, the grid active and reactive powers are proportional to the matrix converter voltage gain as well as both active and reactive powers at the generator side. However, one often-cited problem with matrix converter is its limited voltage gain of 0.866 [16]. Having a limited voltage gain can also result in a limited operation range for the system since at the low wind speeds the output voltage is reduced and the problem of limited voltage gain will become highlighted [14]. Additionally, the MC has to employ commutation methods to avoid accidental input short-circuit and/or output line open-circuit. Implementing such commutation methods adds to complexity of the control system. Further, it decreases the quality of MC output waveforms since the MC cannot be controlled during the commutation time. The system also has a comparatively low reliability due to the potential existence of ST resulting from possible gate-drive failures [15].

Quasi-z-source MC (qZSMC) has recently been proposed as an alternative to conventional MC [17]. However, its small-signal stability analysis, control, and applications in WECSs have not been addressed yet. Therefore, the contributions of this paper are:

- To model qZSMC and study its small-signal stability.
- To propose a guide to passive components selection for the qZSMC.
- To propose a new grid interface for variable-speed PMSG-WECS as an alternative to traditional MC.
- To propose a Modified Predictive Control (MPC) to control the proposed WECS.

2. Quasi-Z-Source Matrix Converter (qZSMC)

2.1. Topology

Fig. 1 Shows the detailed circuit model of the qZSMC, composed of an LC input filter followed by a TPQZSN and a MC. The TPQZSN includes a three-phase switch S_0 and passive elements [17]. The qZSMC has two different operation modes: (1) Non-shoot through (NST) state or buck mode, (2) Shoot-through (ST) state or boost mode. The switch S_0 is kept on during the NST state, while the output voltage is synthesized by MC from input active- and zero-voltage switching states. In the ST state or boost operation mode, the MC is shooted-through during the zero-voltage switch states while the switch S_0 is kept off. So, the output voltage is boosted beyond the limited MC voltage gain 0.866.

2.2. Small-signal model

2.2.1. LC input filter model

From Fig. 1, the dynamic of *LC* input filter on a synchronously rotating *d-q* frame aligned with the input voltage space vector can be expressed by following equations:

$$\frac{d\bar{i}_s}{dt} = -\frac{R_s}{L_T}\cdot\bar{i}_s - j\omega_s\cdot\bar{i}_s - \frac{\bar{v}_i}{L_f} + \frac{\bar{v}_s}{L_f} \tag{1}$$

$$\frac{d\bar{v}_i}{dt} = \frac{1}{C_f}\bar{i}_s - j\omega_s\cdot\bar{v}_i - \frac{1}{C_f}\bar{i}_{L2} \tag{2}$$

where $\bar{v}_i$ is voltage vector across the input filter capacitor C_f; $\bar{v}_s$ and $\bar{i}_s$ are the AC source voltage and current vector, respectively; ω_s is the source angular frequency; R_s is the source series resistance; $L_t = L_f + L_s$ in which L_f is the input filter inductance and L_s is the input source series inductance.

2.2.2. TPQZSN model

State-space averaging method [18] is used here to model the TPQZSN. Equivalent circuit of the TPQZSN during the NST and ST states are illustrated by Fig. 2(a) and (b), respectively.

In this sub-section, it is assumed that the TPQZSN is feeding an assumed three-phase *RL* load, instead of feeding a MC. So, the output current of the TPQZSN, $\bar{i}_{i\_MC}$, which is actually the input current into the MC, can be considered as a state variable. The assumed three-phase RL load will be further replaced with MC dynamic equations in next sub-section. So, let us define five space vector based state variables $\bar{i}_{L1}, \bar{i}_{L2}, \bar{v}_{c1}, \bar{v}_{c2}$, and $\bar{i}_{i\_MC}$. The voltage vector across C_f, $\bar{v}_i$, is actually the input voltage vector to the TPQZSN. So, it can be defined as input variable. Assuming $C_1 = C_{1,a} = C_{1,b} = C_{1,c}$; $C_2 = C_{2,a} = C_{2,b} = C_{2,c}$; $L_1 = L_{1,a} = L_{1,b} = L_{1,c}$; $L_2 = L_{2,a} = L_{2,b} = L_{2,c}$, the state-space equations of ST state in space-domain can be written as:

$$\begin{aligned}
&dx/dt = A_1 x + B_1 u\\
&x = \begin{bmatrix}\bar{i}_{L1} & \bar{i}_{L2} & \bar{v}_{C1} & \bar{v}_{C2} & \bar{i}_{i_MC}\end{bmatrix}^T; \quad u = [\bar{v}_i]\\
&A_1 = \begin{bmatrix} -(r_c+r_L)/L_1 & 0 & 1/L_1 & 0 & 0\\ 0 & -(r_c+r_L)/L_2 & 0 & 1/L_2 & 0\\ -1/C_1 & 0 & 0 & 0 & 0\\ 0 & -1/C_2 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & -R_L/L_L \end{bmatrix}\\
&B_1 = \begin{bmatrix}0 & 1/L_2 & 0 & 0 & 0\end{bmatrix}^T,
\end{aligned} \tag{3}$$

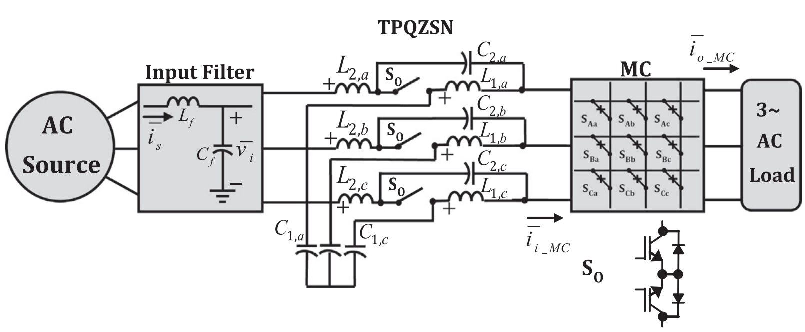

Fig. 1. Detailed circuit model of qZSMC.