DIRECT TORQUE CONTROL FOR FIVE-PHASE SQUIRREL CAGE GENERATOR IN WIND ENERGY SYSTEMS

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Abstract

This paper is about five phase asynchronous generator that uses direct torque control for extracting maximum available power from wind. There are five electrically distinct phases in asynchronous generator and each one is 72^0 apart. More power can be generated in the same machine frame with this configuration than with standard three-phase induction generator, and system is also more stable and study. In this control technique, the asynchronous generator's stator flux is maintained at its nominal value and electromagnetic torque is controlled during every step change in wind speeds. In order to connect asynchronous generator to the grid, voltage source converters (VSCs) must be employed. A two-level converter handles grid-side regulation, whereas a five-phase two-level converter takes machine-side control. The mathematical model analysis for the direct torque control technique using a two-stage rectifier for different wind speed changes is presented and corresponding simulation results obtained using MATLAB/SIMULINK software package.

Keywords:
Direct Torque Control (DTC), Asynchronous Generator (ASG), Wind Energy Systems (WES).

1. Introduction

The generation of electricity from renewable sources including the sun, the wind, and the oceans has recently been acknowledged as potentially promising solution to energy dilemma. Renewable energy sources including solar, tidal, wave, wind, geothermal, etc. are garnering more interest as a way of addressing society's energy needs in light of the global community's growing concern for the environment and the energy it consumes. Generating electricity from the wind has made tremendous strides in recent years. The European Union (EU), which now have 130 GW of onshore and 11 GW of offshore wind power plants, is predicted to develop dramatically in upcoming years. Asynchronous generators are the most often used electric motor in high-performance, and high-efficiency for industrial applications since they are inexpensive, long lasting, and require no maintenance. These features make induction devices perfect for use in wind power systems. [1-2].

Most often, wind energy is converted using an Asynchronous Generator (ASG). It is well knowledge that ASG has many advantages, including durability, affordability, a brushless cage rotor design, no need for a separate DC source, built-in overload protection, and little maintenance. [4-5].

The study of multi-phase machines has received considerable attention in recent decades. Multi-phase induction motors are used for electric vehicles (EVs) that require high power electric drives. Engines used in aircraft and ships, and other forms of aerospace transportation. Multiphase generators can house a library of books, including six-phase and nine-phase freestanding versions, as well as twelve-phase and eighteen-phase grid-based wireless electric power systems. It's still an intriguing topic, especially for harnessing wind energy. In order to create a variable speed wind energy system, it is possible to use voltage source converters and an asynchronous generator (ASG) in series and in parallel (WES). These voltage-switching capacitors (VSCs) are part of the DC link. However, multiphase machines will be useful for wind energy applications. Because of multi-phase induction machine's fault tolerance and more power inside the same machine, WECS is more reliable. Reduced dc-link harmonic currents, decreased torque ripple, etc. are two further advantages of multi-phase machines. When a three-phase induction machine is converted to six-phase one, its original size and weight are increased. [7-13]

Scalar control, vector control, indirect field orientation, and rotor or stator field vector control technique are just a few of the methods that can be used to manipulate an asynchronous generator. Oscillations in torque can be generated using a scalar control strategy. The scalar control method may be easy to learn and implement, but it is not without risk. However, direct vector control requires estimated flux values to set up and control field orientations relations for optimal performance. However, indirect field orientation method is much more sensitive to changes in machinery settings, so it's not a perfect substitute for direct flux measurement. [14]

Direct torque and flux control, or DTC control with fixed frequency, is form of control system characterized by a parallel control architecture (DTFC). DTC has been used successfully in many different types of factories. Hysteresis control, which causes large torque ripples, a variable switching frequency and a significant decrease in the stator flux, greatly hinders the operation of direct torque control (DTC) at low speeds. To determine the magnitude of inaccuracy for stator flux and electromagnetic torque input to the appropriate hysteresis controllers, the standard DTC compares the reference values to estimated values. By utilizing a variety of witching tactics, the system can be brought under control for both steady state and transient conditions. [22-24].

Fewer machine parameters are needed for DTC implementation; however the benefits of fast transient reaction times remain unchanged. However, both of these control methods have a major downside in that they generate a lot of noise when the torque or flux is increased. However, the more common DTC (or variable frequency) of a two-level inverter-driven induction motor is also available. SVPWM method chooses the voltage vector at each sample time in order to maintain the torque and flux within two hysteresis bands. The voltage vector is calculated using electromagnetic torque and the instantaneous error fluxes. Numerous voltage vectors are used for a given flux and torque. DTC-SVM control has been identified as a powerful control solution for high power applications utilizing multilevel inverters..[25-32].

A grid-side inverter guarantees stable DC bus voltage. Grid-side inverter manages the active and reactive currents are transmitted from grid to generator. Because of its built-in redundancy and greater degrees of freedom, ASIG can help improve system efficiency.

It is used by grid-side PWM converters for regulating the transfer of reactive and active power and to keep the DC-link voltage stable. [33].

In this work, a five-phase ASG with a two-stage rectifier and direct torque control is shown in Figure 1

The remaining paper is formatted as follows. Mathematical foundations of wind turbines were discussed in detail in Section 2. Section 3 introduces the arithmetic behind the five-stage ASG provided in the following section. Mathematical model of a five-phase voltage source rectifier was presented in Section 4. In Section 5 Mathematical model for the suggested control strategy is discussed. In Section 6, the simulation findings are presented. Shortly summarizing the whole thing in Section7.

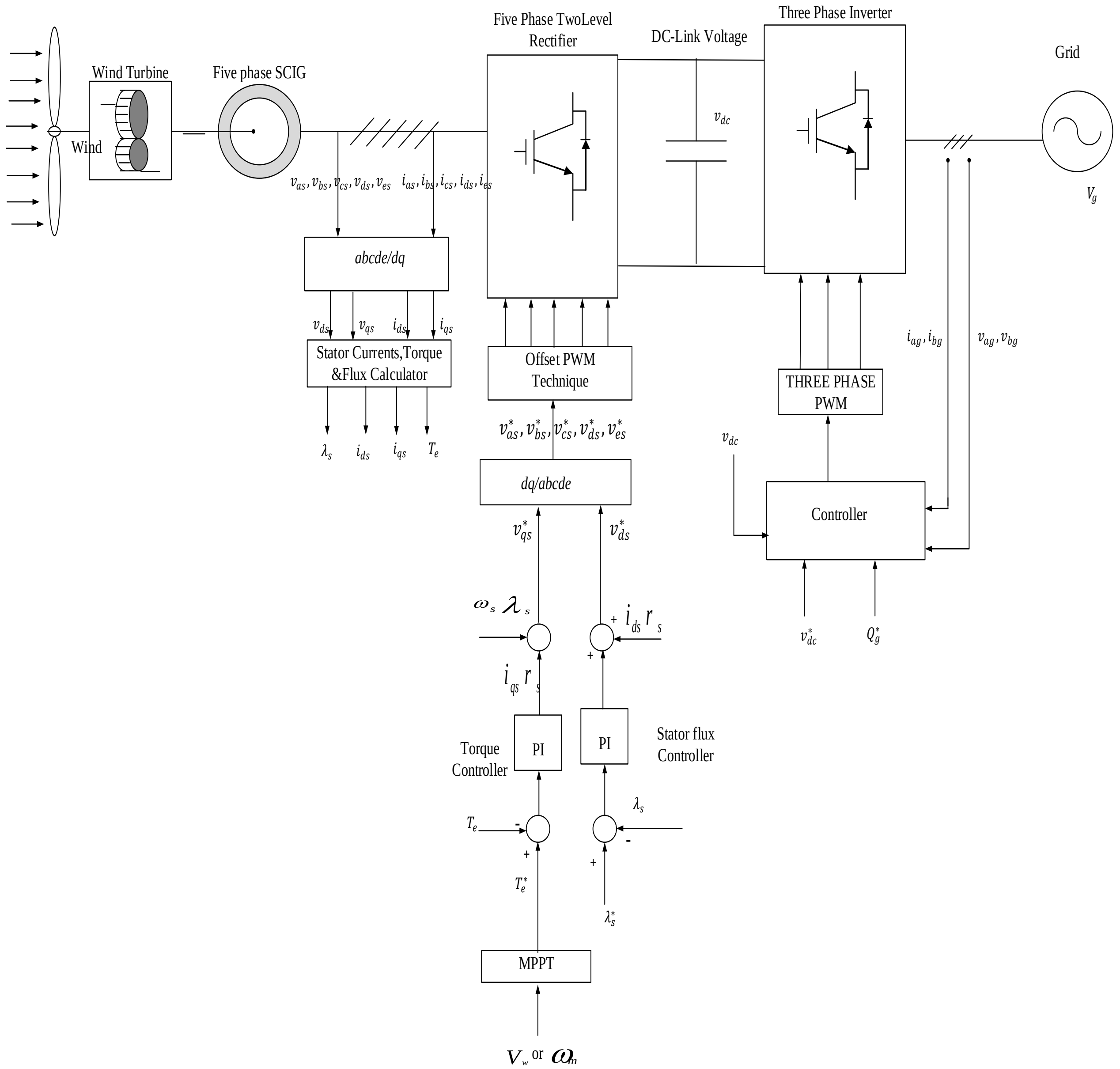

Fig.1.Control Block Diagram for Direct Torque Control of Five Phase Asynchronous Generator

II. WIND TURBINE MATHEMATICAL MODEL

The power co-efficient C_P was utilised in a numerical wind turbine model. Equations are used in wind turbines to figure out how much energy can be extracted from a given volume of air (A) and a certain velocity of air (V) per unit of time (s)... [2]

$$P_w = 0.5\rho A V^3 \qquad \text{........ (1)}$$

P_w : Power of the wind

ρ: air density in kg/m^3

A: Blades Area

*V:*Wind speed

The power coefficient of a wind turbine is a function of the blade's pitch angle (β) and the tip-speed ratio (λ).

$C_P(\lambda, \beta)$. Characteristics are presented in Fig.2.

$$\lambda = \frac{\omega_t R}{V} \qquad \text{........ (2)}$$

ω_tTurbine Speed in radians/sec

V is the wind speed in meter/sec

R is the wind turbine radius in meter

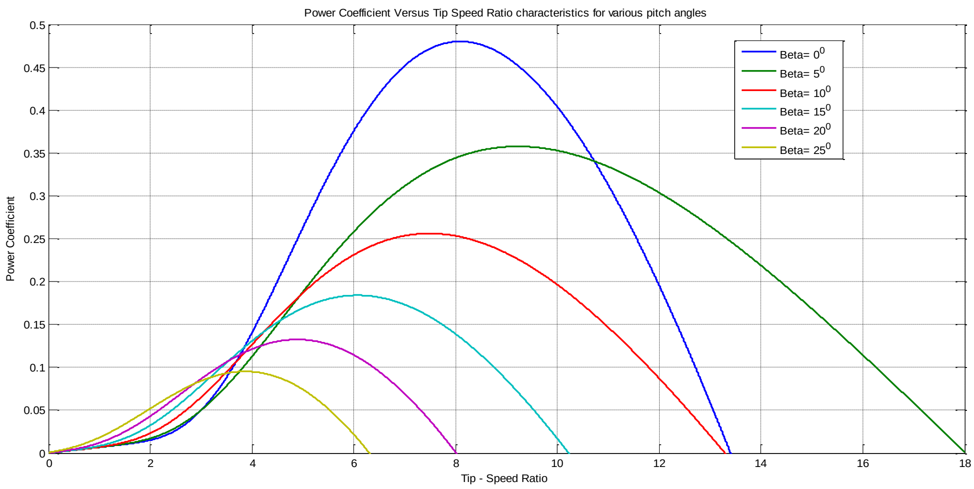

Fig. 2 Characteristics for Power –Coefficient during various pitch angles

Mechanical power is derived from the wind.

$$P_m = 0.5\rho A V^3 C_P(\lambda, \beta) \qquad \ldots\ldots..(3)$$

C_P :Coefficient of power

β : Blade pitch angle

$$C_P = 0.517\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0.068\lambda$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

P_m : Wind turbine Mechanical power

ω_t : Turbine Mechanical speed

The mechanical power parameters are presented for wind speeds ranging from 6 to 13 m/sec. in Fig.3.

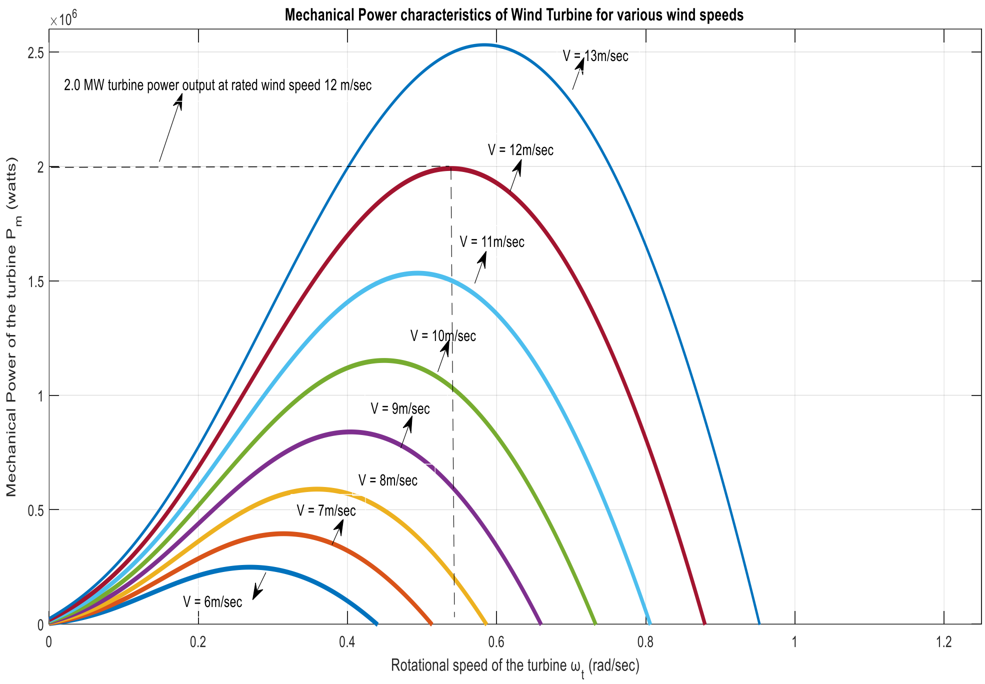

Fig 3. Mechanical Power Characteristics at Different Wind Velocities

From Fig.3 It can be observed that at wind speed, 12m/sec wind turbine produces rated mechanical power of 2.0 MW.

If a turbine's power output is sufficiently high, reducing pitch angle will keep the mechanical power within the rated number. Primarily, we want to optimize wind power throughout a wide range of wind speeds by optimizing speed of the turbine to have the highest tip speed ratio. λopt.

III. Mathematical Model for Five-Phase Asynchronous Generator

The dynamical equations of an asynchronous generator are as follows after converting Phase variables into d-q variables [34]

$$:v_{ds} = i_{ds}r_s + p\phi_{ds} - \omega\phi_{qs} \dots\dots (4)$$

$$v_{qs} = i_{qs}r_s + p\phi_{qs} + \omega\phi_{ds} \dots\dots (5)$$

Rotor side voltage equations

$$v_{dr} = i_{dr}r_r + p\phi_{dr} - (\omega - \omega_r)\phi_{qr} \dots\dots (6)$$

$$v_{qr} = i_{qr}r_r + p\phi_{qr} + (\omega - \omega_r)\phi_{dr} \dots\dots (7)$$

$p = \frac{d}{dt}$is differential operator

$$\phi_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} \dots\dots (8)$$

$$\phi_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr} \dots\dots (9)$$

$$L_{ls} = L_{ls} + 2.5M$$

$$L_m = 2.5M$$

$$\phi_{dr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} \dots\dots (10)$$

$$\phi_{qr} = (L_{lr} + L_m)i_{qr} + L_m i_{qs} \dots\dots (11)$$

$$L_{lr} = L_{lr} + 2.5M$$

$$L_m = 2.5M$$

For an asynchronous generator, electromagnetic torque is defined as product of rotor flux and stator current

$$.T_e = \frac{5}{2}PL_m(i_{qs}\phi_{dr} - i_{ds}\phi_{qr}) \dots\dots (12)$$

$$T_e - T_L = J\frac{d\omega_m}{Pdt} \dots\dots (13)$$

J is Moment of Inertia

P is number of pole pairs

IV. Computational Analysis of a Two-Level Rectifier Fed by a Five-Phase Voltage Source

A five-phase, three-level voltage source rectifier can be modelled using this equation. To make a five-leg circuit work, you'll need two IGBTs and two anti-parallel diodes connected in series pair on each leg. Power switches in the same leg's upper and lower halves work in tandem [34].

If we assume a five-phase star-connected generator, we can write out the formula for the relationship between the phase-to-neutral load voltage and the pole voltages.

$$V_A(t) = V_a(t) + V_{nN}(t)$$

$$V_B(t) = V_b(t) + V_{nN}(t)$$

$$V_C(t) = V_c(t) + V_{nN}(t)$$

$$V_D(t) = V_d(t) + V_{nN}(t)$$

$$V_E(t) = V_e(t) + V_{nN}(t)$$

$$\dots\dots(14)$$

$V\ nN$ = DC bus's negative rail and the load's star point n are at opposite ends of the system, creating a voltage known as common mode voltage.

Adding together all the equations, the total voltage from phase to neutral is

$$V_{nN}(t) = 1/5((V_A(t) + V_B(t) + V_C(t) + V_D(t) + V_E(t))$$

Applying the $V_{nN}(t)$ function to the $V_A(t)$ formula

$$\left.\begin{aligned}
V_a(t) &= \tfrac{4}{5}V_A(t) - 1/5(\ V_B(t) + V_C(t) + V_D(t) + V_E(t)) \\
V_b(t) &= \tfrac{4}{5}V_B(t) - 1/5(\ V_A(t) + V_C(t) + V_D(t) + V_E(t)) \\
V_c(t) &= \tfrac{4}{5}V_C(t) - 1/5(\ V_A(t) + V_B(t) + V_D(t) + V_E(t)) \\
V_d(t) &= \tfrac{4}{5}V_D(t) - 1/5(\ V_A(t) + V_B(t) + V_C(t) + V_E(t)) \\
V_e(t) &= \tfrac{4}{5}V_E(t) - 1/5(\ V_A(t) + V_B(t) + V_C(t) + V_D(t))
\end{aligned}\right\}$$

$$\dots\dots(15)$$

V. Direct Torque Control for five phase Asynchronous Generator

The Mathematical model of induction generator model for stator in space- phasor form given by[14].

$$p\overrightarrow{\phi_s} = \overrightarrow{v_s} - \overrightarrow{\iota_s}R_s \dots\dots(18)$$

$$p = \frac{d}{dt}$$

The derivative of $\overrightarrow{\phi_s}$reacts immediately to changes in $\overrightarrow{v_s}$ in the above equation.

An essential part of dealing with the MPPT management of a wind energy system is ensuring that the generator torque tracks the reference torque T_e^*. To do this, a PI controller can be placed in front of the torque comparator, as shown in figure. For as long as the system remains in steady state, the PI regulator keeps the generator's torque at the level specified by the MPPT scheme. While in steady state, the actual generator speed will be exactly identical to its reference, and there will be no mistakes between $T_e$and T_e^*.

In the stationary frame, the stator flux vector $\overrightarrow{\phi_s}$ can be expressed as

The stator flux vector $\overrightarrow{\phi_s}$ can be represented in the frame of reference at rest as

$$\overrightarrow{\phi_s} = \phi_{ds} + j\ \phi_{qs} \dots\dots(19)$$

$$= \int (v_{ds} - i_{ds}R_s)dt + j\,(v_{qs} - i_{qs}R_s)dt \;\; \dots\dots (20)$$

whose magnitude and angle are derived

$$\phi_s = \sqrt{\phi_{ds}{}^2 + \phi_{qs}{}^2}$$

$$\theta_s = tan^{-1}\left(\frac{\phi_{ds}}{\phi_{qs}}\right).$$

The measured stator voltages and currents are v_{ds}, v_{qs}, i_{ds}, and i_{qs}. You can figure out the generated electromagnetic torque by

$$T_e = \frac{5}{2} PL_m\left(i_{qs}\phi_{ds} - i_{ds}\phi_{qs}\right) \dots\dots (21)$$

For the direct torque driven WECS, the stator flux reference $\phi_s{}^*$ is a parameter that must be fed into the system. Closed loop feedback control ($\phi_s = \phi_s^*$).maintains a constant stator flux in the generator.

As an example of an induction generator's rotor circuit, consider the following:

$$i_{dr}R_r + p\phi_{dr} - \omega_{sl}\phi_{qr} = 0 \;\; \dots\dots (22)$$

$$i_{qr}R_r + p\phi_{qr} + \omega_{sl}\phi_{dr} = 0 \dots\dots (23)$$

As all variables are DC quantities during steady-state, it is possible to reduce the equation above to

$$i_{dr}R_r - \omega_{sl}\phi_{qr} = 0 \dots\dots (24)$$

$$i_{qr}R_r + \omega_{sl}\phi_{dr} = 0 \dots\dots (25)$$

The *dq-axis* rotor currents can be indicated as

$$i_{qr} = \frac{\phi_{dr} - L_m i_{ds}}{L_r} \dots\dots (26)$$

$$i_{qr} = \frac{\phi_{qr} - L_m i_{qs}}{L_r} \dots\dots (27)$$

Substituting (24&25) into (26&27) yields

$$\phi_{dr} - L_m i_{ds} - \tau_r\omega_{sl}\phi_{qr} = 0 \;\; \dots\dots (28)$$

$$\phi_{qr} - L_m i_{qs} + \tau_r\omega_{sl}\phi_{ddr} = 0 \;\; \dots\dots (29)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$

$$\phi_{dr} = \frac{L_r}{L_m}(\phi_{ds} - \sigma L_s i_{ds}) \dots\dots (30)$$

$$\phi_{qr} = \frac{L_r}{L_m}\left(\phi_{qs} - \sigma L_s i_{qs}\right) \dots\dots (31)$$

The fluxes along the dq-axis of the rotor can be written in terms of stator parameters as follows:

$$\phi_{ds} = L_s i_{ds} + \tau_r \omega_{sl}(\phi_{qs} - \sigma L_s i_{qs}) \dots\dots (32)$$

$$\phi_{qs} = L_s i_{qs} - \tau_r \omega_{sl}(\phi_{ds} - \sigma L_s i_{ds}) \dots\dots (33)$$

For the sake of simplicity, let's align the axis of stator flux with that of the synchronous frame's d-axis, that is,

$$\phi_{ds} = \phi_s \text{ and } \phi_{qs} = 0 \dots\dots (34)$$

$$\phi_s = L_s i_{ds} - \sigma L_s \tau_r \omega_{sl} i_{qs} \dots\dots (35)$$

$$L_s i_{qs} = \tau_r \omega_{sl}(\phi_s - \sigma L_s i_{ds}) \dots\dots (36)$$

Substituting (34) into (33) gives

$$i_{ds} = \frac{\phi_s + \sigma L_s \tau_r \omega_{sl} i_{qs}}{L_s} \dots\dots (37)$$

as well as the slip frequency by solving

$$(\tau_r \sigma)^2 \omega_{sl}{}^2 - \frac{(1-\sigma)\phi_s \tau_r}{L_s i_{qs}} \omega_{sl} + 1 = 0 \ \dots\dots (38)$$

Stator frequency can be determined from this information.

$$\omega_s = \omega_{sl} + \omega_r \dots\dots (39)$$

The q-axis stator current i_{qs}in Equations and can be obtained from the torque equation:

To calculate the q-axis stator reference currenti_{qs}^* use the torque equation:

$$T_e = \frac{5}{2} P\left(i_{qs}\phi_{ds} - i_{ds}\phi_{qs}\right) \dots\dots (40)$$

Using the torque equation, it is possible to simplify

$$\phi_{ds} = \phi_s \ and \ \phi_{qs} = 0 \dots\dots (41)$$

$$T_e = \frac{5}{2} P\left(i_{qs}\phi_s\right) \dots\dots (42)$$

$$i_{qs}^* = \frac{2T_e^*}{5P\phi_s} \ \dots\dots (43)$$

In the case of mechanical torque, where $T_e$is calculated by MPPT scheme at a given wind speed and is generally equal to its rated value specified by T_e^*, then mechanical torque

T_m mgenerated by the wind turbine at cut-in speed and rated wind speeds will be equal toT_e^*. Equation (43) yields the reference current along the i_{qs}^*q- axis:

$$i_{qs}^* = \frac{T_e^*}{(K_T \tau_r)} \dots \dots (44)$$

The d-q feedback axis currents depicted in Figure 1 are compared to reference currents (i_{ds}^*andi_{qs}^*), which are calculated using current sensors. Those deviations are then relayed to PI-Controllers, which use them to calculate stator reference voltages. Five-phase offset addition PWM block receive these voltages and use them to create the switching pulses for the five-phase rectifier. They'll be given food. The voltagesv_{as}^*, v_{bs}^*, v_{cs}^*, v_{ds}^*, and $v_{es}^*$are generated by the five phase offset addition block, and v offset is determined by utilising the equation (45)

$$V_{offset} = -\frac{V_{max} + V_{min}}{2} \dots \dots (45)$$

VII. SIMULATION RESULTS

In this paper transients experienced by a 2.3 MW/690 V five-phase ASG in a two-level rectifier wind energy system when the wind speed varies quickly from 7.2 m/sec to 12 m/sec. Active and reactive power injection, three-phase inverter voltage, dc and ac grid currents, dc and ac rotor currents, and dc and ac grid currents simulation results were observed

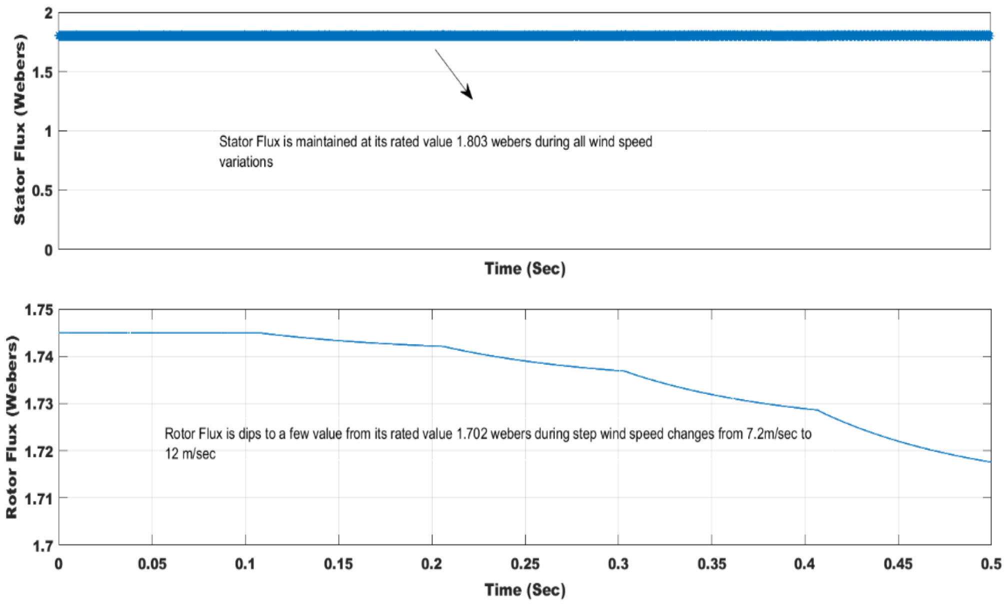

Fig. 4.Stator and Rotor Fluxes

In Fig.4, we can see that the rotor time constant keeps the rotor flux at a negligible value throughout each step change in wind speeds, while the stator flux remains at its rated value of 1.803 webers.

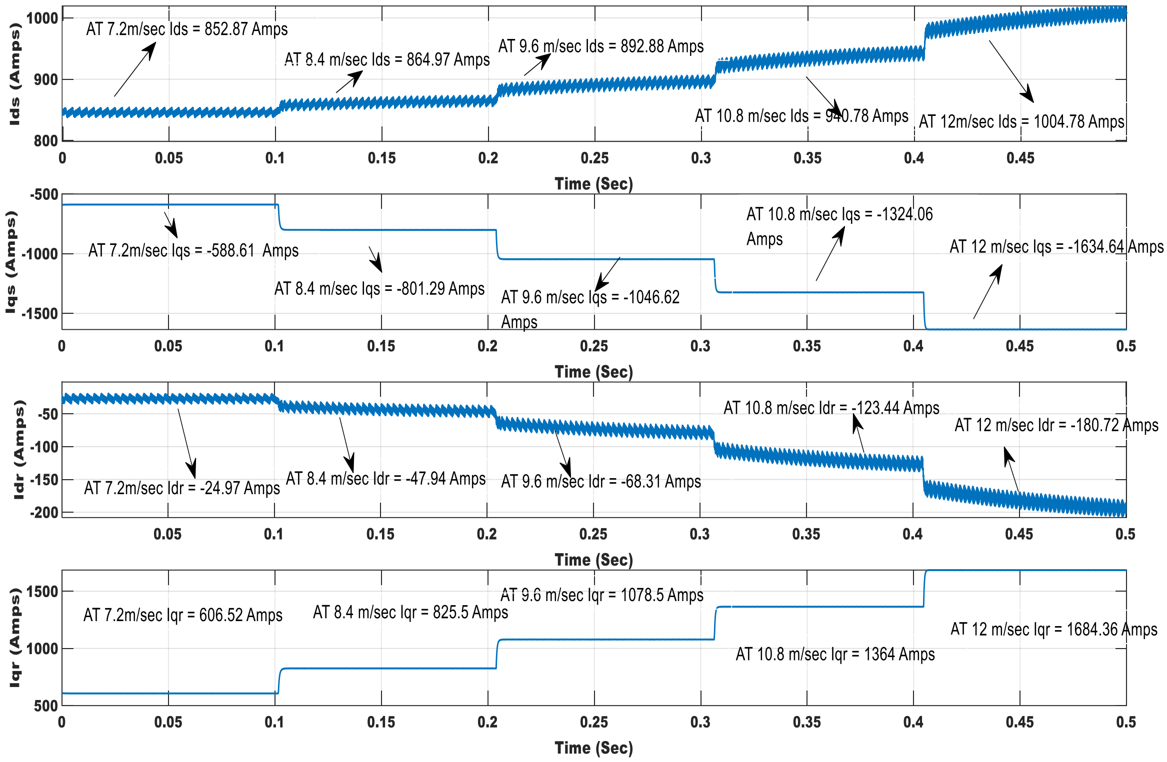

Fig.5.D & Q- axis of Stator and Rotor Currents

According to Fig.5, the d-axis of stator current rises from 852.87 A at 7.2 m/sec to 864.97 A at 8.4 m/sec, 892.8 A at 9.6 m/sec, 940.78 A at 10.8 m/sec, and 1004.7 A at 12 m/sec as the wind speed increases.

Electro Magnetic torque is proportional to stator current along the q-axis. It varies from -588 Amps at 7.2 m/sec to -801.29 Amps at 8.4 m/sec to -1048 Amps at 9.6 m/sec to -1324 Amps at 10.8 m/sec to -1634 Amps at 12 m/sec.

The d-axis of rotor current with value -25 Amperes at 7.2 m/sec, -48 Amperes at 8.4m/sec, -68.31 Amperes at 9.6m/sec, -123.44 Amperes at 10.8m/sec and -180.72 Amperes at 12 m/sec.

The q-axis of rotor current with value 606.52 Amperes at 7.2 m/sec, 825.55Amperes at 8.4m/sec, 1078.5 Amperes at 9.6m/sec, 1364Amperes at 10.8m/sec and 1684.36 Amperes at 12 m/sec.

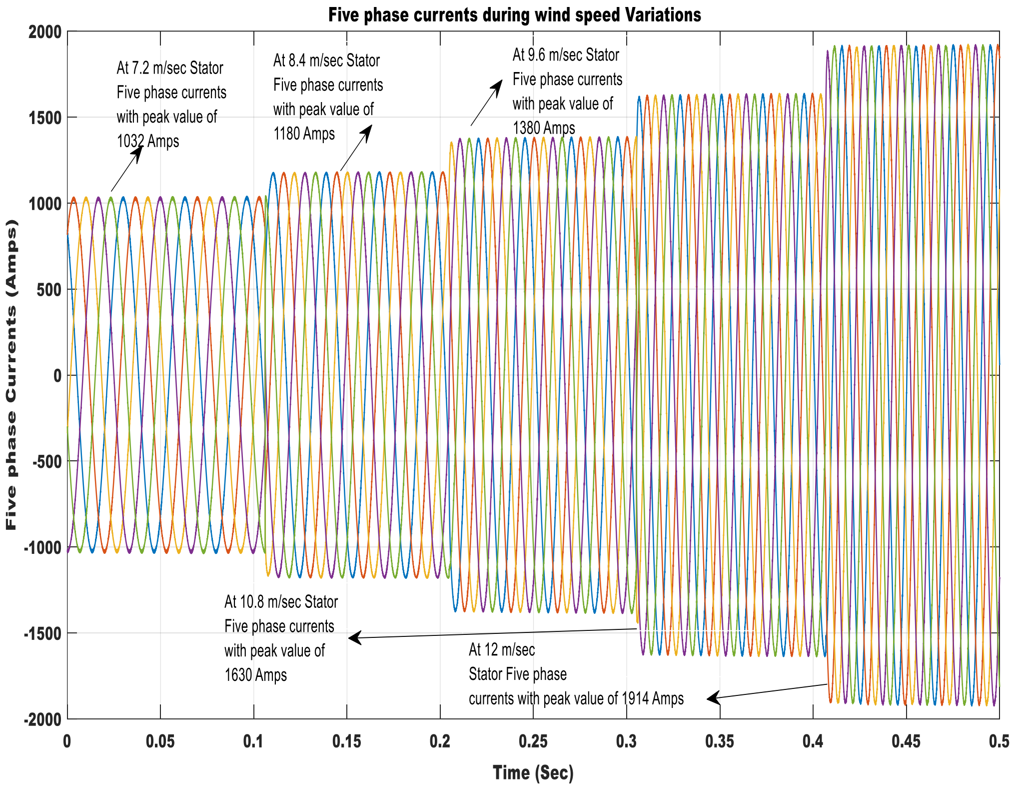

Fig.6. Five-Phase Stator Currents

During a step shift in wind speed, as shown in Fig. 6, the stator currents of a five-phase asynchronous generator increase. Every incremental rise in wind speed increases the current supplied to the asynchronous generator by the wind turbine.its value varies with peak value 1032 Amperes at 7.2 m/sec, with peak value 1180 Amperes at 8.4m/sec, with peak value 1380 Amperes at 9.6m/sec, with peak value 1630 Amperes at 10.8m/sec and with peak value 1914 Amperes at 12 m/sec.

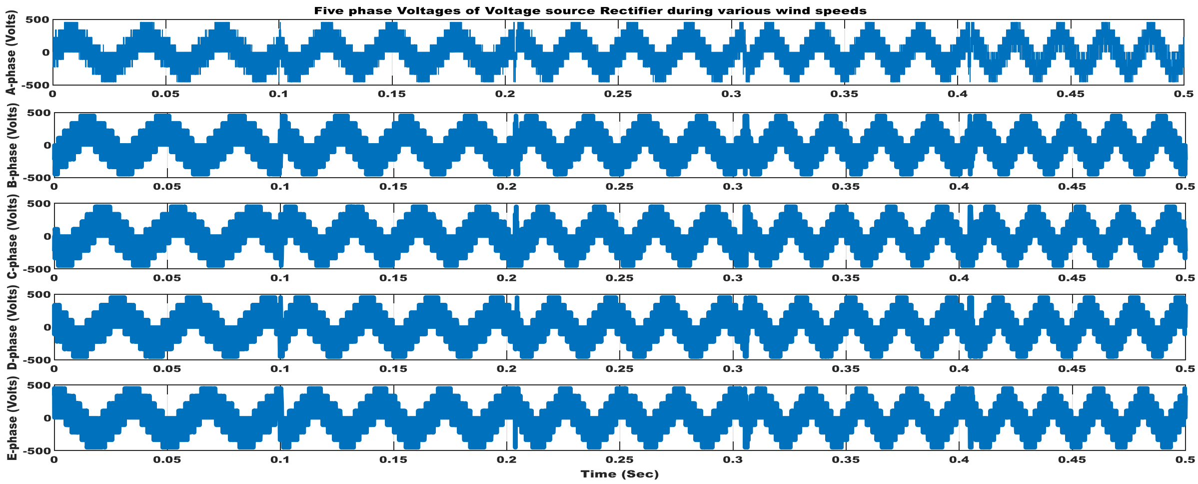

Fig.7. Five-Phase Inverter Voltages

Fig.7 shows the variations of stator voltages applied of the two level rectifier due to change in modulation index value from 0.6 to 1 in for every step change in wind speed with fundamental value of 338 volts at 7.2 m/sec, with fundamental value of 394 volts at 8.4 m/sec, with fundamental value of 450 volts at 9.6 m/sec, -with fundamental value of 507 volts at 10.8 m/sec, with fundamental value of 563.3 volts at 12 m/sec

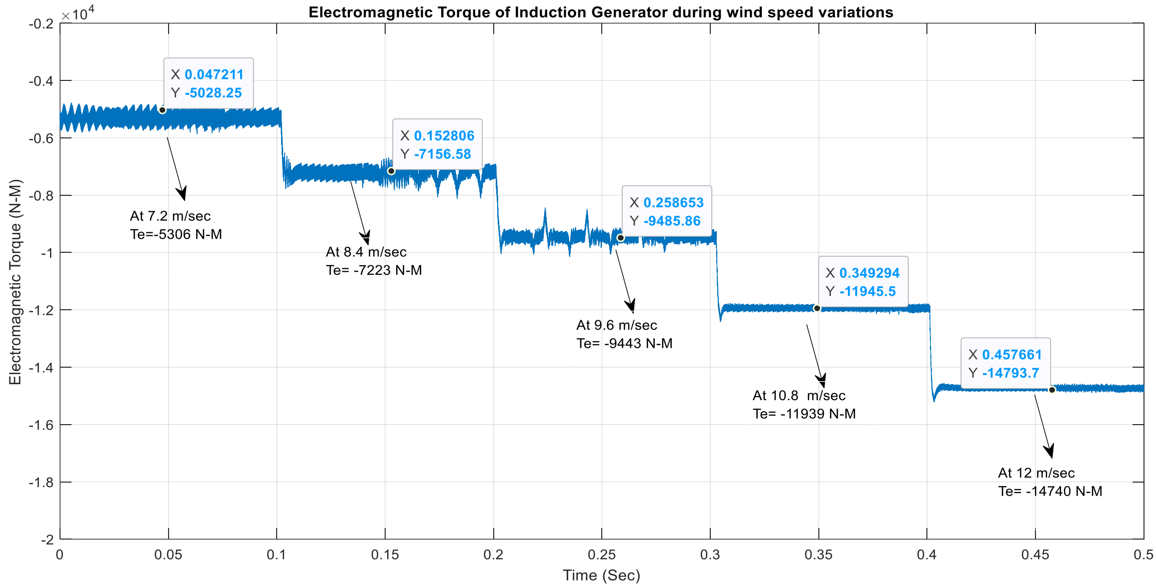

Fig. 8.Electromagnetic Torque of Induction Generator

Alterations in the asynchronous generator's electromagnetic torque are depicted in Fig. 8. The asynchronous generator has an electromagnetic torque rating of -14740 N-m. For every step change of the wind's velocity, the electromagnetic torque was measured, with values ranging from 7.6 m/sec (0.6 p.u of wind speed) to 12 m/sec (1 p.u of wind speed). At 7.2 meters per second, the values are -5306.2 N-m (0.62 per unit of -14740 N-m), -7223 N-m(0.72), -9434 N-m(0.82), -11939 N-m(0.92), and -14740 N-m(1 per unit of -14740 N-m).

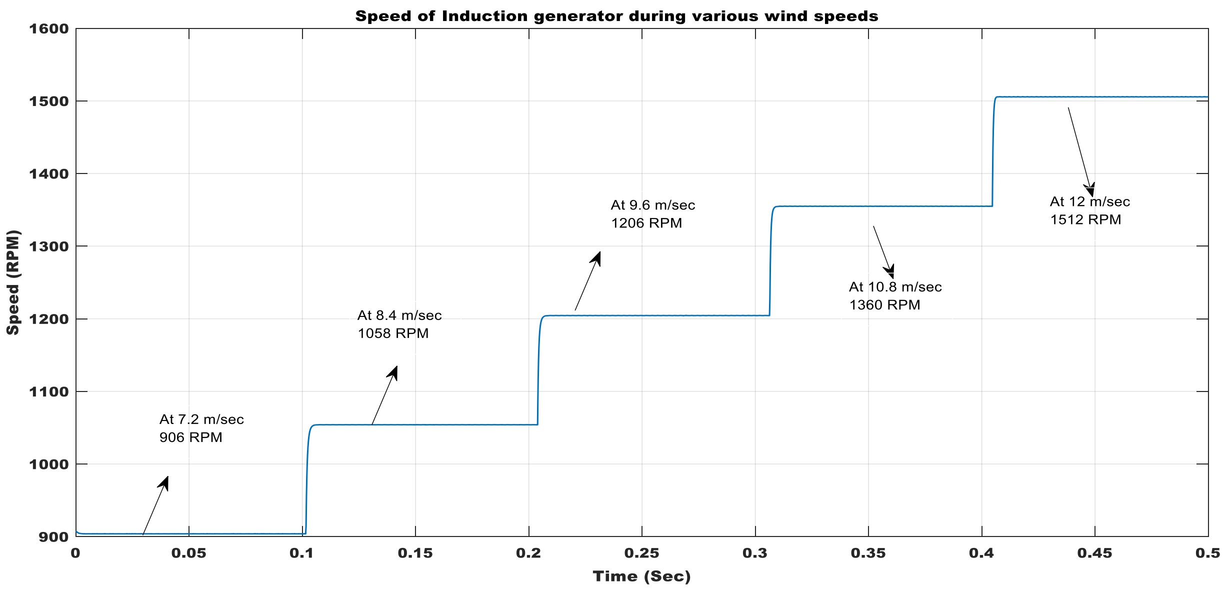

Fig.9. Speed of Induction Generator

When the wind speed is changed in increments, as seen in Fig. 9, the asynchronous generator's rotational speed varies as well. The asynchronous generator has a maximum recommended speed of 1512. Speeds are as follows: 907.6 RPM at 7.2 m/sec (0.6 p.u of 1512 RPM), 1048 RPM at 8.4 m/sec (0.7 p.u of 1512 RPM), 1209.6 RPM at 9.6 m/sec (0.8 p.u of 1512 RPM), 1360.8 RPM at 10.8 m/sec (0.9 p.u of 1512 RPM), and 1512 RPM at 12 m/sec (1 p.u of 1512 RPM).

VII.CONCLUSION

Impact on the functioning of a five-phase, asynchronous generator with a two-level rectifier and direct torque control is explored in light of a rapid rise in wind speed from 7.2 m/s to 12 m/s. In spite of variations in wind speed, the suggested control method maintains the rated stator flux in the asynchronous generator. At each step input change in wind speed, grid-side converters maintain a constant voltage on the DC-link, while voltage-oriented control controls the active and reactive power on the grid side.

Appendix

ASYNCHRONOUS GENERATOR PARAMETERS

Power Rating	2 MW
Rated Voltage	690V
Rated Frequency	50 Hz
Rated speed (RPM)	1512
No Of Poles	4
Stator Resistance R_S	$1.102*10^{-3}\Omega$
Rotor Resistance R_r	$1.497*10^{-3}\Omega$
Stator Inductance L_{ls}	$0.06492*10^{-3}$Henry
Rotor Inductance L_{lr}	$0.06492*10^{-3}$Henry
Mutual Inductance L_m	$2.13461*10^{-3}$Henry
Moment of Inertia J	1200 Kg-m^2

THREE PHASE GRID PARAMETERS

DC link circuit Voltage	1220V
Grid voltage/frequency	690V / 50HZ
Line Resistance	0.0207 ohms
Line inductance	0.1098 mH

WIND TURBINE PARAMETERS

Turbinemake	EnerconE822MW
Regulationmethod	Pitchcontrol(enabled)
Rotordiameter	82m
Hubheight	78m
Numberofblades	3
Cut-inwindspeed	4m/s
Cut-outwindspeed	28m/s
Ratedwindspeed	12m/s(14m/sused)
Rotorspeed	6/18rpm

References

[1] *Wind in power: 2015 European statistics, 2016, [Online] Available:* [*http://windeurope*](http://windeurope).

[2] *A. W. Manyonge1, R. M. Ochieng1, F. N. Onyango 1 and J. M. Shichikha Mathematical Modelling of Wind Turbine in a Wind Energy Conversion System:Power Coefficient Analysis Applied Mathematical Sciences, Vol. 6, 2012, no. 91, 4527 – 4536.*

[3] *M. Tsili, C. Patsiouras, S. Papathanassiou, "Grid code requirements for large wind farms: a review of technical regulations and available wind turbine technologies", European Wind Energy Conference & Exhibition, Brussels, 2008.*

[4] *A. Sikorski, A. Kuzma, "Cooperation of induction squirrel-cage generator with grid connected ac/dc/ac converter", Bulletin of the Polish Academy of Sciences, Technical Sciences 57, pp. 317–322, 2009.*

[5] *N. Caliao, "Dynamic modelling and control of fully rated converter wind turbines", Renewable Energy, vol. 36, no. 8, pp. 2287-2297, 2011.*

[6] *Merabet Boulouiha H, Allali A, Tahri A, Draou A, Denaï M. A simple maximum power point tracking based control strategy applied to a variable speed squirrel cage induction generator. J Renew Sustain Energy 2012;4(053124).*

[7] *G.K. Singh, Multi-phase induction machine drive research survey, Electric PowerSyst. Res. 61 (2) (2002) 139–147.*

[8] *E. Levi, Multiphase electric machines for variable-speed applications, IEEE Trans.Ind. Electron. 55 (5) (2008) 1893–1909.*

[9] *M.J. Duran, F. Barrero, Recent advances in the design, modeling, and control ofmultiphase machines x2014;part ii, IEEE Trans. Ind. Electron. 63 (1) (2016)459–468.*

[10] *M. Duran, F. Barrero, S. Toral, M. Arahal, R. Gregor, R. Marfil, Multi-phase generatorsviability for offshore wind farms with hvdc transmission, InternationalConference on Renewable Energies and Power Quality (2008).*

[11] *Leila Parsa "On Advantages of Multi-Phase Machines" 31st Annual Conference of IEEE Industrial Electronics Society (IECON), pp. 1574-1579, 2005.*

[12] *Jinn Huang , Min Kang, Jia-qiang Yang, Hai-bo Jiang, Dong Liu* **"***Multiphase Machine Theory and Its Applications***"** *International Conference on Electrical Machines and Systems, pp. 1-6, 2008.*

[13] *E. Levi, R. Bojoi, F. Profumo, H.A. Toliyat and S. Williamson "Multiphase induction motor drives – a technology status review",IET Electr. Power Appl.,Vol. 1, no. 4, pp. 489–516, 2007.*

[14] *B. Wu, Y. Lang, N. Zargari, S. Kouro, Power Conversion and Control of Wind EnergySystems, John Wiley & Sons, 2011.*

[15] *R. Leidhold, G. Garca, M.I. Valla, "Field-oriented controlled induction generator with loss minimization", IEEE Transactions on Industrial Electronics, vol: 49, pp. 147–156, 2002.*

[16] *Mrs Jisha L K, jisha, Dr.A A Powly "A Comparative study on scalar and vector control of Induction motor drives", 2015 3rd International Renewable and Sustainable Energy Conference (IRSEC), pp-2380-7393,10-13, 2015.*

[17] *J.L. Domínguez-García, O. Gomis-Bellmunt, L. Trilla-Romero, A. Junyent-Ferré, "Vector control of squirrel cage induction generator for wind power", International Conference on Electrical Machines in Rome, 2010.*

[18] *José Luis Domínguez-García, Oriol Gomis-Bellmunt, Lluís Trilla-Romero, and Adrià Junyent-Ferré, "Indirect vector control of a squirrel cage induction generator wind turbine", Computers & Mathematics with Applications, vol. 65, no. 2, pp. 102-114, 2012.*

[19] *M. Imecs, "A survey of speed and flux control structures of squirrel-cage induction motor drives ", Tech. Rep., Acta Universitatis Sapientiae Electrical and Mechanical Engineering, 2009.*

[20] *J. Holtz, "Sensorless control of induction motor drives", Proceedings of the IEEE, pp. 1359–1394, 2002.*

[21] *M. Imecs, C. Szab, J.J. Incze, "Stator-field-oriented control of the variable-excited synchronous motor: numerical simulation", 7th International Symposium of Hungarian Researchers on Computational Intelligence, Budapest, Hungary, 2006.*

[22] *T. G. Habetler, F. Profumo, M. Pastorelli and L. M. Tolbert, "Direct torque control of induction machines using space vector modulation," in IEEE Transactions on Industry Applications, vol. 28, no. 5, pp. 1045-1053, Sept.-Oct. 1992, doi: 10.1109/28.158828.*

[23] *H.M. Boulouiha, A. Allali, M. Laouer, A. Tahri, M. Denai, A. Draou, Direct torque control of multilevel svpwm inverter in variable speed scig-based wind energy conversion system, Renew. Energy 80 (2015) 140–152.*

[24] *K. Suman, K. Suneeta and M. Sasikala, "Direct Torque Controlled induction motor drive with space vector modulation fed with three-level inverter," 2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), 2012, pp. 1-6, doi: 10.1109/PEDES.2012.6484405.*

[25] *U. Baader, M. Depenbrock and G. Gierse, "Direct self control (DSC) of inverter-fed induction machine: a basis for speed control without speed measurement," in IEEE Transactions on Industry Applications, vol. 28, no. 3, pp. 581-588, May-June 1992, doi: 10.1109/28.137442.*

[26] *H.S. Che, W.P. Hew, N.A. Rahim, E. Levi, M. Jones, M.J. Duran, Current control of a six-phase induction generator for wind energy plants, 2012 15th International Power Electronics and Motion Control Conference (EPE/PEMC) (2012) pp. LS5b.2-1-LS5b.2-7.*

[27] *Y. Zhang, J. Zhu, Z. Zhao, W. Xu and D. G. Dorrell, "An Improved Direct Torque Control for Three-Level Inverter-Fed Induction Motor Sensorless Drive," in IEEE Transactions on Power Electronics, vol. 27, no. 3, pp. 1502-1513, March 2012, doi: 10.1109/TPEL.2010.2043543.*

[28] *J. G. Chaudhari, S. K. Mude and P. G. Gabhane, "High Performance Direct Torque Control of Induction Motor using Space Vector Modulation," 2006 Canadian Conference on Electrical and Computer Engineering, 2006, pp. 1090-1093, doi: 10.1109/CCECE.2006.277414.*

[29] *F. S. Neves, R. P. Landim, T. G. Habetler, B. R. Menezes and S. R. Silva, "Induction motor DTC strategy using discrete-time sliding mode control," Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370), 1999, pp. 79-85 vol.1, doi: 10.1109/IAS.1999.799928.*

[30] *L. Tang, L. Zhong, A. F. Rahman and Y. Hu, "An investigation of a modified direct torque control strategy for flux and torque ripple reduction for induction machine drive system with fixed switching frequency," Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No.02CH37344), 2002, pp. 837-844 vol.2, doi: 10.1109/IAS.2002.1042656.*

[31] *G. Narayanan and V. T. Ranganathan, "Analytical evaluation of harmonic distortion in PWM AC drives using the notion of stator flux ripple," in IEEE Transactions on Power Electronics, vol. 20, no. 2, pp. 466-474, March 2005, doi: 10.1109/TPEL.2004.842961.*

[32] *Sri Gowri, K., Reddy, T.B. & Sai Babu, C. Direct torque control of induction motor based on advanced discontinuous PWM algorithm for reduced current ripple. Electr Eng 92, 245–255 (2010). https://doi.org/10.1007/s00202-010-0182-2e30.*

[33] *K.A. Chinmaya, G.K. Singh, Modeling and experimental analysis of grid-connected six-phase induction generator for variable speed wind energy conversion system, Electric Power Systems Research, Volume 166, 2019, Pages 151-162, ISSN 0378-7796,*

[34] *Atif Iqbal, Sk. Moin Ahmed, Md. Arif Khan, Mohd. Rizwan Khan, and Haitham Abu-Rub "Modeling, Simulation and Implementation of a Five-Phase Induction Motor Drive System", Joint International Conference on Power Electronics, Drives and Energy Systems, pp. 1-6, 2010.*

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