Computation of rotor position of DFIM using Rotor side Phase Locked Loop

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***Abstract*—A new sensor-less technique to compute the rotor position of a Doubly Fed Induction Generator (DFIG) usinga Rotor side Phase Locked Loop (RPLL) is proposed in this paper. The rotor speed and position are computed using the basic induction machine model in a simple andunique procedure. The idea of using RPLL method for rotor position computation is evolved in a similar way as a grid side PLL is used for determining the frequency or positionof the grid flux. The necessity for computing the rotor speed and position is mainly to target high performance closed loop control of drives in motoring operation and for a precise decoupled control of active and reactive power in generating operation. The proposed scheme is simulated in MATLAB/Simulink environment and also validated using experiments. The experimental setup comprises of a 3-hp grid connected Doubly Fed Induction Machine (DFIM) along with a ALTERA cyclone II FPGA based digital controller for control implementation.**

***Index Terms*--Doubly-Fed induction Machine (DFIM), Phase Locked Loop (PLL), Grid unbalance, Sensorless speed estimation.**

NOMENCLATURE

v, i	Instantaneous value of voltage and current
λ	Instantaneous value of flux linkage
α, β	Stator reference frame
α_r, β_r	Rotor reference frame
ω_e, ω_r	Angular velocity of stator flux and rotor
θ_s	Angle between stator voltage vector and β axis
ε	Angle between stator and rotor axis
μ	Angle between stator flux axis and β axis
First Subscripts	
s, r	Stator and rotor
m, l	Mutual and leakage
Second Subscripts	
d, q	Synchronous reference frame

I. INTRODUCTION

In Wind Energy Conversion Systems (WECS) it is beneficial to operate the wind turbines at variable speed. At variable speeds power from the generators needs to be controlled by power electronic converters. Thus, Doubly Fed Induction Generator (DFIG) is an interesting solution for Variable Speed Constant Frequency (VSCF) applications. The back to back converters of DFIG include a Grid Side Converter (GSC) and a Rotor Side Converter (RSC) whichfacilitates four quadrant operation i.e. sub-synchronous motoring and generating and super-synchronous motoring and generating by handling slip power in both directions. In particular, with these power converters in rotor side, power is generatedover a typical range of 0.7 to 1.3 p.u. of synchronous speed at nominal grid voltage and nominal frequency [15].

The function of a GSC is to maintain a constant dc link voltage between the two back to back converters either by absorbing or supplying reactive power from the grid analogous to a STATCOM.However, the RSC facilitates control of speed or torque for motor operation, and independent control of real and reactive power for generator operation through vector control.Thus, for a DFIM to operate as a generator for wind power applications it is essential to control the real and reactive power which requires the rotor position information.Generally shaft-mounted encodersare used to determine the rotor speed and position. However, such sensors have drawbacks such astedious maintenance, added costand cabling, degraded robustness etc. Thus, sensorless schemes are preferred inhigh performance applications.

Various studies on sensorless control of Induction machine are reported in literature which can be broadly classified as open loop [1-6]and closed loop [9-12] techniques.The idea of determining rotor position involves computing the torque angle from the measured rotor currents and voltages [1]. But the response is poorunder low rotor speeds (light load torque). A simple trigonometric computation for speed computation is suggested [2] where the accuracy depends on the magnetizing current. However, the differential terms used in speed determination lead to inaccuracies due to inherent noise in measured signals. Speed is obtained from the stator voltage and currentindependent of machine parameters [3]. A stator flux oriented scheme of DFIM for speed and power control with and without position encoder is presented in [4].In an open loop technique [5, 6]the stator flux in the stationary reference frame is computed using the analytical equivalents of flux in terms of measureable stator and rotor quantities. Slip frequency PLL method [7,8] uses the known values of stator voltages and rotor currents,to compute the instantaneous position of the rotor flux vector. The rotor position PLL operates independent of machine parameters except the magnetization reactance.

Closed loop speed estimation techniques commonly involve Model Reference Adaptive System (MRAS) [9-12]. The rotor position and speed for a standalone system are determined [9] using the stator flux based MRAS method. However, drift errors in integrator limit the low frequency performance. Sensitivity to machine parameters is a limiting feature [10] in rotor current based MRAS method suitable for both grid connected and standalone generators. Adaptive tuning of stator inductance in Rotor Current MRAS Observer (RCMO) [11] and a simplified model [12] evaluate the error in the estimated rotor position. Further, stability of a sensorless DFIM based drive is investigated in [13] where a hysteresis control is used instead of a PI controller. As the system performance is based on the amplitude of rotor current, position estimation during light load conditions is a challenge. Position estimation based on the comparison of the torque from the reference and adaptive models is proposed in [14]. Here the rotor position is estimated from the measured values of voltages and currents, rather than using stator or rotor fluxes.

An improved sensorless control algorithm for DFIG [16]suggests obtaining the slip frequency from the reactive power based adaptive model. Under grid voltage unbalance, the speed is estimated using an adaptive neural network. The practice of using a grid side PLL for obtaining exact grid frequency and position under distorted grid conditions is discussed in [17-18]. A simple, fast and robust PLL for distorted utility conditions is reported in [17]. A PLL with a dynamic feed forward frequency estimator [18] showed thatthe phase error can be reduced by the feedback controller; while a feed forward controller eliminates the frequency error thereby providing precise locking. Thus it is evident that a PLL at grid side is capable of synchronization even under unbalance grid voltages.

Taking this idea into consideration a PLL at rotor side (RPLL) for rotor position estimation under unbalance condition is proposed in this manuscript. Thus the Rotor Phase Locked Loop (RPLL) proposed for rotor positionin this paper is analogous to aconventionalGrid side PLL, commonly used for grid synchronization. The algorithm is simple, relies on machine voltages and currents in real time, isfree from differentiation, inverse trigonometric computations and also from noise. Hence the computed rotor speed and position are accurate.

II. FUNDAMENTAL MACHINE MODELING OF DOUBLY FED INDUCTION MACHINE

For applications involving induction machine, the dynamic model of the machine valid under balanced and unbalanced grid voltage is an important tool which helps to design suitable controllers. Fig.1.shows the space vectors in different reference frames. The α-β axes representing the stationary reference frame are orthogonal to each other with the stationary α-axis being in phase with the stator a-axis. Further, the d-q reference frame rotates at synchronous speed$\omega_e$making an angle θ_s with respect to α-βaxes, where, $\theta_s = \omega_e t = (90° + \mu)$.

The stator voltages in the synchronous reference can be written as follows

$$V_{sq} = R_s i_{sq} + \frac{d}{dt}\varphi_{sq} + \omega_e \varphi_{sd} \quad (1)$$

$$V_{sd} = R_s i_{sd} + \frac{d}{dt}\varphi_{sd} - \omega_e \varphi_{sq} \quad (2)$$

Similarly, the rotor voltage equation in the d-q frame can be written as

$$V_{rq} = R_r i_{rq} + \frac{d}{dt}\varphi_{rq} + (\omega_e - \omega_r)\varphi_{rd} \quad (3)$$

and $$V_{rd} = R_r i_{rd} + \frac{d}{dt}\varphi_{rd} - (\omega_e - \omega_r)\varphi_{rq} \quad (4)$$

where, ω_r is the angular speed of rotor. The stator and rotor flux linkages in terms of the currents in d-q frame can be written as,

$$\varphi_{sq} = L_s i_{sq} + L_m i_{rq} \quad (5)$$

$$\varphi_{sd} = L_s i_{sd} + L_m i_{rd} \quad (6)$$

$$\varphi_{rq} = L_r i_{rq} + L_m i_{sq}$$

(7) $$\varphi_{rd} = L_r i_{rd} + L_m i_{sd}$$

(8)

From the synchronous reference frame machine model it could be visualized that, in steady state all the electrical quantities appear as dc quantities.

III. OPERATION & MODELING OF ROTOR PHASE LOCKED LOOP (RPLL)

A. Rotor Phase Locked Loop (RPLL) operation

With the induction machine model presented in section II, a sensorless means of determining the speed and position of rotor of DFIG is discussed in this section. Fig. 2 shows the block diagram of the proposed RPLL scheme.

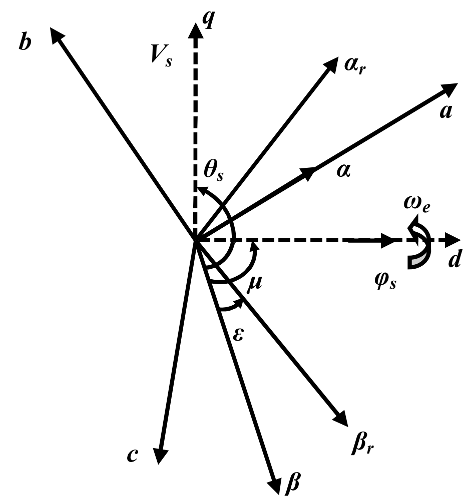

Fig. 1.Space vector diagram.

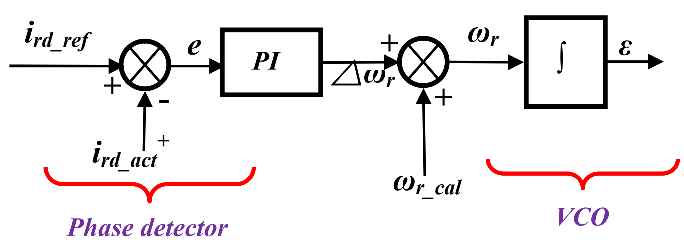

Fig. 2. Block diagram of Rotor Phase Locked Loop(RPLL)

The basic operation of the proposed RPLL is based on the comparison of the reference parameter (i.e. rotor reference currenti_{rd_ref}) with an actual parameter (i.e. actual rotor currenti_{rd_act}) which is given as input to the phase detector where both the currents are positive sequence components. The difference of these two currents generates an error signal 'e' which is set to zero by the PI controller. When this error signal become zero the PLL automatically locks the actual current with the reference current thus providing the exact rotor speed(ω_r)which on integration gives the rotor position(ε). During generating and motoring modes of operationi_{rd_ref} is nothing but the magnetizing currenti_{msd}, required for setting up the flux inside the machine.The bandwidth for tuning the PLL is considered to be 100Hz.

B. Modeling of Rotor Phase Locked Loop (RPLL) for rotor position computation

The inputs to the phase detector are the reference and actual *d*-axis rotor currents i.e. i_{rd_ref} and i_{rd_act} respectively. The difference in the reference and actual rotor currents represented as error *'e'* is given as,

$$e = i_{rd\_ref} - i_{rd\_act} \qquad (9)$$

when$i_{rd_ref} \approx i_{rd_act}$ the error gets minimized by the PI controller to nullify it and thereby locks the PLL and thus acting as a linear control system.

The PI controller needs to be designed accurately to track the phase of the input signal with the output signal in order to obtain the suitable rotor position. The transfer function of the PI is given as follows;

$$\frac{\Delta\omega_r}{e} = k_p + {k_i}/{s} \qquad (10)$$

The rotor speed ω_{r_cal} can be computed from the rotor voltage in *q*-axis as given in (3), by neglecting the rate of change in *q*-axis rotor flux linkage (since, with the stator flux reference frame, *q*-axis stator flux, φ_{sq} and the *d*-axis stator voltage, V_{sd} are zero under balanced grid conditions. Also the rotor flux φ_{rq} can be considered nearly zero due to equal and opposite stator and rotor currents)as follows

$$\omega_{r(cal)} = \omega_e - \frac{V_{rq} - R_r i_{rq}}{\varphi_{rd}} = \omega_e - \frac{V_{rq} - R_r i_{rq}}{L_r i_{rd} + L_m i_{sd}} \qquad (11)$$

From Fig. 3.rotor speed can be written as $\omega_r = \omega_{r_cal} + \Delta\omega_r$where$\Delta\omega_r$is the speed error obtained from PI output.Further, theintegration of ω_r gives the rotor positionε. Thus the rotor speed and position can be obtained. The input of VCO is the angular rotor speed (ω_r) in electrical rad/s and output is the rotor position (ε) in radian. Thus the input, output relationship of VCO can be expressed as, $\frac{\varepsilon}{\omega_r} = \frac{1}{s}$; Thus, the linear open loop transfer function becomes

$$\frac{\varepsilon}{e} = \left[\left(k_p + {k_i}/{s}\right) + w^*_{r\_cal}\right] * \frac{1}{s} \qquad (12)$$

IV. Simulation Results

Simulations for a 3 hp DFIM machine are carried out in MATLAB/Simulink environment. The results obtained under motoring & generating modes with balanced grid voltage are presented in this section. Case i) the DFIM is operated as a motor by short circuiting the rotor with a load of 3Nm applied at 5s under balanced voltage condition and Case ii) the DFIM is operated as generator by switching on the 'RSC' at 5s with speed variation of 1450 rpm to 1540 rpm introduced at 7s.

Case (i) Fig.4(a),(b) depict the supply voltage (balanced) and the rotor phase current respectively. From Fig.4(c) it can be observed that the speed computation algorithm instantaneously tracks the actual speed after RPLL is switched on at t=1s. Further, on applying a load of 3Nm at t=5s (Fig. 4(c)) the speed reduces from 1455rpm to 1427rpm. Moreover, the computed rotor position tracks the actual position even after load change at t=5s (Fig. 4(d)).

In Case (ii) the DFIM is operated as generator at t=5s. The RPLL tracks the rotor position during speed variation from sub synchronous to super synchronous range i.e.1450rpm - 1540rpm, as shown in Fig.5(a) & (b). The frequency change in rotor current during speed transition is also seen in Fig.5(d).

V. Experimental Results

The proposed scheme is verified through the tests on the laboratory setup. The schematic diagram of the experimental setup (Fig.6) comprises of a grid connected 3-hp Doubly Fed Induction Machine and a 5-hp dc motor used as a prime mover. The ALTERA Cyclone II FPGA based digital processor is used for signal processing.The results are presented for motoring and generating cases under balanced grid voltage condition.

A. Validation of proposed RPLL scheme

The machine is started as motor through appropriate switching of devices in the RSC. In this condition, the machine operates as a motorwith rotor windings short circuited. This enables current flow in the rotor phases thereby enabling the RPLL scheme for tracking the speed and position. The test results for different modes of operation are shown as follows.

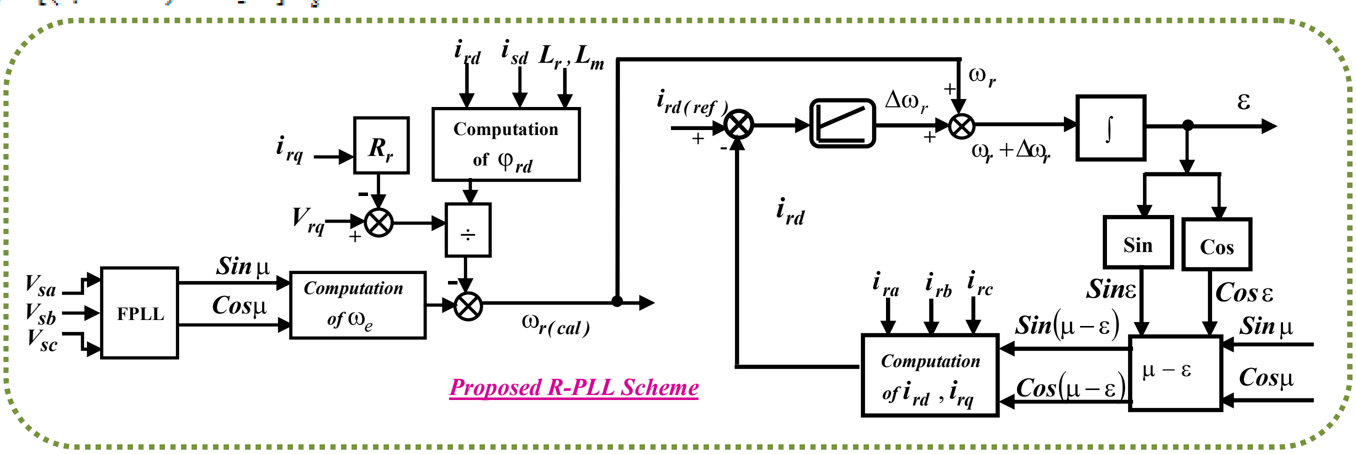

Fig. 3.Block diagram of the proposed rotor speed computation algorithm with the feed forward R-PLL.

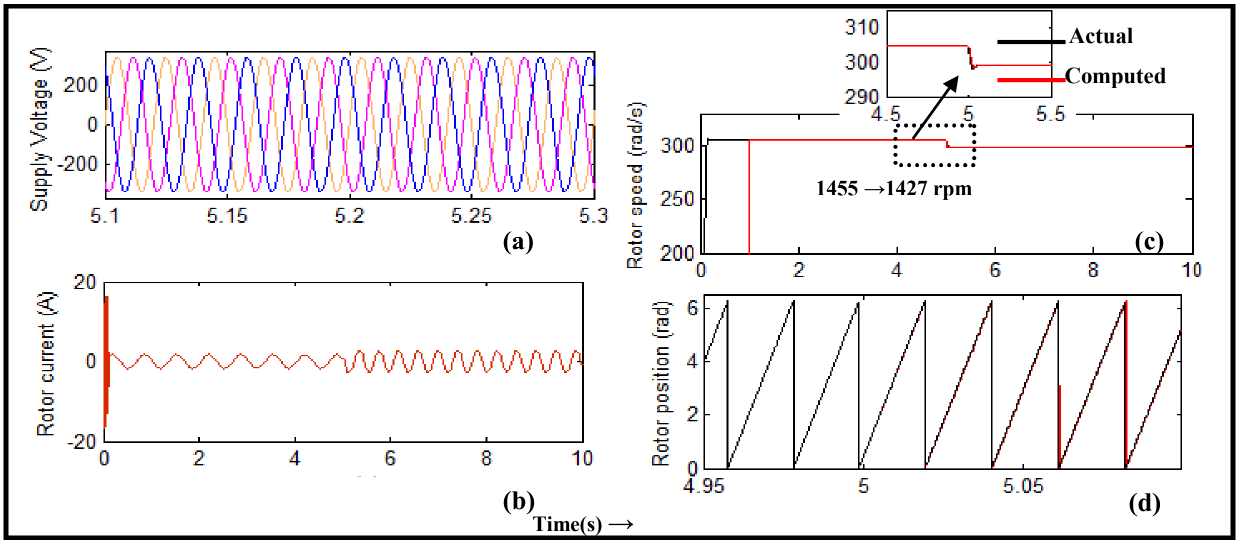

Fig.4.Case-1 : DFIM -motoring operation (a) three phase supply voltage (V), (b) Phase-A rotor current (A), (c) Actual and computed rotor speed (rad/s), (d) Actual and computed rotor position (rad).

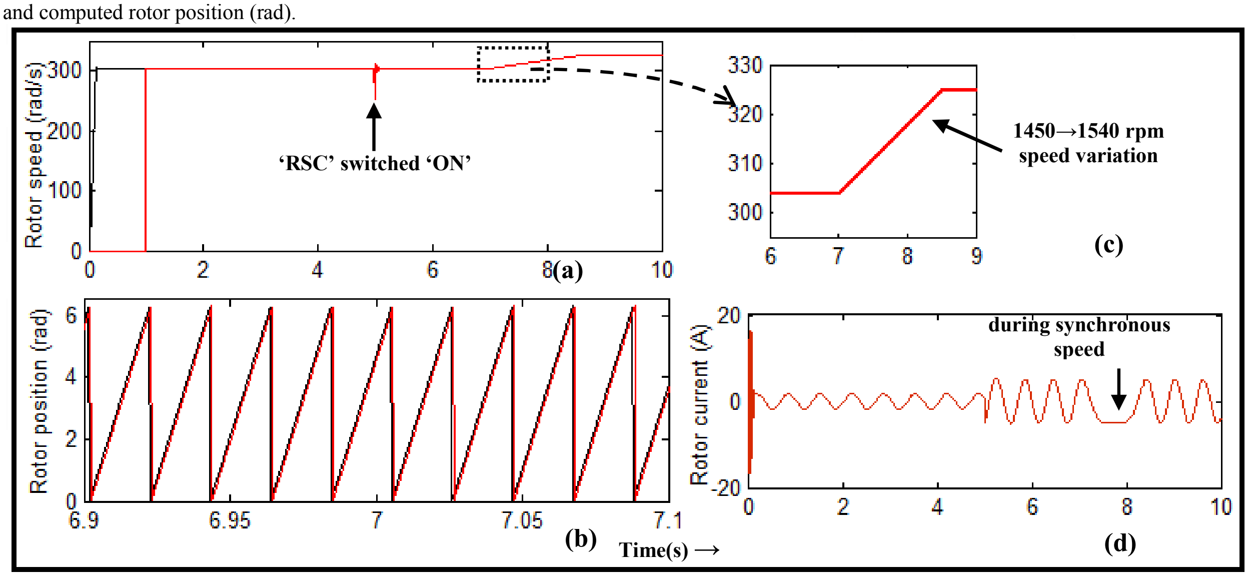

Fig.5.Case-2 : DFIG -generating operation (a)Actual and computed rotor speed (rad/s), (b) Actual and computed rotor position (rad), (c) Enlarged view of rotor speed, (d) Phase-A rotor current(A).

Case (i): Sub-synchronous motoring mode

The computedrotor speed precisely follows the actual one even from 900 rpm as the machine starts from rest (Fig.7(a)). Moreover, the instantaneous variations in speed and the corresponding changes in the rotor current and flux can also be observed (Fig.7(b)) since the computedrotor speed is a function of rotor current and flux as in (11).

It is evident from Fig. 7(c) that the computed rotor position acquired from the RPLL scheme tracks the actual rotor position accurately with a steady stateerror less than 2˚ at 1460 rpm and 1480 rpm. Whereas, under speed transition (1460 - 1480 rpm) the maximum error is 7˚ which persists for a short time only.

Case (ii): Super-synchronous generating mode

The DFIM is operated in generating mode with a dc machine as prime mover by increasing the speed to super synchronous range through field control of the dc motor. Speed variation from sub-synchronous to super-synchronous speed range and vice versa i.e. from 1470-1516 rpm and 1520-1433 rpm respectively is as shown in Fig. 8(a) and (b)respectively.The speed computation algorithm works well at synchronous speed also.

It is evident from Fig. 8(c) that, the RPLL scheme helps to track the rotor position during generating mode also with a minimum error of 2˚ under steady state and with an error of 8˚ during speed transitions.

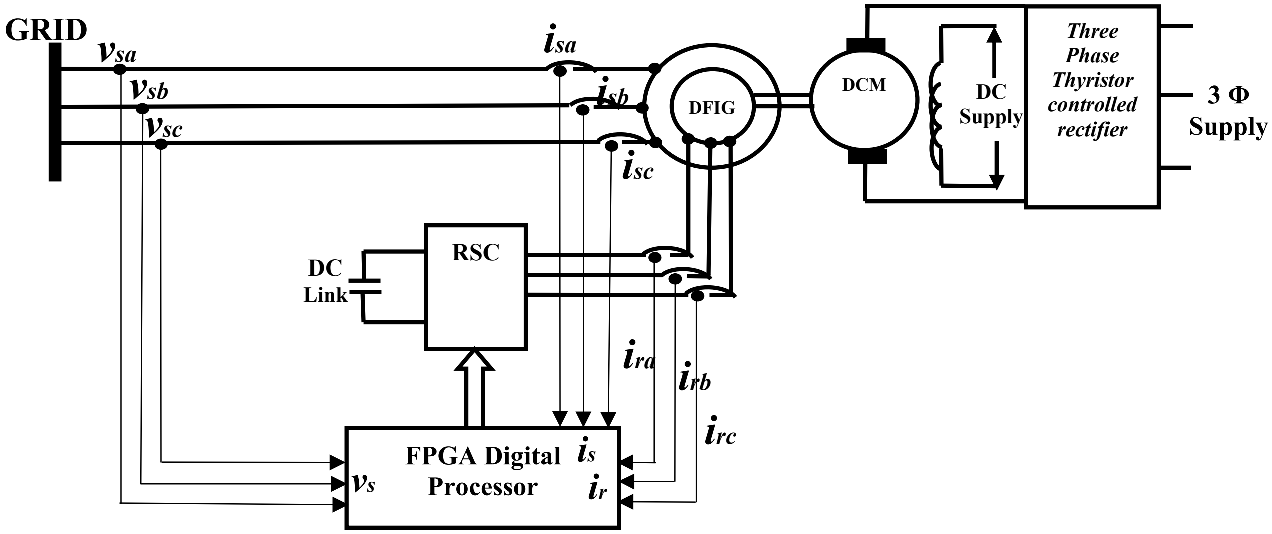

Fig. 6.Schematic diagram of the experimental setup

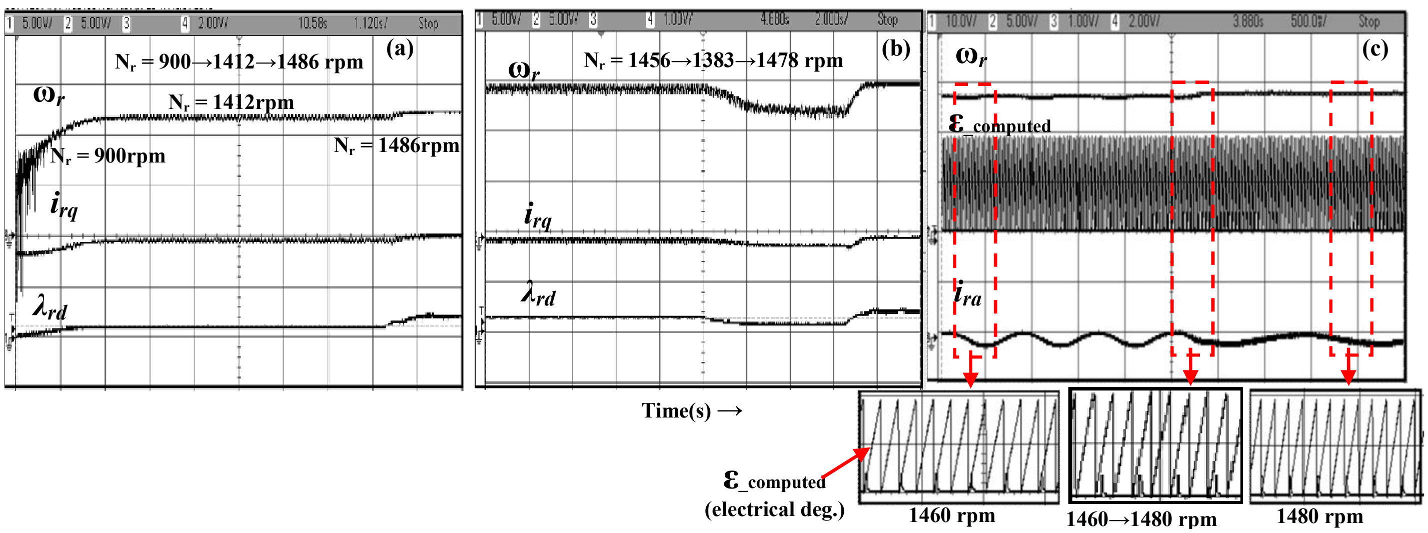

Fig.7.Rotor speed, *q*-axis current and *d*-axis flux – Motoring mode; (a) Rotor speed(600rpm/div), *q*-axis current(10A/div), *d*-axis flux for speed variation 900→1412→1486 rpm (b) Rotor speed(300 rpm/div), *q*-axis current(10A/div), *d*-axis flux for speed 1456→1383→1478 rpm and (c) Computed rotor speed(300rpm/div), computed rotor position and rotor current – Motoring mode during speed transition from 1460 rpm to 1480 rpm.

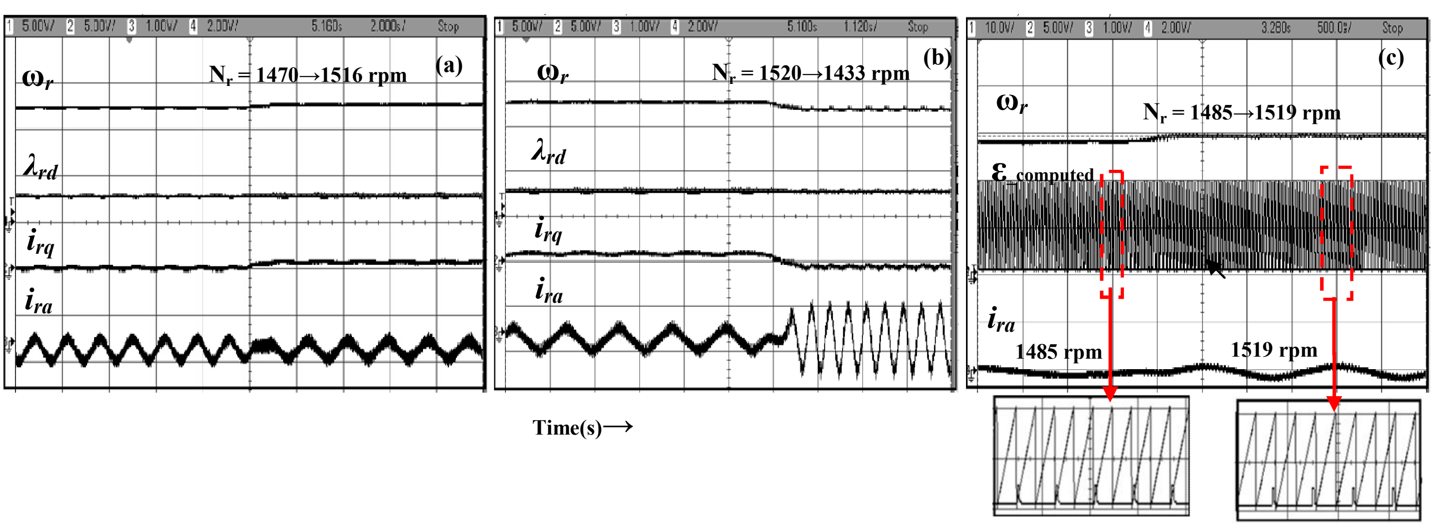

Fig. 8. Rotor speed(600rpm/div), *q*-axis current(10A/div), *d*-axis flux and rotor current – Generating mode; (a) for speed variation 1470→1516 rpm (b) For speed variation 1520→1433 rpm and (c) Computed rotor speed(600rpm/div), computed rotor position and rotor current – Generating mode.

The worst case error in rotor position under different operating conditions with the proposed scheme is compared with the results reported in [6] and is given in a tabular form in Table. 1

Table. 1.
Worst case rotor position error

Scheme	Steady state error		Transient error
	Sub-synchronous speed (1460 rpm)	Super-synchronous speed (1519 rpm)	Speed variations from (1450 to1550 rpm)
Proposed	2°	2°	8°
Implicit Scheme [6]	3.3°	7.5°	-

VI. CONCLUSIONS

A simple and straightforward method free from complex mathematical computations to obtain the rotor speed from the basic machine model is proposed in this paper. The Phase Locked Loop (PLL) concept applied at the rotor side precisely determines the rotor position which works effectively under balanced grid voltage conditions for sub-synchronous, super-synchronous and through synchronous speed. Moreover, it does not involve differentiation thus improving its immunity to noise, delays and spikes in speed computation. Simulation and experimental results validate the efficacy of the proposed scheme.

VII. APPENDIX

TABLE A.1 –Induction Machine Parameters

Parameters of DFIM	Value in SI units
R_s	3.68 Ω
R_r	5.26 Ω
L_s , L_r	0.307 H
L_m	0.282 H
J	0.012 kg-m^2
B	0.033 kg-m^2/s

Doubly fed induction machine:	DC machine:
3 HP, 50 Hz, 4-Pole	5 HP, 1500 rpm
Stator: 415V, 4.7A, Y-connected	Armature: 220 V, 19 A
Rotor: 185V, 7.5A, Y-connected	Field: 220 V, 1 A.

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