IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 10, Issue 1 Ver. II (Jan – Feb. 2015), PP 53-61
www.iosrjournals.org

Power Flow Control in Grid-Connected Wind Energy Conversion System Using PMSG with Harmonic Elimination Added Function

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Abstract: *Renewable energy exploitation along with power quality play a major role in all power distribution systems. This paper presents a new controlling method for decreasing grid current total harmonic distortion as an added function in wind energy conversion using permanent magnet synchronous generator (PMSG). While improving the grid power quality using proposed method, an improved maximum power point tracking (MPPT) algorithm based on optimum torque controlling is employed. Using this improved algorithm makes MPPT efficiency be higher than 97%. A wind energy conversion using PMSG with nominal power of 20 KW at wind speed of 9 m/s is considered for simulation and connected to a nonlinear load and grid. Simulation results including MPPT in three different wind speeds and THD analyzing in presence and absence of harmonic elimination added function show impressive benefits of the proposed method.*

Keywords: *wind energy conversion; permanent magnet synchronous generator; harmonic elimination; maximum power point tracking.*

I. Introduction

In fact electric power sustainability plays a crucial role forcing the renewable energy sources to be implemented for electric energy generation instead of fossil ones. The conventional fossil fuels depletion and environmental pollution go hand-in-hand for making a growth in renewable energy exploitation. These main reasons create awareness in all electrical engineering to harvest electrical power from renewable energy sources such as wind energy and photo-voltaic (PV) systems [1]-[2]. Moreover, renewable energy sources have some enormous advantages including high capability of using wide range power exploitation, low price of produced power and no need of water or other fluids [3].

In the previously mentioned renewable energy sources, wind turbines have increased significantly in the world. Wind energy conversion systems (WECSs) have been utilized in many applications; accordingly, various technologies in all related fields are developed for them. Permanent-magnet synchronous generator (PMSG) generation system shows a major trend in development of wind power applications due to its considerable advantages [1]-[6].

Controlling the injected power in the grid-connected Wind energy conversion systems (GCWECSs) has a paramount of importance due to grid demand necessities. Therefore extracting maximum power from wind and feeding the grid with high-quality electricity are two main aspects for GCWECSs. Despite there are some direct ac-ac converters used in GCWECSs, based on these two key factors the ac-dc-ac converters are more suitable choice [2]-[8].

Fig. 1 shows a conventional configuration of ac–dc–ac topology for PMSG. This configuration involves diode rectifier, boost dc–dc converter and three-phase inverter. In this topology, DC-DC boost converter is controlled in such a way to tracking maximum power point (MPPT) and inverter is controlled to transfer power to the grid [5]-[13].

For several years great effort has been devoted to the study of maximum power point tracking (MPPT) algorithm in GCWECSs. To the author knowledge the most popular MPPT algorithms which are recently considered are including tip speed ratio (TSR) control, power signal feedback (PSF) control, perturb and observe (P&O) control and optimum torque control [14]-[17].

Regarding the fact that TSR is constant in all wind speed, In TSR algorithm TSR should be maintained in its optimum value. Therefore with using the error signal of optimum TSR and real TSR, control signals can be selected in such a way to reduce the error signals. In PSF method, at first optimum power with respect to rotational speed should be evaluated as a look-up table. Then by comparing the optimum power with real power, harvesting maximum power can be readily achieved. In P&O procedure, MPPT can be obtained using an iterative technique. Optimum torque control is based on PMSG torque. The error signal of PMSG optimum and real torques can be used as a controlling signal to extract maximum power. Due to its robustness and low oscillation in comparison with aforementioned algorithms, the authors use this technique and apply it to the interface DC-DC boost converter [14]-[17].

A large part of the total electrical energy produced in the world supplies different types of nonlinear loads, such as variable-frequency drives and high current rectifier. These loads are typically composed of odd harmonic currents, which are multiples of the fundamental frequency. The harmonic currents cannot contribute to active power and need to be eliminated to enhance power quality [18]. Although active power filters (APFs) are designed for this purpose, in GCWECSs the grid-side inverter playing the role of injecting power to the grid can be used to eliminate harmonics as an added function. Using this added function, there would be a significant reduction in investment cost. This paper presents a method to use the grid-side inverter in order to both control power injection and eliminate high-order harmonics.

The remainder of the paper is organized as follows. In the following section control system and its modeling will be discussed. Section III is devoted to discuss system layout and its features. The simulation and its results are entirely discussed in section IV. Finally a conclusion of this work will be drawn.

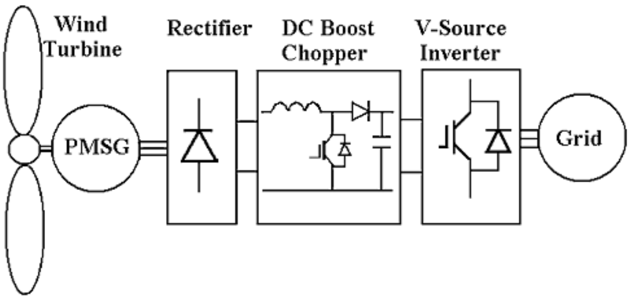


Fig. 1. Conventional PMSG-based WECS with dc-dc boost converter.

II. Control system

The overall structure of the grid-connected wind energy conversion system is shown in Fig. 2. On the whole there are two main control parts:

1- Maximum power point tracking.
2- Control of power delivered to the grid.

As a matter of maximum power extracting, optimum torque control is employed owing to its robustness and low oscillation in comparison with aforementioned algorithms. This technique would be applied to the DC-DC boost interface converter. For controlling injected power to the grid, the conventional vector control will be resorted. Here these two parts would be independently discussed as following.

A. Maximum Power Point Tracking

The block diagram of optimum torque control is illustrated in Fig. 3. This controller extracts the maximum power through comparing the PMSG optimum and real torque.

The mechanical power delivering through wind is calculated by:

$$P = \frac{1}{2}\rho\pi R^2 C_p {V_w}^3$$

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right).e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \qquad (1)$$

Where ρ is the air density, R is the radius of turbine blades, V_w is the wind velocity, and C_p is the power coefficient defined as the ratio of turbine power to wind power and depends on the aerodynamic characteristics of blades. It can be proved that the maximum value of C_p is limited to 0.56. For writing the equation (1) in terms of the rotor speed, we use following equation.

$$V_w = \frac{\omega_b R}{\lambda} \qquad (2)$$

Where λ is tip speed ratio. Therefore

$$P = \frac{1}{2}\rho\pi R^5 C_p \frac{\omega_b^3}{\lambda^3} \qquad (3)$$

Regarding above equation optimum power will be achieved provided that the power coefficient and the tip speed ratio are optimum. Accordingly

$$P_{opt} = \frac{1}{2}\rho\pi R^5 \frac{C_p^{\ opt}}{\lambda_{\ opt^3}}\omega_b^3$$
$$T_m^{opt} = \frac{1}{2}\rho\pi R^5 \frac{C_p^{\ opt}}{\lambda_{\ opt^3}}\omega_b^2 = K^{opt}.\,\omega_b^2 \qquad (4)$$

Now optimum torque is compared with real torque and its error signal is used for the interface DC-DC boost converter to extract maximum power.

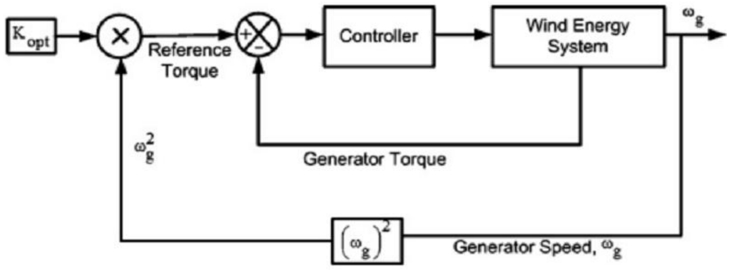


Fig. 3. Block diagram of optimum torque control

B. Control of Power Delivered to the Grid

Grid-tied generator is an electrical energy source including all needed interface units and operating in parallel with the distribution network [10]-[13]. Although some energy sources can be connected directly to the distribution network, but in the case of DC power sources or variable speed wind turbine (VSWT) systems it is necessary to use a power converter that interfaces the source and the grid. Due to the simplicity of vector controlling, here d-q axis theory is employed for power controlling.

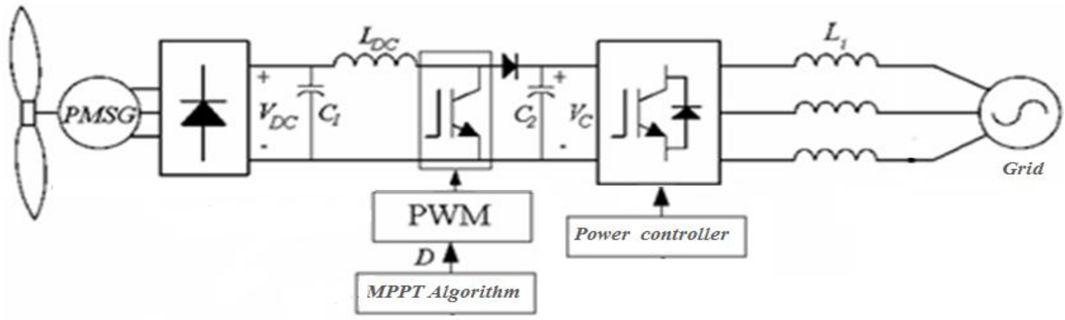


Fig.2. Overall structure of grid-connected wind energy conversion system

The power equations in the synchronous reference frame are given by [19]

$$P = \frac{3}{2}(v_d i_d + v_q i_q)$$
$$Q = \frac{3}{2}(v_q i_d - v_d i_q) \qquad (5)$$

Where P and Q are active and reactive power respectively, '*v*' is grid voltage and '*i*' is the current injected to the grid. The subscripts "*d*" and "*q*" refer to direct and quadrature components respectively. If the reference frame is oriented along the grid voltage, 'v_q' will be equal to zero. Then, active and reactive power may be expressed as

$$P = \frac{3}{2}v_d i_d$$
$$Q = -\frac{3}{2}v_d i_q \qquad (6)$$

According to the above equations, active and reactive power control can be achieved by independently controlling direct and quadrature current components respectively.

These parameters can be controlled as the following paths. With the specified reactive power, the q-axis current reference is set. To acquire unit power factor, the q-axis current reference should be set to 0. Meanwhile, in the extra function state this current should be set such a way that eliminates the higher order harmonics (with opposite sign of current harmonics drawn by local nonlinear load). For injecting maximum power to the grid, an outer capacitor voltage control loop (adjusting dc-link at its desired value) is used to set the d-axis current reference for active power control. This guarantees that all the power coming from the rectifier is transferred to the grid.

III. System LAYOUT

The main objective of this paper is to eliminate higher-order currents harmonics resulted from nonlinear load as an added function without using active power filter. The overall schematic of simulated GCWECS is illustrated in Fig. 4(a). Regarding this figure power flow control is performed in d-q reference frame where in reactive power is controlled by d-axis current. A nonlinear load is connected to grid leading to draw nonlinear current. This nonlinear load current is transferred to d-q reference frame. Because the angular position is obtained from grid voltage via PLL, so the d-axis current represents active power while q-axis one represents reactive power. Accordingly, by adjusting q-axis current, the reactive power drawn with three-phase rectifier can be cancelled. With performing this strategy, the total harmonic distortion (THD) of grid would be significantly diminished. If a selective harmonic elimination is required, we would be able to employ a band-pass filter in q-axis current to pass only considered harmonic for eliminating.

Furthermore, Fig. 4(b) demonstrates the MPPT controlling system. As it can be seen, rectifier output voltage and current are used to harvest maximum power based on equation (4). This method never applied to interface DC-DC boost converter. Therefore there is an aspect of novelty in addition to harmonic elimination added function.

As a case study and validation of new strategy, a wind turbine equipped with PMSG is considered. Their characteristics are listed in Table. 1 and Table. 2 respectively.

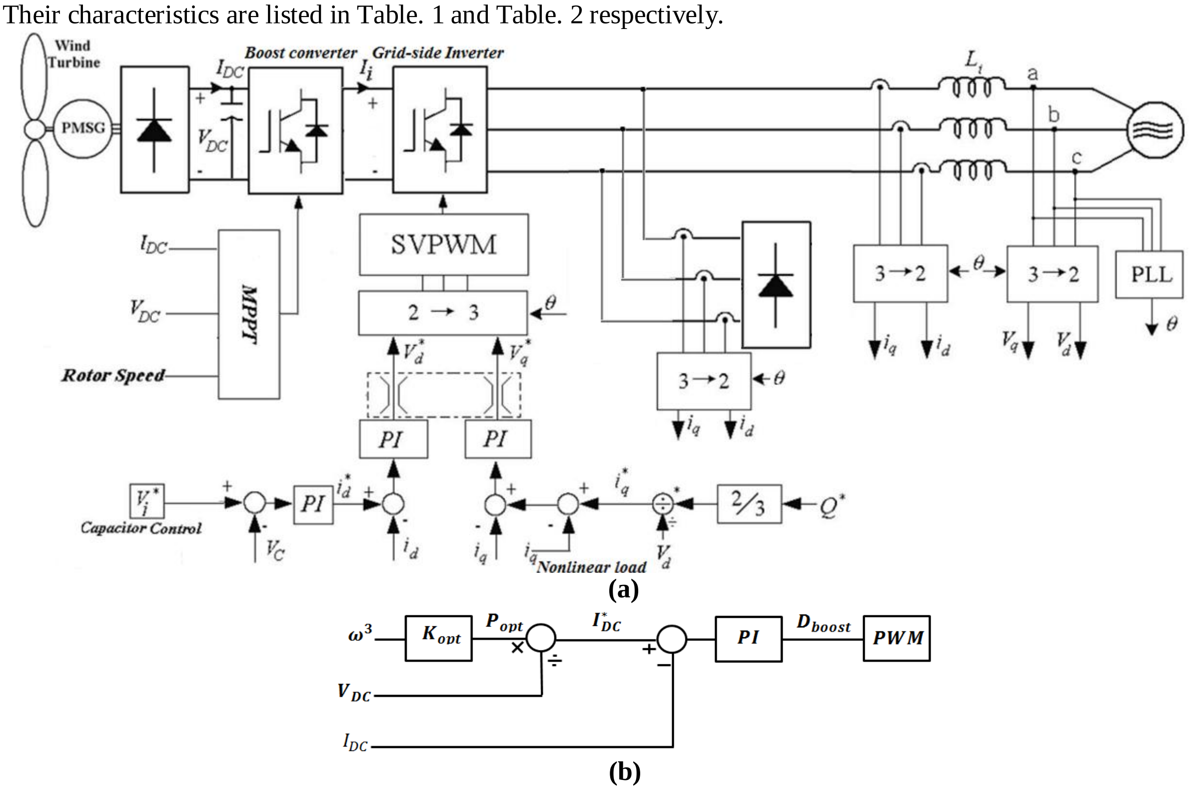


Fig.4. a) overall control system, b) MPPT algorithm implementation

Table. 1. Wind Turbine and PMSG Parameter

Wind Turbine and PMSG Parameter	Value
Turbine Blade Radius	*4.3 m*
Cut-in speed	*2 m/s*
Cut-off speed	*15 m/s*
Turbine efficiency	*0.905*
Air density	*1.225 Kg/m*^{3}

Table. 2. PMSG Parameter

PMSG Parameter	Value/Type
Phase Number	*3*
Rotor Type	*Round*
Stator Resistance	*0.895 Ω*
Stator Inductance	*12.45 mH*
Linkage Flux	*1.61 V.s*
Inertia	*1.47 Kg/m*^{2}

Moreover, the interface DC-DC boost parameters are given in Table.3. The calculation procedure of this converter is beyond this study and the interested readers are referred to [20]. Based on above mentioned objectives and the strategy depicted in Fig. 4, the PI coefficients in all controlling parts are obtained from system modeling and required dynamic response and listed in Table. 4.

It should be mentioned that the grid line-to-line voltage and its frequency are 380V and 60 Hz respectively. For being able to inject reactive power to the grid the Link-DC voltage should fixed near 800V (1.5*380*1.41). Therefore, V_i reference is constant and equal to 800V.

Table. 3. DC-DC Boost Parameters

DC-DC Boost Parameters	Value/Type
Inductance	*5 mH*
Input Capacitance	*1 mF*
Output Capacitance	*12 mF*
Switching Frequency	*100 KHz*

Table.4. Current and Voltage Regulators Parameters

Regulators Parameters	Value/Type
MPPT-K_P	*0.0031*
MPPT-K_i	*0.00018*
Inverter Link DC-K_P	*10*
Inverter Link DC-K_i	*800*
d-axis Current Regulator-K_P	*0.3*
d-axis Current Regulator -K_i	*20*
q-axis Current Regulator-K_P	*0.3*
q-axis Current Regulator -K_i	*20*

IV. Simulation Results

The wind speed pattern applying to the considered system is depicted in Fig. 5. These speeds are in cut-in/off limitation. For wind speed of 7, 9 and 11 m/s, the corresponding turbine powers are 5.3, 11.05 and 18.5 KW respectively. Based on equation (1), optimum C_P is evaluated around 0.47. Fig. 6 shows the PMSG output power versus its rotor speed. MPPT algorithm should perform in such way to make rotor speed be in desired value for catering maximum power harvesting.

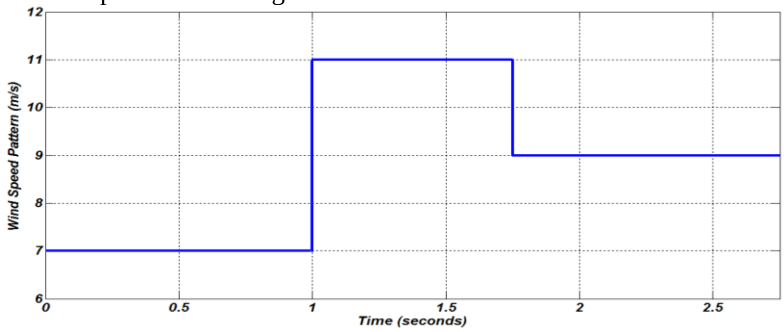


Fig.5. Considered wind speed pattern

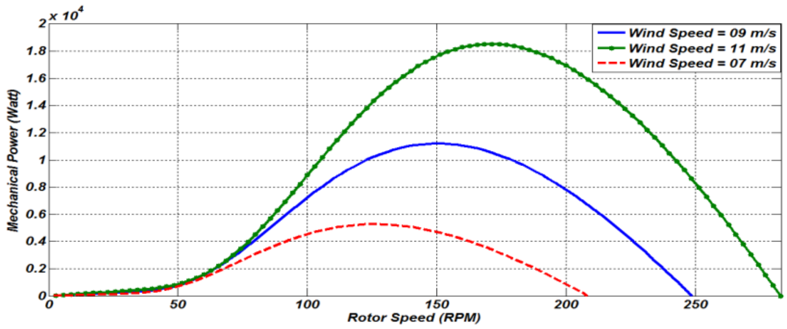
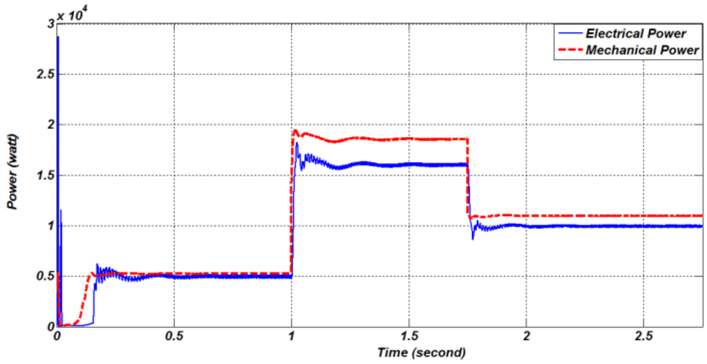
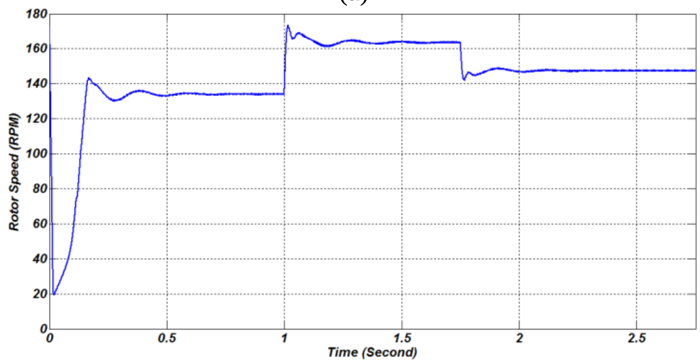


Fig.6. Mechanical Power versus Rotor Speed

While fig. 7(a) shows the wind turbine output power along with PMSG output power. The differences between these two powers are led from power loss in PMSG as well as turbine mechanical loss; Fig. 7(b) demonstrates rotor speed tracking the optimum speed. For a quantative comparison, the expected and real power and speed values are listed in Table. 5.



(a)



(b)

Fig. 7. a) Electrical and Mechanical Power, b) PMSG Rotor Speed.

Table.5. MPPT Features Comparison Based On Rotor Speed Turbine Power.

Wind Speed	Optimum Rotor Speed	Real Rotor Speed	Optimum Turbine Power	Real Turbine Power
7 m/s	*135 RPM*	*134 RPM*	*5.3 KW*	*5.1 KW*
9 m/s	*150 RPM*	*148 RPM*	*11.05 KW*	*11 KW*
11 m/s	*168 RPM*	*166 RPM*	*18.5 KW*	*18.1 KW*

Fig. 8 shows the link-DC voltage. Regarding this figure the link-DC voltage is fixed around 800V. The maximum settling time overshoot in this voltage are limited to0.55 sec and 6% respectively.

Fig. 9 demonstrates inverter output voltage and current. This figure is captured when the nonlinear load is not connected to the grid. Therefore current waveform is sinusoidal and low-harmonic. It is mentioned that in next part the nonlinear effects and proposed strategy would be discussed.

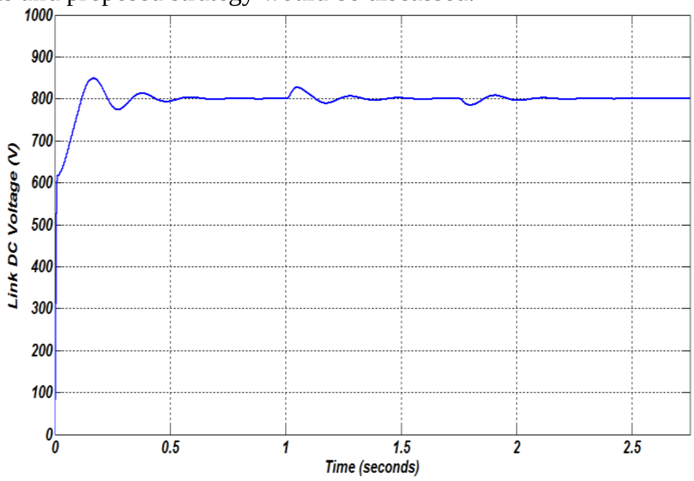
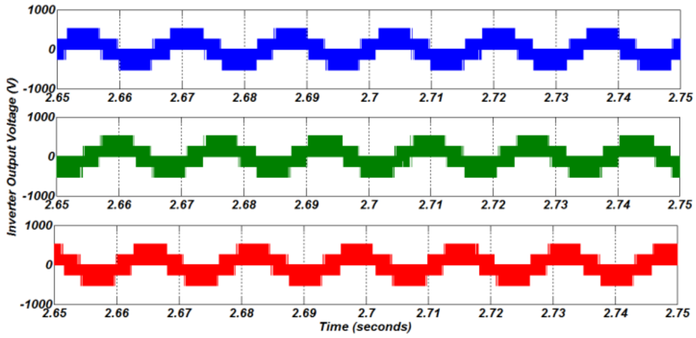
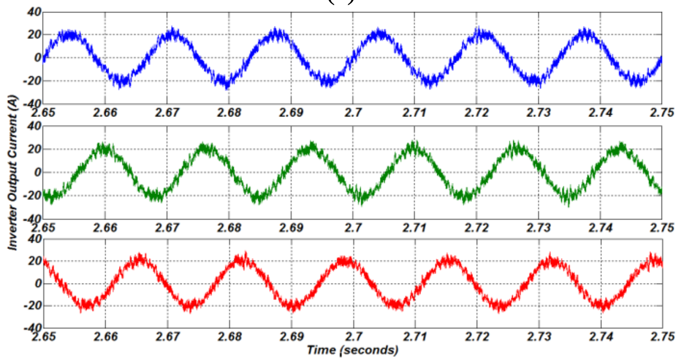


Fig.8. Link-DC Voltage During All Wind Speed.



(a)



(b)

Fig. 9. a) Inverter Output Voltage, b) Inverter Output Current.

For discussing proposed strategy merit, it is considered that a nonlinear load is connected to the grid while the wind speed is around 9 m/s and 11 KW active power is injected to the grid. Aiming to have low-harmonic grid current, nonlinear load current has been sensed and then based on this current; this new method would be applied. With using nonlinear load q-axis current and subtracting this current from reference q-axis current, this method can be performed.

Fig. 10 illustrates grid current waveform when the given strategy is not applied. As it is shown current THD is 63.47%. This high THD leads to EMI problems for communication as well as reducing the capacity of power transferring. Behaviors of grid under same condition when the proposed strategy is employed are depicted in Fig. 11. With regard to this figure, THD has been reduced to 19.19%. Accordingly, using GCWECS as a harmonic elimination added function without increasing the number of power electronic devices leads to near 42% THD reduction.

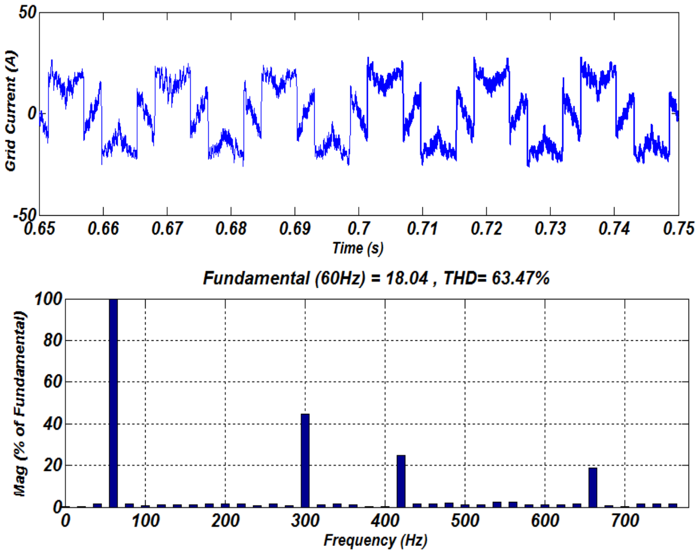


Fig.10. Grid current and its FFT analysis when proposed technique is not applied.

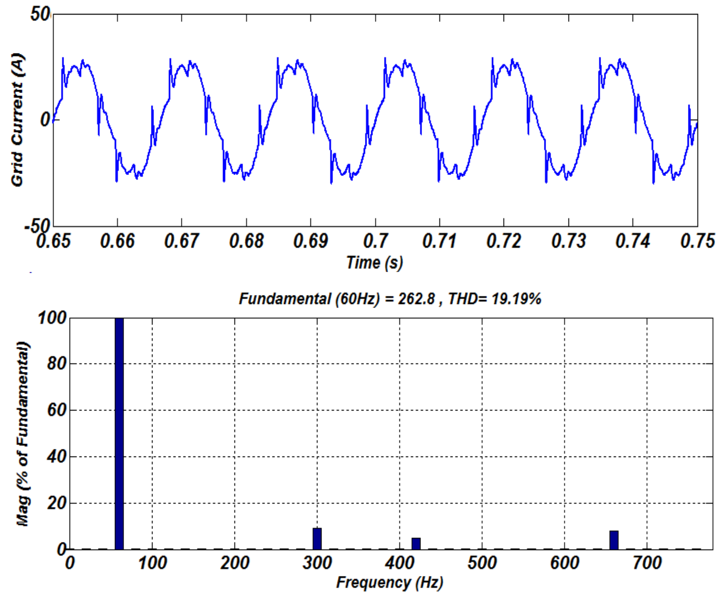


Fig.11. Grid current and its FFT analysis when proposed technique is applied.

V. Conclusion

A new grid-connected wind energy conversion system with current harmonic elimination as an extra function is presented. With employing this modified power controlling technique, the grid current harmonic reduction without employing any active power filters is achieved while a nonlinear load is connected to the grid. This is done with using q-axis current controlling by means of a voltage source inverter fired based on space vector modulation. Furthermore, a proposed MPPT algorithm based on optimum torque controlling is introduced and led to make MPPT efficiency at least around 97%. This MPPT is performed thorough an interface DC-DC boost converter. The capability of extracting maximum power, controlling power flow and current harmonic elimination as an extra function creates possibilities for many manufacturers dealing with nonlinear load to use GCWECSs as an extra electrical energy source.

Acknowledgement

The authors thank Islamic Azad University Central Tehran Branch for all helps and supports.

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