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Small Scale Wind Generation System: Part II–A Novel Quasi-Z-Source Inverter and FRG-QZSI-Micro Grid Interface

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ABSTRACT

This paper proposes modelling, analysis and control of a small scale wind energy conversion system employing a direct driven Flux Reversal Generator (FRG) connected to the micro grid through a quasi-Z-source inverter (QZSI). This entire research is made up of two major parts viz., FRG and QZSI. In the part I report of this research work, the role of FRG has been thoroughly modelled and verified. In this part II, the modelling and analysis of QZSI for this purpose is presented. In addition, the modified space vector PWM (SVPWM) technique is proposed in this paper to satisfy the shoot-through characteristic of QZSI, which is a novel. The interface of FRG and QZSI to inject power in to micro grid has been finally presented. The simulation results are validated with the analytical results. Section I discusses the open loop control of QZSI. The mathematical modelling of QZSI for this purpose is given and analytically validated. This flowed by section II in which the proposed SVPWM is presented. The procedure to obtain triggering pulses using this proposed modulation technique is discussed. Section III presents closed loop control strategies for QZSI. Section IV presents the micro grid interface and power injection.

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1. SIMULATION DETAILS OF FRG WITH GRID CONNECTED DIRECT POWER CONTROLLED (DPC) QUASI Z SOURCE INVERTER

1.1. The overall working principle

Figure 1 shows the block diagram representation of the proposed small scale wind generator system using flux reversal technology connected to AC micro grid through QZSI [1], [2]. The single stage DC-AC boost happens using the QZSI, which is another major contribution in this research work. The absence of QZSI will increase the size, components, cost and weight of the main system.

QZSI has a power block and a control block associated with it. The power block of QZSI consists of wind FRG cum three phase bridge rectifier (simulated in the earlier sections), QZSI and C filter. The control block of it contain outer power loop, inner current controller, MPPT-duty ratio block, and finally modified SVPWM generator which controlled by the above three.

The whole block of QZSI starts at the filtered *abc* AC voltage. This 3-phase voltage is tapped out and converted into a $\alpha-\beta$ two phase voltage to use in $d-q$ reference at *abc*-$\alpha\beta$-dq sub block. The v_d, v_q, i_d and i_q derived out of this sub-block are taken for P_{out} and Q_{out} calculations. There are command signals at the reference of outer power loop, and these are P^*_{out} and Q^*_{out}. The obtained error signals of (

$P_{out} - P_{out}^{*}$) and ($Q_{out} - Q_{out}^{*}$) form the inner current controller block. The PI controller provides the controlled v_d^* and v_q^*. These voltages are then converted into *abc* AC voltage. This forms one of the inputs for modified SVPWM, which provides the switching pulses for the QZSI.

There is uniqueness in the proposed modified SVPWM technique. A new modulated technique is proposed at modified SVPWM for producing gate pulses to QZSI which forms the claim in this research. The modulation of the present V_{abc} at the modified SVPWM is important, which is achieved by the duty ratio '*D*' of MPPT.

These pulses are able to boost the output V_{abc} at QZSI to a high level. Consider the QZSI characteristic, shown in Figure 2. It can be seen that the output voltage goes to kV's just by training the duty cycle. However, keeping a safer operating zone, it is possible to boost the V_{abc} at QZSI to a notable higher value.

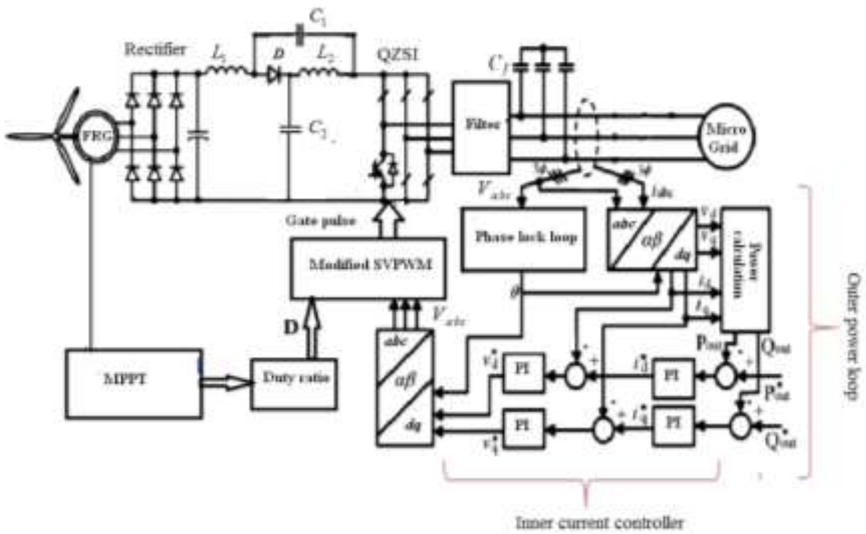


Figure 1. Block diagram of FRG with grid connected QZSI

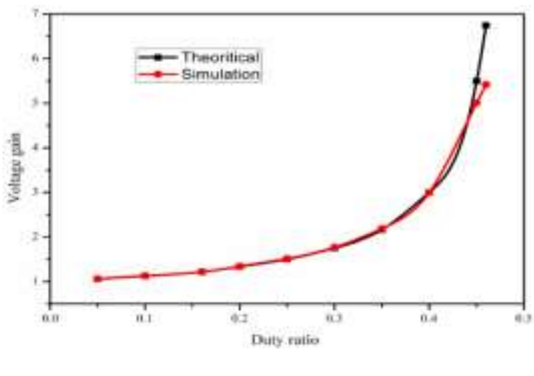


Figure 2. Voltage gain vs duty ratio

1.2. Quasi-Z-source inverter topology

Operating principle and circuit analysis of QZSI consists of two major modes, which are: (i) Non-shoot through mode (active mode) and (ii) Shoot through mode. The operation under these two modes is explained below. The governing equations for these modes are also derived.

(i). Non-shoot through mode (active mode).

In the non-shoot through mode, the switching pattern for the QZSI is similar to that of a VSI. The inverter bridge, viewed from the DC side is equivalent to a current source. The input dc voltage is available as DC link voltage input to the inverter, which makes the QZSI behave similar to a VSI.

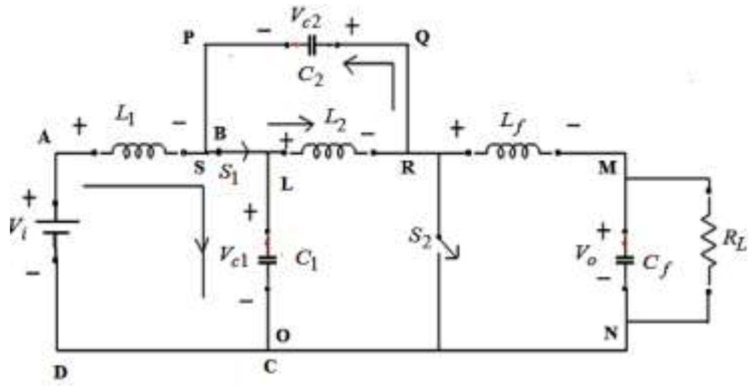


Figure 3. Circuit analysis of QZSI during the non-shoot through state

In the non-shoot-through state, the inverter bridge can be modelled as an equivalent current source as shown in Figure 3. The governing equations for the individual loops (loop ABCDA, PQRSP and LMNOL) are put in matrix form as:

$$\begin{pmatrix} L_1 \dfrac{d_{iL1}}{dx} \\ L_2 \dfrac{d_{iL2}}{dx} \\ L_f \dfrac{d_{iLf}}{dx} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 1 & 1 & -1 \end{pmatrix} \begin{pmatrix} V_{c1} \\ V_{c2} \\ V_0 \end{pmatrix} + \begin{pmatrix} V_i \\ 0 \\ 0 \end{pmatrix} \tag{1}$$

*(ii). Shoot through mode***.**

In the shoot through mode, switches of the same phase in the inverter bridge are switched on simultaneously for a very short duration. The source however does not get short circuited when attempted to do so because of the presence of LC network, while boosting the output voltage. The DC link voltage during the shoot through states is boosted by a boost factor. The value of boost factor depends on the shoot through duty ratio for a given modulation index.

In the shoot-through state, the inverter bridge as shown in Figure 4. The governing equations for the individual loops (loop ABCDEFA, PQRSP and LMNOL) are put in matrix form as:

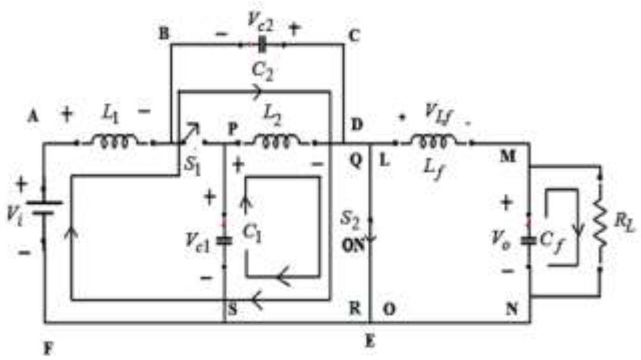


Figure 4. Circuit analysis of the QZSI during the shoot through state

$$\begin{pmatrix} L_1 \frac{d_{iL1}}{dx} \\ L_2 \frac{d_{iL2}}{dx} \\ L_f \frac{d_{iLf}}{dx} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} V_{c1} \\ V_{c2} \\ V_0 \end{pmatrix} + \begin{pmatrix} V_i \\ 0 \\ 0 \end{pmatrix} \tag{2}$$

The average value of the inductor voltages are separately found out.

$$\int_0^{(1-D)} (V_i + V_{c1})\, dt + \int_{(1-D)T}^{T} (V_i + V_{c2})\, dt = 0 \tag{3}$$

$$\int_0^{(1-D)T} (-V_{c2})\, dt + \int_{(1-D)T}^{T} (V_{c1})\, dt = 0 \tag{4}$$

$$\int_0^{(1-D)T} (V_{c1} + V_{c2} - V_0 + V_i)\, dt + \int_{(1-D)T}^{T} (-V_0)\, dt = 0 \tag{5}$$

$$\begin{pmatrix} (1-D) & D & 0 \\ D & -(1-D) & 0 \\ (1-D) & (1-D) & -1 \end{pmatrix} \begin{pmatrix} V_{c1} \\ V_{c2} \\ V_0 \end{pmatrix} + \begin{pmatrix} V_i \\ 0 \\ V_i \end{pmatrix} \tag{6}$$

$$V_0 = V_{c1} = \frac{(1-D)V_i}{(1-2D)} \tag{7}$$

$$V_{c2} = \frac{DV_i}{(1-2D)} \tag{8}$$

The dc link voltage obtained is the sum of capacitor voltages V_{c1} and V_{c2}

$$V_{dcp} = V_{c1} + V_{c1} = \frac{D}{(1-2D)} V_i = BV_i \tag{9}$$

$$V_0 = MB \frac{V_i}{2} \tag{10}$$

Along with the operation of QZSI, this section shows that the dc link voltage will be the multiplication of the boost factor and the input voltage. So, the output voltage will be the product of the boost factor B and the modulation index (MI). Thus, in the proposed control topology, the boost factor and the modulation index are changed separately to control the inverter output voltage.

The simulation diagram of QZSI is shown in the Figure 5. In the impedance network, the values of C_1 and C_2 are respectively 10μF. The values of L_1 and L_2 are respectively 1mH. The Figures 22 and 21 shows the boosted output line and phase voltages of the QZSI at the input DC voltage and with duty ratio (D)=0.3. Modulation Index (MI)=0.923.

The DC obtained 170 volts is inverted into 500 volts AC, maximum (Figure 6).

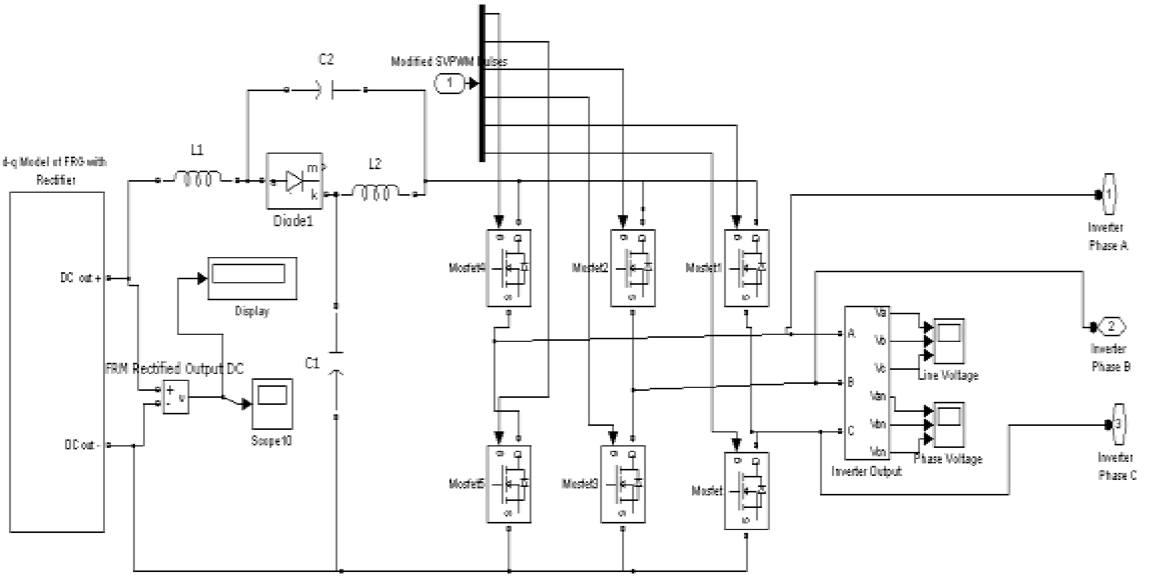


Figure 5. Simulation model of QZSI

Proof

The output voltage of the QZSI is given by $V_0 = \frac{V_{in}}{(1-2D)}$, where D=0.3 and V_{in}=170, Substitution of this given the output voltage V_0=500V, which is shown in Figure 6.

The output of the QZSI is given to the LC filter block to get a pure sine wave. The LC filter parameters are set as L_{ph}=5mH and C_{ph}=1000μF. Figure 6 shows the principle of operation of QZSI. After this, the paper with proceed to elaborate upon the proposed modified SVPWM generator, which provides the gate triggering for the inverter. This then will be followed by a detail discussion. In how the 3 inputs of this modified SVPWM generator is obtained (that is control strategies of QZSI).

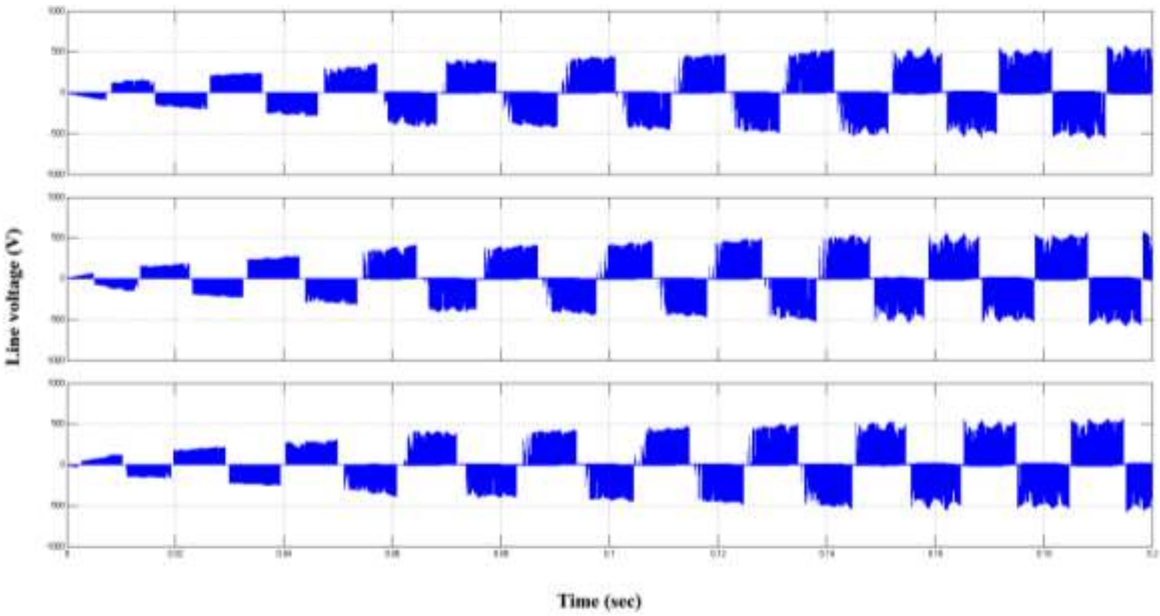


Figure 6. Line voltage of QZSI without filter (duty ratio=0.3).

2. MODELLING OF PROPOSED MODIFIED SVPWM SIGNAL GENERATOR

The QZSI gets the necessary pulses from the newly proposed modified SVPWM signal generator. The development of gate triggering pulses for MOSFET of QZSI is detailed in this section.

The whole SVPWM control system has three main subsystems viz., (i) SVPWM Modulation wave generator, (ii) Shoot through control wave generator and (iii) Modified SVPWM logic block. These are shown in Figure 7, and explained below.

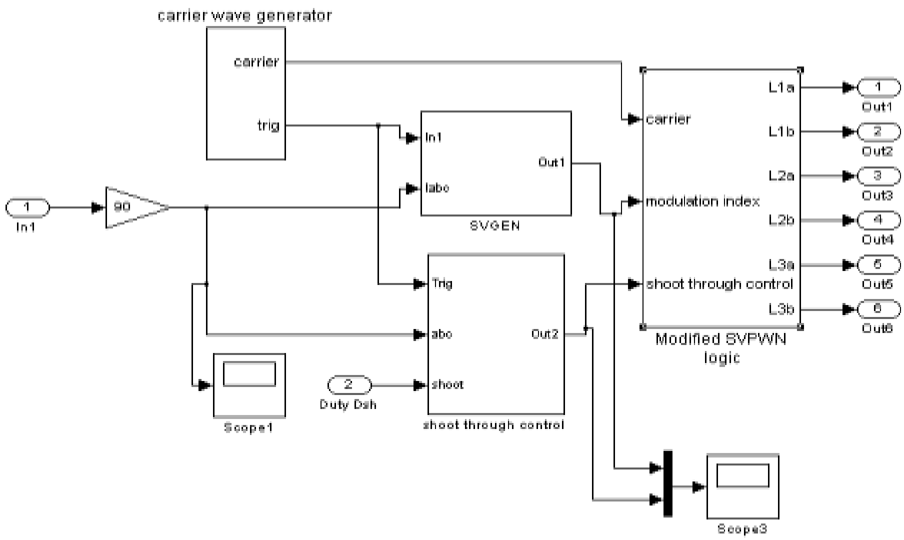


Figure 7. Modified SVPWM signal generator

(i) SVPWM Modulation wave generator (SVGEN) subsystem:

SVGEN is also called as Clarke transformation block (Figure 8). The Clarke transformation block is used to convert three-phase *abc* control voltage signal from power controller in stationary frame to two-phase α-β voltage in stationary frame. The α-β output voltage of the Clarke transformation is shown in Figure 9.

Then the converted α-β voltage will be used in sector selection block to generate SVPWM modulation wave. In a 3-phase waveform structure, the 60 degree crossing of the waveforms forms one sector and the amplitude of which forms the control signal. The simulation of sector selection block of one phase is shown in Figure 10. This block estimates the sector and also the control signal which is used in the next Modified SVPWM logic block to generate SVPWM gate pulses. This block is used to determine which sector is working out of 8 sectors. Six sectors are active and two are null sectors. This block also determines the value of time duration for operating MOSFETs in three phase full bridge. This sector is then compared with triangular carrier wave to generate the pulses.

The output switching pattern sequences depend up on which sector is working and selector will choose it as space vector modulation wave output. The space vector modulation waveform of upper and lower switch of one leg is shown in the Figure 11. Then this will be compared with carrier waveform to generate SVPWM gate pulses as shown in Figure 12 in next block.

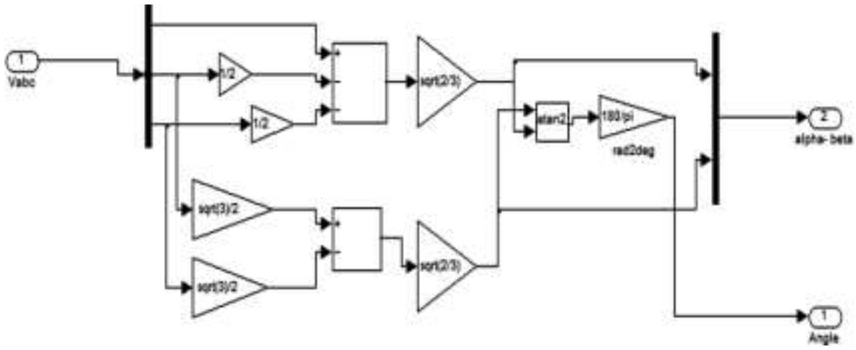


Figure 8. Clark transformation block

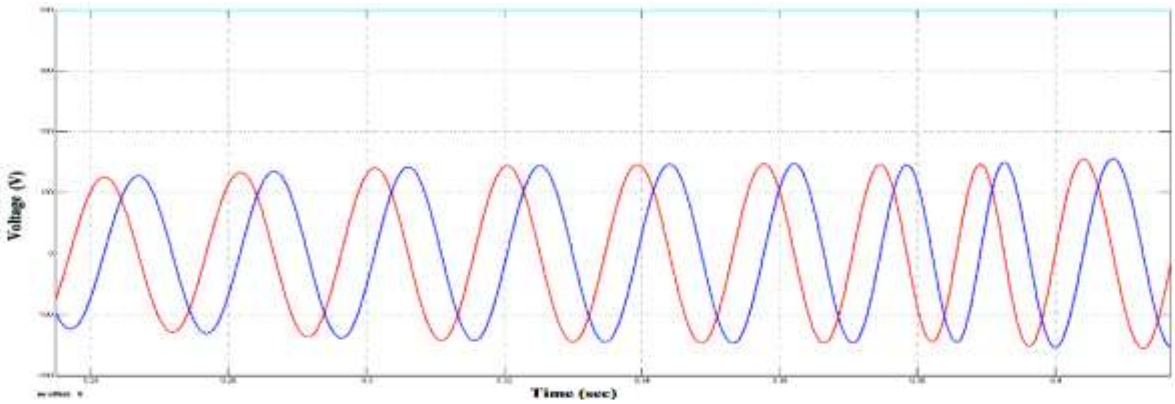


Figure 9. Output α-β voltage of clark transformation

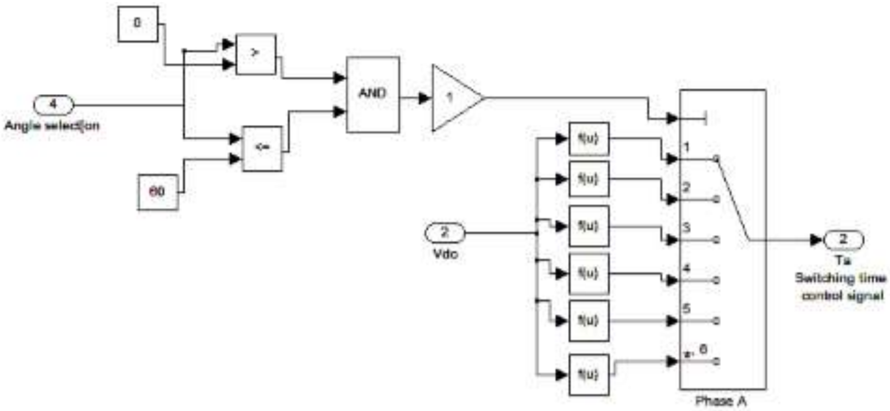


Figure 10. Block of sector selection

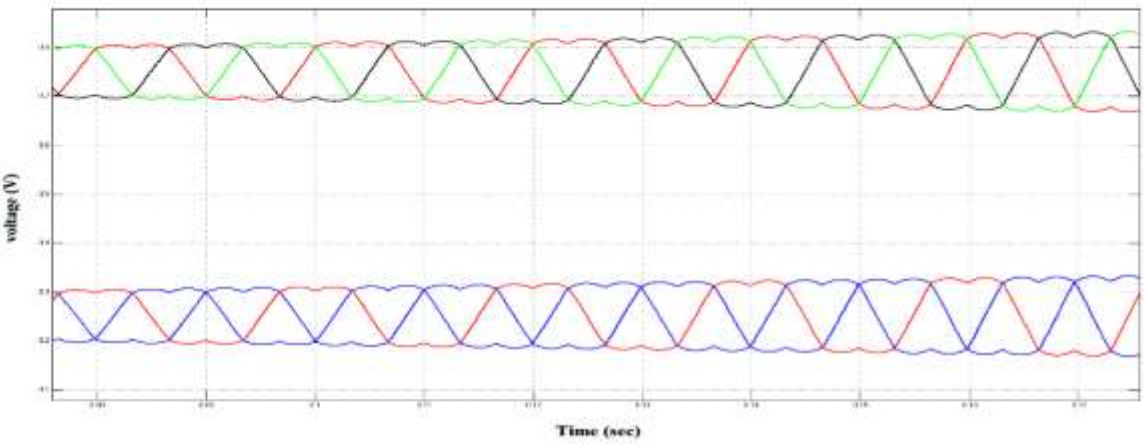


Figure 11. Conventional space vector modulation waveform

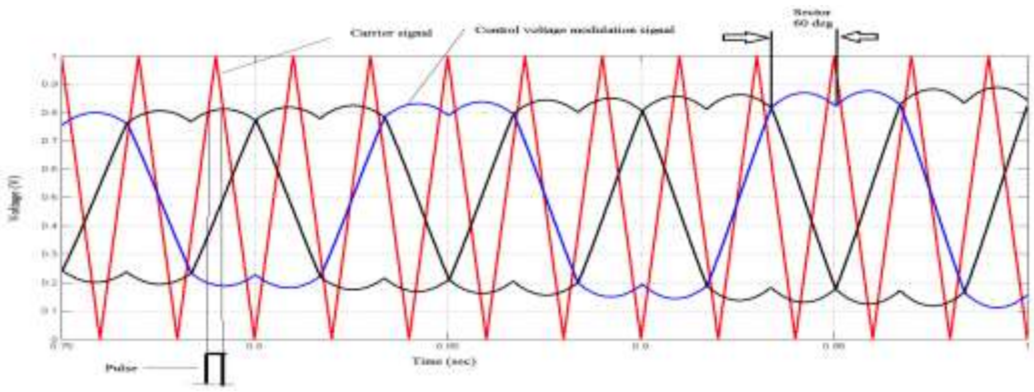


Figure 12. SVPWM gate pulse generation

(ii). Shoot through control wave generator

SVPWM in three phase voltage source inverters offers improved DC link voltage and reduced harmonic distortion, and has been therefore recognized as the preferred PWM method, especially in the case of digital implementation. The output voltage control by SVPWM consists of switching between the two active and one zero voltage vector in such a way that the time average within each switching cycle corresponds to the voltage command. In order to apply this concept for QZSI, a novel modified SVPWM is needed to introduce the shoot-through states into the zero vectors. The modified SVPWM wave pattern for one sector is shown in Figure 13. The shoot through period insertion is accomplished without disturbing the active vectors in the space region. It is evenly assigned to each phase within the null or zero state periods.

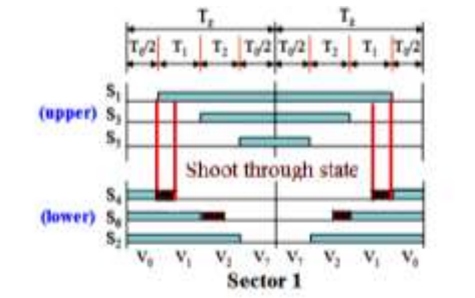


Figure 13. Modified SVPWM pulse pattern for first sector

The shoot through control wave generator block has three main subsystems, consisting of modified shoot through V_{abc} control voltage generator, clark transformation (*abc* to $\alpha\beta$) and switching time generator (sector block). The subsystem of shoot through control block is shown in Figure 14.

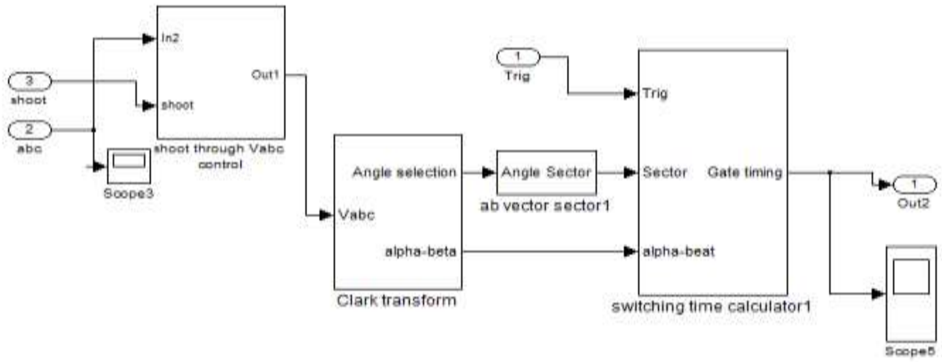


Figure 14. Subsystem of shoot through control wave generator block

The details of modified shoot through V_{abc} control voltage generator block is shown in Figure 15. In this control block, the V_{abc} control signal which is obtained from power controller is fed to the *abc – dqo* transformation block. The *abc – dq0* transformation block transforms *abc* to *dq* values with Phase Locked Loop (PLL) synchronization. In Re-Im and Complex to Magnitude-angle blocks, the *dq0* voltages are converted into Magnitude and angle. The magnitude is subtracted with shoot through reference value and again transformed into three phase *abc* control voltages. The shoot through time period can be varied by varying the magnitude of the V_{abc} output control voltage. Figure 16 shows the comparison of input V_{abc} input control voltage and V_{abc} output control voltage. This figure shows the magnitude variation of input and output voltage.

For carrier based implementation, the modified reference signals needed to produce the modified switching pulses. In this block the offset is used to maintain equal null durations at start and end of a half carrier period.

The V_{abc} output control voltage wave generator is converted to two phase voltage using Clark transformation block and then it is given to the sector selection block. The magnitude comparison of conventional SVPWM and modified SVPWM is modulation voltages are shown in Figure 17. These two control voltages are given to the modified SVPWM logic block to generate to SVPWM gate pulses.

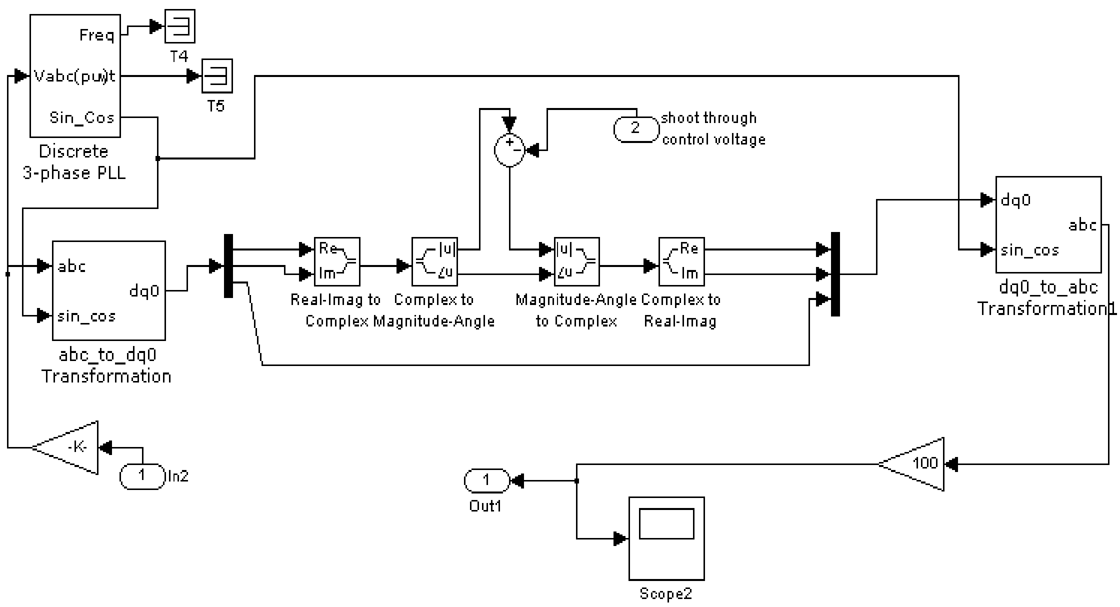


Figure 15. Simulation model of proposed modified shoot through V_{abc} control voltage generator

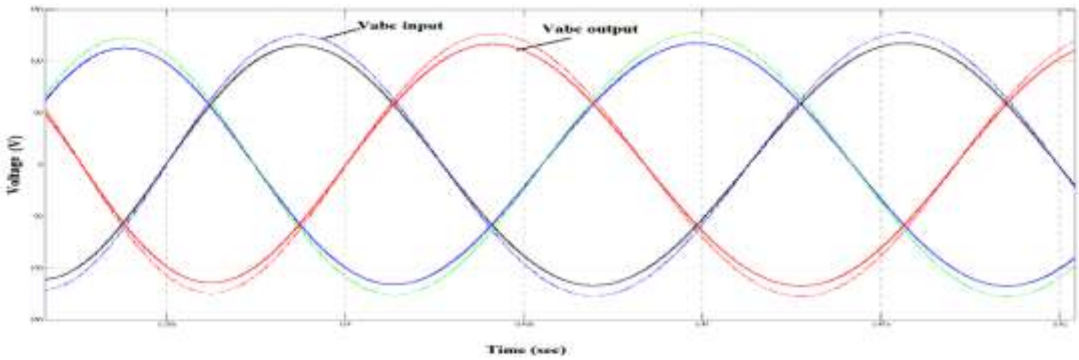


Figure 16. V_{abc} input and output control voltage from controller

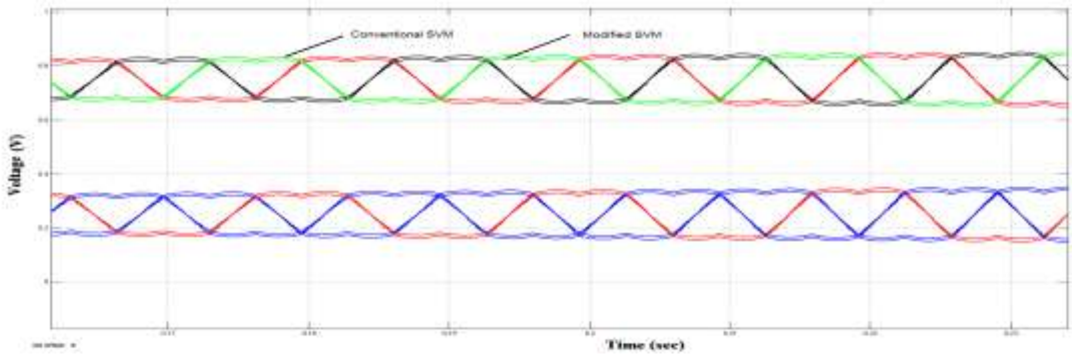


Figure 17.Comparison of conventional and modified space vector modulation voltage

(iii) Proposed modified SVPWM gate pulse generator

The subsystem of the modified SVPWM gate pulse generator is shown in Figure 18. In this block, modulation index SVM signal and shoot through SVM signal is compared with 10 *kHz* triangular carrier wave to generate modified SVPWM. The shoot though pulses are inserted in the SVPWM pulses using AND and OR Logic blocks. The pulse pattern is shown in Figure 19. The zoomed view of pulse pattern shows the shoot through state is shown in Figure 20.

This section presented the pulse production of the proposed SVPWM generator. Modified SVPWM has control inputs. Amongst the inputs V_{abc} is one whose evaluation was brought at in section III.A. The other inputs to the modified SVPWM are from MPPT control. This is explained in the next section.

3. CONTROL STRATAGIES OF QZSI

Figure 1 is redrawn in Figure 21 to focusing the control block in detail. Generally, grid tied inverters are operated in different modes as grid-feeding, grid-supporting and stand-alone modes.

In this research, the QZSI is designed for Grid-feeding mode and Voltage Oriented Control (VOC) strategy, along with MPPT control for modulating its output AC voltage, V_{abc}. VOC strategy decouples the active and reactive power to control the both powers independently. Figure 21 shows VOC and MPPT control. It also shows the component of VOC viz, outer power loops and inner current controller. Each of these two, controls the operation of the modified SVPWM.

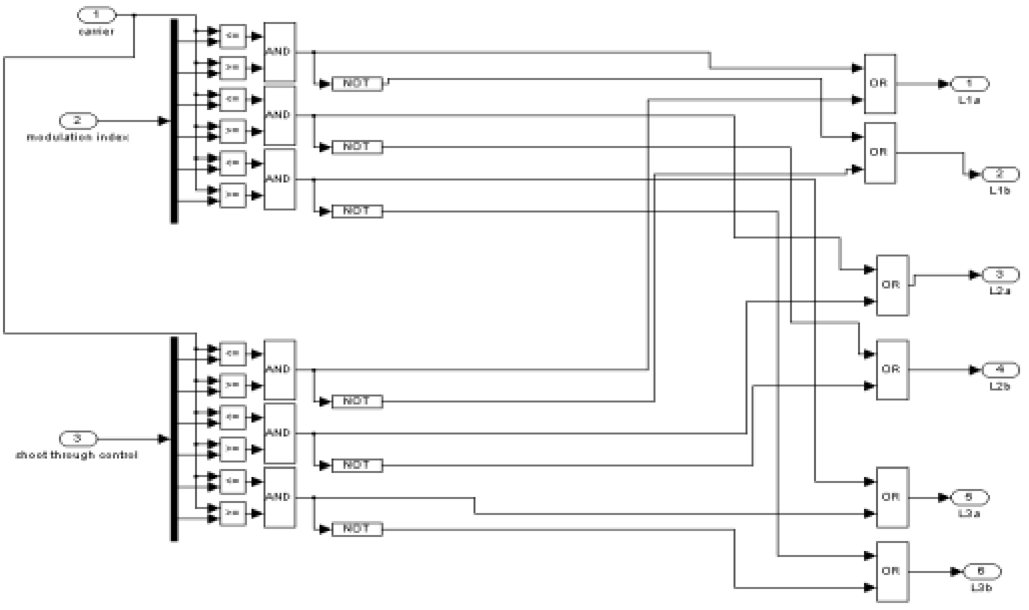


Figure 18. Proposed modified gate pulses

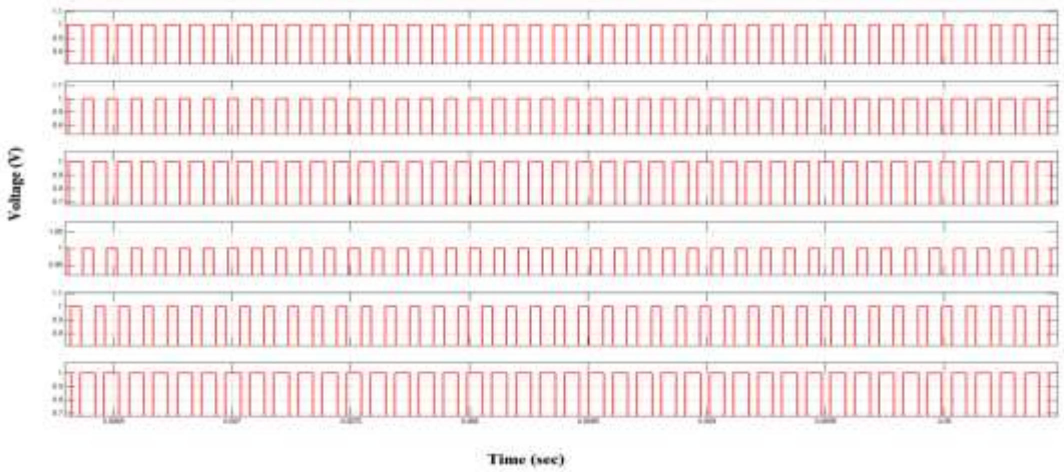


Figure 19. Modified gate pulse

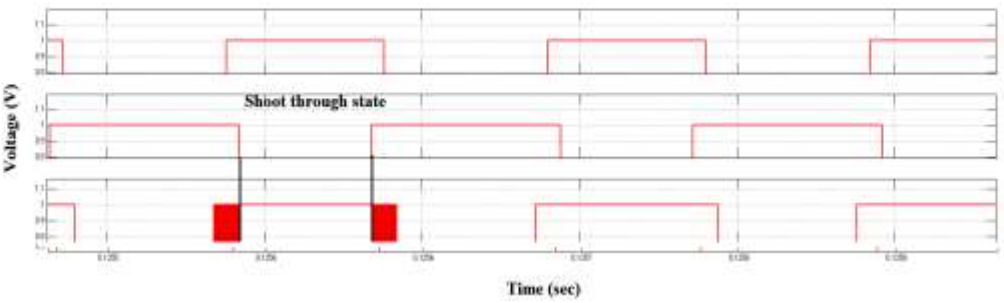


Figure 20. Zoomed view of modified gate pulse with shoot through state

3.1. MPPT control

From equations (7) and (9), the relationship between capacitor voltage V_{c1} and the DC link voltage is obtained as

$$V_{dc} = \frac{V_{c1}}{(1-D)} \tag{11}$$

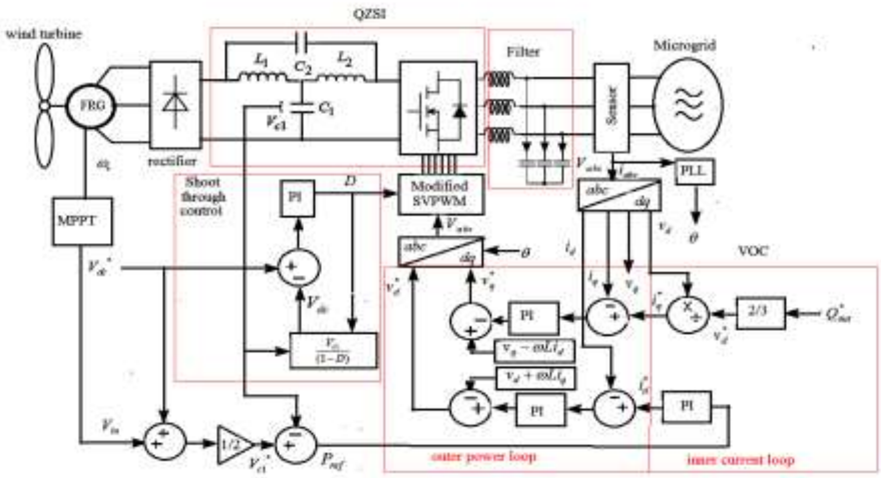


Figure 21. Block diagram of expanded view of control strategies

The equation (11) is modeled in simulink to achieve desired shoot through duty ratio, as shown in the Figure 22. If the capacitor voltage V_{c1} of QZSI is maintained constant, the input voltage V_i decreases as the shoot through duty ratio increases. This will reduce V_{dc} (refer Figure 21).

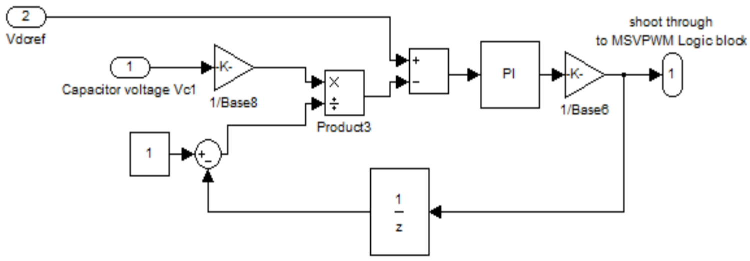


Figure 22. Shoot through duty cycle block

FRG is driven by wind turbine whose speed is uncertain. It depends up on atmospheric air velocity. Let the air velocity droops down. This brings down the speed of turbine and hence FRG and so the obtained V_{in} will be less. V_{c1} is also accordingly reduced, as can be seen in Figure 21. Note that these voltages are to be kept constant based up on the system's requirements. This value of V_{c1} is sensed and given to the shoot through duty angle loop. This loop, in accordance with the equation (x) modifies D to maintain V_{c1} and

V_{dcl} a constant at the required value. This approach has controlled V_{dc} independently at the desired value. Value of duty ratio D is one of the three inputs to QZSI.

3.2. VOC control

In the VOC, the error signal obtained with V_{c1} and V_{c1}^{*} forms the basis for the real power to be injected to the grid. As the air velocity is being assumed to have drooped down, V_{c1}^{*} would be low when compared with the duty-cycle-adjusted new V_{c1}. Error signal given command i_d^{*}. Already id has been calculated from *abc-αβ-dq* transformation. i_d is a measure of real power P. The error signal $i_d^{*} \sim i_d$ provides the variation of control voltage V_d^{*} to QZSI.

Again in VOC, the error signal is obtained with the difference between Q^{*} (set up by the user) and i_q. The quadrature current i_q is a measure for reactive power Q. The error signal $i_q^{*} \sim i_q$ provides the variation of control voltage $V_q *$ to QZSI.

So if the capacitor voltage V_{c1} is controlled and kept constant, the outer power control loop can inject power to the grid. Thus the three inputs *D*, $V_d^{*}, V_q *$ to QZSI-SVPWM of Figure 21 are obtained.

As said earlier, in VOC control, voltage and current are transformed from the *abc* frame of reference to the *dq0* frame of reference. In addition an angle of the input line voltage is required for this transformation. The Phase Locked Loop PLL plays a crucial role of calculating the angle of this transformation. PLL measures the voltage angle θ of the three-phase supply. This angle is used for the *abc* – *dq0* transformations. The reference current i_d controls the active power and the DC voltage, while the reference i_q controls the reactive power and utility power angle. If the reference frame is oriented along the grid voltage. As the PLL used in the system is voltage oriented the q-axis component of voltage is zero, the power equations in the synchronous reference frame are expressed as

$$P_{out} = \frac{3}{2} v_d i_d \tag{12}$$

$$Q_{out} = -\frac{3}{2} v_d i_q \tag{13}$$

where P_{out} and Q_{out} are active and reactive power of FRG, respectively.

From this, it can be seen that the independent control of P_{out} and Q_{out} can be achieved by controlling the direct and quadrature components of the grid currents i_d and i_q. The decoupling algorithm is

$$v_d^{*} = v_d - (k_p + \frac{k_i}{s})(i_d^{*} - i_d) + \omega L i_q \tag{14}$$

$$v_q^{*} = v_q - (k_p + \frac{k_i}{s})(i_q^{*} - i_q) - \omega L i_d \tag{15}$$

Through the decoupling control, the direct and quadrature components of the voltage v_d and v_q can be obtained. Then they are converted to the *abc* stationary reference frame by *dq0 –abc* transformation block. The simulation model of VOC control method is shown in Figure 23. From this method, the AC side grid-connected control can be achieved

The variable D can be eliminated using relationship between V_{c1} and V_{in}. Then the command signal of V_{c1}^{*} is

$$V_{c1}^{*} = \frac{1}{2}(V_{in} + V_{dc}^{*}) \qquad (16)$$

where V_{dc} is set by grid requirements, while V_{in} is obtained from wind MPPT block. Consequently, V_{c1} is used as reference voltage for outer active power control loop.

Figure 24 shows the active power reference block for outer loop. If the V_c^{*} voltage which is obtained from MPPT control is higher than the capacitor voltage, the error is reflected as the positive active power reference P_{ref}.

The output P_{ref} is given to the current controller block to calculate the i_d^{*} for inner current loop. And then, the current reference (i_d^{*}) is increased. So, the power can be injected to the grid as generated power by FRG. If the reactive power reference Q* is zero, the output current is in phase by PLL.

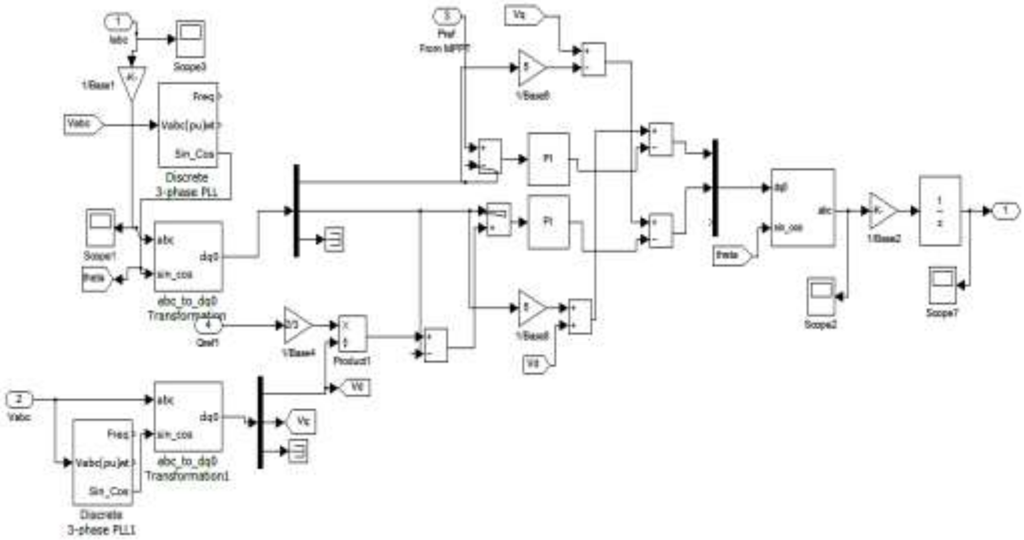


Figure 23. VOC control block

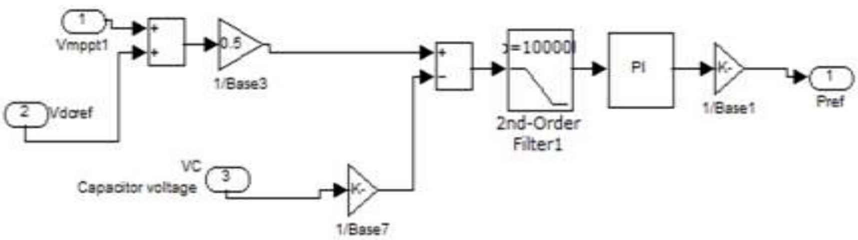


Figure 24. Active power reference block for outer loop

The functioning of FRG-cum-QZSI [3] is explained in this section, along with the proposed modified SVPWM generator and its control circuitry. The interface of modified will be discussed in the next section.

4. POWER INJECTION IN TO MICRO GRID INVOLVING FRG AND SVPWM CONTROLLED QZSI

The generalized block diagram of FRG connected to AC micro grid [4], [5] and [6] through QZSI is shown in Figure 25. Output voltage of FRG is converted to DC voltage using a Rectifier. The output DC voltage is filtered and fed to micro grid. This grid has been already tied with another source. From the grid the power is fed to the local utility grid through the circuit breaker. The utility grid feeds the power to the houses and small scale industries etc.

The proposed controller is designed in grid-connected mode. The inverter is working in grid feeding mode and inject the generated power to the grid. The output active and reactive power of the FRG system is controlled using VOC along with MPPT technique.

The whole simulation model of power injection in to micro grid involving FRG and SVPWM controlled QZSI [7] is shown in Figure 26. The output DC voltage of the FRG is 170 V. The inductance and capacitance of the Z-network are 10 µF and 40µH.

In order to track the MPPT, the capacitor voltage is continuously measured and given to the shoot-through duty ratio control loop. So the shoot-through duty ratio is determined by the MPPT characteristics of the wind turbine. Moreover, the MPPT control voltage decides the command signal (V_{c1}^*) of outer power control loop. In the simulation purpose, the MPPT control voltage is changed from 0.1 p.u - 4 p.u.

The switching frequency is 10 kHz. The grid line voltage is 200 V. The test values are given as follows: V_{dc}^*=2 p.u and Q_{ref}=0, load values are $P = 25kW\ Q = 3kVAR$. Another three phase source simulink block is used as a grid tied renewable energy source.

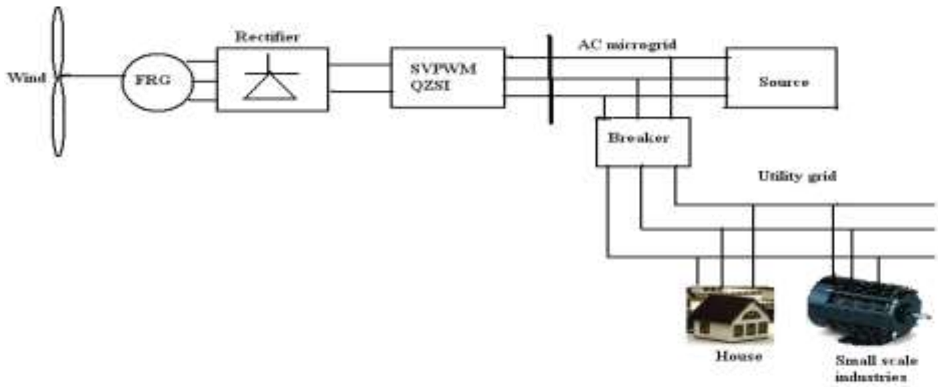


Figure 25. Generalized block diagram of FRG connected to AC micro grid through

Figure 27 shows the grid voltage and Figure 28 and 29 shows the Load voltage and load current. The Figure 30 shows the injected values of real and reactive power to the grid at different MPPT values. The Figure 30 shows that the expected generated power is injected to the grid. Summation of FRG generated power and second renewable energy generated power is equal to load Power. The inverter output reactive power has been transferred to the grid.

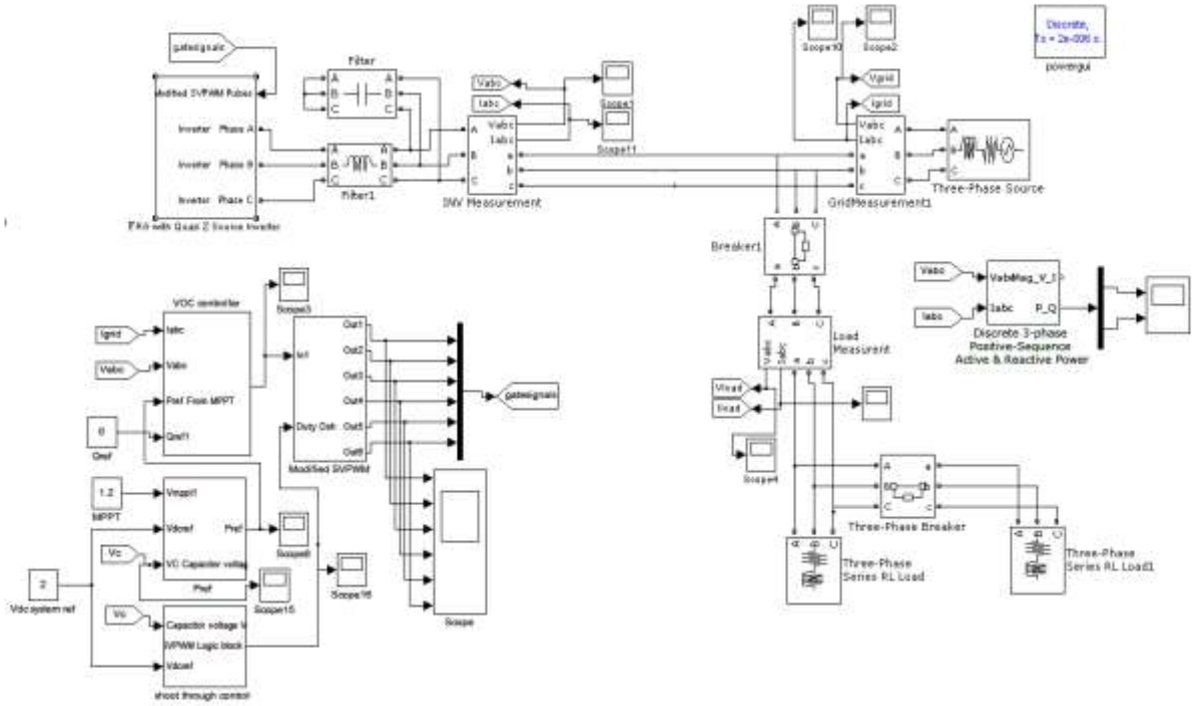


Figure 26. Simulation model of power injection in to micro grid involving FRG and SVPWM controlled QZSI

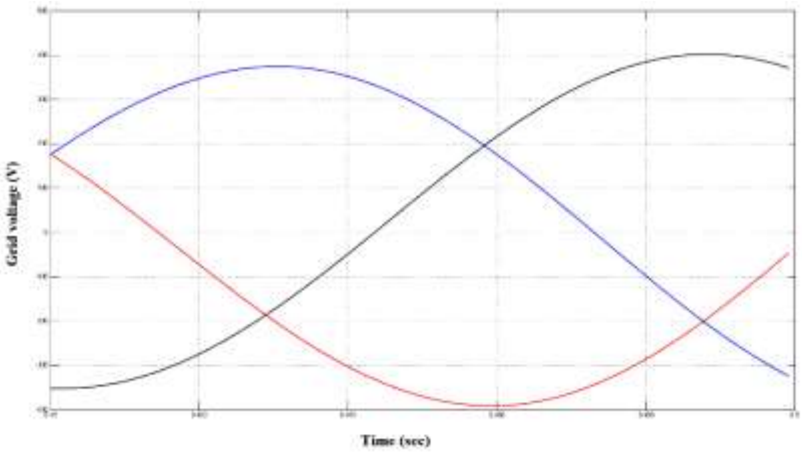


Figure 27.Grid voltage

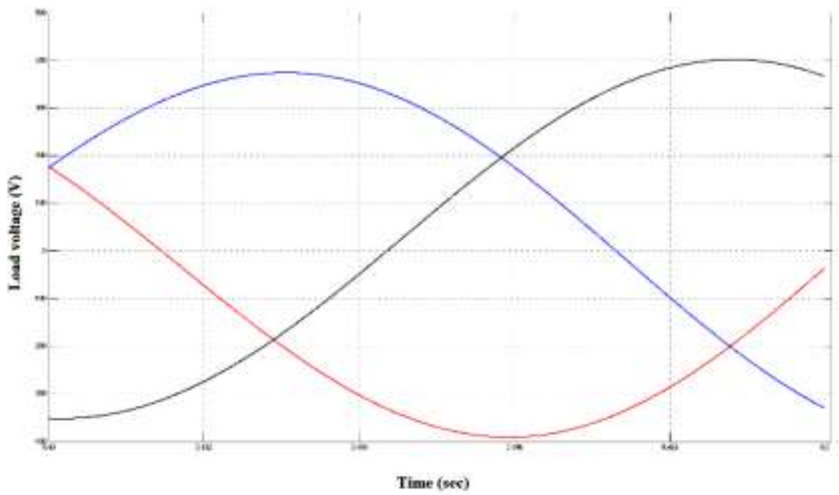


Figure 28. Load voltage

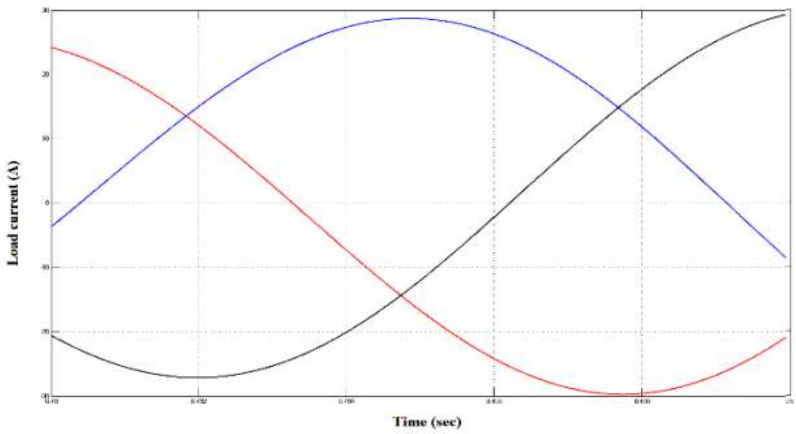
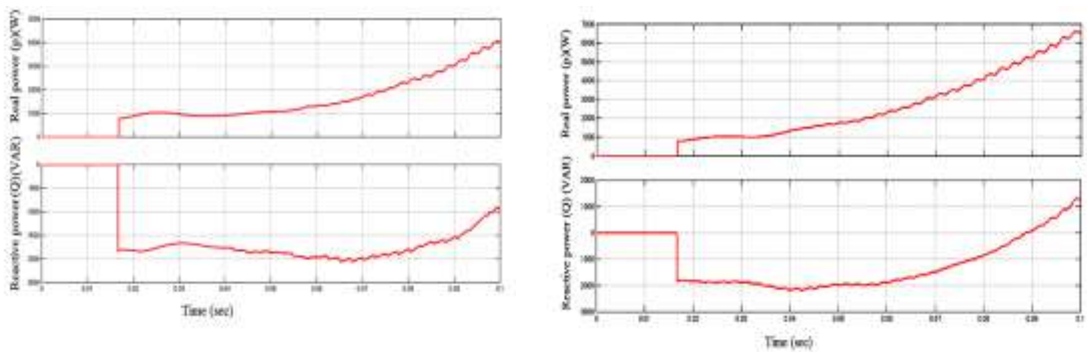


Figure 29. Load current



(a) (b)

Figure 30. Real and reactive power (a) MPPT 0.1 p.u (b) MPPT 4 p.u

5. CONCLUSION

This research paper presented a small scale wind generator system using flux reversal technology connected to microgrid through quasi-Z-source inverter. Part II of this research was organized to discuss in length about the design, model, simulation and analytical verification of (i) QZSI (ii) its associated modified

SVPWM and its control circuitry and (iii) the injection of power into the microgrid. References [1-5] provided helpful foundation to suggest FRG as an alternate machine for PMSG in wind power applications.

There are following contribution made in this paper: (a) use of low speed FRG to wind energy system serving a microgrid, (b) QZSI in modified and (c) a modified gate pulses and SVPWM to the MOSFET of inverter.

The prototyping of small scale FRG has been completed and verified. QZSI experimental set up is taken up now, on the basis of the encouraging and verified results presented here. Notwithstanding the fact that the experimental settings are pending, the entire simulations of the proposed small scale wind energy system presented in this paper have been verified by rigorous analytical equations, and they are encouraging.

It is believed that the above three new proposals made in this paper will take wind energy system as well as its association with the micro grids a long way in the near future.

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