5. ZSI BASED WIND POWER CONVERSION SYSTEMS - Simulation results and discussion

5.1. Introduction

The purpose of designing closed-loop controllers is to achieve better output voltage tracking and disturbance rejection. Control variables are changed continuously with the variations in wind conversion system inputs and outputs. This chapter presents the study of the closed loop system with the controllers. The Z-source inverter operates as a buck-boost converter by having variable inverter modulation index (M) and boost factor (B) associated with the z-source impedance network. However both the control parameters depends on each other to a certain extent as change in one parameter imposes a limitation on the changeability of the other due to the insertion of shoot-through inside the null period. This makes controlling little difficult. However it is simplified with setting maximum limit on control variables.

In this work formation of an inner loop through sensing of the voltage across the capacitor of impedance network is done and measured signal is fed-forward via PI controller. For simplicity capacitor voltage is only considered as the system variable and the shoot-through duty cycle rather boost factor is controlled accordingly. PI controller is used to remove the steady state error and to get good reference tracking and disturbance rejection. The load current variation also can be considered as a disturbance and can be compensated for. System configurations, designing through MATLAB-SIMULINK and corresponding results employing different topology z-source inverters are presented here for advanced power conditioning of wind energy systems.

5.2. Closed loop control of zsi

The Figure 5.1 represents the proposed closed loop control of Z-Source inverter used for variable speed permanent magnet synchronous generator wind power conversion. The wind turbine is directly coupled with non-salient pole permanent magnet synchronous generator. The power capture at the wide range of wind velocity is converted to DC output power by synchronous machine and rectifier. It is fed to Z-Source inverter[2]. Under variable-speed
operation, the Z-Source inverter in the system plays an important role transferring the PMSG output power in the form of variable voltage and variable frequency to the fixed voltage fixed frequency. The voltage across the capacitor is directly proportional to the input variation. It is sensed by a voltage sensor and fed to a PID controller. The processed output is compared with a high frequency triangular signal to generate shoot through pulses. It is ORed with six third harmonic injected sine PWM pulses and finally fed to VSI. The filtered three phase output is connected to load. The decrease in wind speed is compensated by increase in shoot through duty ratio to produce the desired output voltage. The increase of wind speed is associated with the corresponding reduction of the shoot through duty ratio for constant 440 V output line voltage. The simulation parameters are presented in Table 5.8

Figure 5.1 Block diagram of the closed loop system

Figure 5.2 represents the simulink model developed for simple z-source inverter based closed loop system.

Figure 5.3 represents the PID Control section.

Abbreviation used in the circuit is

\( V_c \) = Capacitor voltage

\( V_{carrier} \) = High frequency triangular wave.

ss_up, = PID output
Figure 5.2 ZSI Closed loop simulink model for dynamic analysis
Table 5.1 Simulation Parameters for ZSI based system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three phase output line voltage across variation of PMSG</td>
<td>250-190-250 V</td>
</tr>
<tr>
<td>DC input voltage across Z network</td>
<td>340-260-340 V</td>
</tr>
<tr>
<td>L1=L2</td>
<td>1.5mH</td>
</tr>
<tr>
<td>C1=C2</td>
<td>1100uF</td>
</tr>
<tr>
<td>IGBT internal and Snubber resistance</td>
<td>1Mohm,100Kohm</td>
</tr>
<tr>
<td>Delta connected 3-phase load</td>
<td>Active power =4021.87 Watt</td>
</tr>
<tr>
<td>Triangular frequency</td>
<td>10KHz</td>
</tr>
<tr>
<td>Sine wave frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>PID tuning parameters</td>
<td>$K_p=1$, $K_i=0.005$, $K_d=0.0001$, Time constant for Derivative=0.001, *set point=0.03</td>
</tr>
<tr>
<td>Filter Inductors and capacitors</td>
<td>25mH,20uF</td>
</tr>
<tr>
<td>Three phase output line voltage</td>
<td>440V rms</td>
</tr>
</tbody>
</table>

*The set value 0.03 is achieved by manual tuning.

Figure 5.3 represents the PID Controller section. The capacitor voltage is condensed by multiplying with gain k. It is then subtracted from the set point and fed to the PID controller.

![PID Controller section](image)

Figure 5.4 and Figure 5.5 represents the PWM and shoot through pulse section. $V_{a1}$, $V_{b1}$ and $V_{c1}$ are three sinusoidal reference signals having peak amplitude 1 volt and frequency 50
Hz. These are injected with three more sinusoidal signals $V_{a2}, V_{b2}$ and $V_{c2}$ having three times frequency and amplitude $16\%$ of the fundamental waves. These results third harmonic injected sine waves as shown in Figure 5.6. These are compared with high frequency triangular wave to generate PWM pulses as shown in Figure 5.7. These are complemented and to generate another set of pwm pulses. These pwm pulses are ORed with shoot through pulses to generate $S_1$ to $S_6$ pulses for the IGBT.

Figure 5.4 PWM and Shoot through pulse Blocks

Figure 5.5 Circuit model for Switching pulse generation
The simulink model developed is first tested with steady state variable generator voltage. For simplicity single phase variable source is initially connected as generator output and the closed loop performance is verified. Table 5.2 presents the results. It shows excellent power conditioning and boosting capabilities at different level inputs. The traditional PWM inverter having same modulation index could not supply voltage at these levels.

Table 5.3 calculates the efficiency of the system for its mean values of parameters. In the next phase the simulink model is studied under dynamic states. The three phase generated voltage is suddenly applied sag and surge separately. Figure 5.9 represents the output voltage generated from permanent magnet synchronous generator under sag condition which applied voltage level changes from 250 vrms to 190 vrms the system is fed to the three phase bridge rectifier. Figure 5.10 represents the three phase output voltage from the closed loop control system of the Z-Source inverter. Figure 5.11 and Figure 5.12 represents the corresponding change in the capacitor voltage and inductor current due to input variation. It is clear from the figure that during the sag period capacitor voltage decreases as well as inductor current increases to supply the shoot through current as well as shoot through duty ratio increases to boost the output voltage to the desired level.

Figure 5.6 Third harmonic injected sine wave
CHAPTER 5, ZSI BASED WIND POWER CONVERSION SYSTEMS—simulation results and discussion

Figure 5.7 THI Sine wave compared with triangular signal (Top) output pwm pulse (bottom)

Figure 5.8 PWM Pulses (Pink) ORed with shoot through pulses (yellow in bottom) and resultant pulse (top)

Table 5.2 Comparison between Proposed and Traditional Inverter

<table>
<thead>
<tr>
<th>Wind Generator output single phase voltage (volt rms)</th>
<th>Three phase output line voltage of proposed system ($V_{out}$)</th>
<th>With traditional PWM Inverter $V_{line}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>185</td>
<td>407</td>
<td>72</td>
</tr>
<tr>
<td>190</td>
<td>408</td>
<td>74</td>
</tr>
<tr>
<td>200</td>
<td>408</td>
<td>78</td>
</tr>
</tbody>
</table>
Table 5.3 Efficiency of the ZSI closed loop system

<table>
<thead>
<tr>
<th>Mean output of rectifier</th>
<th>Mean DC input current</th>
<th>Input power (Watt)</th>
<th>Three phase output line voltage (RMS)</th>
<th>Output line current (RMS)</th>
<th>Load power factor</th>
<th>Output power</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>283V</td>
<td>18.29A</td>
<td>5176</td>
<td>440 V</td>
<td>3.864 A</td>
<td>0.97</td>
<td>2856watt</td>
<td>55.2</td>
</tr>
</tbody>
</table>
The same simulink circuit is run for surge voltage from 190 to 250 volt. Figure 5.13 represents the three phase input surge voltage across the permanent magnet synchronous generator. Figure 5.14 represents the three phase constant line output voltage. Figure 5.15 and Figure 5.16 represents the capacitor voltage and inductor current. It is clear from the figure that during the surge period capacitor voltage increases and the inductor current decreases to buck the output voltage to the desired level as well as shoot through duty ratio decreases.
CHAPTER 5, ZSI BASED WIND POWER CONVERSION SYSTEMS - simulation results and discussion

Figure 5.13 Input Voltage (Surge Condition)

Figure 5.14 Output Voltage

Figure 5.15 Capacitor Voltage

Figure 5.16 Inductor Current
The transfer function of the system is obtained by control design liner analysis tools in MATLAB and is found to be a stable system.

\[
T(s) = \frac{4.38 \times 10^{-19} (s+3.323 \times 10^6)(s-0.229)(s^2+76.88s+2.532 \times 10^9)(s^2+5.49 \times 10^5s+2.41 \times 10^{12})}{(s+3.5)(s+1.82)(s^2+262.2s+5 \times 10^6)(s^2+102.3s+2.53 \times 10^{-9})}
\]

\[
T(s) = \frac{-5.002 \times 10^{-7} (s+1436)(s+778.5)(s-778.5)}{(s^2+1.997 \times 10^6s+3.998 \times 10^{12})}
\]

\[
T(s) = \frac{1430(s^2+41.17s+6.126 \times 10^5)(s^2+1359s+1.988 \times 10^5)}{(s^2+1.997 \times 10^6s+3.998 \times 10^{12})}
\]

All the poles of the transfer function \( T(s) \) lie in the left half of the s-plane hence the closed loop system is found to be a stable system. The transient stability analysis of the system is observed by the step response shown in Figure 5.17 also supports that. FFT analysis of the output voltage is presented in Figure 5.18.

![Figure 5.17 Step response of the closed loop system](image1)

![Figure 5.18 FFT analysis of the output voltage without filter](image2)
5.3. Closed loop control of Quasi-Zsource inverter

A control system for quasi (z)-source inverter [54] is designed for wind power conversion. The variable three phase ac output of wind generator due to unpredictable variation in wind speed is suitably controlled through a closed loop system employing the buck-boost capability of quasi impedance source inverter. The quasi ZSI PWM inverter replacing the conventional PWM inverter provides the unique output voltage regulation by making an appropriate choice of boost factor under both variable generator voltage and variable load conditions. The closed loop controller carefully monitors the wind generator voltage and controls the shoot-through and non-shoot through duty cycles of the inverter to develop a three phase steady boosting voltage, which is not possible by conventional PWM control. The whole system is designed and verified through simulation. The system is simulated under arbitrary generator output condition both in surge and sag states and results steady three phase voltages across load. Similar steady output is also observed in case of variable load condition. The proposed closed loop system, therefore, can be used for smooth and effective dynamic and steady state control maintaining the level of three phase output at a desired level. The variable AC power from the generator is rectified first into DC and then is regulated for constant voltage by using dc to dc converter. The constant DC output then is fed to the load at the required level of voltage and frequency employing a PWM inverter.

The major requirement in this wind energy system is to realize and maintain consistently a constant voltage at the load terminal using minimum amount of circuitry. The focus in this section is to employ quasi impedance source inverter in place of conventional system and converting the variable voltage variable frequency supply to a three phase regulated supply through a simple closed loop control. The buck-boost capabilities of impedance source inverter are expected to take care both the generator output voltage and load variations. A number of switching methods have been proposed so far to control Z-source inverter shoot-through and non-shoot through states. The methods include the sinusoidal PWM simple boost control, maximum boost control and maximum constant boost control method. For the proposed closed loop control Third harmonic injected MCBC switching technique is used which is discussed in detail in chapter -5. This controller is used to regulate and boost the generator voltage to deliver quality stable power to the three phase R-L load. The control loop compares the voltage of capacitor C2 of the quasi z-network to a set value and the error is fed to the PID controller to create a reference signal. This reference signal is then compared with a 10 kHz frequency triangular pulse and generates shoot-through pulse. The lower the reference signal amplitude the higher the shoot-through duty cycle as well as
the boost factor. Same triangular pulse is used to generate the Third harmonic injected sine PWM signals for bridge inverter. Finally, the set of PWM pulses is OR-ed with the shoot through pulse and sent to the six switches of the inverter.

![Block diagram of QZSI closed loop system](image)

**Figure 5.19** Block diagram of QZSI closed loop system

**Table 5.4 Simulation parameters for QZSI**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation in DC input voltage across Z network</td>
<td>340-260-340 V</td>
</tr>
<tr>
<td>L1=L2</td>
<td>0.79mH</td>
</tr>
<tr>
<td>C1=C2</td>
<td>0.5uF</td>
</tr>
<tr>
<td>IGBT internal and Snubber resistance</td>
<td>1mohm,100Kohm</td>
</tr>
<tr>
<td>Modulation index</td>
<td>0.9</td>
</tr>
<tr>
<td>Delta connected 3-phase load</td>
<td>Active power =4021.87 Watt</td>
</tr>
<tr>
<td>Triangular frequency</td>
<td>10KHz</td>
</tr>
<tr>
<td>Sine wave frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>PID tuning parameters</td>
<td>$K_p=0.00899$, $K_i=20$, $K_d=0.001$, TIME constant for Derivative=10000, set point=9.94</td>
</tr>
<tr>
<td>Filter Inductors and capacitors</td>
<td>40mH,10uF</td>
</tr>
<tr>
<td>Three phase output line voltage</td>
<td>440 V rms</td>
</tr>
</tbody>
</table>
Figure 5.20 QZSI closed loop system with THI SIN PWM
Closed loop analysis of the simulated system.

The transfer function of the system is obtained by control design linear analysis tools in MATLAB and is found to be a stable system.

\[
T(s) = \frac{-5.0022 \times 10^{-7}(s + 1436)(s + 778.5)(s - 778.5)(s^2 + 1.997 \times 10^6s + 3.998 \times 10^{12})}{(s + 1430)(s^2 + 41.17s + 6.126 \times 10^5)(s^2 + 1359s + 1.988 \times 10^6)}
\]

All the poles of the transfer function \(T(s)\) lie in the left half of the s-plane hence the closed loop system is found to be a stable system. The transient stability analysis of the system is observed by the step response shown in Figure 5.21 also supports that.

![Step Response](image)

Figure 5.21 Step response of the simulated system

Figure 5.22 presents the FFT of output voltage. Figure 5.23 represents a particular phase of wind generator sag voltage. Figure 5.24 represents the regulated three phase output line voltage obtained through simulation. Figure 5.25 and Figure 5.26 represents the corresponding capacitor voltage and output current respectively.
Figure 5.22 Output voltage FFT (without filter)

Figure 5.23 Wind Generator sag voltage (One phase)

Figure 5.24 Output Voltage (Three phase)

Figure 5.25 Voltage across capacitor
The same simulink model with same parameters is tested for input surge condition. Figure 5.27 represents the one phase of wind generator surge voltage. Figure 5.28 represents the regulated three phase output voltage. Figure 5.29 and Figure 5.30 represents corresponding change in the voltage across the capacitor C2 and output current respectively.
To verify the steady state performance, the proposed system is run with a set of different discrete values of generator single phase voltages. Table 5.5 represents the corresponding values of output (load) line to line voltages that show almost regulated and steady. The table also contains the corresponding output voltage which could be obtained in case of a traditional single phase to three phase PWM converter with same modulation index and other parameters. It proves the boosting capability of the proposed system. Another set of
simulation is carried out with steady generator voltage but under variable load condition. It also shows regulation. The corresponding results are shown in Table 5.6.

5.1. Closed Loop control of TRANS Q-ZSI

A control system for the Trans-quasi (z)-source inverter[56] is designed for wind power conversion. The variable three phase ac output of wind generator due to unpredictable variation in wind speed is suitably controlled through a closed loop system employing the buck-boost capability of trans-quasi Z-source inverter. The closed loop controller carefully monitors the wind generator voltage and controls the shoot-through and non-shoot through duty cycles of the inverter to develop a three phase steady boosting voltage across the load as shown in Figure 5.34. The system is simulated under arbitrary generator output condition both in surge and sag states.

Table 5.5 Output under variable input condition

<table>
<thead>
<tr>
<th>Wind Generator Output</th>
<th>Three phase output with the proposed system</th>
<th>With Traditional PWM inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single phase (volt)</td>
<td>Vline (volt)</td>
<td>Vline (volt)</td>
</tr>
<tr>
<td>288.79</td>
<td>445.5</td>
<td>204.36</td>
</tr>
<tr>
<td>300.00</td>
<td>446.4</td>
<td>212.22</td>
</tr>
<tr>
<td>311.00</td>
<td>447.1</td>
<td>220.08</td>
</tr>
<tr>
<td>322.11</td>
<td>447.2</td>
<td>227.94</td>
</tr>
<tr>
<td>333.00</td>
<td>446.5</td>
<td>235.80</td>
</tr>
<tr>
<td>344.00</td>
<td>446.4</td>
<td>243.67</td>
</tr>
<tr>
<td>355.50</td>
<td>446.2</td>
<td>223.28</td>
</tr>
<tr>
<td>366.54</td>
<td>445.2</td>
<td>259.38</td>
</tr>
<tr>
<td>377.64</td>
<td>445.0</td>
<td>267.24</td>
</tr>
</tbody>
</table>

Table 5.6 Output variation under variable load condition (for Constant generator voltage)

<table>
<thead>
<tr>
<th>R-L Load Star per phase</th>
<th>Three phase output with the proposed system</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{\text{line}}$ (volt)</td>
<td>$I_{\text{line}}$ (amp)</td>
</tr>
<tr>
<td>5021.87 watt</td>
<td>439.0</td>
<td>8.82</td>
</tr>
<tr>
<td>4021.87 watt</td>
<td>444.9</td>
<td>0.72</td>
</tr>
<tr>
<td>502.87 watt</td>
<td>448.3</td>
<td>0.90</td>
</tr>
<tr>
<td>3021.87 watt</td>
<td>450.8</td>
<td>5.45</td>
</tr>
<tr>
<td>402.87 watt</td>
<td>445.0</td>
<td>7.15</td>
</tr>
<tr>
<td>302.87 watt</td>
<td>444.4</td>
<td>0.54</td>
</tr>
<tr>
<td>302.87 watt+400VAR</td>
<td>438</td>
<td>2.38</td>
</tr>
<tr>
<td>302.87 watt+500VAR</td>
<td>435</td>
<td>2.41</td>
</tr>
</tbody>
</table>
The proposed closed loop system, therefore, can be used for smooth and effective dynamic and steady state control maintaining the level of three phase output at a desired level. The variable AC power from the generator is rectified first into DC and then is regulated for constant voltage by using dc to dc converter. The constant DC output then is fed to the Trans –quasi Z-network. The buck-boost capabilities of impedance source inverter are expected to take care both the generator output voltage and load variations. The control loop compares the voltage of capacitor C2 of the trans quasi z-network to a set value and the error is fed to the PID controller to create a reference signal proportional to the input. It is then compared with a 10 kHz frequency triangular pulse to generate shoot-through pulse. The lower the reference signal amplitude the higher the shoot-through duty cycle as well as the boost factor. Same triangular pulse is used to generate the third harmonic injected sine PWM signals for bridge inverter. Finally, the set of PWM pulses is OR-ed with the shoot through pulse and sent to the six switches of the inverter. Figure 5.35 represents the three phase load current for both the sag and surge condition. Figure 5.36 represents the capacitor voltage for input surge condition. It is clear from the figure that during the surge condition the capacitor voltage is also increases to decrease the shoot through duty cycle which reflected the steady output voltage across the load. FFT analysis of output voltage without filter is represented in Figure 5.37.

![Figure 5.31 Block Diagram of T-Quasi closed loop system](image.png)
Figure 5.32 Simulink model of the quasi-ZSI Sag and Surge condition
### Table 5.7 Simulation parameters for T-QZSI Sag and Surge condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variation of DC input voltage across Z network</td>
<td>380-260-380-260</td>
</tr>
<tr>
<td>L1=L2</td>
<td>0.02uH</td>
</tr>
<tr>
<td>Turns ratio</td>
<td>2</td>
</tr>
<tr>
<td>Magnetising resistance and inductance</td>
<td>0.001 Ohm, 207 uH</td>
</tr>
<tr>
<td>C1</td>
<td>50uF</td>
</tr>
<tr>
<td>IGBT internal and Snubber resistance</td>
<td>1 mohm, 100Kohm</td>
</tr>
<tr>
<td>Delta connected 3-phase load</td>
<td>Active power = 4021.87 Watt</td>
</tr>
<tr>
<td>Triangular frequency</td>
<td>10KHz</td>
</tr>
<tr>
<td>Sine wave frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Modulation index</td>
<td>0.9</td>
</tr>
<tr>
<td>PID tuning parameters</td>
<td>$K_p=1.23, K_i=0.002, K_d=0.01$, time constant for Derivative = 3, set point = 0.6</td>
</tr>
<tr>
<td>Filter Inductors and capacitors</td>
<td>105 mH, 60uF</td>
</tr>
</tbody>
</table>

Figure 5.33 Three phase Input Voltage (Surge Condition)

Figure 5.34 Output Voltage (Three phase)
CHAPTER 5, ZSI BASED WIND POWER CONVERSION SYSTEMS - simulation results and discussion

Figure 5.35 Load Current (Three phase)

Figure 5.36 Voltage across capacitor C1

Figure 5.37 Output voltage FFT without filter
5.2. Study on proposed Z-Source ac-ac converter as voltage regulator system.

This section proposes a new type of voltage regulator based on single-phase z-source converter that compensates wide range voltage variations. It is not only capable of compensating variations at a much higher bandwidth but also boost the voltage level even twice that of input supply. In this section, a single phase voltage-fed z-source ac–ac power converter is presented with a different kind of switch topology. The converter is fitted with a simple feed-forward controller which will run the converter as a perfect voltage regulator under wide range input variable condition. High frequency switching of two set of bi-directional switches through proper control of duty ratio provides the variable boost factor and hence the required stable single phase ac voltage.

![Block diagram of the proposed Z-Source ac-ac converter and bidirectional switches](image)

Figure 5.38 Block diagram of the proposed Z-Source ac-ac converter and bidirectional switches

Figure 5.38 shows the overall proposed closed loop system based on single-phase z-source ac-ac converter. It consists of the AC input, a z-network, two bi-directional switches, filter and a control circuit. The load is chosen as an R–L load. The symmetrical z-network, a combination of two inductors and two capacitors is the main elements here which store or release energy accordingly to drive the circuit as a perfect regulator.
The control circuit after getting the sense of input voltage condition generates PWM signal for the two switches. The higher value of switching frequency of PWM signal is selected to keep the value of inductor and capacitor of z-source network low. S1 and S2 are the bi-directional switches which are able to block voltage and to conduct current in both directions. These two switches are turned on and off in complement. That means if switch S2 is turned on with duty cycle D, the S1 is turned on with duty cycle \(1-D\). Here, a bi-directional switch is realized as a set of two IGBTs connected in common emitter mode back to back with two diodes as shown in Figure 5.38. The diodes are included to provide the reverse blocking capability. The filter is a common L–C filter, used to filter out the high frequency components from the output voltage.

### 5.2.1. Working principle of ac-ac Z-Source converter

Now, to explain the operation of the open loop z-source converter, two states exist in this circuit. Figure 5.40 is the equivalent circuit models during the two states. Considering the inductors and capacitors of the z-network identical as L and C respectively, the network becomes symmetrical. In state 1, the bi-directional switch S1 is turned on and S2 turned off. The ac source charges the z-network capacitors and energy is transferred to the load by the
inductors. The interval of the converter operating in this state is \((1 - D)T\), where \(D\) is the duty ratio of switch \(S2\), and \(T\) is the switching cycle.

![Diagram of state 1 and state 2](image)

Figure 5.40 State 1 \(S1\) on (LHS figure) and \(S2\) off, State 2 \(S1\) off and \(S2\) on (RHS figure)

As a result, one has

\[
v_c = v_i - v_L \quad v_o = v_i - 2v_L
\]  

Equation (5.1)

\(v_c\) and \(v_L\) are the instantaneous voltages across \(C\) and \(L\) respectively. \(v_i\) and \(v_o\) are inputs and output voltages. In case of state 2, the bi-directional switch \(S2\) is turned on and \(S1\) is turned off. The \(Z\)-network capacitors discharge, while the inductors charge and store energy. The interval of the converter operating in this state is \(DT\). This relation is plotted as Figure 5.41 getting the simulation results in open circuit condition.

We may write

\[
v_c = v_L \quad v_o = 0
\]  

Equation (5.2)

Now, considering the average voltage of the inductors over one period in steady state zero, from (5.1) and (5.2) we have

\[
V_L = \bar{v}_L = \int [v_c \cdot DT + (v_i - v_c) \cdot (1-D)T] \, dt = 0
\]  

Equation (5.3)

\[
\frac{V_c}{V_i} = \left| \frac{1-D}{1-2D} \right|
\]  

Equation (5.4)
Assuming the filter and z-network inductors very small and no line frequency voltage drop across the inductor, the voltage across the load should equal $V_c$, the voltage across the capacitor of the z-network, that is

$$V_o = \frac{1 - D}{1 - 2D} V_i \quad (5.5)$$

From the (5.5) it is clear that, by controlling the duty ratio $D$, the output voltage of the converter can be bucked or boosted. This relation is plotted in open circuit condition in

Now from Figure 5.42 Pulse width modulated signal generation

From (5.5) the duty cycle can be expressed as a function of gain as

$$D = \frac{G - 1}{2G - 1} \quad (5.6)$$

For the generation of PWM signal, a triangular signal and dc signal comparison method is applied. Now from the property of similarity between the two triangles from the Figure 5.42, we get
\[
\frac{h}{T} = \frac{h - v_{dc}}{t_{on}} \quad \text{so} \quad v_{dc} = 1 - \frac{t_{on}}{T}
\]  

(5.7)

As the height of the DC signal is chosen as unity.

\[ v_{dc} = 1 - D \]  

(5.8)

So, in the proposed system shown in Figure 5.38, the input voltage rms value is sensed through a voltage sensor. The desired output voltage rms value is the set value here, which is divided by the input voltage to calculate the instantaneous value of gain. With the help of simple mathematical blocks, the value of \( v_{dc} \) is calculated which is then sent to comparator to generate the corresponding PWM output. The PWM output is fed to bi-directional switch S2 directly and the complement of the signal to switch S1.

Table 5.8 Performance of ac-ac Z-source inverter at variable input condition

<table>
<thead>
<tr>
<th>( V_{in} ) (rms)</th>
<th>( V_{out} ) (rms)</th>
<th>( I_{in} ) (rms)</th>
<th>( I_{out} ) (rms)</th>
<th>Gain</th>
<th>( V_{dc} ) (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>315.6</td>
<td>6.52</td>
<td>.507</td>
<td>1.99</td>
<td>.667</td>
</tr>
<tr>
<td>180</td>
<td>309.3</td>
<td>5.76</td>
<td>.511</td>
<td>1.72</td>
<td>.696</td>
</tr>
<tr>
<td>190</td>
<td>312</td>
<td>5.59</td>
<td>.488</td>
<td>1.67</td>
<td>.712</td>
</tr>
<tr>
<td>220</td>
<td>317.8</td>
<td>4.88</td>
<td>.476</td>
<td>1.44</td>
<td>.764</td>
</tr>
<tr>
<td>230</td>
<td>314.7</td>
<td>4.47</td>
<td>.480</td>
<td>1.38</td>
<td>.782</td>
</tr>
<tr>
<td>240</td>
<td>312.8</td>
<td>4.07</td>
<td>.478</td>
<td>1.32</td>
<td>.802</td>
</tr>
<tr>
<td>250</td>
<td>318</td>
<td>3.95</td>
<td>.484</td>
<td>1.27</td>
<td>.822</td>
</tr>
<tr>
<td>260</td>
<td>317.8</td>
<td>3.54</td>
<td>.476</td>
<td>1.22</td>
<td>.844</td>
</tr>
</tbody>
</table>

Figure 5.43 Variation of output voltage with Input voltage of the converter
5.2.2. Results and discussion

The new single phase ac-ac regulator has the capability to buck/boost voltage it is used to overcome voltage sag or voltage rise across the source. Simulation is carried out based on the proposed control system. The z-source network is selected after optimization with the value of C=5 uF, L=800 uH. A R-L type load is selected with R=1 Kohm and L=500mH for the simulation. The filter parameters are selected as L=10 mH and C=3 uF. The frequency of the PWM switching signal is chosen as 12 KHz. A set of discrete input voltage is selected over a wide range 160 volt to 260 volt as presented in Table 5.8 Performance of ac-ac Z-source inverter at variable input condition. The feed-forward system automatically selects the value of gain and accordingly the value of \( V_{dc} \). This modulates the width of pulses applied to two switches. The set of data calculated from different runs are tabulated in Table 1.9. In the results, it is observed that the variation of output voltage is only less than 9 volt which is about 1.3% with reference to base value 314 volt. It is not only providing almost steady output voltage but also providing necessary voltage boosting ranging from 1.22 to 1.99. An output voltage graph is plotted based on input voltage variations and shown in Figure 5.43.

In a second stage of simulation work, input line voltage is suddenly varied and the output voltage and current are recorded. First a 60% voltage sag is applied at steady running condition from 260 volt rms to 100 volt rms and then 60% surge is applied over the steady voltages from 260 volt rms to 420 volt rms. The output voltage waveforms are recorded and it shows a steady value except some small transients during change over instants in both the cases.

The two results separately shown in Figure 5.44 and Figure 5.45 also contain the input current waveforms, which clearly show the mechanism behind the steady regulated output voltage at different input voltage variation. Though most of the time it is operated under boost mode, its operating mode can be easily changed between buck and boost when needed. The input currents in both the cases contain high frequency harmonics which is measured as total harmonic distortion (THD) around 1.76% (which is below the acceptable level of < 5% under IEEE Standard).

Figure 5.46 is also presented, where the output voltage waveforms without and with filter are shown. High frequency harmonics are removed with the help of the LC filter.
CHAPTER 5, ZSI BASED WIND POWER CONVERSION SYSTEMS—simulation results and discussion

Figure 5.44 Waveforms during input voltage sag condition (a) Input voltage (b) Output voltage and (c) Input current

Figure 5.45 Waveforms during Input voltage surge condition (a) Input voltage (b) Output voltage and (c) Input current
5.2.1. Conclusion

In this section a new single-phase PWM z-source ac-ac converter system with a simplistic approach to closed-loop feed-forward control is proposed. The proposed single-phase ac-ac z-source converter can keep the output voltage steady by operating at boost mode. It has the capability to overcome the voltage sag or voltage surge in the power line.

![Output voltage waveform without and with filter](image)

Figure 5.46 Output voltage waveform without and with filter

This work has shown that ac-ac converter performs well during the voltage fluctuation. Operating principle, steady-state and transient analysis of the system was presented. To verify the proposed system, the simulations were implemented to compensate voltage variation over 100 volts in steady state as well as 60% voltage sag and 60% voltage surge in transient condition. For future work, hardware implementation with simple microcontroller based control will help establish this approach to voltage regulation as a viable solution.

5.3. Proposed system with three phase Z-Source ac-ac converter

This section proposes a new type of voltage regulator as shown in Figure 5.47 based on three-phase z-source converter that compensates wide range voltage variations. It has the facility of boosting the input voltage without using transformer.
It becomes a solid state transformer with variable turns ratio. The converter is fitted with a simple feed-forward controller which will run the converter as a perfect ac regulator under input variable condition. High frequency switching of two set of bi-directional switches through proper control of duty ratio provides the variable boost factor and hence the required stable three phase ac voltage. Three phase ac-ac z-source converter is presented only in [78].

Figure 5.47 Circuit topology of three phase ac-ac Z-Source inverter

Figure 5.48 Block diagram of the proposed three phase Z-Source ac-ac converter based system
Figure 5.48 shows the overall proposed closed loop system based on three phase z-source ac-ac converter. It consists of the three phase AC input, three inductors, three conductors, six bi-directional switches, filter and a control circuit. The load is chosen as three phase R–L load. The z-network components a combination of three inductors and three capacitors are the main elements here which store or release energy accordingly to drive the circuit as a perfect regulator. The control circuit after getting the sense of input voltage condition generates PWM signal for the six switches. Three switches S1-S3 are connected in series to the three phase source and the other three bidirectional switches S4-S6 are connected in parallel to the three phase load. The higher value of switching frequency of PWM signal is selected to keep the value of inductor and capacitor of z-source network low. Here, a bi-directional switch is realized as a set of two IGBTs connected in common emitter mode back to back with two diodes as shown in Figure 5.38. The switches are able to block voltage and to conduct current in both directions. These series and parallel switches are turned on and off in complement to each other. That means if switch S1 is turned on with duty cycle D, the S4 is turned on with duty cycle (1-D). The diodes are included to provide the reverse blocking capability. The filter is a common L–C filter, used to filter out the high frequency components from the output voltage.
5.3.1. Working principle of three phase ac-ac Z-Source converter

Now, to explain the operation of the open loop z-source converter, two states exist in this circuit. Figure 5.50 is the equivalent circuit models during the shoot through states. Figure represents the non shoot through state equivalent circuit. In non shoot through state the bi-directional switches S1, S2, S3 are turned on and S4, S5, S6 are turned off as shown in Figure 5.50. The ac source charges the z-network capacitors and as well as energy is transferred to the load by the inductor. The inductors also release the stored energy at the same time. The interval of the converter operating in this state is \((1 - D)T\), where \(D\) is the duty ratio of switch S4, S5, S6 and T is the switching cycle. Figure 5.50 represents the shoot through state of the z-source converter. Here the electrostatic energy of the capacitor is stored in the inductor which is utilised to boost the output voltage in the non shoot through state.

To find the transfer function of the open loop system under different duty cycle.

Let the three phase line voltage of the system be

\[
\begin{bmatrix}
V_{ab} \\
V_{bc} \\
V_{ca}
\end{bmatrix} = V_i \begin{bmatrix}
\sin(\omega t) \\
\sin(\omega t - 120) \\
\sin(\omega t + 120)
\end{bmatrix}
\]

(5.9)
Voltage across the inductors

\[
\begin{bmatrix}
V_{L1} \\
V_{L2} \\
V_{L3}
\end{bmatrix} = \omega L \begin{bmatrix}
\sin(\omega t + \theta_L) \\
\sin(\omega t + \theta_L - 120) \\
\sin(\omega t + \theta_L + 120)
\end{bmatrix}
\]  
(5.10)

Voltage across the capacitors

\[
\begin{bmatrix}
V_{C1} \\
V_{C2} \\
V_{C3}
\end{bmatrix} = V_c \begin{bmatrix}
\sin(\omega t + \theta_C) \\
\sin(\omega t + \theta_C - 120) \\
\sin(\omega t + \theta_C + 120)
\end{bmatrix}
\]  
(5.11)

The output line voltages are

\[
\begin{bmatrix}
V_A \\
V_B \\
V_C
\end{bmatrix} = V_0 \begin{bmatrix}
\sin(\omega t + \theta_0) \\
\sin(\omega t + \theta_0 - 120) \\
\sin(\omega t + \theta_0 + 120)
\end{bmatrix}
\]  
(5.12)

In the shoot through state as shown in Figure 5.50 in time \( T_0 \)

In the shoot through state

\[
\begin{bmatrix}
V_{L1} \\
V_{L2} \\
V_{L3}
\end{bmatrix} = \begin{bmatrix}
V_{C1} \\
V_{C2} \\
V_{C3}
\end{bmatrix}
\]  
(5.13)

In the non shoot through state as shown in Figure 5.50 in time \( T_1 \)

\[
V_{ab} = V_{c1} - V_{L2}, \ V_{bc} = V_{c2} - V_{L3}, \ V_{ca} = V_{c3} - V_{L1}
\]

And

\[
V_{AB} = V_{c1} - V_{L1}, \ V_{AC} = V_{c2} - V_{L2}, \ V_{CA} = V_{c3} - V_{L3}
\]  
(5.14)

Capacitor and inductor voltages represented in matrix form

\[
\begin{bmatrix}
V_{ab} \\
V_{bc} \\
V_{ca}
\end{bmatrix} = \begin{bmatrix}
V_{c1} \\
V_{c2} \\
V_{c3}
\end{bmatrix} - \begin{bmatrix}
V_{L1} \\
V_{L2} \\
V_{L3}
\end{bmatrix}
\]  
(5.15)

From (5.15) we may write

In the non-shoot through state

\[
\begin{bmatrix}
V_{L1} \\
V_{L2} \\
V_{L3}
\end{bmatrix} = \begin{bmatrix}
V_{c3} \\
V_{c1} \\
V_{c2}
\end{bmatrix} - \begin{bmatrix}
V_{ab} \\
V_{bc}
\end{bmatrix}
\]  
(5.16)

Now as average voltage across inductor over a complete time period \( T \) is zero so we may write. from (5.13) and (5.14)

\[
D \begin{bmatrix}
V_{c1} \\
V_{c2} \\
V_{c3}
\end{bmatrix} + (1-D) \begin{bmatrix}
V_{c3} \\
V_{c1} \\
V_{c2}
\end{bmatrix} - \begin{bmatrix}
V_{ab} \\
V_{bc}
\end{bmatrix} = 0
\]  
(5.17)

\[
DV_{c1,c2,c3} + (1-D)(V_{c3,c1,c2} - V_{ca,ab,bc}) = 0
\]

Therefore

\[
\frac{V_{c1,c2,c3}}{V_i} = \frac{(1-D)\sin(\omega t + 120)}{D\sin(\omega t) + (1-D)\sin(\omega t + 120)}
\]  
(5.18)

(neglecting the effect of network component)
Replacing sin function by the exponential one as \( \sin(\omega t) = e^{-i0} = 1, \sin(\omega t + 120) = e^{-i\cdot120} \)

We get \( \frac{V_{c1,c2,c3}}{V_i} = \frac{1-D}{\sqrt{3D^2 - 3D + 1}} \)

Assuming the filter and z-network inductors very small and no line frequency voltage drop across the inductor, the voltage across the load should equal \( V_c \), the voltage across the capacitor of the z-network, that is (5.17)

\[
\frac{V_{c1,c2,c3}}{V_i} = \frac{V_0}{V_i} = G = \frac{1-D}{\sqrt{3D^2 - 3D + 1}}
\]

To find the maximum gain of the system

\[
\frac{dG}{dD} = \frac{(3D - 1)}{(3D^2 - 3D + 1)^{\frac{1}{2}}} = 0 \quad (5.20)
\]

\[
G_{max} = 1.1547 \quad for \ D = 0.33
\]

Table 5.9 Simulation result of the open loop configuration

<table>
<thead>
<tr>
<th>Duty cycle</th>
<th>Input line voltage</th>
<th>Output line voltage</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>500 Rms</td>
<td>576.6Rms</td>
<td>1.154</td>
</tr>
</tbody>
</table>

From (5.19) duty cycle can be represented as the function of open loop gain of the system as

\[
\frac{dG}{dD} = \frac{(3D - 1)}{(3D^2 - 3D + 1)^{\frac{1}{2}}} = 0 \quad (5.21)
\]
\[
D = \frac{3G^2 - 2 \pm \sqrt{4 - 3G^2}}{6G^2 - 2}
\]  
(5.22)

The plot of open loop system gain and duty cycle is presented in Figure 5.51. For the generation of PWM signal, a triangular signal and dc signal comparison method is applied. Now from the property of similarity between the two triangles from the Figure 5.42 we get

\[
\frac{h}{T} = \frac{h - v_{dc}}{t_{on}} \quad \text{so} \quad v_{dc} = 1 - \frac{t_{on}}{T}
\]  
(5.23)

As the height of the DC signal is chosen as unity.

\[
v_{dc} = 1 - D
\]  
(5.24)

So, in the proposed system shown in Figure 5.48, the input line voltage rms value is sensed through a voltage sensor. The desired output voltage rms value is the set value here, which is divided by the input voltage to calculate the instantaneous value of gain. With the help of simple mathematical blocks, the value of \(v_{dc}\) is calculated which is then sent to comparator to generate the corresponding PWM output. The PWM output is fed to bi-directional switch S4, S5, S6 directly and the complement of the signal to switch S1, S2, and S3.

![Figure 5.51 Open loop characteristics of the ac-ac three phase Z-Source inverter](image)

Figure 5.51 Open loop characteristics of the ac-ac three phase Z-Source inverter
Table 5.10 Performance of three phase ac-ac Z-source inverter at variable input condition

<table>
<thead>
<tr>
<th>$V_{\text{in}}$ (rms) (volt)</th>
<th>$V_{\text{out}}$ (rms) (volt)</th>
<th>$I_{\text{in}}$ (rms) (Amp)</th>
<th>$I_{\text{out}}$ (rms) (Amp)</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>249</td>
<td>15.93</td>
<td>0.72</td>
<td>0.83</td>
</tr>
<tr>
<td>290</td>
<td>253</td>
<td>14.89</td>
<td>0.68</td>
<td>0.87</td>
</tr>
<tr>
<td>280</td>
<td>257</td>
<td>13.45</td>
<td>0.62</td>
<td>0.92</td>
</tr>
<tr>
<td>240</td>
<td>245</td>
<td>7.51</td>
<td>0.37</td>
<td>1.02</td>
</tr>
</tbody>
</table>

5.3.2. Results and discussion

The new three phase ac-ac regulator has the capability to buck/boost voltage. It is used to overcome voltage sag or voltage rise across the source. Simulation is carried out based on the proposed control system.

Simulation parameters

$L_1 = L_2 = L_3 = 600 \mu H$ = Three phase Z-network Inductor
$C_1 = C_2 = C_3 = 1 \mu F$ = Three phase Z-network Capacitor
$R_L = 1000 \Omega$ = Load resistance, $L_L = \text{Load inductance} = 500 mH$.
$L_f = 10 mH$ = Filter inductance
$C_f = 3 \mu F$ = Filter Capacitor

Triangular wave frequency = 5 kHz

A set of discrete input voltage is selected over a range 300 volt to 240 volt as presented in Table 5.8 Performance of ac-ac Z-source inverter at variable input condition. The feed-forward system automatically selects the value of gain and accordingly the value of $V_{dc}$. This modulates the width of pulses applied to series and parallel switches. The set of data calculated from different runs are tabulated in Table 5.8 Performance of ac-ac Z-source inverter at variable input condition. In the results, it is observed that the variation of output voltage is very less. It is not only providing almost steady output voltage but also providing necessary voltage boosting. In a second stage of simulation work, input line voltage is suddenly varied and the output voltage and current are recorded. First a 20% voltage sag is applied at steady running condition from 300 volt rms line voltage to 240 volt rms and then 20% surge is applied over the steady voltages from 300 volt rms to 360 volt rms. The output voltage waveforms are recorded and it shows a steady value except some small transients during change over instants in both the cases.
The results shown in Figure 5.53 and Figure 5.54 represents the three phase input and output voltage during sag condition. Figure 5.54 represents the zoomed output voltage during the sag condition which clearly shows the mechanism behind the steady regulated output voltage at variable input voltage variation. Though most of the time it is operated under boost mode, its operating mode can be easily changed between buck and boost when needed.

The input currents in both the cases contain high frequency harmonics which is measured as total harmonic distortion (THD) around 2.3% (which is well below the acceptable level of < 5% under IEEE Standard).
Figure 5.52 is also presented, where the output voltage waveforms without and with filter are shown. High frequency harmonics are removed with the help of the LC filter.

Figure 5.54 Boosted output voltage during the sag condition

Figure 5.55 Input phase current during Sag condition

5.3.3. Surge condition

Figure 5.56 represents the three phase input and output voltage during the input voltage surge condition. Figure 5.57 represents the corresponding output phase current.
5.3.4. Conclusion

In this section a new three-phase PWM z-source ac-ac converter system with a simplistic approach to closed-loop feed-forward control is proposed. The proposed three-phase ac-ac z-source converter can keep the output voltage steady by operating at boost mode. It has the capability to overcome the voltage sag or voltage surge in the power line. This work has shown that ac-ac converter performs well during the voltage fluctuation. Operating principle, steady-state and transient analysis of the system was presented. Proposed system is a direct ac-ac system which can be used in discrete variable voltage power system only and cannot tagged with a variable voltage variable frequency dynamic system.