Simulation of Three-Phase Grid Interactive Inverter for Wind Energy Systems

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Abstract— **Electrical energy's transfer, obtained from the wind energy systems, directly to the grid or load is not possible in terms of efficiency and usability. For these reasons, grid interactive inverters are largely used for wind energy systems. In this study, three phase grid interactive Voltage Source Inverter (VSI) controlled by Space Vector Pulse Width Modulation (SVPWM) has been performed. The current controller model, Proportional-Integral (PI) controller regulated the injected grid current, has been implemented as the grid interactive VSI control model. In order to operate between inverter and grid synchronously, the phase angle of grid voltage is detected by using Phase Locked Loop (PLL) in dq-synchronous reference frame. This system has been simulated under MATLAB/SIMULINK. Simulation results illustrate that inverter output voltages are in same phase and frequency with grid voltages.**

Keywords—*grid interactive inverter; PLL; SVPWM; synchronous reference frame; VSI;*

I. INTRODUCTION

Wind energy systems (WES) have grown very rapidly in the last years by means of being clean, economic and reliable energy systems. Since the wind speed is always not stable, amplitude and frequency of the voltage of the produced AC energy vary permanently. So electrical energy's transfer to the utility grid or load directly is not possible in terms of efficiency and usability. Thus, many WES have an AC-DC-AC pattern. On the AC-DC pattern, uncontrolled diode rectifier is usually used due to the simple and inexpensive. On the DC-AC pattern, grid interactive VSI controlled by Space Vector Pulse Width Modulation is extensively used. Electrical energy obtained from the WES is preferred to transfer to grid instead of storing energy. In order to transfer energy to the grid, many conditions such as fixed-frequency, continuity of electrical energy, sinusoidal-shaped waveform, being balanced of the phase voltages, to be within certain limits of current harmonics must be carried out. In this sense, the grid interactive inverter and its control technique is fairly important [1-3].

Grid interactive inverters can be projected as current source inverter (CSI) or voltage source inverter (VSI). Although CSI has some superiority such as showing high resistance to short circuits and blocking reverse voltage, VSI are preferred in many applications due to less conduction losses and easier control [4].

Recently, various methods have been recommended for controlling the three-phase grid interactive VSI. Some of these methods are hysteresis current control (HCC), sinusoidal pulse width modulation (SPWM) and SVPWM. In HCC method, dynamic response is good, but switching frequency and harmonics of current are variable. SPWM method is not difficult to implement, but it has high switching losses, needs reference and carrier signals, and cannot use DC link voltage effectively. At the present time, due to the drawbacks of HCC and SPWM, SVPWM method is largely used to control the three-phase VSI. The basic advances of SVPWM method are lower switching losses, low harmonic content, fixed switching frequency, and higher DC link usage [1, 5].

The amount of power that grid interactive inverters transfer to utility grid can be realized as a voltage or current controlled. In grid interactive inverters controlled by voltage, the obligation of monitoring the grid voltage sensitively both makes difficult to control algorithm and increases the cost of processor required for controlling. In case of not being monitored the grid voltage in precise, if a small synchronization error occurs, grid interactive inverter will be overloaded and so faults will take place. In current controlled grid interactive inverters, since inverter is much less sensitive to this situation, this method is proposed to control in the practices of power transmission to the utility grid. Furthermore, while active and reactive power cannot be controlled independently in voltage controlled inverter, in current controlled inverter, active and reactive power can be controlled independently. Because of this reason, current controlled grid interactive inverter can operate to unity power factor [3, 6]. Due to these advantages, current controlled model has been used in grid interactive three-phase VSI.

Varies control techniques such as fuzzy logic, hysteresis, and PI have been submitted for current controlled inverter. In fuzzy logic controller based inverters, the control algorithm becomes difficult and consequently the processor cost increases. Another method used in the inverter current control is the hysteresis controller method. In this method, the current is constantly kept within the selected reference band, and the gate signals which are necessary for the switches are produced by the current position in the reference band. Also additional algorithms needed to in the hysteresis method, are restricted in this method in terms of using on one-phase systems. PI

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controller resulted from the combination of the proportional and integral control action, and successfully used in different application areas is one of the control techniques. In this technique, as being simple algorithm structure reduces the processor cost, this technique can be easily used in three-phase system [6]. Therefore, in the current control of grid interactive three-phase inverter, PI control technique has been generally applied.

An algorithm must be run for the grid interactive inverter with the utility grid to operate synchronously [7]. That is to say, the current injected to the grid have to be in same phase with the grid voltage [3]. For this reason, synchronization algorithm plays a major role for wind energy systems [8]. To accomplish this, the grid voltage's phase angle must be accurately determined to control the inverter. To determine the grid voltage's phase angle, the zero crossing detection, filtering of grid voltages, and phase lock loop (PLL) are used as methods [7]. In the zero crossing detection method that is one of the simplest methods for assessing the phase-angle, the zero crossing points of the grid voltages are obtained. As the zero crossing points are able to be just obtained at every half cycle of the grid voltage frequency accurately, the dynamic response of this method is not good [9]. Besides, since the zero crossing method is very susceptible to noise and distortion on the grid, it is only suitable for using where the utility voltages are stable and have sinusoidal-shape waveform [10]. In filtering of grid voltages method, different reference frames can be used such as αβ or dq frame. Its dynamic response is better than the zero crossing detection method, however, when grid errors and variations come into existence, this method comes across with challenges to determine the phase-angle. Also, filtering of grid voltages method necessitates the use of the arctan function to define the phase-angle of the grid voltage [8]. Nowadays, the most extensively accepted synchronization method is phase lock loop because of drawbacks of the zero crossing detection and filtering of grid voltages methods [11]. PLL method can be widely used in different industrial areas such as communication systems owing to its perfect noise rejection capability, the speed control of electric motors, contact-free power supplies and induction heating power supplies [11, 12]. In grid interactive applications, PLL method is used for synchronization between three-phase VSI and the utility grid [11]. PLL has a better compensation of grid harmonics, disturbances, flickers, sags, swells and notches, however, in order to be up to grid unbalance, it needs extra improvements such as various filtering techniques [8]. Moreover, PLL has a very fast and precise detection capability of phase-angle during change of wind speed [12]. Hereby, because the system will be affected negatively in case of determining phase-angle falsely, PLL constitutes of the heart of the system.

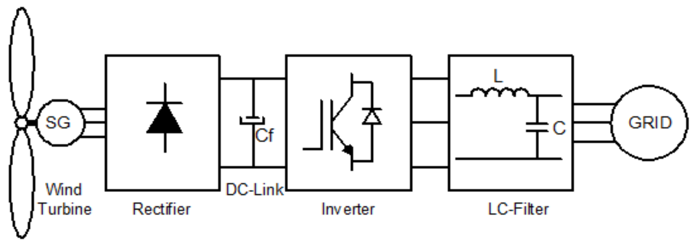

Fig. 1. Block diagram of grid interactive wind energy system

The main purpose of this paper is to simulate three-phase grid-interactive VSI under MATLAB/SIMULINK. VSI controlled with SVPWM method has been designed as current controlled and this system has been run. The all system is explained in Section II. The current control algorithm, model of a three-phase inverter, and PLL controller are explained in Section III. The MATLAB/SIMULINK model of the grid interactive VSI and simulation results are given in Section IV.

II. Characterisation of Overall System

In this study, grid interactive wind energy system consists of synchronous generator, uncontrolled rectifier, filter capacitor for DC-link, VSI, and LC filter and overall of this system is shown in Fig. 1. The amplitude and frequency of the AC energy that is produced by three phase synchronous generator change perpetually depending on the wind speed. Therefore, the AC energy is not transmitted directly to the three phase grid with 380V and 50Hz in Turkey. At first, AC voltages with the variable amplitude and frequency must be converted to impure-DC voltage with diode rectifier and subsequently, to purify DC voltage, impure-DC voltage is filtered by large value capacitors. In this way, pure DC-link voltage is obtained simply. The DC energy is transferred to the utility grid with voltage source IGBT inverter controlled with SVPWM at fixed switching frequency.

In order to minimalize the current's high frequency harmonic components, LC filter is used between VSI and the grid. The output current total harmonic distortion (THD) is decreased by means of LC filter [3].

III. Control Structure of The Grid Interactive Inverter

Three-phase grid interactive inverter system comprises of current and phase-angle control pattern. The block scheme of the control algorithm is shown in Fig. 2 [13].

A. Current Control

In the simulated control structure, the currents transferred to the grid are converted from the natural abc frame to the stationary αβ frame by Clarke transformation. Then, the current signals in the αβ frame are converted to the synchronous dq frame via the Park transformation [6]. For this conversion processes, Clarke transformation matrix and Park transformation matrix are given in (1) and (2).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}. \tag{1}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \tag{2}$$

To realize the Park transformation, phase-angle information is needed. The phase-angle is determined by the result of applying the grid voltages to PLL block. The current values obtained from the Park transformation are applied to the PI controller blocks for using grid interactive VSI current control [6]. The transfer function of PI current controllers are defined as in (3).

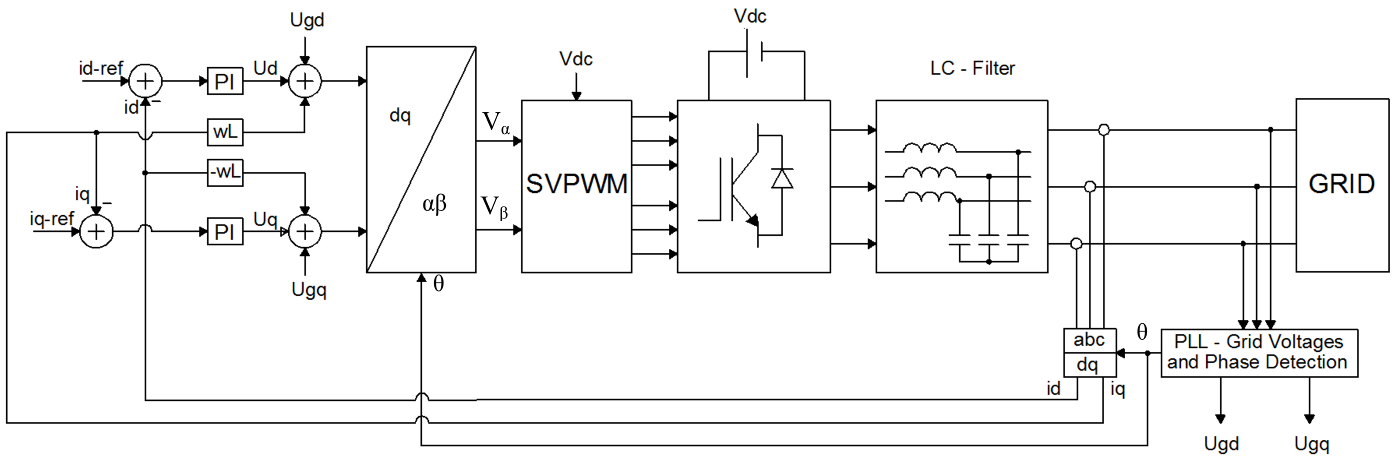

Fig. 2. Block diagram of control structure

$$G_{PI}(s)_{dq} = \begin{bmatrix} K_P + \frac{K_I}{s} & 0 \\ 0 & K_P + \frac{K_I}{s} \end{bmatrix}. \quad (3)$$

In fact, while the d-axis reference current $i_{d\text{-}ref}$ is controlled to arrange the active power variation and typically to fulfill the DC voltage regulation, q-axis reference current $i_{q\text{-}ref}$ is controlled to arrange the reactive power variation and typically to achieve a unity power factor. In practice, in order to obtain the operation at unity power factor, $i_{q\text{-}ref}$ should be zero, but it should be noted that $i_{q\text{-}ref}$ is nonzero value [13].

According to the current values obtained by Park transformation compared with reference input values of the simulation, the obtained output values from the PI controllers, which are trying to bring the actual currents to theirs references [12], are applied the reverse Park transformation. With reverse Park transformation, these currents are transferred from dq frame to αβ frame again and reverse Park transformation matrix is given in (4). This angle information required for transformation is again obtained by the PLL block. The current signals converted αβ frame are applied to SVPWM block and in this way, the switching signals are obtained for grid interactive VSI. Since phase-angle is determined by PLL algorithm, three-phase voltages produced by VSI are in same phase and frequency with grid voltages [6].

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}. \quad (4)$$

In Fig. 2, to improve the performance of PI controller and reduce the effect of grid harmonics, cross-coupling terms (ωL) and voltage feedforward (U_{gd} and U_{gq}) are generally used [5, 8].

B. SVPWM Controlled Three-phase VSI

In three-phase grid interactive VSI, the output of the inverter is linked to the grid. To provide power flow from the inverter to the grid, the output voltage of inverter has to be higher than the grid voltage [14].

The standard circuit of three-phase two-level VSI is given in Fig. 3. In this figure, V_{DC} stands for the rectified voltage of wind turbine. Switching position of each phase leg are separately controlled by switching variables of a, b and c. In this circuit, there are six-IGBT power switches (S_1, S_2, S_3, S_4, S_5, and S_6) controlled by a, b and c. In operation of the three-phase VSI, the switches in the same leg require not to be conduction at the same time. When one of the switches in the upper leg is turned on, i.e. a, b or c is 1, the relevant switch in the lower leg has to be turned off, i.e. is 0 [1].

According to the inverter switching state, phase-to-neutral voltage values are shown in Table I. Depending on the switching state, VSI generates eight different voltage vectors (six-active and two-zero vectors). In Fig. 4, V_1-V_6 are active vectors, while V_0 and V_7 are zero vectors. While active vectors allow for the change of the inverter output voltage, zero voltage vectors make zero the output voltage value by short-circuiting lower or upper set of switches [1].

The inverter, depending on the current reference value to be supplied to the grid, produces the output voltage vector as called reference vector. This vector is produced with the SVPWM by using the active adjacent vectors and zero vectors located in the same region [1] and it can be taken more information in [1].

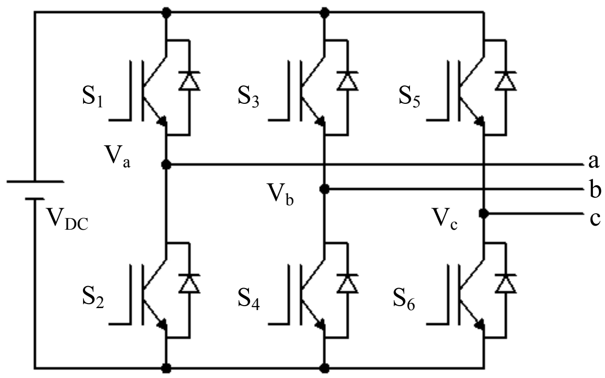

Fig. 3. Three-Phase VSI

TABLE I. SWITCHING VECTOR AND PHASE TO NEUTRAL VOLTAGE

Voltage Vector	Switching State			Phase-to-Neutral Voltage		
	a	b	c	V_a	V_b	V_c
V_1	1	0	0	2/3	-1/3	-1/3
V_2	1	1	0	1/3	1/3	-2/3
V_3	0	1	0	-1/3	2/3	-1/3
V_4	0	1	1	-2/3	1/3	1/3
V_5	0	0	1	-1/3	-1/3	2/3
V_6	1	0	1	1/3	-2/3	1/3
V_7	1	1	1	0	0	0
V_0	0	0	0	0	0	0

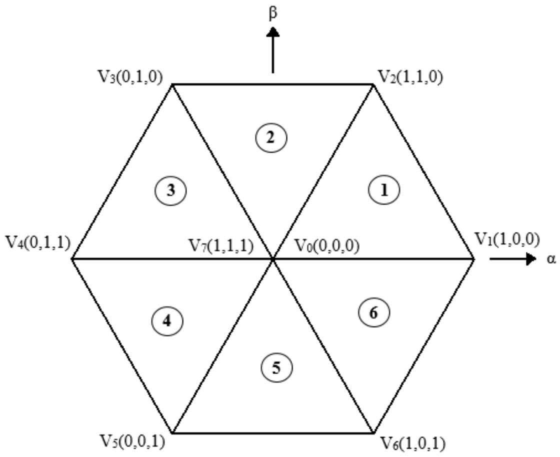

Fig. 4. Active and zero vectors

C. *PLL Algrorithm*

The PLL algorithm that is used to synchronize the phase of VSI output voltage with the utility grid voltage at the grid interactive operation is a typical closed-loop servo system [15-16], where the instantaneous phase-angle of the grid voltage, θ, is detected [11]. The block scheme of PLL designed in dq synchronous-rotating reference frame is illustrated in Fig. 5. As seen from the figure, the three-phase grid voltages V_a, V_b, V_c are measured and transformed into the stationary reference voltages V_α and V_β like in (1), then converted to the rotating reference voltages V_d and V_q like in (2) [12]. V_d and V_q appear as DC quantities. The PI worked as a loop filter of PLL is usually used to control V_q parameter, and under ideal conditions such as no harmonics, balanced grid voltages, V_q value is zero while V_d is equal to the maximum value of the grid voltage. On the other part, the output of PI controller becomes the grid frequency by adding feedforward angular frequency of the grid (where angular frequency, $\omega_g = 2\pi f$ and f is the fundamental frequency of the grid voltage waveform). θ is determined by the integration of angular frequency,. The estimated phase-angle is fed back into the αβ-dq transformation block [8, 12]. Also, the grid voltage frequency, f, can be determined in this control system [11].

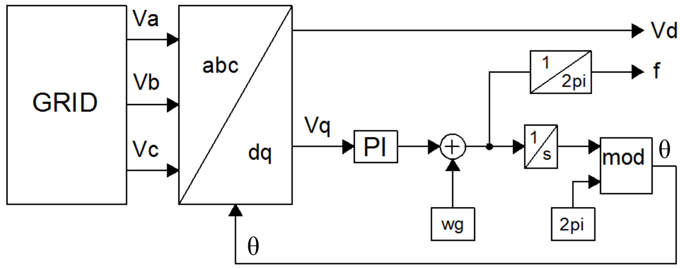

Fig. 5. Basic block diagram of the dq-PLL

IV. SIMULATION RESULTS BASED ON MATLAB / SIMULINK

In this section, a SVPWM controlled 3-phase grid interactive VSI model is simulated with MATLAB/SIMULINK and in order to prove the accuracy of the synchronization between the inverter and the grid, the simulation results are given. The Simulink model is shown in Fig. 6. The reference current values, $i_{d\text{-}ref}$ and $i_{q\text{-}ref}$, are entered into simulation 10A and 0A, respectively. The simulation parameters are listed in Table II. The phase angle obtained by PLL and the grid voltage, V_{α}, are shown in Fig. 7. In this way, it is understood that the phase angle is correct. The three-phase balanced inverter output voltages and inverter-grid voltages (yellow one is inverter voltage, pink one is grid voltage) are given in Fig. 8 and Fig. 9, respectively. The inverter voltage is in the same phase with the grid voltage. As seen in Fig. 9, according to the grid voltage, the voltage produced by the inverter has higher frequency harmonics. Hence, in order to compensate high frequency harmonics, the switching frequency of the VSI can be increased or the filter which is at the inverter output can be optimized.

TABLE II. SIMULATION PARAMETRES

DC link voltage (V_{DC})	540V
Phase to Neutral Voltage	220V
Fundamental frequency	50Hz
Switching frequency	5kHz
Amplitude of the triangle wave	0.0002V
Frequency of the triangle wave	5kHz
Simulation step time	1E-6
Filter inductance (L)	0.5mH
Filter capacitance (C)	25μF
Inductance resistor	0.1Ω
Kp; Ki	2; 0.1

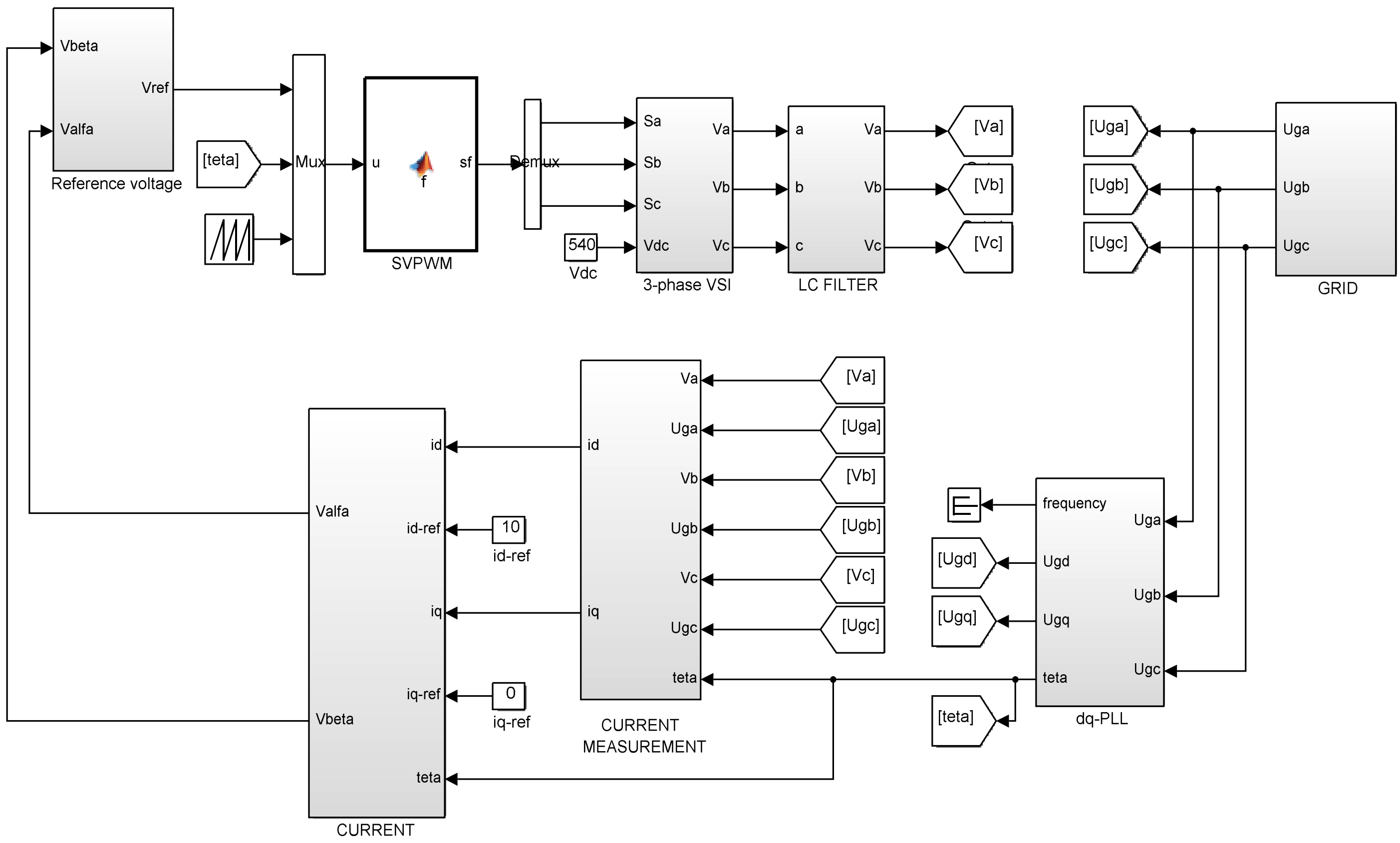

Fig. 6. Simulink model of the system

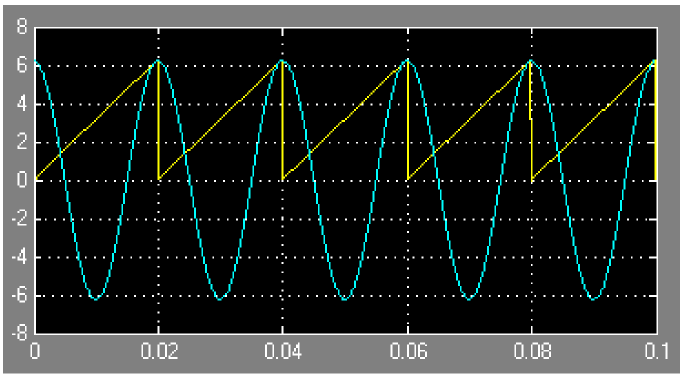

Fig. 7. Phase angle and V_{α}

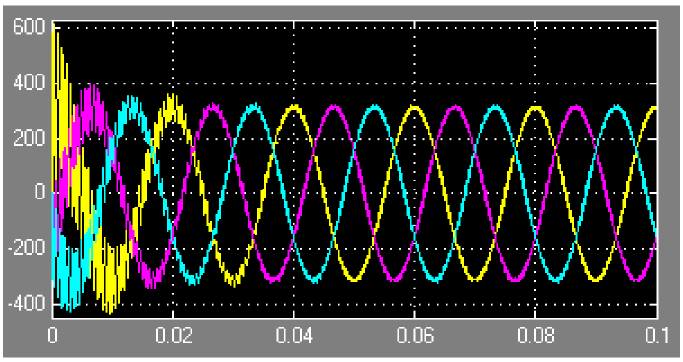

Fig. 8. Inverter output voltages

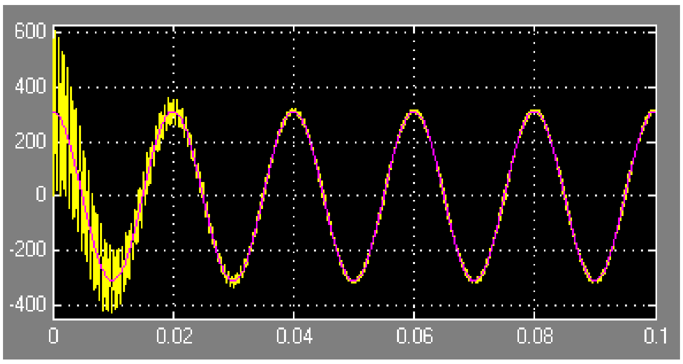

Fig. 9. Inverter and grid voltages

V. CONCLUSION

In this paper, the model of three-phase grid interactive VSI is simulated under MATLAB/SIMULINK. The three-phase VSI is controlled with SVPWM algorithm and PLL controller is used to operate between the VSI and the grid synchronously. The PI current controller model is implemented as the grid interactive VSI control model. In order to compensate high frequency harmonic components, LC filter is used between VSI and the grid. Simulation results prove that three-phase voltages produced by VSI are in same phase and frequency with grid voltages.

REFERENCES

[1] F. Sevilmiş, and H. Karaca, "Simulation and analysis of SVPWM based VSI for wind energy systems, " Electronics, Computers and Artificial Intelligence (ECAI), International Conf., vol. 6, no.1, Bucharest, Romania, pp. 71-75, 23-25 Oct. 2014.

[2] E. Isen, A. F. Bakan, "Three-phase grid-connected inverters with space vector modulation control," 4th Symposium on Energy Efficiency and Quality, EVK, Kocaeli, Turkey, 2011, pp. 32-36.

[3] I. Sefa, N. Altın, and S. Ozdemir, "An implementation of grid interactive inverter with reactive power support capability for renewable energy sources," Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives, Torremolinos (Malaga), Spain, pp. 1-6, May 2011.

[4] I. Sefa, N. Altın, and S. Ozdemir, "Three phase grid interactive inverter for renewable energy sources," 5th İnternational Advanced Technology Symposium (IATS'09), Karabuk, Turkey, 13-15 May 2009.

[5] E. Isen, A. F. Bakan, "10 kW grid-connected three-phase inverter system: control, simulation and experimental results," Power Electronics for Distributed Generation Systems (PEDG), 2012 3rd IEEE International Symposium, Aalborg, pp. 836-840, 25-28 June 2012.

[6] Ş. Demirbaş and S. Bayhan, "DSP based three phase grid interactive inverter for renewable energy sources," Fırat University Engineering Sciences Magazine, 23(1), 2011, pp. 21-33.

[7] F. Iov, and F. Blaabjerg, "Power electronics control of wind energy in distributed power systems," Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference on pp. 29-44, 22-24 May 2008.

[8] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," IEEE Transactions on Industrial Electronics, vol. 53, no. 5, Oct. 2006.

[9] A. Timbus, R. Teodorescu, F. Blaabjerg, and M. Liserre, "Synchronization methods for three phase distributed power generation systems. An overview and evaluation" Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th, pp. 2474-2481, June 2005.

[10] E. Isen, "Development of a grid connected three phase inverter system with low harmonics and high efficiency for renewable energy sources," PhD Thesis, Yıldız Technical University Institute of Science, Istanbul, Turkey, 2011.

[11] X.-Q. Guo, W.-Y. Wu, and H.-R. Gu, "Phase locked loop and synchronization methods for grid-interfaced converters: a review," Electical Review, vol. 87, no. 4, pp. 182-187, 2011.

[12] M. M. Amin, and O. A. Mohammed, "Software phase locked loop technique for grid-connected wind energy conversion systems," Control and Modeling for Power Electronics (COMPEL), IEEE 12th Workshop on pp. 1-8, 28-30 June, 2010.

[13] R. Teodorescu, M. Liserre, and P. Rodriguez, "Grid converters for photovoltaic and wind power systems," John Wiley & Sons, Ltd, 2011.

[14] P. Ghani, V. Asadzadeh, and H. M. Kojabadi, "Implementation of three-phase grid-connected inverter using TMS320LF2407A microprocessor," Power Electronics, Drive Systems and Technologies Conference (PEDSTC) 2nd, pp. 305-310, Feb. 2011.

[15] T.-V. Tran, T.-W. Chun, H.-H. Lee, H.-G. Kim, and E.-C. Nho, "Control for grid-connected and stand-alone operations of three-phase grid-connected inverter," Renewable Energy Research and Applications (ICRERA), International Conference on pp. 1-5, Nagasaki, Japan, 11-14 Nov. 2012.

[16] F. D. Freijedo, and et al., "Grid-synchronization methods for power converters," Industrial Electronics Society Annual Conference (IES), Spain, pp. 522-529, 3-5 Nov. 2009.