Research Journal of Applied Sciences, Engineering and Technology 10(6): 630-639, 2015
DOI:10.19026/rjaset.10.2472
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: December 26, 2014 Accepted: February 5, 2015 Published: June 20, 2015

Research Article

An Efficient Genetics Algorithm based Z-source Converter for Grid Connected System

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Abstract: This study deals with a simulation of robust and reliable three phase grid power interface system for photo voltaic modules using genetics algorithm based optimization technique. A control system is designed to harvest maximum solar energy under varied weather conditions with the use of a genetics algorithm based SVPWM controlled Z source fed multilevel inverter. Using Z-source networks, the system can work within a wider range of PV array output voltages than for a conventional boost converter. This study describes an modified genetics algorithm that reduces the computational burden and optimum switching angles are determined to eliminate lower order harmonics and reduces total harmonics distortion. The simulation is done using MATLAB and the simulation results are presented.

Keywords: Genetics algorithm, MPPT, multilevel inverter, PV array, total harmonic distortion, voltage source inverter

INTRODUCTION

Alternate Energy Sources such as Solar, Fuel Cell and Wind have a wide voltage change range due to the nature of sources. Photovoltaic cells voltage varies with temperature and irradiation. The efficient ZSI have recently been proposed as an alternative power conversion concept as it has both voltage buck and boost capabilities. The developed Z source network provides a second order filter and it can reduce the line harmonics, improves power factor, increases reliability and extends output voltage range. Therefore, the inductor and capacitor requirement should be smaller than the traditional inverters.

In the voltage source inverters two switches of any phase leg can never be triggered at the same time, since otherwise, a short circuit (shoot through) will occur, destroying the inverter. The Z source network control is to turn null states into shoot through states and keep the active switching states unchanged (Tang *et al*., 2009). The Z-Source Inverter (ZSI) in the proposed system has two independent control variables: shoot-through and modulation index.

GA's is promising methods for solving difficult technological problems and for machine learning. In this study genetic algorithm is used to calculate the optimal control parameters of the inverter and the MPPT algorithm. Genetic algorithm is a computational procedure that mimics the natural process of evolution (Varsek *et al*., 1993). It works by evolving a population of solutions over a number of generations.

The Space Vector Pulse Width Modulation (SVPWM) method is an advanced, computation intensive PWM method and possibly the best among all the PWM techniques for variable frequency drive application (Mallika and Saravana Kumar, 2012; Moreira *et al*., 2000; Pan and Peng, 2006). A control algorithm with standard Perturbation and Observation (P and O) is proposed to achieve commanded values of dc voltages necessary for Maximum Power Point Tracking (MPPT) of PV panels by using genetics algorithm (Shen *et al*., 2004; Peng, 2003) Beside power generation the system can function as an active filter, with the additional capabilities of load balancing, harmonics compensation and reactive power injection. Because the Z source inverter is used in a PV system, a genetics algorithm controlled multilevel inverter and Phase Locked Loop (PLL) scheme is employed to keep the output current sinusoidal and to have high dynamic performance under rapidly changing atmospheric conditions and to maintain the power factor at near unity. Simulation results are presented to validate the proposed configuration (Yao *et al*., 2008; Nguyen *et al*., 2005). The proposed methodology offer lower Total Harmonics Distortion (THD), improved step response and quality of power. Finally, the designed system is simulated using MATLAB/SIMULINK for verification purposes.

METHODOLOGY

Figure 1 shows the power circuit and control system configuration of the proposed photovoltaic grid connected system. The Z-source inverter can boost DC link voltage to a required value at low PV array output power. The whole control system consists of three

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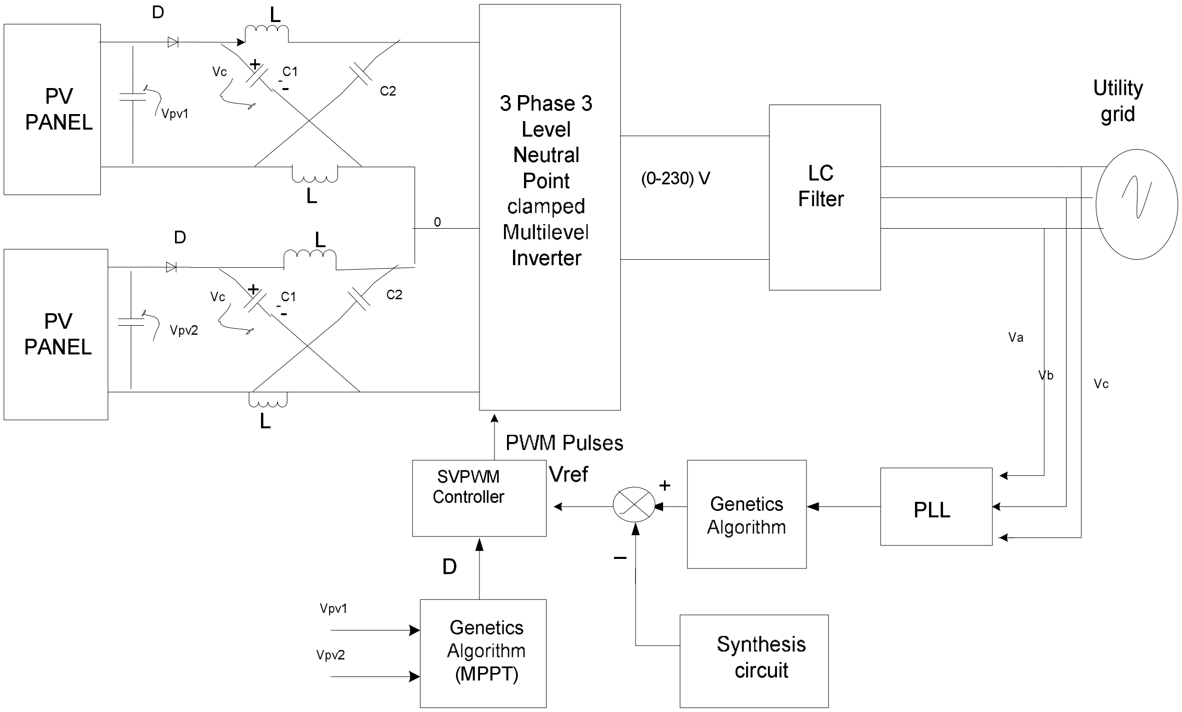

Fig. 1: Power circuit diagram

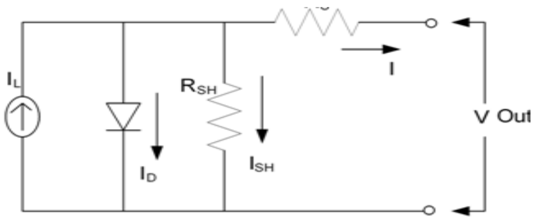

Fig. 2: The equivalent circuit of photovoltaic cell

close-loop controls: MPPT control loop, Z-source capacitor voltage control loop and compensation current loop. The maximum power is obtained from PV array with MPPT control loop by using genetics algorithm. Though the Z-source capacitor voltage control loop, a shoot through duty ratio is calculated to guarantee a relatively stable voltage of Z-source capacitors. The genetics algorithm and current/voltage control loop is used to produce active modulation index in order to follow the reference current signal accurately.

Modeling of PV panel: An electrical circuit representing a solar cell is shown in Fig. 2. The optical loss is represented by the current source itself, where the generated current I_{ph} is proportional to the light input. The recombination losses are represented by the diode connected parallel to the current source, but in the reverse direction. The ohmic losses in the cell occur due to the series and shunt resistance denoted by Rs and Rsh, respectively (Solanki, 2011).

Applying Kirchoff's voltage law to the input side node, we get:

$$I_L = I_D + I_{SH} + I \tag{1}$$

The photovoltaic output current equation for the cell is:

$$I = I_L - I_o\, [exp\, (\frac{V+IR_S}{V_T}) -1] - [(\frac{V+IR_S}{R_P})] \tag{2}$$

where,

I_L = The Insolation current
I = The Cell current
I_o = The Reverse saturation current
V = The Cell voltage
R_s = The Series resistance
R_p = The Parallel resistance
V_T = The Thermal voltage (kt/q)
K = The Boltzman constant
T = The Temperature in Kelvin
q = The Charge of an electron

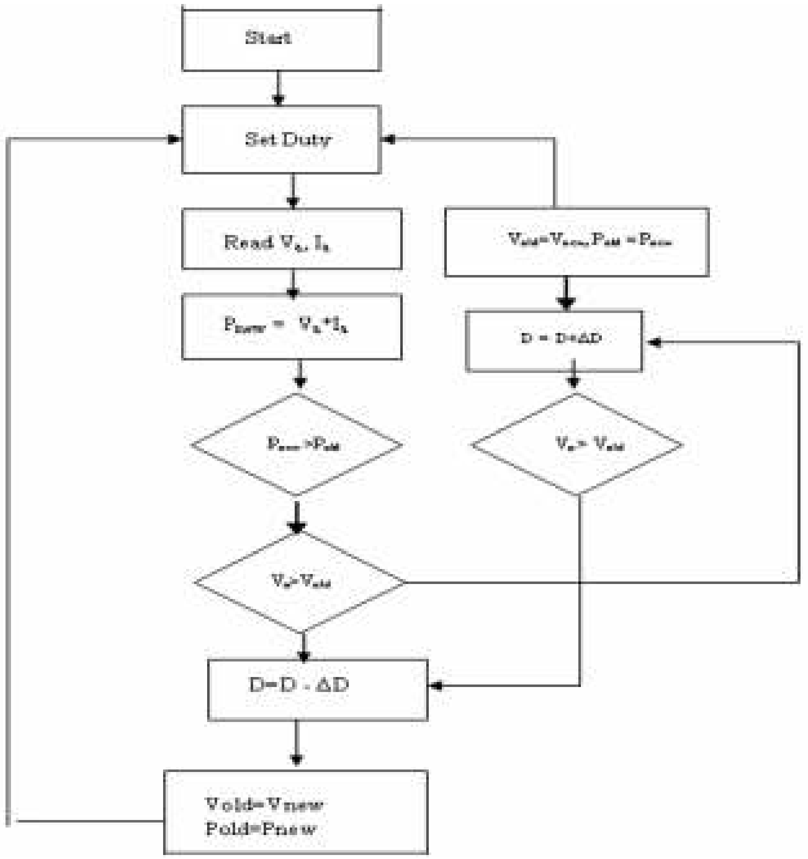

Fig. 3: Flow chart of perturbation and observation algorithm

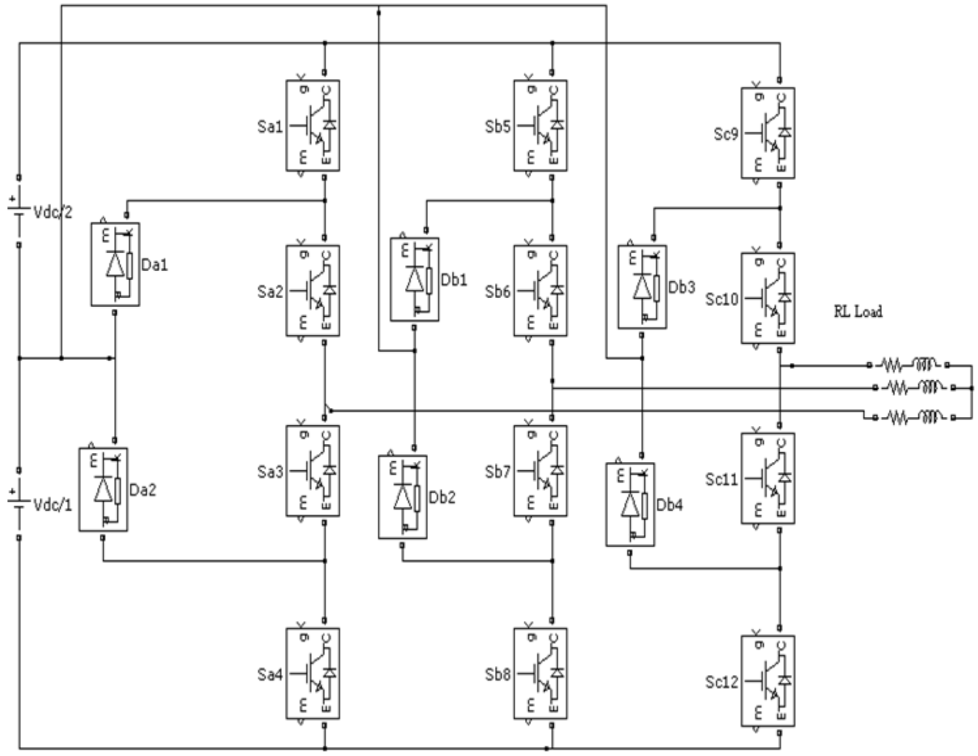

Fig. 4: Power circuit for three levels NPC inverter

Table 1: Switching states for phase A

V_{ao}	S_{a1}	S_{a2}	S'_{a2}	S'_{a1}	S_a
$+V_{dc}/2$	ON	ON	OFF	OFF	2
0	OFF	ON	ON	OFF	1
$-V_{dc}/2$	OFF	OFF	ON	ON	0

MPPT algorithm: The flow chart of genetics algorithm based MPPT algorithm is shown in Fig. 3. The perturbation and observation algorithm is applied by perturbing the duty cycle D at regular intervals and by recording the resulting array current and voltage values, thereby obtaining the power. Once the power is known, a check for the slope of the PV curve or the operating region is carried out and then the change in D is effected in a direction so that the operating point approaches MPP on the power voltage characteristic (Shimizu *et al*., 2003).

Multilevel inverter topology: Basically, NPC multilevel inverters synthesize the small step of staircase output voltage from several levels of DC capacitor voltages. An m-level NPC inverter consists of (m-1) capacitors on the DC bus, 2 (m-1) switching devices per phase and 2 (m-2) clamping diodes per phase. Figure 4, shows the structure of 3-level NPC. The DC bus voltage is split into 3 levels by using 2 DC capacitors, C1 and C2. Each capacitor has Vdc/2 volts and each voltage stress will be limited to one capacitor level through clamping diodes (Dai *et al*., 2006).

The switching table for phase A is shown in Table 1. The switching states of each bridge leg of three-phase three-level inverter are described by using switching variables Sa, Sb and Sc. The difference is that, in three-level inverter, each bridge leg has three different switching states.

Modeling of Z source inverter: For grid connected PV systems, a boost dc-dc converter is needed because the V-source inverter cannot produce an ac voltage that is greater than the dc voltage. Figure 5 shows a Z-source inverter for such solar-cell applications, which can directly produce an ac voltage greater and less than the solar-cell voltage. A Z source inverter that consists of a energy storage elements such as split-inductor L_1, L_2 and capacitors C_1 and C_2 connected in X shape is employed to provide an impedance source coupling the converter to the PV array to produce a dc source.

Assume the Z source network is symmetrical, that is:

$$V_{C1} = V_{C2} = V_C \tag{3}$$

$$V_{L1} = V_{L2} = V_L \tag{4}$$

$$V_L = V_C,\ V_{pv} = 2V_C,\ V_{output} = 0$$

During the switching cycle T:

$$V_L = V_{pv} - V_C \tag{5}$$

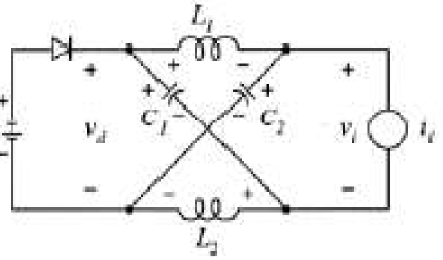

Fig. 5: Equivalent circuit of ZSI

$$V_{output} = V_C - V_L = V_C - (V_{pv} - V_C) \tag{6}$$

$$V_{output} = 2V_C - V_{pv}$$

where, V_{pv} is the output DC voltage of the PV panel. And:

$$T = T_{on} + T_{off}$$

The peak DC link voltage across the inverter is:

$$V_{output} = V_c - V_L = 2V_c - V_{pv}$$

$$V_{output} = \frac{T}{T_1 - T_o} V_{pv} = bV_{pv} \tag{7}$$

where,

$$b = boost\ factor = \frac{T}{T_1 - T_o} \geq 1 = \frac{T}{1 - 2\frac{T_o}{T}} \geq 1$$

The output peak phase voltage from the inverter will be:

$$V_{ac} = M\frac{V_o}{2} \tag{8}$$

where, M is the modulation index.

The Boost Factor B can be controlled by the duty cycle of the shoot through zero state over the non-shoot through states of the PWM inverter. The shoot through state does not affect PWM control of the inverter, because it equivalently produces the same zero voltage to the load terminal. The available shoot through period is limited by the zero state periods that are determined by the modulation index.

SVPWM control: The process of switching the power devices in power converter topologies from one state to another is called modulation. A space vector PWM is used, it is one of the most efficient method. The modulation index m is maintained between 0 to 1.

If the output voltages are pure sinusoids, then:

$$V_{ref} = me^{j\omega t}$$

where, m is the modulation index which varies from 0<m<1, ω is the output frequency and V_{ref} is the locus of a circle. The ideal trajectory for V_{ref} should be a circle and should rotate at uniform angular velocity. The instantaneous values of the line-to-line voltages of the inverter is given by:

$$V_{an} = V_m \mathrm{Sin}\omega t \tag{9}$$

$$V_{bn} = V_m \sin(\omega t - 120^o) \tag{10}$$

$$V_{cn} = V_m \sin(\omega t + 120^o) \tag{11}$$

It is assumed that the three-phase system is balanced then:

$$V_{an} + V_{bn} + V_{cn} = 0 \tag{12}$$

When the three phase voltages are applied to a AC machine a rotating flux is created. This flux is represented as one rotating voltage vector. To implement the space vector PWM, the voltage equations in the *abc* reference frame can be transformed into the stationary *dq* reference frame that consists of the horizontal (d) and vertical (q) axes.
The reference voltage can then be expresses:

$$V_{ref} = V_{an} + V_{bn} e^{\frac{j2\pi}{3}} + V_{cn} e^{\frac{-j2\pi}{3}} \tag{13}$$

$$\overrightarrow{V_{ref}} = \frac{3}{2} V_m [\sin\omega t - j\cos\omega t] \tag{14}$$

$\overrightarrow{V_{ref}}$ is a vector having a magnitude of $\frac{2}{3}V_m$ and rotates in space at ω rad/sec:

$$V_{ref} = V_d + jV_q \tag{15}$$

$$V_d = V_{an} - \frac{1}{2}[V_{bn} + V_{cn}] = \frac{3}{2} V_{an} \tag{16}$$

$$V_q = \frac{\sqrt{3}}{2}[V_{bn} - V_{cn}] \tag{17}$$

$$\therefore \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

The voltage vectors on the V_d and V_q axis can then be described as:

$$\left| \overrightarrow{V_{ref}} \right| = \sqrt{V_d^2 + V_b^2} \tag{18}$$

$$\alpha = \tan^{-1} \frac{V_d}{V_q} \tag{19}$$

Having calculated V_d, V_q, V_s and the reference angle, the first step is taken. The next step is to calculate the duration time for each vector V1-V6. There are 27 switching States are used and each vector for T/6 period. The space vector diagram for three level inverter is shown in Fig. 6.

Genetic algorithm: GA is a method for moving from one population of "chromosomes" to a new population by using a kind of "natural selection" together with the genetics-inspired operators of crossover, mutation and inversion. The chromosomes in a GA population typically take the form of bit strings. Each locus in the chromosome has two possible alleles: 0 and 1. Each chromosome can be thought of as a point in the search space of candidate solutions. The GA processes populations of chromosomes, successively replacing one such population with another. The GA most often requires a fitness function that assigns a score (fitness) to each chromosome in the current population. The fitness of a chromosome depends on how well that chromosome solves the problem at hand.

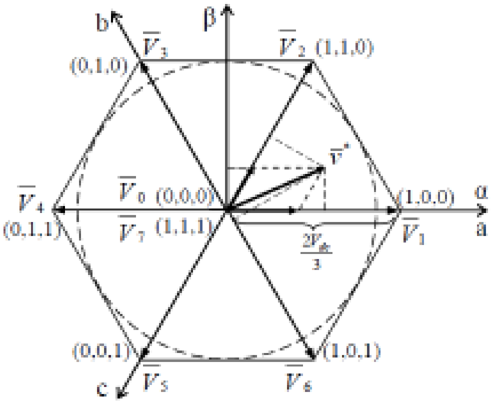

Fig. 6: Space vector diagram

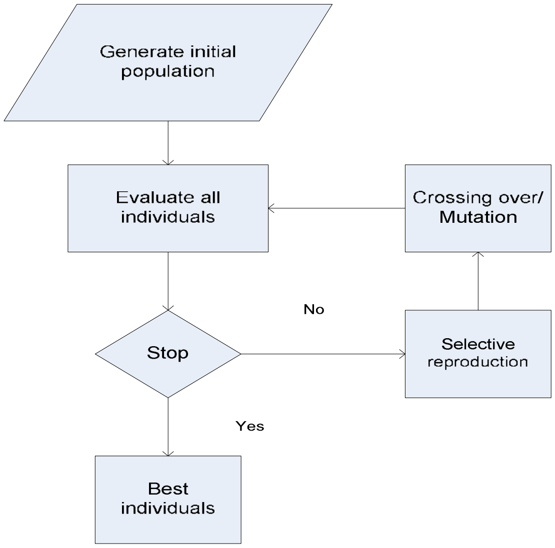

Fig. 7: Flow chart of genetics algorithm

The fitness function is to analysis the function of steady state error, peak overshoot, rise time and settling time. The flow chart of the genetics algorithm to find the fitness function is shown in Fig. 7.

Harmonic analysis: As per the Fourier theorem the periodic output voltage V (ωt) can be described by a constant term plus an infinite series of sine and cosine terms of frequency nω, where n is an integer.
Therefore V (t) in general, can be expressed as:

$$V_o(t) = \frac{a_o}{2} + \sum_{n=1}^{\alpha} (a_n \cos n\omega t + b_n \sin n\omega t) \tag{20}$$

$$a_n = \frac{1}{\pi} \int_0^{2\pi} V_o(t) \cos(n\omega t) d(\omega t)$$

$$b_n = \frac{1}{\pi} \int_0^{2\pi} V_o(t) \sin(n\omega t) d(\omega t)$$

where, ‘nwt’ is the switching angle and n is the harmonic order. As the voltage waveform possesses half wave symmetries, only odd b_n component is presented in the fourier series, which is given by:

$$b_n = \frac{4V_L}{n\pi}$$

where, V_L is the rms value of the output voltage. The rms value of the n th component is:

$$V_n = \frac{4V_L}{n\pi\sqrt{2}}$$

By using the harmonic analysis the THD calculated is 48% for the two level inverter.

Estimation of switching angles: Fourier series of the quarter-wave symmetric NPC multilevel inverter output waveform is written as given in Eq. (20) in which θs are the optimized switching angles, which must satisfy the following condition:

$$\theta 1 < \theta 2 < \theta 3 \dots \dots \dots \dots \theta s < \pi/2$$

The method to solve the optimized harmonic switching angles will be explained in this section. From equation:

- The amplitude of dc component equals zero
- The amplitude of all even harmonics equal zero

Thus, only the odd harmonics in the quarter-wave symmetric multilevel waveform need to be eliminated. The switching angles of the waveform will be adjusted to get the lowest THD in the output voltage:

$$[\cos\theta_1 + \cos\theta_2 + \cos\theta_3 + \dots] = M \tag{21}$$

If needed to control the peak value of the output voltage to be V1 and eliminate the fifth and seventh order harmonics, the modulation index is given by:

$$\mathrm{M} = \frac{nV_1}{4V_{dc}}$$

The resulting harmonic equations are:

$$\frac{4V_1}{4V_{dc}} = [\cos\theta_1 + \cos\theta_2 + \cos\theta_3 + \dots] = V_1 \tag{22}$$

$$[\cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 + \dots] = 0 \tag{23}$$

$$[cos7\theta_1 + cos7\theta_2 + cos7\theta_3 + \ldots] = 0 \qquad (24)$$

Equation (1) is written as:

$$[cos\theta_1 + cos\theta_2 + cos\theta_3 + \ldots] = M \qquad (25)$$

Theoretical calculation: The input voltage to the z-source is the output of the photovoltaic panel. The output voltage and current are taken from the simulation output of PV panel. The input voltage and current of z-source inverter be Vdc = 110 volts, Idc = 3 A.

Modulation index M = $\frac{A_r}{A_c} = \frac{0.6}{1} = 0.6$.

Duty ratio can also be find using Modulation index which is given by:

D0 = 1 - M, D0 = 1 - 0.6 = 0.4

Boost factor:

$$b = \frac{1}{1-2d} = \frac{1}{1-2*0.4} = 5$$

Therefore using input voltage, modulation index and boost factor we can find the output voltage of the z-source inverter which is given by Output voltage Vac = M. b.

The switching loss is calculated by:

$$Switching\ loss = \frac{1}{2}\, V_o\, I_o\, f_s\, (T_{c(ON)} + T_{c(OFF)}) \qquad (26)$$

where,

$T_{C(ON)}$ = Circuit turn on time

$T_{C(OFF)}$ = Circuit turnoff time

F_s = Switching frequency

V_o = Output voltage

I_o = Output current

The switching loss of the main switch is 0.82 W and the auxiliary switch is 0.21 W.

RESULTS AND DISCUSSION

The simulation model of the proposed system consists of PV Panel model, subsystem of Z source inverter and the genetics algorithm based SVPWM controller. The PV panel model consists of six series connected PV cells to generate the required voltage for the 25°C temperature and irradiance 1000 W/m^2. The PV cell model is modeled using the basic circuit Eq. (1) to (2). The voltage generated by the PV cell is 110 volt.

The prinicipal characteristics of WAREE WS 100 PV module is summarized in Table 2.

The output of the PV array is 110 V and the voltage is applied to the Z source inverter. The voltage and power relation of the PV cell is shown in Fig. 8. The outputs of the inverter are 230 V and 50 Hz. Figure 9 shows the output voltage of Z source inverter 1 and 2.

The closed loop current controller output is shown in Fig. 10. The grid voltage and current waveform is almost a pure sine wave as shown in Fig. 11 and 12, respectively.

Table 2: PV module specifications of wareews100

Parameters	Values
Maximum Power (Pmax)	10 W
Voltage at maximum power (Vmp)	17 V
Current at max power (Imp)	0.59 A
Open circuit voltage	21 V
Short circuit current	0.62 A
Tolerance	5%
Power measured at standard test load	1000 W/m^2, 25c, AM 1.5
Temperature co-efficient of power	-0.47% IK
Temperature co-efficient of voltage	-0.123 V/K
Operation temperature	-40 to 85 °C
Nominal operating cell temp	48°C
Maximum system voltage	1000 VDC

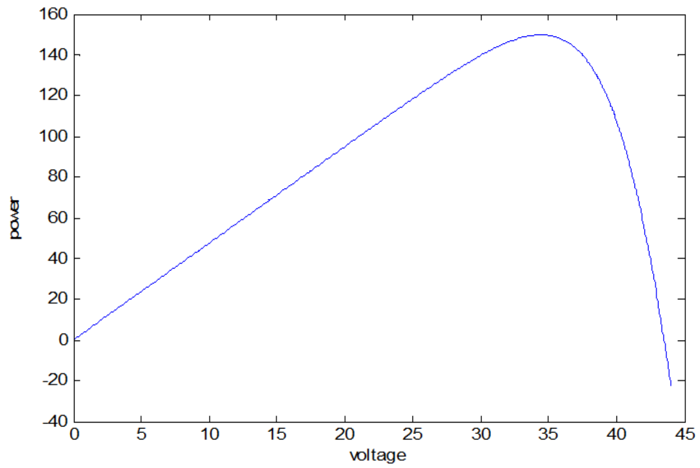

Fig. 8: Voltage-power waveform of PV

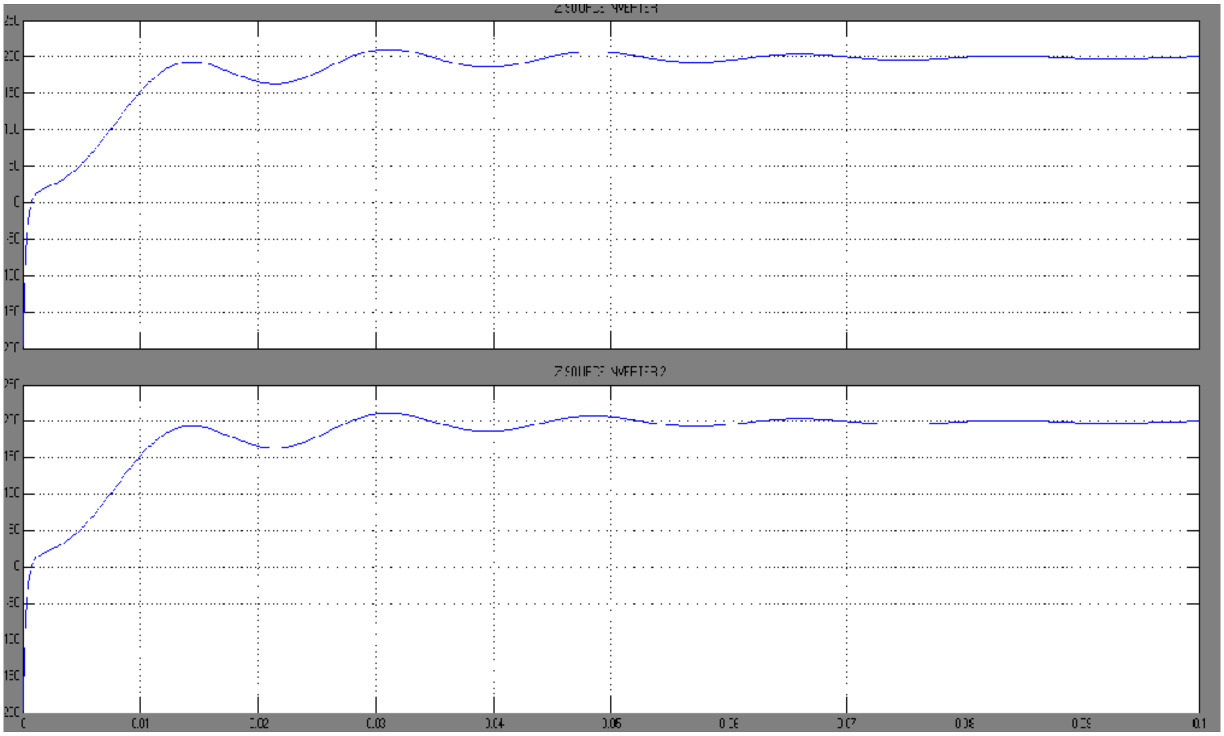

Fig. 9: Output voltage of Z source inverter 1 and 2

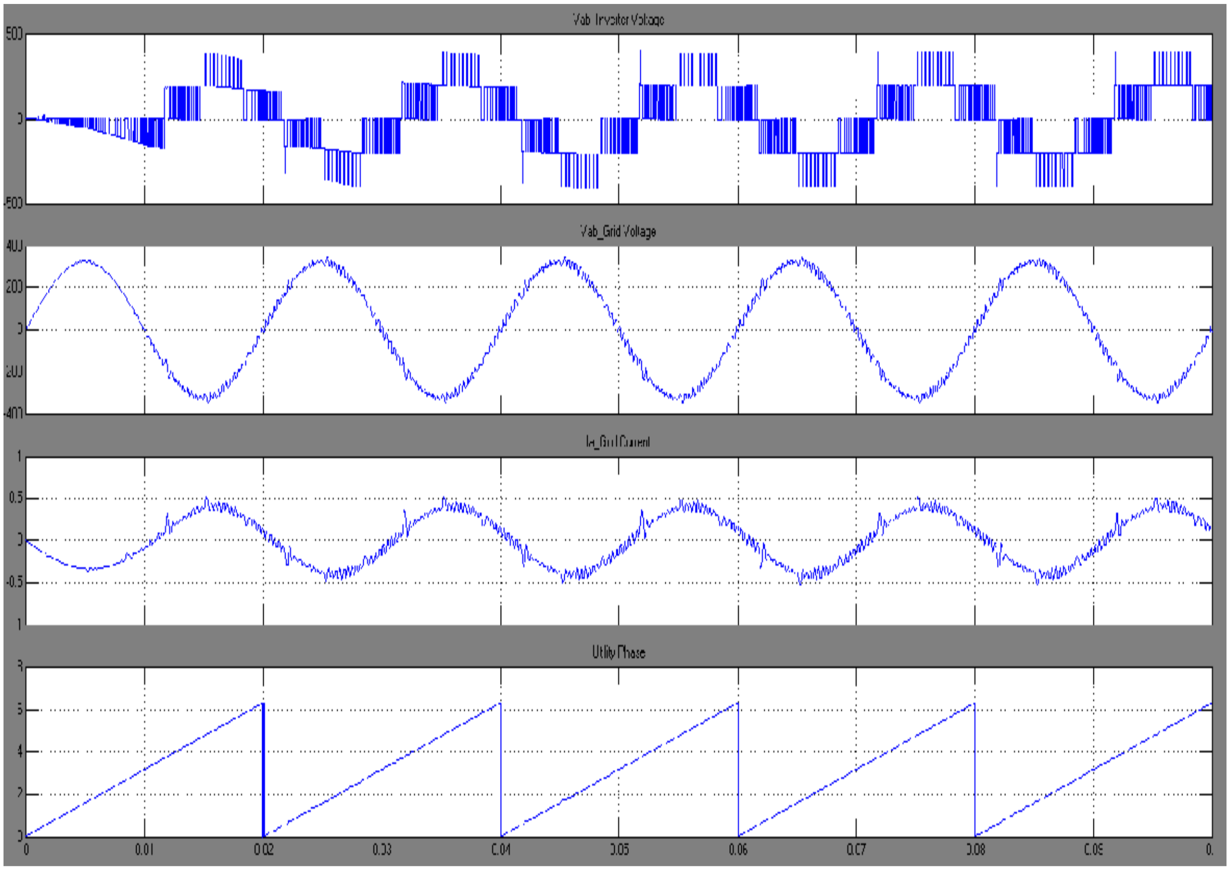

Fig. 10: Closed loop circuit waveform

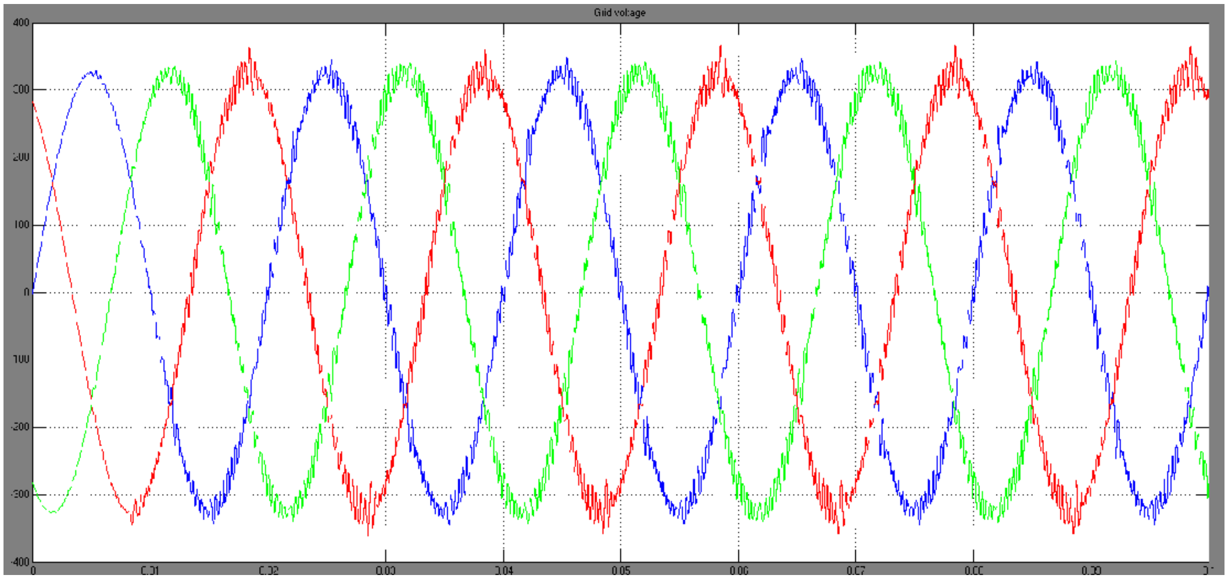

Fig.11: Output voltage of the grid

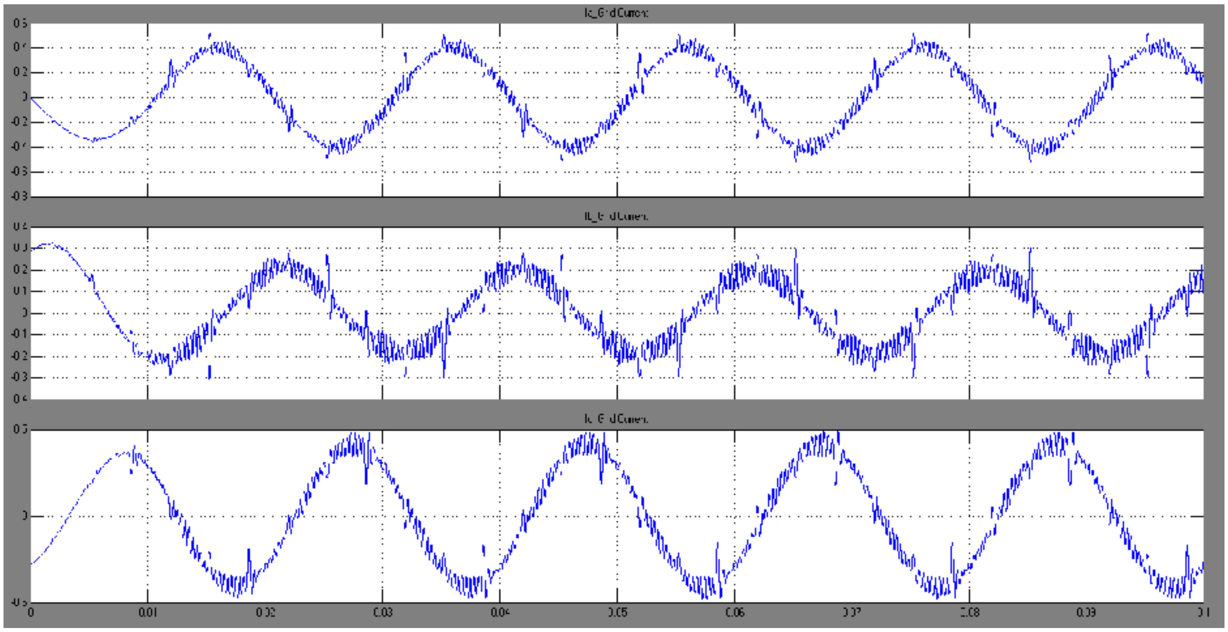

Fig. 12: Three phase output grid current

Table 3: Harmonic analysis comparison of controllers

	Without genetics controller		With genetics algorithm	
Configuration	Voltage (%)	Current (%)	Voltage (%)	Current (%)
Two level	68.39	5.78	10.20	4.38
Three level	45.42	2.08	5.60	2.01

The sampling frequency is 3 Khz. The simulation was carried out to observe the improvements in the line voltage THD and line current THD for grid connected system by using FFT analysis and its harmonic spectrum is shown in Fig. 13. The comparison between conventional and proposed method harmonic analysis is listed in Table 3.

CONCLUSION

In this study the Genetics algorithm controlled Z-source based multilevel inverter is presented. The Z-source network is capable of boosting low voltage from the PV system to the rated level. The ripple in the output of the PV array and the inverter is reduced by

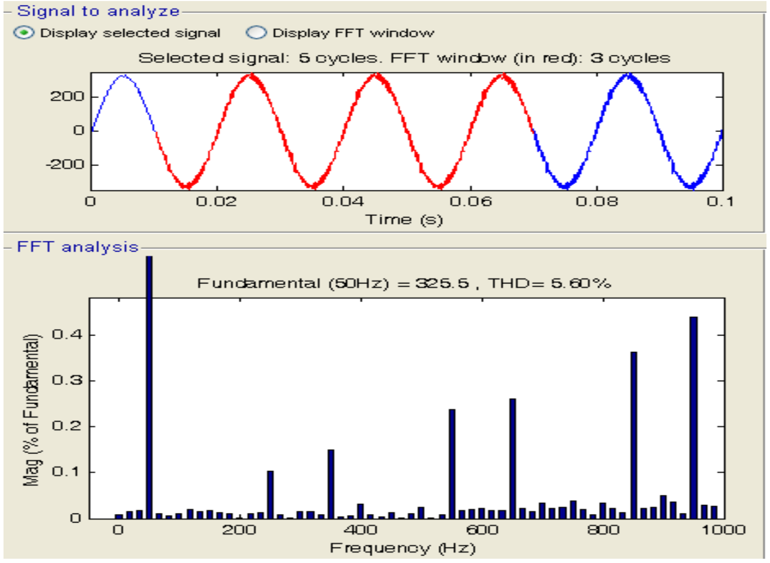
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Fig. 13: Harmonics FFT spectrum

using Z-network. The Z source network with neutral clamped multilevel inverter structure enhances the reliability of the system. Therefore the small ratings of passive components are adequate to compensate the unpredictable solar input; thereby efficiency mitigation of output can be avoided. The disadvantage of the system is that the passive component counts and their summarized values will be increased. Analytical models are verified using MATLAB SIMULINK and the results are presented.

ACKNOWLEDGMENT

Authors acknowledge the support, encouragement and facilities provided by the School of Electrical Engineering and the management of VIT University, Vellore, Tamilnadu, India in carryout the presented research work. And also thank the IIT Bombay, Department of Energy Science and Engineering for provided the solar kit.

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