Performance of Type-4 Direct Driven PMSG Based Wind Energy Conversion System under Nonlinear Load Demand

Surinder Singh¹ and Deepak Kumar²*

¹ Department of Instrumentation, Kurukshetra University, Haryana, India
²* Department of EEE, U.I.E.T Panjab University Chandigarh, India

* E-mail: deepak212@rediffmail.com

Abstract. The wind power installed capacity in wind power generation increasing day by day and having a substantial amount of share in total electrical power generation. As a result, there is lot of research going on in wind power generation system for the improvement in its steady-state and transient operation by choosing better controllers. In this paper, the control schemes have been developed for the switching of power converters which interfaced with common back-to-back dc-link in Type-4 PMSG based WECS configuration. The proposed system has been tested under non-linear reactive load demand, the controllers of generator-side and grid-side converters operates independently to fulfill the active and reactive power demand, by maintaining the DC link voltage constant. The performance of proposed Type-4 PMSG based WECS system has been evaluated in MATLAB/SIMULINK software under dynamic operation and simulation results verify the proposed control scheme.

1. Introduction
The rapid growth in wind energy in past few decades makes it one of the popular sources among the available renewable energy sources. Since mid of 90’s, the installed capacity of wind power has expanded substantially [1, 2]. According to the statistical GWEC Report published in 2019 the global cumulative installed capacity is now 651GW which is around 10% more than the last year [1]. The cumulative installed capacity has been rise exponentially from 23.8 GW to 651 GW in almost last two decades [3]. In global electrical market, the percentage share of electricity generated by the wind turbine generators has increased exponentially, which encourage and pay the intention and interest of researcher in wind technology [4, 5].

The recent rapid development in modern wind power generation technology, various wind turbine concepts based wind energy conversion systems has been introduced [6]. Broadly there are three different types of configurations exist for wind turbines electrical power generation. The first type of power generation system operates at fixed-speed. It comprises a multi-stage gearbox and a squirrel-cage induction generator (SCIG) which directly connected to the grid. The second type of power generation system operates at variable speed wind turbine system. Its main components are a multi-stage gearbox and a doubly fed induction generator (DFIG). Here, stator winding of DFIG is directly connected to the grid and rotor winding is connected through power electronic circuit. The power electronic converter feed the rotor winding and feed only 25–30 percent power rating of its capacity. The configuration with gearbox has some drawbacks like gearbox wear and tear maintenances cost, frictional and heat loses, noise pollution [7-9].
The third type is a variable speed wind turbine system, which is a gearless wind turbine system with a directly coupled to generator. It comprises a generator operates at variable speed and a full-scale power electronic converter circuits. The variable-speed wind turbine energy systems always preferred over fixed-speed due to their better wind power extraction and efficiency [7, 8]. The doubly-fed induction generator (DFIG) and direct driven PMSG based is the most used implementation for variable-speed wind systems, because of the reduced power rating of the converter. Make a use of magnet material permanently on rotor eliminates the rotor winding, its copper losses and its wear-tear cost. The PMSG based system is much more efficient with reduced size and relatively high power density. The doubly-fed induction generator (DFIG) always has an issue of sensitiveness under different faults conditions and their ride through capability solutions. Therefore, a variable-speed wind system configuration based on a directly coupled permanent-magnet synchronous generator (PMSG) with a full power converter is used. In comparison with the DFIG, it has more power capture capability at wide range of rotor speed. Moreover, it provides full decoupled arrangement between the wind turbine generating system and the grid for power flow [10-14].

Here, the proposed system, a variable speed PMSG (Type-4 Direct Driven) based grid connected WECS has been considered. Here, wind turbine system having a controlled generator converter arrangement and connected to common DC link for Maximum Power Point Tracking Control algorithm [15, 16]. The grid side inverter and its controller have been used to synchronize the wind power flow from wind turbine power generation to main grid source.

The paper has been organized with the details description and modeling of proposed system along with their respective control strategies. Then simulation results and analysis has been carried out for the feasibility of the proposed system control strategy.

2. Direct-Driven PMSG based wind energy conversion system

The direct drive is always preferable than multi stage drive based wind turbine due to its inherent advantages because it generate and deliver the power at variable wind speed. In this arrangement, the rotor of wind turbine as well as the rotor of generator is mechanically coupled to a common shaft and both are run at same speed as shown in figure 1. Due to this reason, the permanent magnet synchronous generator based wind energy conversion system possesses better mechanical capability for direct-drive wind turbines and hence there is no requirement of gear box [17].

Figure 1. Grid connected Type-4 PMSG based WECS

The directly coupling (mechanically) of wind turbine to a common shaft will reduces its wear-tear losses, reduces maintenance cost and enhance the life of the system.

Among various types of power converter topologies back-to-back (BTB) is used with common DC-link between generator-side converter and grid-side inverter. This back-to-back DC-link arrangement will provide the best solution because the power generation takes place at variable frequency whereas main grid source always operate at fixed frequency. So this back-to-back DC-link act as isolation link
between the wind turbine and main grid. Therefore, it provides the best solution by maintaining the both direction of power flow from variable voltage/frequency (i.e. generated power) to fixed voltage/frequency (grid source) and vice versa.

2.1. PMGS modeling in dq-axis frame

The generalized modeling of Permanent Magnet Synchronous Machine in d-q reference frame for generating mode is given by equation (1) and (2). Here, the direction of current in stator windings is opposite to motoring action i.e. in outward direction as shown in figure 2. Therefore, as per sign convention of rotating machinery theory the current direction in the voltage equations will be of opposite sign as in PMSM it means that a permanent magnet synchronous generator equation in dq-reference can be expressed as:

\[
v_d = -R_s i_d - L_d \left( \frac{di_d}{dt} \right) + \omega_r L_q i_q
\]

\[
v_q = -R_s i_q - L_q \left( \frac{di_q}{dt} \right) + \omega_r \left( -L_d i_d + \lambda_m \right)
\]

\[d-axis\]
\[q-axis\]

\[v_d = v_d\]
\[v_q = v_q\]
\[i_d = i_d\]
\[i_q = i_q\]
\[L_d, L_q\]
\[R_s\]
\[w_r\]
\[\lambda_m\]
\[P\]

Figure 2. PMSG equivalent circuit diagram in d- q-axis

The permanent magnet synchronous generator equivalent circuit diagrams in d-axis and q-axis are shown in figure 2.

Here, surface mounted permanent magnet synchronous machine is used due to its inherent advantages of symmetrical and simple design. The surface mounted permanent magnet synchronous machine (SMPM) have equal path reluctance/ inductances \((L_d=L_q)\) in both \(d\)-axis and \(q\)-axis respectively.

So by taking, \(L_d=L_q\) in the electromagnetic torque equation and can be expressed as:

\[T_e = 0.75(P\lambda_m \cdot i_q)\]

Where,
\[v_d, v_q\] d-axis and q- axis reference voltages
\[i_d, i_q\] d-axis and q- axis reference currents
\[L_d, R_s\] Winding inductance and resistance
\[w_r\] Rotor flux electrical speed
\[\lambda_m\] Flux linkage
\[P\] number of poles
The above mentioned equation (3) clearly shows that the electromagnetic torque will be directly proportional to q-axis component of stator current due to constant rotor flux linkage in the SMPM. Therefore, quadrature-axis current component can be used to control the electromagnetic torque.

2.2. Generator Side Control Scheme

The vector control of Permanent Magnet Synchronous Generator gives the freedom of independent control of field flux and machine torque. The main motive of PMSG side converter and its control scheme is to accomplish maximum power point tracking (MPPT) at variable wind speed [17]. Here, the generator side control has been implemented by using Power-Speed Characteristics. Based on this characteristic, the reference speed of generator will be decided and then control action execute according to this reference speed.

Here, wind turbine output power is match to the wind turbine power characteristic given by manufacturer in order to calculate reference rotor speed. Error comes after the comparison of actual rotor speed and reference speed is fed to PI regulator. Further, the output of PI regulator sets q-axis reference current component \( i_q^* \) to control the electromagnetic torque of PMSG. Therefore, the equation of reference electromagnetic torque of generator and q-axis reference current component may be expressed as:

\[
T_e^* = \left( K_p + \frac{K_s}{s} \right) (\omega_r^* - \omega_r)
\]

(4)

\[
i_q^* = \frac{4}{3} \left( \frac{T_e^*}{P \lambda_m} \right)
\]

(5)

The d-axis reference current component \( i_d^* \) is set at zero so that maximum torque can be achieved. The Park’s transformation i.e. \( dq \) to \( abc \) transformation may be used to determine three phase reference currents for generator. The actual and reference three phase currents are fed to hysteresis regulator for generating triggering pulses for generator side converter control [15-17]. The comprehensive control scheme diagram for PMSG control has been shown in figure 3.

![Figure 3. Generator side control Scheme](image-url)
2.3. Grid Side Inverter Control Scheme

The main motive of outer controllers is to regulate DC link voltage, Grid side AC voltage, reactive and active power at grid frequency. The outer control loop algorithm set the reference values for inner control loop. The main purpose of inner current controller to perform the task while protect the inverter from any kind of disturbances by controlling its terminal current within specified limit. The key motive of grid inverter is to deliver the wind power to main grid at constant rated frequency therefore the inverter control algorithm is utilized to maintain the smooth power flow between DC-link and main grid as shown in figure 4. The grid inverter also resolves power quality issue by injecting reactive and harmonic current compensation for non-linear load demand at PCC [17].

From figure 5, the direct-quadrature reference frame of grid inverter in dq-frame may be chalked out by equations given below:

\[
\begin{align*}
  u_{do} &= R_{fo} i_{do} + L_{fo} \frac{di_{do}}{dt} + (-\omega \cdot L_{fo} i_{qo}) + v_{do} \\
  u_{qo} &= R_{fo} i_{qo} + L_{fo} \frac{di_{qo}}{dt} + (\omega \cdot L_{fo} i_{do}) + v_{qo}
\end{align*}
\]

(6)

Figure 4. Grid side control Scheme

Figure 5. Equivalent Model of Grid Inverter in d-q frame
It may be written by after rearranging the above equation

\[
\begin{align*}
 v_{do} &= -R_{fo} \cdot i_{do} - L_{fo} \cdot \left( \frac{di_{do}}{dt} \right) + (\omega_{fo} \cdot L_{fo} \cdot i_{qo}) + u_{do} \\
 v_{qo} &= -R_{fo} \cdot i_{qo} - L_{fo} \cdot \left( \frac{di_{qo}}{dt} \right) + (-\omega_{fo} \cdot L_{fo} \cdot i_{do}) + u_{qo}
\end{align*}
\]

(7)

In similar manner, the dc-link in d-q reference frame can be explained by equations as below:

\[
C \cdot \left( \frac{dV_{dc}}{dt} \right) = \left( \frac{U_{di}}{V_{dc}} \right) \cdot i_{di} + \left( \frac{U_{qi}}{V_{dc}} \right) \cdot i_{qi} - \left[ \left( \frac{u_{do}}{V_{dc}} \right) \cdot i_{do} + \left( \frac{u_{qo}}{V_{dc}} \right) \cdot i_{qo} \right]
\]

(8)

So a voltage equation of grid connected inverter which is electrically coupled to grid through some filtering element as shown in Figure and given by the equation (6) which can also be further re-write in terms of Laplace’s transformation.

\[
\begin{align*}
 u_{do}(s) &= \left( R_{fo} + sL_{fo} \right) \cdot i_{do}(s) - \omega_{fo} \cdot L_{fo} \cdot i_{qo}(s) + v_{do}(s) \\
 u_{qo}(s) &= \left( R_{fo} + sL_{fo} \right) \cdot i_{qo}(s) + \omega_{fo} \cdot L_{fo} \cdot i_{do}(s) + v_{qo}(s)
\end{align*}
\]

(9)

The desired inverter current can be determined from its voltage equation which essential for controller design. There some error occurs due to system parameters and must be compensated through proportional and integral gains. Under these situations the system equations can be modified as.

\[
\begin{align*}
 u_{do} &= R_{fo} \cdot i_{do} + L_{fo} \cdot \left( \frac{di_{do}}{dt} \right) - \omega_{fo} \cdot L_{fo} \cdot i_{qo} + v_{do} = \Delta v_{do} + v_{do} - \omega_{fo} \cdot L_{fo} \cdot i_{qo} \\
 u_{qo} &= R_{fo} \cdot i_{qo} + L_{fo} \cdot \left( \frac{di_{qo}}{dt} \right) + \omega_{fo} \cdot L_{fo} \cdot i_{do} + v_{qo} = \Delta v_{qo} + v_{qo} + \omega_{fo} \cdot L_{fo} \cdot i_{do}
\end{align*}
\]

(10)

Where,

\[
\begin{align*}
 \Delta v_{do} &= i_{do} \cdot R_{fo} + L_{fo} \cdot \left( \frac{di_{do}}{dt} \right) \\
 \Delta v_{qo} &= i_{qo} \cdot R_{fo} + L_{fo} \cdot \left( \frac{di_{qo}}{dt} \right)
\end{align*}
\]

(11)

The main motive of grid inverter controller to set reference currents and have two kinds of control loops as given in figure 4. Outer control algorithm loop set a reference d- axis current component by comparing actual and reference DC link voltages. The output of PI regulator will set the reference d-axis current and it is further compared with actual d-axis grid current component and fed to current-controller in order to get the reference d-axis voltage. In similar manner, the actual current component in q -axis are fed to PI current controller in order to extract the reference q-axis voltage. The phase angle for grid synchronization is taken out from phase lock loop (PLL) method.

All the reference d-q currents and voltages equations of grid inverter are expressed as follows:

\[
\begin{align*}
 i_{d}^* &= \left( K_{pl} + \frac{K_{ri}}{s} \right) \left( V_{dc}^{*} - V_{dc} \right) \\
 i_{q}^* &= 0
\end{align*}
\]

(12)
\[
\begin{align*}
\bar{v}_d^* &= e_d + \omega Li_q - \Delta v_d \\
\bar{v}_q^* &= e_q - \omega Li_d - \Delta v_q
\end{align*}
\] (13)
\[
\begin{align*}
\Delta v_d &= K_p (i_d^* - i_d) + K_i \int (i_d^* - i_d) dt \\
\Delta v_q &= K_p (i_q^* - i_q) + K_i \int (i_q^* - i_q) dt
\end{align*}
\] (14)

By using dq to abc voltage transformation, the reference dq-voltages are transform into reference three phase voltages. After that these reference voltages signals fed to Pulse Width Modulation controller to extract the desired control signals for the switching of inverter. As result of that the grid side inverter able to deliver the power at it rated value and synchronizes the grid at constant DC link voltage.

3. Simulation Results and Discussions

The dynamic operation of the proposed system is simulated by using MATLAB software with a toolbox SimPower System. The dynamic operative ability of the controllers are to be evaluated on the basis of analysis of various parameters like grid side \(V_{\text{grid}}\) voltage and generator current \(I_{\text{gen}}\), generator-speed \(\omega_r\), dc-link voltage \(V_{dc}\) respectively. The various types of current equations at PCC may be expressed as follows:

\[
I_{\text{inv}} = I_{ld} \pm I_{\text{grid}} \\
I_{\text{grid}} = I_{lr} = I_{\text{actv}} \\
I_{ld} = I_{lr} + I_{ntr} \\
I_{ntr} = I_{\text{actv}} + I_{\text{rectv}} + I_{\text{hrmc}}
\] (15) (16) (17) (18)

Where, \(I_{\text{inv}}\) = Inverter current, \(I_{ld}\) = Load current, \(I_{\text{grid}}\) = Grid current, \(I_{lr}\) = Linear load current component, \(I_{ntr}\) = Non-linear current component, \(I_{\text{actv}}\) = Active current component, \(I_{\text{rectv}}\) = Reactive current component, \(I_{\text{hrmc}}\) = Harmonics current component respectively.

Dynamic operation and performance of WECS with nonlinear load

The dynamic operation of type-4 PMSG based WECS at variable rotor speed of wind turbine are as shown in figure 6. The proposed WECS system has been connected with a nonlinear load at point of common coupling between grid side inverter and grid source.

![Figure 6. Generator Current, Rotor Speed and DC-link voltage](image-url)
Initially at $t=0$ sec, as generator run at low speed and the generated power is lesser than the load demand. Under this situation, the rest of required load demand is fulfilled by the AC grid source as shown in figure 7. As the rotor speed increase due to increase in wind velocity (at instant $t=3$ sec), the generated power is also increases gradually and reaches up to a sufficient level. Under this situation, it not only to fulfill the constant load demand but also feed the AC grid source with its remaining surplus active power. At this instant, the grid side inverter injected both active as well as reactive power to meet the required load demand and also feed the grid source with active power only. Moreover, the grid side inverter also injects required reactive and nonlinear current components in order to meet constant nonlinear load current demand and ensure harmonic free power to grid source figure 8 and figure 9.

![Figure 7. Power flow under variable speed](image)

![Figure 8. Three phase grid voltage and different currents waveforms under variable speed](image)
Fundamentally, the voltage harmonics always come in the system due to the flow of harmonic currents generated by nonlinear loads and can cause overheating of electrical equipment, magnetic saturation and malfunctioning of electronic devices. Therefore, the nonlinear load demand have to be compensated otherwise it increases the system losses and come degrade the system efficiency.

From above mention results, actual and reference rotor speeds as shown in figure 6 endorse the control scheme at variable wind velocity. At the same instant, the current controlled voltage source inverter compensates all the non-linear and reactive power components support. The grid source always operates at unity power factor under non-linear load demand at PCC and regulates dc-link voltage constant. Therefore, it ensures trouble free power flow under all these varying conditions as shown in figure 6 and figure 7.

4. Conclusions
A power-speed characteristics based MPPT control algorithm for generator side converter under variable frequency operation has been developed. The actual and reference rotor speeds certify the effective implementation of PMSG side speed control scheme. The performance of grid controller under non-linear load demand is quite satisfactory with a precise regulated dc-link voltage and smooth power flow at the point of common coupling. Grid side inverter operates in multiple modes and gets a pure sinusoidal harmonic free voltage at point of common coupling. When power generated is greater than load demand, then grid side inverter feed both main grid source and connected nonlinear load. Here, grid side inverter able to feed the total active, reactive and harmonics load demand. At the same time, it delivers rest of the active power to the main grid source with a pure sinusoidal current which certifies the unity power factor operation and validates the successful control strategy.

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