Design of Z Source Inverter based VSWECS with Improved PWM Control

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Abstract—With rapid development in Wind Energy Conversion Systems (WECS), various methods have been used to increase power generation from wind. In order to reach voltage gain as maximum in a variable speed WECS, an improved PWM method through varying shoot through time for Impedance source inverter is implemented in this paper. For a given modulation index, the correlation of voltage gain with capacitor voltage, and the device stress are analyzed in detail. For ‘various shoot through time’, the simulation results of voltage across capacitor, current through inductor, output current and output voltage are obtained by using Simpower system tool in MATLAB/Simulink and compared. The results have been confirmed for the developed experimental model.

Keywords: Z source inverter, wind Energy conversion systems, voltage Boost, Pulse width Modulations.

1. INTRODUCTION

Nowadays, renewable energy resources are being preferred to non-renewable energy sources due to its contribution to green environment. Hence, Wind Energy Conversion Systems play an significant role in generating high amount of electricity from wind. The wind energy can be converted using conventional systems, which consists of diode rectifier and three-phase inverter. Conventional systems possess some advantages such as simple design, less cost and maximum bus voltage [1]–[6]. Due to liability voltage characteristics in Voltage Source Inverter (VSI), the bus voltage gets maximum, which effect on the working range of wind power turbine during constant frequency and change in speed conditions.

To overcome this drawback, the boost converter is coupled in the middle of three phase diode bridge rectifier and three phase inverter [2]–[10]. These types of converters reduce the system efficiency and increase the total cost. The WECS based on Impedance source inverter is an eye catching method for conversion of wind energy, [11]–[16].

Figure 1. Impedance-source Inverter

Wind Energy Conversion System based on Impedance source inverter is depicted in figure 1. It increases or decreases the output voltage without connecting any additional switch. The reliability of the system does also increases due to the solicitation of ‘shoot through state’. It is not conceivable in case of voltage source inverter [17]. The set dead time is not needed, which leads to reduction of voltage distortion in inverter. This feature of Z-source inverter makes it extensively used in wind generating as added Zero vectors that were not used in conventional voltage source inverter [18] systems and other system established on renewable energy. In the Impedance source inverter both devices of phase arm cannot be turned on instantaneously which results in short circuit and subsequently brings damage to the inverter [19]–[22].

However, the Impedance-source inverter uses this ‘shoot through state’ to increase the DC bus voltage by triggering both higher and lesser devices of a phase leg. Using Impedance -source inverter, it is conceivable to get the desired voltage output, higher than voltage DC.

Figure 2. Simulation arrangement of the Z source inverter based WECS

In the proposed work, a new improved Pulse width Modulated scheme is implemented in the impedance-source inverter coupled with three-phase VSI. The relationship among voltage gain and ‘Shoot through duty ratio’ is evaluated. The voltage gain values, boost factor, modulation index, voltage across the capacitor and stress voltage are calculated. Characteristics between those parameters are also drawn and investigated. For variable wind speed, the buck-boost voltage at load side can be derived by changing modulation index value and ‘shoot through duty ratio’ which is further investigated in detail.

II. Z SOURCE INVERTER

Simulation model of the suggested system is depicted in Figure 2. The method has an impedance circuit, constructed...
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Using two capacitors and two inductors i.e., \( C_{1Z}, C_{2Z}, L_{1Z} \) and \( L_{2Z} \). This impedance circuit appears nearby DC and it connects the DC source with inverter. The conventional VSI has two zero states and six active states. However, the impedance-source inverters have one extra zero state. It is also known as ‘shoot through state’ vector. Through this condition, the output ports are short circuited through together upper switch and lower switch of any one of the phase arm. Figure 3 depicts the equivalent circuit of the Impedance-source inverter.

\[ V_i = B_f V_{dc} \]  
\[ V_o = M_i B_f \frac{V_{dc}}{2} \]  
\[ V_C = V_{C1Z} = V_{C2Z} = \frac{T_{on}}{T_{on} T} V_{dc} \]

The DC link voltage \( V_i \) can be given in terms of voltage across capacitor as,
\[ V_{dc} = 2V_C - V_{dc} \]

Inductors ripple current can be expressed by
\[ \Delta I = \frac{V_{dc} T_{on}}{T_{on} T} \]

III.IMPROVED PWM METHOD

Nowadays, it is being given importance to reduce the voltage stress for a necessary voltage gain in the Impedance-source inverter. As described above, the voltage gain is given as the product of Modulation index and Boost factor. The figures 4 and 5 show ‘Non shoot through state’ and ‘shoot through state’ circuits of the Z-source inverter respectively. Voltage stress of the switch can be calculated using the equation \( B_f V_{dc} \). Therefore, the \( B_f \) should be minimized and \( M_i \) should be increased so as to decrease the stress voltage for a particular voltage gain. Otherwise, \( B_f \) may be increased for a particular modulation index to obtain high voltage gain. Accordingly, from the equation (2), it is conceivable to set the ‘shoot through duty ratio’ as high as conceivable. The Fig 6 shows the improved pulse width modulation method, which is similar to traditional carrier-based PWM. The important point is that this novel
and improved pulse width modulation method keeps active vectors remain unaffected and turn all zero to ‘shoot through zero states’. Thus, the peak ‘shoot through time’ \( T_{on} \) and Boost factor can attained for any \( M_i \) without affecting output waveforms.

As given in Figure 6, the circuit works in ‘shoot through state’, if the triangular carrier wave is higher than extreme reference curves\((V_a, V_b, V_c)\) or lower than smallest reference curves. The shoot through duty cycle ratio changes for each cycle. Thus, the voltage gain depends on the mean ‘shoot through duty cycle’.

One switching cycle in the period \((\pi/6, \pi/2)\) can be written by.

\[
\frac{T_{on}(\theta)}{T} = 1 - \frac{(M_i \sin \theta - M_i \sin(\theta - 2\pi/3))}{2}
\]

The mean ‘shoot through state duty cycle ratio can considered using the following expression

\[
\frac{T_{on}}{T} = \frac{\int_{\pi/6}^{\pi/2} \left( \frac{1}{M_i} \sin \theta - \frac{1}{M_i} \sin(\theta - 2\pi/3) \right) d\theta}{\pi/6} = \frac{2\pi - 5.196M_i}{2\pi} = 1 - 0.83M_i
\]

From equation (2), the Boost factor \((B_f)\) is expressed by

\[
B_f = \frac{1}{1 - \frac{T_{on}}{T}} = \frac{\pi}{5.196M_i - \pi}
\]

In this method, the voltage gain is calculated using \( M_i \) as

\[
G = M_i B_f = \frac{\pi M_i}{5.196M_i - \pi}
\]

The inverter output voltage \( V_o \) determines voltage in the capacitor. For the desired modulation index, if we get more inverter output voltage, then it results in increasing capacitor voltage \( V_c \) which leads to increased stress on the device. This analysis is shown in the Fig 7.

![Figure 7 Voltage gain (G) vs Vc, Vst](image)

![Figure 8 Boost factor vs V0, Vc and Vst](image)

IV. SIMULATION RESULTS

The above analysis can be confirmed through simulation using MATLAB/ Simulink. To simulate the circuit, the designated parameters are Input DC voltage \( V_{dc} = 220V \)and the values of Z source circuit parameters are \( L_1Z = L_2Z = 112\mu H \) and \( C_1Z = C_2Z = 1200\mu F \). Figure 10 shows the simulation results of PMSG. This voltage is converted into DC using uncontrolled rectifier as shown in figure14. Simulation was performed in PMSG at variable speed conditions from which various parameters such as rotor speed, torque and stator current wave forms are depicted in fig 15. The key purpose of the proposed work is to produce three phase ac voltage from variable speed wind. In this analysis, the modulation index \( M_i \) is equal to .612 and the shoot through state duty ratio \( T_{on}/T=0.312 \). The switching frequency was fixed as 12KHz. The shoot through state was spread consistently between all the three-phase arm to achieve corresponding frequency of 8 KHz as seen from Impedance-source circuit. Soon occasion of DC inductor L is decreased. As per the mentioned impedance source parameters assigned, the following theoretical calculations are performed.

**Boost Factor**

\[
B_f = \frac{1}{1 - 2\frac{T_{on}}{T}} = 2.659
\]

**Capacitor voltage**

\[
V_{c1} = V_{c2} = V_c = \frac{1}{1 - 2\frac{T_{on}}{T}} V_{dc} = 409V
\]
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Figure 9. Shoot through Time (Ton) vs Voltage Gain (G)

Output AC voltage
\[ V_o = M_i B f \frac{V_{dc}}{2} = 0.612 \times 2.659 \times 220 / 2 = 179V \]  
(13)

Voltage gain
\[ G = \frac{V_o}{V_{dc}/2} = \frac{179}{110} = 1.63 \]  
(14)

In the current paper, 179 V line voltages and 409 V Peak-to-Peak voltage were calculated. The above theoretical results resemble the obtained simulation results. From the above analysis, the theoretical boost factor, voltage stress, capacitor voltage, the inverter output voltage and gain for the various shoot through time are tabulated (Refer Table 1).

Table 1. Theoretical calculations of various parameters

| Working Conditions | B     | V_{st} | V_{0}  | V_{c}  | G     |
|-------------------|-------|--------|--------|--------|-------|
| Ton/T=0.31, Mi=0.88, Vdc=180 | 2.63  | 474    | 361    | 379    | 2.31  |
| Ton/T=0.32, Mi=0.98, Vdc=190 | 2.78  | 528    | 401    | 437    | 2.72  |
| Ton/T=0.33, Mi=1.08, Vdc=200 | 2.94  | 588    | 551    | 654    | 3.18  |
| Ton/T=0.34, Mi=1.18, Vdc=210 | 3.13  | 657    | 671    | 799    | 3.69  |
| Ton/T=0.35, Mi=1.28, Vdc=220 | 3.33  | 733    | 814    | 1018   | 4.27  |

Case 1:
Input DC voltage Vdc=220V, Modulation Index Mi=0.612, Shoot through duty time Period Ton=0.02598 msec, Duty ratio=0.312. With these parameters, the obtained simulation results are given below (refer Fig. 11)
- Boost factor (B_1)=2.659
- Voltage stress of the device (V_{st})=585 V
- Voltage across the capacitors (V_{c})=403 V
- Inverter output voltage(V_{0})=310 V
- Voltage gain (G)=1.63

Figure 11. Simulation output for Shoot through time (Ton)=0.025 msec

Case 2:
Input DC voltage Vdc=220V, Modulation Index Mi=0.612, the shoot through duty time Period Ton=0.02848 msec, Duty ratio=0.342. With these parameters, the obtained simulation results are given below (Refer Fig. 12)
- Boost factor (B_2)=3.165
- Voltage stress of the device (V_{st})=696 V
- Voltage across the capacitors (V_{c})=458 V
- Inverter output voltage(V_{0})=369 V
- Voltage gain (G)=1.94

Figure 10. PMSG three phase output voltage
Case 3:
Input DC voltage $V_{dc}=220\text{V}$,
Modulation Index $M_i=0.612$,
Shoot through duty time Period $T_{on}=0.02932\ \text{m sec}$,
Duty ratio=0.352.
With these factors, the obtained results of simulation are given in Fig 13

- Boost factor ($B_f$)=3.165
- Voltage stress of the device ($V_{st}$)=743V
- Voltage across the capacitors ($V_c$)=482V
- Inverter output voltage ($V_0$)=389 V
- Voltage gain ($G$)=2.07
V. CONCLUSION
An improved PWM Method has been implemented in the proposed Impedance-source inverter-based PMSG WECS, to generate maximum voltage. PMSG generates ac voltage. However, owing to the existence of Impedance-source network, it is conceivable to achieve the desired boosted AC voltage output. In this novel method of varying ‘shoot through time’, various parameters such as voltage across capacitor, device voltage stress and inverter voltage are analyzed in detail. The correlation between the Boost factor and ‘shoot through duty ratio’ is explained through graphical representation and necessary equations.

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