Postprint of Machine-Side Harmonic Suppression in Z-Source Grid-Connected Wind Power Generation System

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Date: 2019-03-05T00:00:00+00:00

Abstract

Traditional Z-source grid-connected wind power generation systems employ three-phase uncontrolled rectification on the rectifier side. The stator-side current harmonics not only increase the generator' s copper and iron losses, thereby reducing power generation efficiency, but may also lead to generator saturation and loss of control, severely compromising system stability. This paper applies the VIENNA rectifier to Z-source grid-connected wind power generation systems and proposes a novel grid-connected converter control method. The method divides one period of the stator output voltage into six sectors and provides a current path for the non-conducting phase in each sector through a sector decision controller, thereby improving the nonlinear relationship between machine-side current and machine-side voltage. A comparison is made of the machine-side current harmonics in Z-source grid-connected wind power generation systems employing three-phase uncontrolled rectifiers versus VIENNA rectifiers, as well as under maximum boost control versus improved SVPWM control. Simulation and experimental results demonstrate that the proposed method effectively reduces stator-side current harmonics and enhances system efficiency and stability.

Full Text

Preamble

Harmonic Suppression for the Motor-Side Converter of the Z-Source Grid-Connected Wind Generation System

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Abstract

Traditional Z-source grid-connected wind power generation systems employ a three-phase uncontrolled rectifier on the generator side. The resulting stator current harmonics not only increase copper and iron losses in the generator, reducing power generation efficiency, but may also cause motor saturation and runaway phenomena, severely compromising system stability. This paper applies the VIENNA rectifier to a Z-source grid-connected wind power generation system and proposes a novel grid-connected converter control method. By dividing one period of the stator output voltage into six sectors and employing a sector decision controller to provide current paths for the non-conducting phase in each sector, the nonlinear relationship between the machine-side current and voltage is improved. The paper compares the machine-side current harmonics of Z-source grid-connected wind power generation systems under three-phase uncontrolled rectification versus VIENNA rectification, as well as under maximum boost control versus improved SVPWM control. Simulation and experimental results demonstrate that the proposed method reduces stator-side current harmonics and improves system efficiency and stability.

Keywords: Z-source inverter, VIENNA rectifier, wind power generation, harmonic suppression

1 Introduction

Compared with conventional inverters, Z-source inverters offer several advantages [1-6]: output voltage buck-boost capability; AC loads can be either inductive or capacitive; the main circuit can be used for both voltage-source and current-source inverters; and the control of switching devices allows shoot-through operation (eliminating the need for dead-time insertion), thereby enhancing system reliability and electromagnetic compatibility.

In recent years, Z-source inverters have been widely applied in new energy generation systems such as wind power. Literature [7] discusses a small-scale wind grid-connected generation system using a Z-source converter, achieving unity power factor operation of the grid current inner loop and voltage stabilization of the Z-source network capacitor voltage outer loop through control of the sinusoidal modulation factor. Literature [8] combines the traditional three-phase PWM grid-connected inverter model with an equivalent Z-source network model to establish a mathematical model of the three-phase Z-source grid-connected inverter, analyzes the impact of shoot-through duty cycle variations on the system, and proposes a control strategy for obtaining stable Z-network capacitor voltage and decoupled d-q axis grid-side current components under grid-connected conditions, with experimental verification on a small permanent magnet synchronous generator wind power platform based on Z-source inverters. Literature [9] proposes applying a novel three-phase Z-source inverter to direct-drive wind grid-connected generation systems, establishing a mathematical model and presenting a control strategy for stable Z-network capacitor voltage and decoupled d-q axis grid-side current components. Literature [10-12] primarily investigates nonlinear control methods for Z-source inverter DC-link voltage stability. However, research on motor-side harmonic suppression for Z-source grid-connected wind power generation systems remains scarce both domestically and internationally.

Traditional Z-source grid-connected wind power generation systems typically employ a structure consisting of a direct-drive permanent magnet synchronous generator, a three-phase uncontrolled rectifier, and a Z-source inverter. Within each sector, only two diodes of the three-phase uncontrolled rectifier conduct, resulting in machine-side current harmonics that not only increase generator losses but may also cause motor saturation and runaway phenomena, severely affecting system stability. This paper applies the VIENNA rectifier to the Z-source grid-connected wind power generation system to replace the conventional three-phase uncontrolled rectifier and proposes a novel machine-side converter control method. By dividing one period of the stator output voltage into six sectors and utilizing the unique topology of the VIENNA rectifier, a sector decision controller provides current paths for the non-conducting phase in each sector, thereby improving the nonlinear relationship between machine-side current and voltage, reducing stator-side current harmonics, and enhancing system efficiency and stability.

2 System Structure and Model Analysis

The permanent magnet direct-drive wind power generation system based on a Z-source inverter is shown in [Figure 1: see original paper]. The system comprises a wind turbine, permanent magnet synchronous generator, VIENNA rectifier, Z-source inverter unit, and grid-connected transformer.

[Figure 1: see original paper] shows the topology of the proposed Z-source inverter for wind power systems. [Figure 2: see original paper] divides one AC input period into six sectors. Within each sector, only the diodes of the two phases with the maximum voltage difference can conduct. The sector decision controller then provides a current path for the non-conducting phase in each sector. Since the inverter switching period is much longer than the AC input period, the input voltage can be considered constant within one switching period. The series-connected diodes conduct and block simultaneously and can therefore be equivalent to a single diode, enabling analysis of the system' s equivalent circuit within one switching period using fundamental Z-source inverter theory.

Taking the first sector as an example, assuming the current direction as shown in [Figure 3: see original paper], diodes VD1, VD7 and VD6, VD14 conduct. After detecting the current sector, the sector decision controller turns on switching device VT2, creating a current path through VD16, VT2, and VD18 for phase C, which originally had no current flow. When the Z-source inverter operates in the non-shoot-through zero state, diode VD19 remains continuously conducting, and the inverter bridge can be equivalent to a current source. The system' s equivalent circuit in this state is shown in [Figure 3: see original paper].

From the symmetry of the Z-source network [13-16]:

$$VC_1 = VC_2 = VC$$

$$VL_1 = VL_2 = VL$$

From [Figure 3: see original paper]:

$$v'_d = v_a - v_c - 2L_Z \frac{di'_L}{dt} - V_i$$

Adding equations (4) and (5):

$$V_{in} = V_L + V_C$$

$$V_i = 2V_C - V_0$$

$$V_d = V_{in}$$

$$i_D = 2i_L - i_i$$

$$L_{in} \frac{di_{in}}{dt} = v_a - v_b - v_c - 4L_Z \frac{di'_L}{dt} - 2V_i$$

where i_D is the current through diode VD19. When designing the Z-source network inductor, to avoid output voltage distortion of the Z-source network caused by the false turn-off of diode VD19 during non-shoot-through operation:

$$L_1 = L_2 = \frac{D_0(1 - D_0)Z}{2(1 - 2D_0)M \cos\phi - 1} \geq 0$$

where D_0 is the shoot-through duty cycle of the Z-source inverter; f_S is the switching frequency of the Z-source inverter; Z is the load; M is the modulation index of the Z-source inverter; and ϕ is the output power factor angle of the Z-source inverter.

From Kirchhoff' s voltage law:

$$L_{in} \frac{di_{in}}{dt} = v_a - v_b - 2L_Z \frac{di'_L}{dt} - V_i$$

where L_{in} is the generator input inductance and L_Z is the Z-source network inductance.

Within each sector, only the diodes of the two phases with the maximum voltage difference can conduct. From the symmetry of the three-phase input voltage:

$$L_{in}\frac{di_{in}}{dt} = 3v_a - 4L_Z\frac{di'_L}{dt} - 2V_i$$

Due to the magnitude of the Z-source inverter input voltage V_d, the diode rectifier bridge may not conduct, causing flat-topping of the sinusoidal waveform and zero-current phenomena near the zero-crossing points. Additionally, because only two diodes conduct in each sector, the machine-side current sinusoidal waveform becomes distorted. The sector decision controller provides a current path for the non-conducting phase in each sector, making the sum of the last two terms in equation (7) zero and ensuring current flows through all three phases at any moment, thereby reducing stator-side current harmonics.

When the Z-source inverter operates in the shoot-through zero state, the inverter bridge can be considered short-circuited, diode VD19 turns off, and the system' s equivalent circuit is shown in [Figure 4: see original paper].

From the equivalent circuit during shoot-through:

$$V_L = V_C$$

$$V_d = 2V_C$$

$$V_i = 0$$

[Figure 4: see original paper] shows the equivalent circuit of the Z-source inverter when the inverter bridge is in the shoot-through zero state.

Since the average voltage across the inductor over one switching period T must be zero:

$$\frac{T_0}{T}V_C + \frac{T_1}{T}(V_{in} - V_C) = 0$$

The shoot-through duty cycle of the Z-source inverter fluctuates at six times the output frequency. When utilizing shoot-through zero vectors to the maximum extent, the shoot-through zero vector magnitude varies each switching period because the traditional zero vector itself changes each period. This not only introduces significant low-order harmonic content in the inductor current but also causes distortion in the rectifier-side current waveform. Moreover, since shoot-through zero vectors are inserted within traditional zero vectors, the number of switching actions per switching period doubles, which is detrimental to increasing the system switching frequency. Therefore, this paper employs an improved SVPWM shoot-through zero vector insertion method as shown in [Figure 5b: see original paper]. By advancing or delaying the turn-on/off times of power devices in the conventional SVPWM strategy, shoot-through zero vectors are inserted at switching transition moments without requiring additional switching actions. The shoot-through zero vectors in one switching period are evenly divided into six portions and inserted between two active vectors and on both sides of traditional zero vectors. Due to its space vector approach, this method offers easy digital implementation, wide linear modulation range, high voltage utilization, and low current harmonics, making it more suitable for Z-source inverters.

3 Control Strategy for Grid-Connected Z-Source Inverter

The permanent magnet direct-drive wind power control system based on a Z-source inverter employs dual-loop voltage-current control and dual-loop speed-current control. By tracking the reference value of the Z-source network inductor current, shoot-through zero vectors are generated. The sector decision controller generates pulse signals to trigger the switching devices of the VIENNA rectifier, providing current paths for non-conducting phases in each sector. The control objectives include maintaining stable Z-source network capacitor voltage, achieving grid-connected currents with low harmonic content and good sinusoidal quality with fast dynamic response, while also realizing high power factor, good current sinusoidal quality, and low harmonic content on the machine side.

3.1 Shoot-Through Zero Vector Insertion Method

The principle of maximum boost SPWM shoot-through zero vector insertion for Z-source inverters is shown in [Figure 5a: see original paper]. When the three-phase sinusoidal modulation wave are greater than the triangular carrier wave, high-level pulses are output; when they are smaller, low-level pulses are output. Based on this, the minimum value of the three-phase trigger pulses during the traditional zero state—that is, the maximum value achievable for shoot-through during the zero state—is used as the shoot-through zero vector reference to maximize the boost function. However, under this method, the shoot-through zero vector magnitude of the impedance source network inverter varies, leading to significant low-order harmonic content in the inductor current. The shoot-through zero vectors in one switching period are evenly divided into six portions and inserted between two active vectors and on both sides of traditional zero vectors. Due to its space vector approach, this method offers easy digital implementation, wide linear modulation range, high voltage utilization, and low current harmonics, making it more suitable for Z-source inverters.

Based on conventional SVPWM, an additional shoot-through zero vector generation stage is implemented. The specific method is as follows: T_{a1}, T_{b1}, T_{c1} generated by equation (11) are compared with the triangular carrier wave to produce pulses for driving the three upper bridge arm switches, while T_{a2}, T_{b2}, T_{c2} generated by equation (12) are compared with the triangular carrier wave and then inverted to drive the three lower bridge arm switches.

$$\begin{aligned} T_{a1} &= (T_{PWM} - T_1 - T_2 - T_0)/4 \\ T_{b1} &= T_{a1} + T_1/2 + T_0/6 \\ T_{c1} &= T_{b1} + T_2/2 + T_0/6 \end{aligned}$$

$$\begin{aligned} T_{a2} &= T_{a1} + T_0/6 \\ T_{b2} &= T_{b1} + T_0/6 \\ T_{c2} &= T_{c1} + T_0/6 \end{aligned}$$

3.2 Dual-Loop Control

The permanent magnet direct-drive wind power system based on a Z-source inverter employs voltage-current dual-loop control during grid-connected operation. From equations (8) and (9), the average DC voltage applied to the inverter is:

$$V_i = \frac{T_0 \cdot 0 + T_1 \cdot (2V_C - V_{in})}{T} = \frac{T - T_0}{T - 2T_0} V_{in} = \frac{1 - D_0}{1 - 2D_0} V_{in} = V_C$$

where T_0 is the shoot-through zero vector time in one switching period and T_1 is the non-shoot-through zero vector time.

Equation (13) shows that when the shoot-through duty cycle remains constant, maintaining a constant Z-source network capacitor voltage yields a stable average DC input voltage to the inverter bridge, ensuring stable AC output voltage from the Z-source inverter. Therefore, for the voltage outer loop control, this paper directly controls the Z-source network capacitor voltage. Due to the trade-off relationship between shoot-through duty cycle and modulation index, increasing the shoot-through duty cycle raises the average DC input voltage to the inverter while reducing the modulation index, and vice versa. With stable capacitor voltage, the inverter input DC voltage can be flexibly controlled through the shoot-through duty cycle.

The current inner loop employs a current control strategy based on dq coordinate transformation, where the d-axis serves as the active power reference axis and the q-axis as the reactive power reference axis, enabling independent control of active and reactive power. When the upper bridge arm conducts and the lower bridge arm blocks, the switching function $S_K = 1$; when the upper bridge arm blocks and the lower bridge arm conducts, $S_K = 0$, where $K = a, b, c$.

After synchronous rotating coordinate transformation:

$$L \frac{di_d}{dt} = -Ri_d + \omega L i_q + e_d - S_d V_{in}$$

$$L\frac{di_q}{dt} = -Ri_q - \omega Li_d + e_q - S_qV_{in}$$

where S_d and S_q are the switching functions S_K transformed to the dq coordinate system.

Since the dq-axis variables are coupled, controller design presents certain difficulties. Therefore, when employing PI control for the current regulator, feedforward decoupling control can be applied to decouple the dq-axis variables. The control laws for v_d and v_q are:

$$v_q = -\left(K_P + \frac{K_I}{s}\right)(i_q^* - i_q) - \omega Li_d + e_q$$
$$v_d = -\left(K_P + \frac{K_I}{s}\right)(i_d^* - i_d) + \omega Li_q + e_d$$

where K_P and K_I are the proportional and integral gains of the current inner loop, and i_d^* and i_q^* are the command current values for the dq-axis components.

By aligning the d-axis with the grid voltage vector, the d-axis current represents the active component and the q-axis current represents the reactive component. To ensure good sinusoidal quality and low harmonic content in the grid-connected current, the q-axis current command value is set to zero. In SVPWM modulation, the shoot-through duty cycle is generated by controlling the Z-source network inductor current, where the reference value for the Z-source network inductor current is obtained through a PI controller from the D-PMSG speed difference, thereby tracking the optimal Z-source network input voltage and achieving maximum power point tracking for the wind turbine. The control block diagram of the three-phase grid-connected Z-source inverter for the direct-drive wind power generation system is shown in [Figure 6: see original paper].

4 Simulation Research

The main parameters of the simulation system are listed in the table below. The Z-source network inductor current and output voltage are shown in [Figure 7: see original paper] and [Figure 8: see original paper]. It can be observed that during shoot-through intervals, the Z-source network capacitor charges the inductor, causing the inductor current to rise, while during non-shoot-through intervals, the Z-source network inductor discharges, causing the inductor current to decrease. The inverter input voltage is a normal square wave without voltage drop, indicating that during shoot-through intervals, the diode current is zero, and during non-shoot-through intervals, the diode current does not drop to zero. The Z-source network inductor is sufficiently large, preventing false turn-off of the diode during non-shoot-through states and avoiding abnormal operation of the Z-source inverter.

[Figure 9: see original paper] shows the Z-source network capacitor voltage waveform, which remains essentially stable at the set value with small voltage overshoot and short response time. Since the initial Z-source network capacitor voltage is set to 400V, the Z-source network capacitor is charged by the grid at startup, resulting in a negative Z-source network inductor current for a period at the beginning.

As shown in [Figure 10: see original paper], the grid-connected currents are symmetrical with good sinusoidal quality and fast dynamic response. Comparing [Figure 11: see original paper] and [Figure 12: see original paper] reveals that when using the VIENNA rectifier, the stator current waveform is closer to sinusoidal with significantly reduced harmonic content. Under maximum boost control, the harmonic content at the 2nd, 3rd, 4th, 5th, 7th, and 13th orders is much higher than under improved boost control.

5 Experimental Research

A hardware platform was built to verify the performance of the proposed novel Z-source grid-connected inverter system. An asynchronous machine drives the permanent magnet synchronous generator, and the electrical energy generated by the permanent magnet synchronous generator is fed into the grid through a voltage-type three-phase Z-source inverter after passing through the VIENNA rectifier. Experimental results were collected using a QualityStar power analyzer. The controller employs a TMS320F28335, the Z-source network capacitor uses a capacitor bank composed of 2 series and 6 parallel 450V/680 F electrolytic capacitors, the Z-source network inductor is 5mH, and the switching frequency is 5kHz. The main parameters of the experimental system are listed in the table above.

[Figure 13: see original paper] shows the steady-state experimental waveforms of the Z-source inverter and enlarged waveforms of the Z-source network inductor current and output voltage after the Z-source network. It can be seen that the Z-source network capacitor voltage remains essentially constant. During the shoot-through state, the Z-source network capacitor charges the inductor, the inductor current rises, and the Z-source network output voltage is zero. During the non-shoot-through state, the Z-source network inductor discharges, the inductor current decreases, and the Z-source network output voltage remains essentially stable.

Experimental comparisons of stator current harmonics under different control methods and rectifiers are shown in [Figure 14: see original paper] and [Figure 15: see original paper]. [Figure 14: see original paper] shows that when the stator current passes through a three-phase uncontrolled rectifier, the harmonic amplitudes at the 2nd, 3rd, 4th, 5th, 7th, and 13th orders under maximum gain control are much larger than those under improved boost control. [Figure 15: see original paper] shows that when the stator current passes through the VIENNA rectifier, the harmonic amplitudes at the 2nd, 3rd, 4th, and 13th orders under improved boost control are much smaller than those under maximum gain control. This is because the shoot-through duty cycle under maximum gain control is larger than that under improved boost control, resulting in longer diode turn-off times. Additionally, since the shoot-through duty cycle under maximum gain control varies, low-order harmonics are introduced. Comparing [FIGURE:15b, 15d] with [FIGURE:14b, 14d] shows that under improved boost control, the harmonic content in the stator current is much lower with the VIENNA rectifier than with the three-phase uncontrolled rectifier. This is because when the stator current passes through the VIENNA rectifier, the sector decision controller provides current paths for the non-conducting phase in each sector, thereby improving the machine-side current harmonics.

6 Conclusion

This paper combines the Z-source inverter with the VIENNA rectifier and applies it to a permanent magnet direct-drive wind power generation system. Through analysis of the system mathematical model and operating principle, a grid-connected Z-source inverter control strategy using improved SVPWM boost control is proposed to address the machine-side current harmonic issues caused by three-phase uncontrolled rectification. Theoretical analysis, simulation, and experiments demonstrate that:

1) In Z-source grid-connected wind power generation systems, the maximum gain control method results in varying shoot-through zero vector magnitudes, which introduces significant low-order harmonic content in the inductor current. Moreover, the larger shoot-through duty cycle under maximum gain control compared to improved boost control leads to longer diode turn-off times, causing distortion in the rectifier-side current waveform.

2) Applying the VIENNA rectifier to the Z-source inverter-based wind power grid-connected system and using a sector decision controller to provide current paths for non-conducting phases in each sector improves the nonlinear relationship between machine-side current and voltage, reducing the harmonic currents in the generator stator.

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Note: Figure translations are in progress. See original paper for figures.