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Indirect Vector Control for Five-Phase Asynchronous Generator Using Three Level Rectifier in Wind Energy Systems

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ABSTRACT- Five-phase induction generators in variable-speed wind energy systems are a focus of this study, and a unique method of regulating them utilizing indirect vector control is proposed in wind energy systems. Grid-side regulation is handled by a two-level converter, whereas machine-side control is handled by a five-phase three-level converter. There are five electrically distinct phases in ASG, and each one is 72^0 apart. More power can be generated in the same machine frame with this configuration than with a normal three-phase induction generator, and the system is also more stable and sturdier. In order to connect ASIG to the grid, voltage source converters (VSCs) must be employed. A mathematical analysis of the suggested control system is performed, and simulation results are generated in the MATLAB/ SIMULINK software package to account for the various ramps in wind speed. The simulation findings reveal a decrease in low harmonic distortion in injected grid currents, leading to a reduction in of harmonics in stator harmonic currents results in increase in the overall efficiency of the asynchronous generator.

Keywords: Direct Field Oriented Control (DFOC), Indirect Vector Control (IOC), Squirrel Cage Induction Generator (SCIG), Wind Energy Systems (WES).

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1. INTRODUCTION

Due to the depletion of natural resources such as coal and gas for generation of electrical power. Wind power is most promising renewable energy sources in now a days [2]. Wind energy penetration is increasing (Denmark is at 20%, Portugal is at 15%, Spain is at 14%, and Germany is at 9%), prompting the creation of grid codes. [2]. SCIG's (squirrel cage induction generators) had employed as fixed or variable-speed generators using full-rated power converter between grid and the generators. Less cost, dependability, and robustness are the key advantages of employing squirrel cage induction generator topologies [3-5].

In wind energy systems multiphase generators usage will result in operation that is fault-tolerant, lower phase current, and decrease in torque pulsations. [6]. A number of phases greater than three is referred to as "multiphase". Multiphase machines are now considered a viable option because advantages such as reduced amplitude of rotor harmonic currents, higher fault tolerance, DC link current harmonics, higher frequency of torque currents, and less current per phase without changing per-phase voltage [6-7].

Various strategies such as direct and indirect field control, rotor or stator field control, and scalar or vector control can be used to achieve SCIG control. Torque oscillations are produced via the scalar control approach. The scalar control technique is simple to use, but it causes stability problems. [9-12]. Direct vector control yields superior results, but it needs the use of perceived to establish and regulate field orientation relations, and use flux values. Direct flux detection is less susceptible to machine settings than the indirect field-orientation method. In order to attain high performance, the induction generator needs a better control strategy. This can be achieved using indirect field-oriented control (IFOC) method. To determine the rotor flux angle, the rotor position and key parameters are estimated. The rotor position is calculated using the generator feedback signal of rotor. [16-20].

Figure 1 shows complete block diagram for indirect vector control method for five phase asynchronous generator using three-level rectifier. The rest of the work is structured as follows. Mathematical model for wind turbine is described and examined in *Section 2*. *Section 3* introduces five-level mathematical SCIG model. Mathematical model for five-phase three-level voltage source rectifier is described in *Section 4*. *Section 5* presents mathematical model of proposed control technology. In section 6 the simulation results are discussed. Conclusions are summarized in *Section 7*.

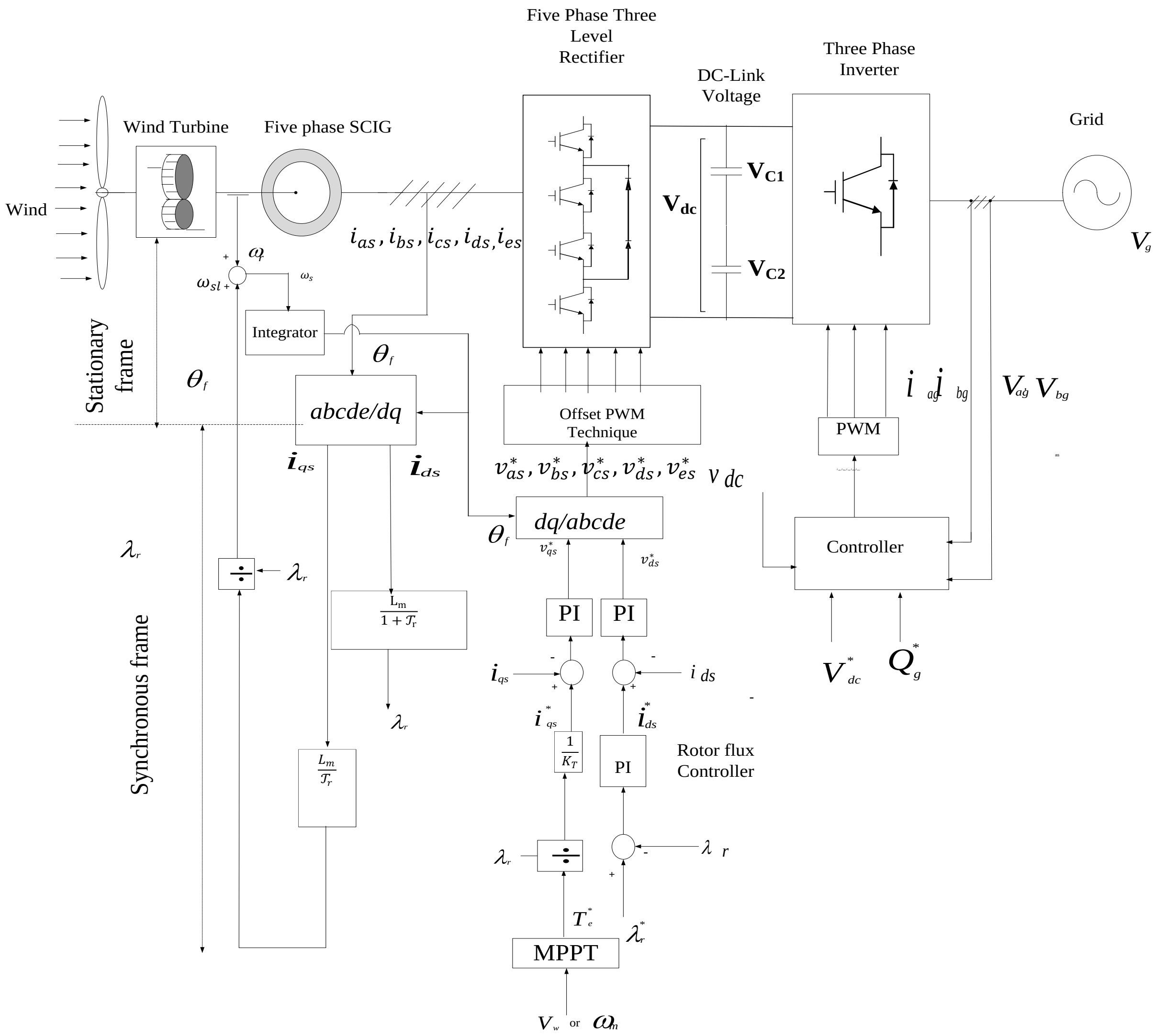

Figure.1 Schematic Representation of the Three-Level Rectifier Used in Indirect Vector Control of a Five-Phase Asynchronous Generator

2. MATHEMATICAL MODEL FOR WIND TURBINE

A numerical model of wind turbine was built using the power coefficient C_P. Equations were used to calculate the power produced by air moving through area A of wind turbine at speed of V m/sec. [14]

$$P_w = 0.5\rho A V^3 \quad …….. (1)$$

P_w : Power of the wind
ρ: air density in kg/m^3
A: Blades Area
V: Wind speed

Using the turbine's power coefficient, the amount of wind power that a turbine can capture is determined. $C_P(\lambda, \beta)$.

β is the pitch angle
λ is the tip-speed ratio

$$\lambda = \frac{\omega_t R}{V} \quad …….. (2)$$

ω_t is the turbine's speed in rad/sec.
V represents the wind speed in metres per second.
R is the wind turbine's radius in metres.
$C_P(\lambda, \beta)$. Characteristics are presented in *figure 2*.

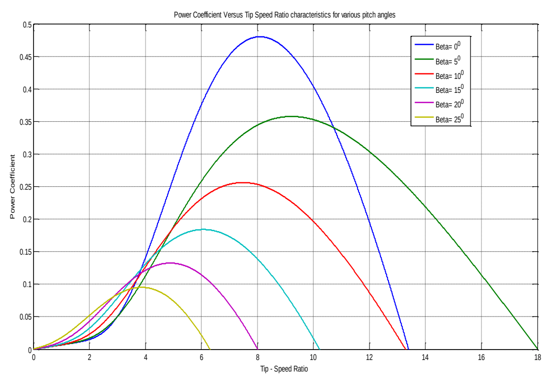

Figure 2: Characteristics for Power -Coefficient during various pitch angles

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Mechanical power is derived from the wind.

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

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 *figure 3*.

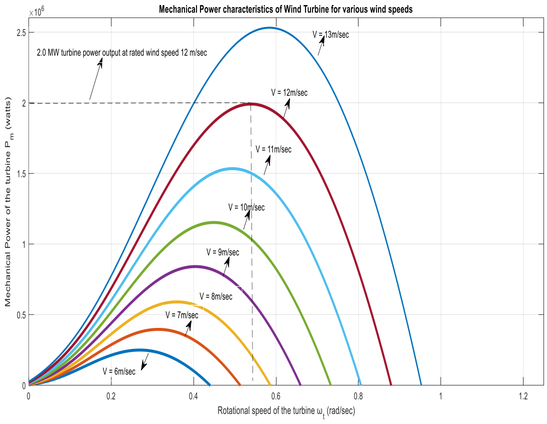

Figure 3: Characteristics of mechanical power in different wind conditions

According to *figure 3*, a wind turbine with wind speed of 12 m/s delivers mechanical nominal power of 2.0 MW.

By changing the angle of attack, the mechanical power of turbine can be reduced and, if rated value is higher, maintained at the rated value. By altering turbine speed to produce the optimal tip speed ratio, the primary objective is to optimise wind output at a range of wind speeds λopt.

3. 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 [27]

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

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

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

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

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

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

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

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

$$L_m = 2.5M$$

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

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

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

$$L_m = 2.5M$$

The electromagnetic torque for asynchronous generator related to rotor flux and stator current,

$$T_e = \frac{5}{2}PL_m(i_{qs}\phi_{dr} - i_{ds}\phi_{qr}) \ \ldots\ldots(12)$$
$$T_e - T_L = J\frac{d\omega_m}{Pdt} \quad \ldots\ldots(13)$$

J is generator's moment of inertia.
P is amount of pole pairs.

4. THREE-LEVEL RECTIFIER WITH FIVE-PHASE VOLTAGE SOURCE MATHEMATICAL MODELING

[27] Gives the mathematical formulation for a voltage source rectifier with three levels and five phases. Each leg of a five-leg circuit has a series pair connection with two IGBTs and two anti-parallel diodes.

Assuming star-connected five-phase generator, relationship between phase-to-neutral load voltage and pole voltages can be written as [27].

$$\left.\begin{aligned} V_A(t) &= V_a(t) + V_{nN}(t) \\ V_B(t) &= V_b(t) + V_{nN}(t) \\ V_C(t) &= V_c(t) + V_{nN}(t) \\ V_D(t) &= V_d(t) + V_{nN}(t) \\ V_E(t) &= V_e(t) + V_{nN}(t) \end{aligned}\right\} \quad \ldots\ldots(14)$$

VnN = Common mode voltage is difference between the negative rail of the DC bus N and the star point n for the load.

For a three-stage voltage source rectifier, the sum of the phase to neutral voltages from all equations is

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

Substituting $V_{nN}(t)$ into $V_A(t)$ equation

$$\left.\begin{aligned} V_a(t) &= \tfrac{4}{5}V_A(t) - 1/5(V_B(t) + V_C(t) + V_D(t) + V_E(t)) \\ V_b(t) &= \tfrac{4}{5}V_B(t) - 1/5(V_A(t) + V_C(t) + V_D(t) + V_E(t)) \\ V_c(t) &= \tfrac{4}{5}V_C(t) - 1/5(V_A(t) + V_B(t) + V_D(t) + V_E(t)) \\ V_d(t) &= \tfrac{4}{5}V_D(t) - 1/5(V_A(t) + V_B(t) + V_C(t) + V_E(t)) \\ V_e(V_d(t) &= \frac{4}{5}V_E(t) - \frac{1}{5(V_A(t) + V_B(t) + V_C(t) + V_D(t))} \end{aligned}\right\}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots(15)$$

$V_A(t)$ will be consisting of two switches S_1 & S_2. Similarly, for the remaining phases, it will contain two switches.

5. INDIRECT VECTOR CONTROL FOR FIVE PHASE ASYNCHRONOUS GENERATOR

Stator flux and rotor flux orientation are examples of field-oriented control techniques for asynchronous generators. The stator current space vector for an asynchronous generator has two components. i_{ds} and i_{qs} . i_{ds} Produces the rotor flux component and i_{qs} produces the torque-producing component in rotor flux orientation. [14, 28]

The equation can be used to compute the flux angle of the rotor in the indirect vector control technique as shown in *figure 1*.

$$\theta_f = \int \omega_r + \omega_{sl}\ dt \quad \dots\dots (16)$$

ω_r generator's rotor speed was measured and ω_{sl} is slip frequency.

The rotor space vector equation is used to calculate the slip frequency.

$$\overrightarrow{v_r} = \overrightarrow{i_r}R_r + p\overrightarrow{\phi_r} + j\omega_{sl}\overrightarrow{\phi_r} \quad \dots\dots (17)$$

Using *equation* (17) rotor voltage $\overrightarrow{v_r} = 0$ and calculating $p\overrightarrow{\phi_r}$

$$p\overrightarrow{\phi_r} = -\overrightarrow{i_r}R_r - j\omega_{sl}\overrightarrow{\phi_r} \quad \dots\dots (18)$$

$$\overrightarrow{\phi_r} = L_r\overrightarrow{i_r} + L_m\overrightarrow{i_s} \dots\dots (19)$$

Using *equation* (19) the current of rotor will be

$$\overrightarrow{i_r} = \frac{1}{L_r}(\overrightarrow{\phi_r} - L_m\overrightarrow{i_s})$$

$\overrightarrow{i_r}$ is added to *equation (18)*, which results in

$$p\overrightarrow{\phi_r} = \frac{R_r}{L_r}(\overrightarrow{\phi_r} - L_m\overrightarrow{i_s}) - j\omega_{sl}\overrightarrow{\phi_r} \quad \dots\dots (20)$$

From which

$$\overrightarrow{\phi_r} = \left(1 + \tau_r(p + j\omega_{sl})\right) = L_m\overrightarrow{i_s} \quad \dots\dots (21)$$

Where τ_r is the rotor time constant

$$\tau_r = \frac{L_r}{R_r}$$

Splitting *equation* (21) to dq-*axis* components and considering rotor flux orientation (ϕ_{qr}= 0 and ϕ_{dr}=ϕ_r), we have

$$\phi_r(1 + p\tau_r) = L_m i_{ds} \dots\dots (22)$$
$$\omega_{sl}\tau_r\phi_r = L_m i_{qs} \dots\dots (23)$$

Using *equation (23)* slip frequency is obtained:

$$\omega_{sl} = \frac{L_m}{\tau_r\phi_r} i_{qs} \quad \dots\dots (24)$$

Rotor flux reference value ϕ_r^* is constant at rated value, i.e. 1.7107 webers

Equation (22) can be used to calculate rotor flux.

$$\phi_r(1 + p\tau_r) = L_m i_{ds} \dots\dots (25)$$

Using an *equation (25)* reference amount fori_{ds} provided by

$$i_{ds}^* = \frac{\phi_r(1 + p\tau_r)}{L_m} \quad \dots\dots (26)$$

Equation (12) for calculating the asynchronous generator's magnetic torque in terms of stator current and

In case of three phase machine

$$T_e = \frac{3}{2}PL_m(i_{qs}\phi_{dr} - i_{ds}\phi_{qr})$$

But in case of five-phase Machine

$$T_e = \frac{5}{2}PL_m(i_{qs}\phi_{dr} - i_{ds}\phi_{qr}) \text{ -----} (27)$$

Rotor flux component in complex coordinates can be expresse d as:

$$\overrightarrow{\phi_r} = \overrightarrow{\phi_{dr}} + j\overrightarrow{\phi_{qr}} \dots\dots (28)$$

Aligning *equation* (28) to synchronous reference frame then

$$\phi_{qr} = 0$$
$$\phi_{dr} = \phi_r$$

Substituting in *equation (27)* then

$$T_e = \frac{5}{2}PL_m(i_{qs}\phi_r) \dots\dots (29)$$

In *equation* (29) if Ψ_r is constant throughout the entire operation of generator according to electromagnetic equation.T_e is directly related to i_{qs}

$$T_e = K_T i_{qs}$$
$$K_T = \frac{5}{2}PL_m\phi_r$$

K_T is known as torque constant

Considering that the mechanical torque T_m a wind turbine produces between its cut-in speed and its rated wind speeds will be equal to T_e^*. The i_{qs}^* q- axis reference current calculated using *equation (30)*:

$$i_{qs}^* = \frac{T_e^*}{(K_T\tau_r)} \quad \dots\dots (30)$$

The feedback d-q axis currents from *figure 1* $i_{ds}$and i_{qs} are calculated using current sensors, and reference currents were compared. i_{ds}^* and i_{qs}^* . Stator reference voltages will be produced using the faults by PI-Controllers. v^*_{ds} and v^*_{qs}. The v^*_{ds} and v^*_{qs} will be fed to the five-phase offset addition PWM block using *equation (31)* for providing the required switching pulses to five phase rectifier.

$$V_{offset} = -\frac{V_{max}+V_{min}}{2} \qquad \dots\dots(31)$$

6. SIMULATION RESULTS

In this work, step increases in wind speeds from 7.2 m/sec to 12 m/sec are explored for 690V/2.3 MW five phase SCIG wind energy system using a three-level rectifier.

Figure 3 shows that d-axis of stator flux and rotor flux maintains at its rated value and q- axis of stator flux reduced to very small value during step change in wind speeds.

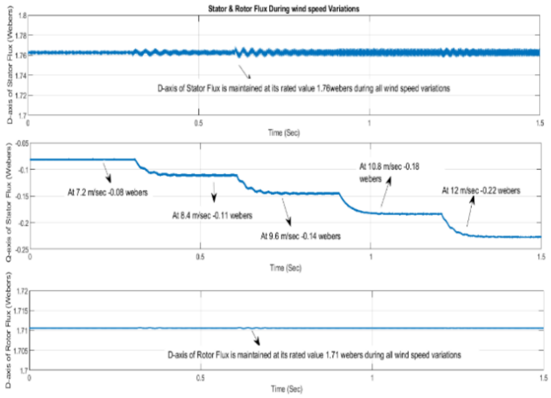

Figure 3: D & Q axis of Stator and Rotor Fluxes

Figure 4 shows that d-axis of stator current maintained at rated value 801.4Amperes during all step change in wind speeds to control d- axis rotor flux and q- axis stator currents is varied -639.28 Amperes at 7.2m/sec, -870.13 Amperes at 8.4 m/sec, -1136.5Amperes at 9.6m/sec,-1438.64 Amperes at 10.8 m/sec and -1775.8 Amperes at 12 m/sec. and rotor flux maintains at its rated value and q- axis of stator flux reduced to very small value during step change in wind speeds.

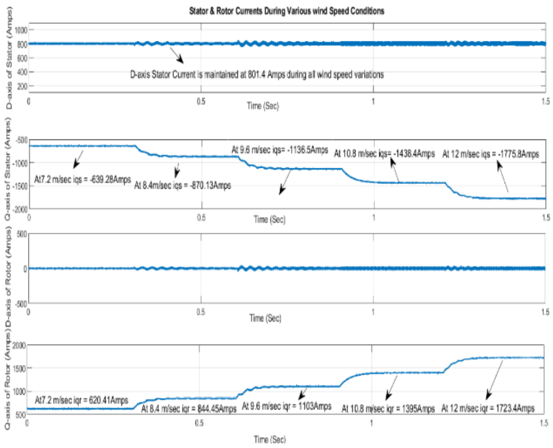

Figure 4: D & Q axis of Stator and Rotor Currents

Figure 5 shows that stator currents of five phase asynchronous generator with peak value 1045 Amperes at 7.2 m/sec, 1200 Amperes at 8.4m/sec, 1400 Amperes at 9.6m/sec, 1650 Amperes at 10.8m/sec and 1950 Amperes at 12 m/sec.

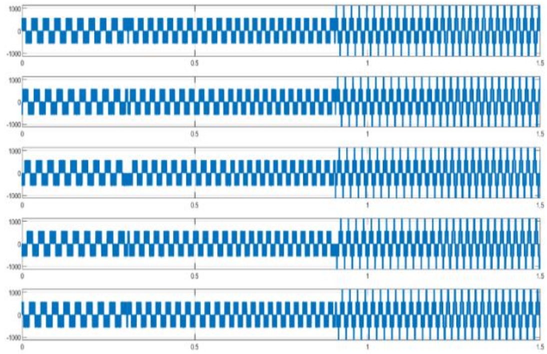

Figure 5: Five phase Stator Currents

Figure 6 shows the variations of line-to line voltages of the three-level rectifier during step change in wind speeds with value of fundamental value of 563.3 to 1100 volts.

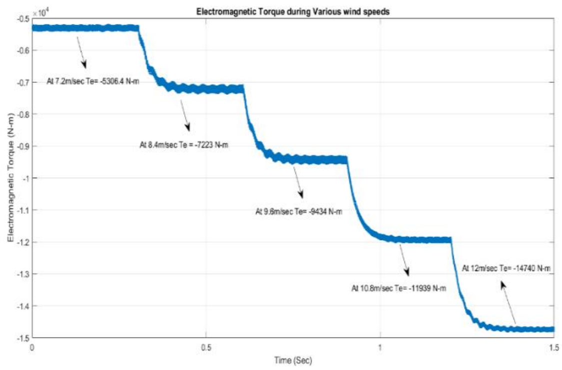

Figure 6: Line to Line Voltages of Five phase three level rectifier

Figure 7 shows the variations of Electromagnetic torque of asynchronous generator with values of -5306.2) N-M at 7.2 m/sec, -7223N-M at 8.4 m/sec, -9434 N-M at 9.6 m/sec, -11939N-M at 10.8m/sec and -14740N-M at 12 m/sec.

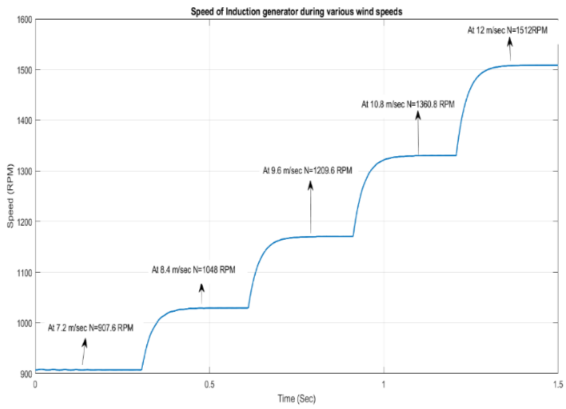

Figure 7: Electromagnetic Torque of asynchronous generator

Figure 8 shows the variations of speed of asynchronous generator with values of 907.6 RPM at 7.2 m/sec, 1048RPM at 8.4 m/sec, 1209.6 RPM at 9.6 m/sec, 1360.8 RPM at 10.8m/sec and 1512 RPM at 12 m/sec.

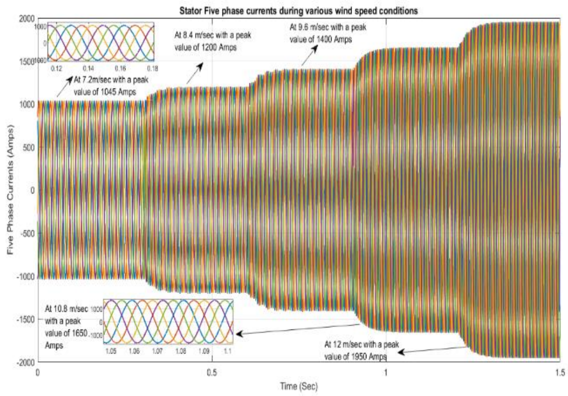

Figure 8: Speed of asynchronous generator

7. CONCLUSION

The performance of the five phase SCIG employing a three-level rectifier and indirect vector control technique is discussed in this research for various wind speeds, and the relevant simulation results are depicted using MATLAB/SIM-ULINK. Using Simulation results it can be observed that harmonic distortion for stator currents in five phase asynchronous generator reduced from 0.88% in two level rectifiers to 0.44% using three level rectifiers.

APPENDIX

Power Rating	2 MW
Rated Voltage	690V
Rated Frequency	50 Hz
Rated speed (RPM)	1512
No of Poles	4
Stator Resistance R_S	$1.102*10^{-3}$ Ω
Rotor Resistance R_r	$1.497*10^{-3}$ Ω
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

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