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Vector Control Of Wind Driven Self Excited Induction Generator Connected To Grid Using Twenty Four Pulse AC-DC Converter Employing Pulse Doubling Technique

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Abstract

This paper deals with multipulse AC-DC converters for improving the power quality in vector-controlled wind driven self excited induction generator at the point of common coupling. These multipulse AC-DC converters are realized using a reduced rating autotransformer. Moreover, DC ripple reinjection is used to double the rectification pulses resulting in an effective harmonic mitigation. The proposed AC-DC converter is able to eliminate up to 21st harmonics in the supply current. The effect of load variation on Vector Controlled Self Excited Induction Generator(VCSEIG) is also studied to demonstrate the effectiveness of the proposed AC-DC converter. A set of power quality indices on input AC mains and on the DC bus for a VCSEIG fed from different AC-DC converters .The complete electromechanical system is modeled and simulated in MATLAB using Simulink and simpower system block set. The simulated results are presented and compared for regulating voltage and frequency of SEIG driven by wind turbine

Keywords: Autotransformer, Multipulse AC—DC converter, DC ripple reinjection, Pulse doubling, VCSEIG.

1. Introduction

Since the 1930s, it has been known that a three-phase induction machine can work as a self-excited induction generator (SEIG) [1, 2]. Due to their simplicity, robustness, and small size per kW generated, induction generators are favoured for small hydroelectric and wind powered plants. One distinct advantage of the SEIG is its much lower unit cost compared with the conventional synchronous generator [3]. Recent widespread adaptation of power electronics and microcontrollers has enabled use of these generators with increased efficiency, for power generation of up to 500 kW when connected to the power grid. In contrast, the maximum power of a stand-alone SEIG does not go much beyond 15 kW [4].

In isolated applications, an induction generator operates with three AC capacitors connected to the stator terminals, or with a power converter and a single dc capacitor [5]. Once an induction generator is excited, the capacitor maintains the excitation. The minimum dc capacitance required for the initiation of voltage buildup can be found in reference [6]. For a given capacitance,self-excitation can only be achieved and maintained over certain load and speed ranges. Even when the capacitor is properly chosen, additional mechanisms must be added to avoid demagnetization and to achieve better control of the voltage produced. Some of these mechanisms include field-oriented techniques [7]. Contemporary research focuses on control mechanisms using stator flux orientation as well as those using rotor flux orientation.

Harmonics can be reduced using different active or passive wave shaping techniques. However, they require careful application and may produce unwanted side effects, particularly in the presence of power factor (PF) correction capacitors. The most rugged, reliable and cost effective solution to mitigate these harmonics is to use multipulse methods [4].

In multipulse converters, the autotransformer-based configurations provide the reduction in magnetic rating as the transformer magnetic coupling transfers only a small portion of the total kVA of the induction motor drive. Various 6-pulse-based rectification schemes have been reported and used in practice for the purpose of line current harmonic reduction [7]. With the use of a higher number of multiple converters, the power quality indices show an improvement, but at the cost of large magnetics resulting in a higher cost of the drive. To achieve similar performance in terms of harmonic current reduction, DC ripple reinjection has been used.

This paper investigates a control system for an induction generator that uses the stator flux orientation. Systematic analysis of this control system is carried out for wide ranges of both load and speed. The induction generator supplies a variable dc load. This paper presents an autotransformer-based 24-pulse AC-DC converter with reduced rating magnetics. A pulse multiplication technique is used to improve various power quality indices to comply with the IEEE standard 519 [8]. This arrangement results in elimination up to the 21*harmonic in the input line current.Moreover, the effect of load variation on the vector-controlled induction motor drive (VCIMD) is also studied. The proposed AC—DC converter is able to achieve near unity PF in a wide operating range of the drive.

2. System Configuration

The proposed system is as shown in Fig.1

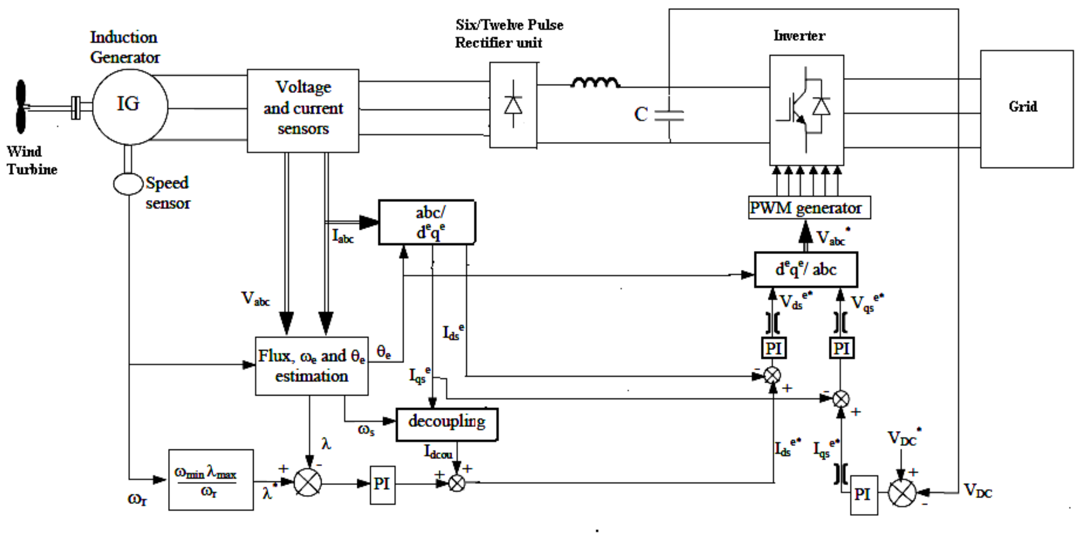


Fig.1. Overall system description

2.1. System Description

Fig. 1 shows the wind driven self excited induction generator with excitation capacitor, consumer loads, and conventional six-pulse diode rectifier. The diode bridge is used to convert ac terminal voltage of SEIG to dc voltage. The output dc voltage has the ripples, which should be filtered, and therefore, a filtering capacitor is used to smoothen the dc voltage. An inverter is used to provide AC voltage across the grid which is the load for SEIG. The sensed terminal voltage is compared with reference voltage and error signal is processed through PI controller. According to the principle of operation of the system, the suitable value of capacitors is connected to generate rated voltage at desired power. The input power of the SEIG is held constant at varying consumer loads.

2.2. Design Of The Model

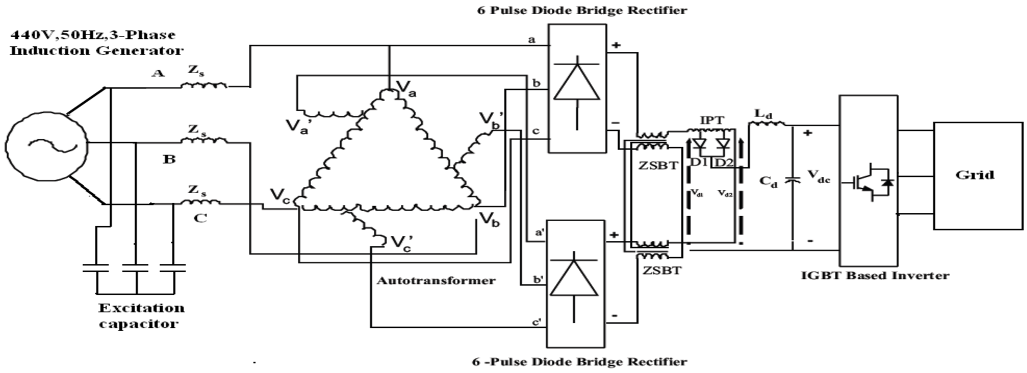


Fig.2. Twenty Four pulse Diode Bridge

In the above fig.2 the constant prime mover shaft was connected to Induction generator shaft. In this paper uncontrolled wind turbine is used as a constant prime mover. A.3.5KW, 440V, 50HZ Induction machine is used as SEIG and modeled using available power electronics block set like diode bridge rectifier and connected to a 440 V grid supplying to the college laboratories. Simulation is carried out in MATLAB version of 10 above at discrete step of 50E-6.Detailed simulation and analysis are given in the fallowing section. The parameters of the induction machine are R_s = 0.69 Ω, R_r = 0.74Ω, L_{ls} = L_{lr} = 1.1 mH, J = 0.23kg/m2, $L_{ss} = L_{ls} + L_m$ and $L_{rr} = L_{lr} + L_m$. Excitation capacitor C = 15 µF/ phase and Capacitor at rectifier C=3200 µF. The magnetic rating are 12-pulse-based converter: Autotransformer rating 12Kva,Interphase transformers 2.7kVA, passive filter 3kVA.References.

3. Control scheme

Stator flux oriented control is used in this paper. Its accuracy is dependent only on the stator resistance variation. In addition, it is insensitive to the variation in the leakage inductance of the machine. In induction motor the application of stator flux oriented control the parameter variation of resistance R_s tends to reduce the accuracy of the estimated signal at low voltage [1]. However, at higher voltage the effect of parameter variation in R_s can be neglected. Flux estimation accuracy in rotor flux oriented control is affected by rotor parameters. The rotor resistance variation becomes dominant by temperature and skin effect in squirrel cage induction machines [3].Compensation of this parameter is difficult because of inaccessibility, but it easier to compensate R_s [4].

3.1. Determination of control parameters

To find the decoupling signal given in Fig. 1 some of the equations of an induction machine in the excitation reference frame are considered[5]. Since in the stator oriented reference frame all variables are expressed in a reference frame oriented to the stator flux linkage space vector, a mathematical model needs to be developed to find the relationship between the stator flux linkage and the stator currents

$$\lambda_{ds}^e = L_s i_{ds}^e + L_m i_{dr}^e \quad (1)$$

$$\lambda_{dr}^e = L_m i_{ds}^e + L_r i_{dr}^e \quad (2)$$

$$\lambda_{qs}^e = L_s i_{qs}^e + L_m i_{qr}^e \quad (3)$$

$$\lambda_{qr}^e = L_m i_{qs}^e + L_r i_{qr}^e \quad (4)$$

$$0 = R_r i_{dr}^e + p\lambda_{dr}^e - (\omega_e - \omega_r)\lambda_{qr}^e \quad (5)$$

$$0 = R_r i_{qr}^e + p\lambda_{qr}^e - (\omega_e - \omega_r)\lambda_{dr}^e \quad (6)$$

From equations (1) and (2)

$$\lambda_{dr}^e = \frac{L_r}{L_m}(\lambda_{ds}^e - \sigma L_s i_{ds}^e) \quad (7)$$

And from equation (3) and (4)

$$\lambda_{qr}^e = \frac{L_r}{L_m}(\lambda_{qs}^e - \sigma L_s i_{qs}^e) \quad (8)$$

Where

$$\sigma = 1 \quad \frac{L_m^2}{L_r L_s} \quad (9)$$

From the equations (1) and (2) the rotor currents can be expressed as

$$i_{dr}^e = \frac{\lambda_{ds}^e - L_s i_{ds}^e}{L_m} \quad (10)$$

$$i_{qr}^e = \frac{\lambda_{qs}^e - L_s i_{qs}^e}{L_m} \quad (11)$$

With stator flux oriented vector control, illustrated in Fig.4, the total stator flux is aligned along the d-axis of the synchronously rotating reference frame so that

$$\lambda_{ds}^e = \lambda_s \quad (12)$$

And

$$\lambda_{qs}^e = 0 \quad (13)$$

Then

$$\frac{d\lambda_{qs}^e}{dt} = 0 \quad (14)$$

Equations (7),(8),(9) and (10) are substituted in the voltage equations given in (5) and (6) to eliminate the rotor flux linkages and rotor currents from the induction machine equations and to express the machine equations in the reference frame fixed to the stator flux linkage space vector. Simplifying the equations using (12), (13) and (14) the new expressions are given by

$$(1 + T_r p)\lambda_s - (1 + \sigma T_r p)L_s i_{ds}^e - \omega_{sl} T_r \sigma L_s i_{qs}^e \quad (15)$$

$$\omega_{sl} T_r (\lambda_s - \sigma L_s i_{ds}^e) - L_s((1 + \sigma T_r p))i_{qs}^e \quad (16)$$

where *p* is the differential operator, i.e. $p = \frac{d}{dt}$, $T_r = \frac{L_r}{R_r}$ and ω_{sl} is the slip frequency expressed as $\omega_{sl} = \omega_e - \omega_r$

As given in (15), with the stator flux oriented vector control, which is based on an impressed stator current controller, the total stator flux linkage, λ_s, and the q-axis stator current, i_{qs}^e, are coupled. This means that any change in i_{qs}^e without changing i_{ds}^e will cause unwanted transients to occur in the stator flux linkage.

The undesirable coupling can be eliminated by utilizing a decoupling circuit in the flux linkage control loop. The decoupling circuit is implemented at the output of the stator flux linkage controller. The stator flux linkage controller is a PI controller and its output is designed to be the d-axis current required to produce the reference stator flux linkage say i_{ds1}^e given by

$$i_{ds1}^e = G(\lambda_s^* - \lambda_s) \quad (17)$$

where *G* is the transfer function of a PI controller.

However, due to the coupling problem i_{ds1}^e does not have total control over the stator flux linkage. The reference d-axis current, i_{ds}^e with full control of the stator flux linkage is expressed as

$$i_{ds1}^{e*} = i_{ds1}^e + i_{deco} \quad (18)$$

Substituting (17) in (18) gives

$$i_{ds}^{e*} = G(\lambda_s^* - \lambda_s) + i_{deco} \quad (19)$$

Substituting eq(19) in eq(15) gives,

$$(1 + T_r p)\lambda_s = (1 + \sigma T_r p)L_s G(\lambda_s^* - \lambda_s) - (1 + \sigma T_r p)L_s i_{deco} - \omega_{sl} T_r \sigma L_s i_{qs}^e \quad (20)$$

For decoupled control with the help of i_{deco} the two last terms of Equation (20) can be cancelled i.e,

$$(1 + \sigma T_r p)L_s i_{deco} - \omega_{sl} T_r \sigma L_s i_{qs}^e = 0 \quad (21)$$

So that,

$$i_{deco} = \frac{\omega_{sl} T_r \sigma L_s i_{qs}^e}{(1+\sigma T_r p)} \quad (22)$$

The angular slip frequency is available from (16) and is given by

$$\omega_{sl} = \frac{(1+\sigma T_r p)L_s i_{qs}^e}{T_r(\lambda_s - \sigma L_s i_{ds}^e)} \quad (23)$$

The reference flux linkage required at any speed is calculated based on this maximum flux linkage, λ_{max} which corresponds to the minimum rotor speed, ω_{rmin}. Hence at any rotor speed, ω_r, the reference stator flux linkage is given by,

$$\lambda = \frac{\omega_{rmin}}{\omega_r}\lambda_{max} \quad (24)$$

3.2. Design of the proposed 24-pulse AC-DC converter

This section presents the design technique for achieving 24-pulse rectification in the proposed AC-DC converter. To achieve the 24 pulse rectification, the necessary requirement is the generation of two sets of line voltages of equal magnitude that are 30^0 out of phase with respect to each other.The number of turns required for the 0^0 and 30^0phase shift is calculated as follows:

Consider phase A:

$$V_a' = V_a + K_1 V_{ca} - K_2 V_{bc} \qquad V_b' = V_b + K_1 V_{ab} - K_2 V_{ca} \quad (25)$$

Assume the following set of voltages:

$$\left.\begin{array}{lll} V_a = V\angle 0^0 & V_b = V\angle -120^0 & V_c = V\angle 120^0 \\ V_{ab} = 1.732V\angle 30^0 & V_b = 1.732V\angle 90^0 & V_c = 1.732V\angle -30^0 \end{array}\right\} \quad (26)$$

Similarly,

$$V_a' = V\angle 30^0 \qquad V_b' = V\angle -90^0 \qquad V_c' = V\angle 150^0 \quad (27)$$

Where V is the RMS value of the phase voltage.Using the above equations,K_1, K_2 can be calculated.These equations result in $K_1 = 0.0843, K_2 = 0.229$ for the desired phase shift in the auto transformer.The phase-shifted voltages for phase A are:

$$V_a' = V_a + 0.0843V_{bc} + 0.229V_{ca} \quad (28)$$

The kVA rating of the interphase transformer and the Zero Sequence Blocking Transformer(ZSBT) is also calculated.

The AC-DC converter output voltage V_{dc} and the voltage across the interphase reactor is given by:

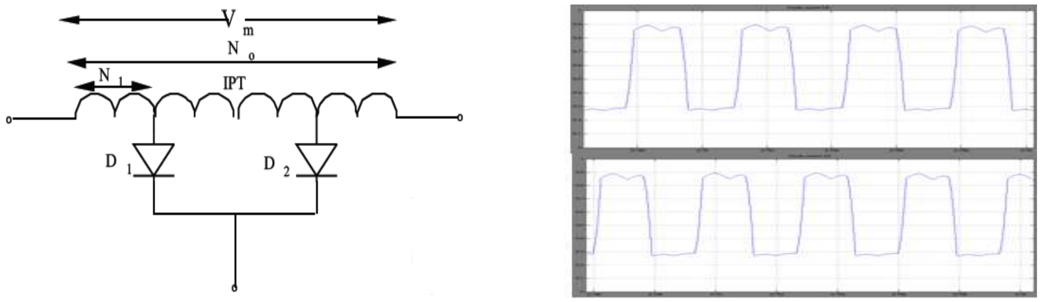
$$V_{dc} = \frac{V_{d1}+V_{d2}}{2} \qquad V_m = V_{d1} - V_{d2} \quad (29)$$

V_m is an Ac voltage ripple of six times the source frequency.

3.3. Design of interphase reactor and ZSBT

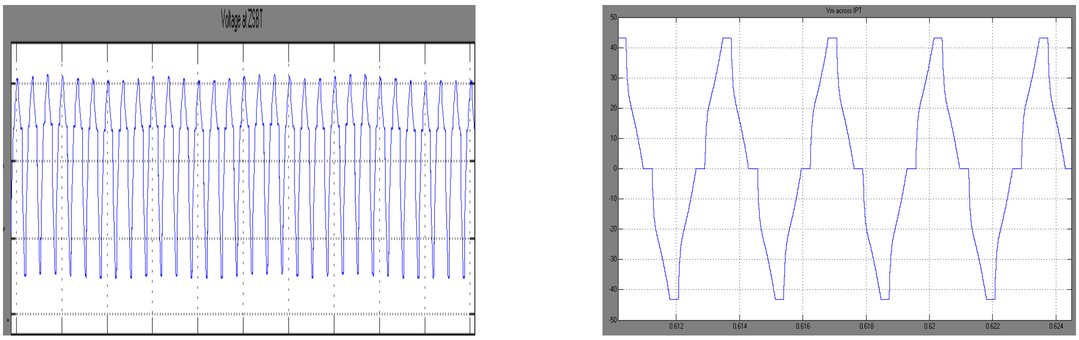
Pulse multiplication has been obtained for controlled converters with a tapped interephase reactor and two additional diodes. The turns ratio of the interphase reactor is given by $\frac{N_1}{N_2}$=0.2457.The waveforms of the diode currents are as shown Fig.3(a) and (b) respectively.

The ZSBT helps in achieving an independent operation of the rectifier bridges,thus eliminating the unwanted conducting sequence of the rectifier diodes..The voltage waveforms across ZSBT and IPT are as shown in Fig.4(a) and (b) respectively.



(a) **(b)**

Fig.3.(a).Tapped interphase reactor along witht the diodes (b).Diodes D_1 and D_2 voltage waveforms



(a) **(b)**

Fig.4.(a).Voltage waveforms across IPT (b) Voltage waveform across ZSBT

4. MATLAB based Simulation and Results

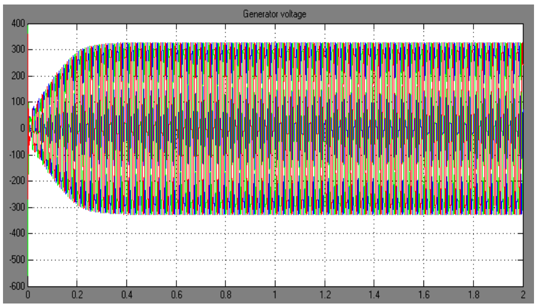
The simulation stator oriented vector control is implemented using MATLAB/SIMULINK. The features in the Power Systems Blockset are used to model an inverter, rectifier and all circuit components. The induction machine model in the Power Systems Blockset is modified to include speed as an input and to update the variation of magnetizing inductance as the voltage builds up during self-excitation. To get the right control parameters and performance it is simply a matter of tuning the PI controllers in the DC voltage controller and flux linkage controller given in Fig. 1.

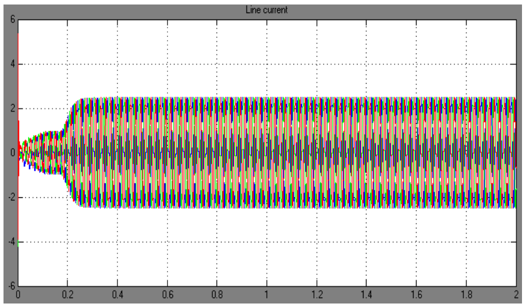
The dynamics of the DC voltage at the start of the voltage build up process, for a rotor speed of 1.48p.u with capacitance value of 3200µF is as shown in Fig.10(a). When the capacitance is large it takes longer to reach its steady state value. If the capacitance is too small there will not be enough exciting current and as a result there will not be voltage build up. Fig.10(b) shows the no load build up of generated line to line voltage at the terminals of the induction generator during the start of self excitation. The voltage build up process is under the no load condition. If there is load, with magnitude above a given minimum value, the voltage build up process will fail.

The frequency of the generated voltage is estimated as :

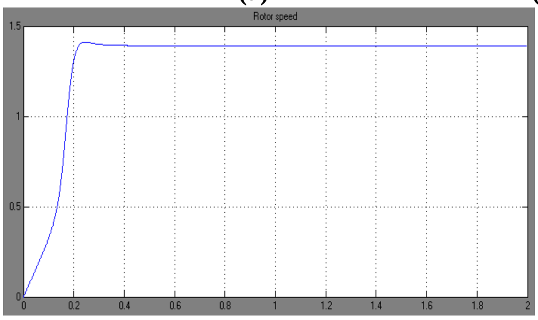
$$\omega_e = \frac{(V_{qs}-i_{qs}R_s)\lambda_{ds}-(V_{ds}-i_{ds}R_s)\lambda_{qs}}{\lambda_{qs}^2+\lambda_{ds}^2} \quad (30)$$

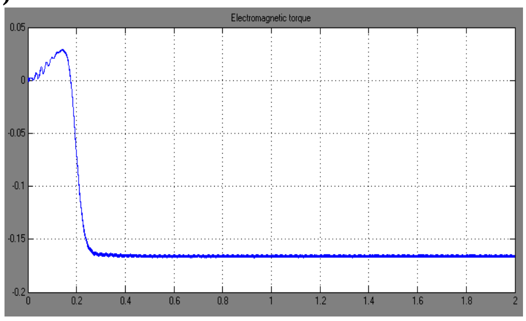
Here, transient waveforms of the generator voltage (Vabc), generator current (Igabc), Speed of the generator ,Electromagnetic torque, rectifier current , voltage at capacitor,inverter voltage, grid voltage, grid current are given under the sudden application and short circuit at grid for conventional six pulse rectifier is as shown in Fig.5 respectively.The Simulink model for the six pulse diode rectifier is as shown in Fig.6.



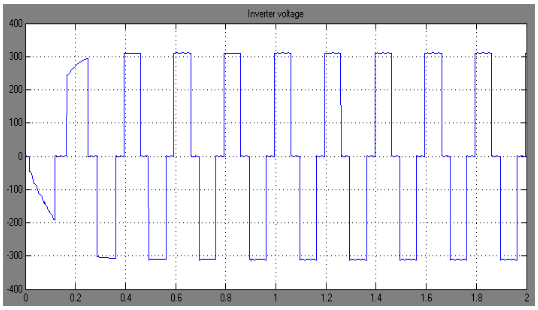


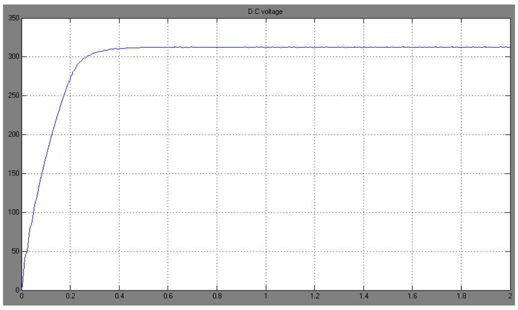
(a) **(b)**





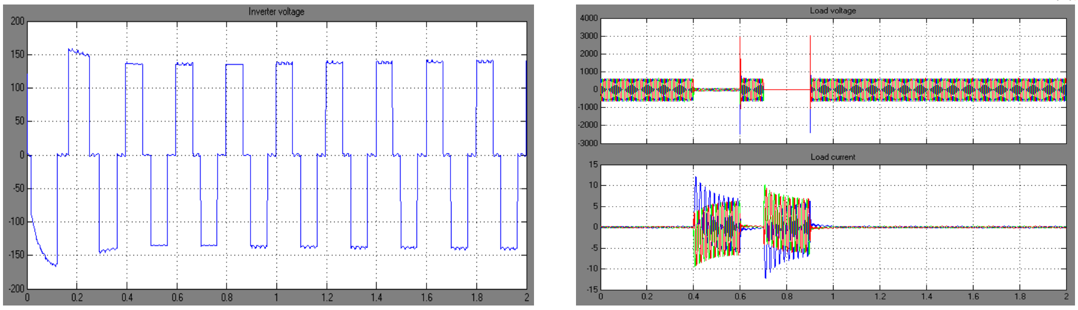
(c) **(d)**





(e)

(f)



(g)

(h)

Fig.5. The experimental transient waveforms (a).Generated voltage (b). Line current. (c).Rotor speed (d).Electromagnetic torque (e).Rectifier current (f).Voltage at capacitor (g).Inverter voltage (h).Grid voltage and grid current.

The proposed AC-DC converter along with the VCSEIG is simulated in the MATLAB environment along with the Simulink The load is suddenly applied at the grid at 0.8 to 1Seconds and the shortcircuit occurs at grid at 1 to 1.2 seconds.The variation is due to these load variations are very slightly observed due to the application of the vector control and 24pulse..Fig.5.Shows the dynamic performance of the proposed AC-DC converter at start and load perturbation on VCSEIG.It consists of Generated voltage,supply current,rotor speed,electromagnetic torque,inverter voltage and DC link voltage.

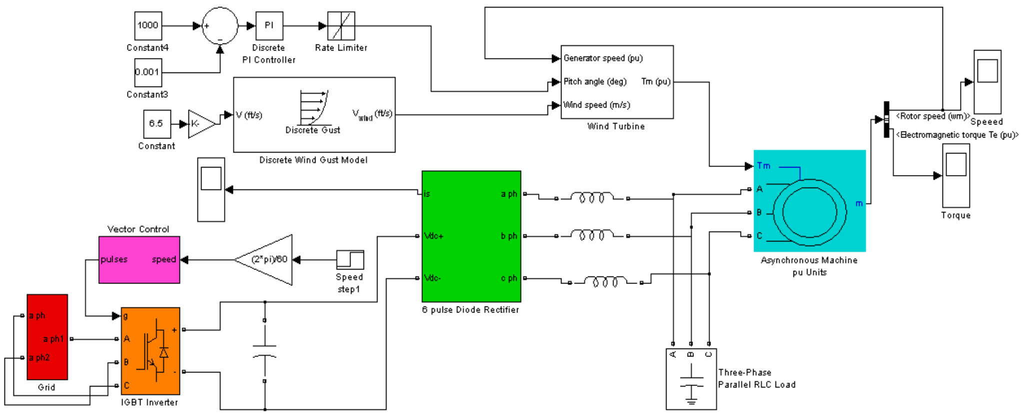


Fig.6. Simulink/MATLAB model for Twenty Four pulse controller

5. **Conclusions**

The voltage build up process of an induction generator with a single capacitor on the DC side of the inverter using stator flux oriented vector control is discussed. Since the induction generator operates at a frequency away from the DC frequency any integration offset error is removed by a low pass filter at a reasonable small time constant.

The total flux is aligned to the d-axis of the stator flux in the excitation reference frame. A decoupling signal is also generated the effect of q-axis current on the d-axis flux. The main advantage of stator flux oriented vector control is the magnitude of the estimated flux depends only on the stator resistance. Unlike the rotor resistance the variation of stator resistance depends manly on temperature.

If the variation of stator resistance is causing a significant error then a compensation block can be added in the model.

The power quality has been improved using 24pulse uncontrolled diode rectifier and an inverter and harmonics are reduced compared to 6 pulse. The proposed method is able to achieve unity PF with a good DC link voltage regulation in the wide operating range of the drive, and has resulted in a reduction in the rating of the magnetic, leading to the saving in the overall cost of the drive. It can easily replace the existing six-pulse converters without much alteration in the existing system layout and equipments.

Appendix

1. **Machine Parameters**

The parameters of the 3.5 kW,440V, 7.5A, 50 Hz,4-pole induction machine are given below.

R_s = 0.69 Ω, R_r = 0.74Ω, L_{ls} = L_{lr} = 1.1 mH, J = 0.23kg/m2,

$L_{ss} = L_{ls} + L_m$ and $L_{rr} = L_{lr} + L_m$.

2. **Excitation capacitor** C = 15 μF/ phase and Capacitor at rectifier C=3200 μF
3. **Air gap voltage**:

The piecewise linearization of magnetization characteristic of machine is given by:

$E_1=0$	$X_m \geq 260$
$E_1=1632.58-6.2X_m$	$233.2 \leq X_m \leq 260$
$E_1=1314.98-4.8X_m$	$214.6 \leq X_m \leq 233.2$
$E_1=1183.11-4.22X_m$	$206 \leq X_m \leq 214.6$
$E_1=1120.4-3.9.2X_m$	$203.5 \leq X_m \leq 206$
$E_1=557.65-1.144X_m$	$197.3 \leq X_m \leq 203.5$
$E_1=320.56-0.578X_m$	$X_m \leq 197.3$

4. **Magnetics Rating:**

12-pulse-based converter: Autotransformer rating 12Kva,
Interphase transformers 2.7kVA, passive filter 3kVA.References

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