Performance of Wound Rotor Induction Motor Operated Under Rotor Windings Asymmetry with Different Connections

R. R. Abdel-Wahab   T. M. Abdo   H. H. Hanafy

Electrical Power and Machines Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt

r_ragab2011@yahoo.com   tam2k0@gmail.com   hanafy_hassan@hotmail.com

Abstract: *This paper presents the performance of a 3-phase wound rotor induction motor (WRIM) under the condition of opening one of the rotor phases including the starting interval. The behavior of WRIM was simulated under faulty conditions for four different possible connections of rotor windings in the ABC frame. Experimental works were carried out for faulty rotor circuit to validate the simulation results. Good agreement between the simulated and the experimental results have been achieved. The results proved that for the faulty rotor windings conditions; the stator and rotor currents increase while the motor speed decreases to nearly half its synchronous speed and the ripples of speed and electromagnetic torque increase. The paper proposes a delta connection with reversed one phase to improve motor performance under faulty conditions. The results proved that the performance of the faulty motor is affected by the connection of rotor windings and the proposed delta connected rotor windings has an acceptable performance.*

Key words: *Wound rotor induction motor, Rotor windings asymmetry, Open phase fault, Gorges phenomenon.*

Nomenclature

V_s	Stator voltage vector (V)
V_r	Rotor voltage vector referred to stator (V)
I_s	Stator current vector (A)
I_r	Rotor current vector referred to stator (A)
R_s	Stator resistance per phase (ohm)
R_r	Rotor resistance per phase referred to stator (ohm)
L_s	Stator self-inductance per phase (H)
L_r	Rotor self-inductance per phase referred to stator (H)
L_o	Maximum mutual inductance (H)
L_{ls}	Stator leakage inductance per phase (H)
L_{lr}	Rotor leakage inductance per phase (H)
θ_r	Rotor position in electrical degree
T_{em}	Electromechanical torque (Nm)
ω_r	Motor speed (electrical rad. /sec)
ω_m	Motor speed (rad./sec)
P	Number of pair-poles

1. Introduction

Robust construction, low cost, high efficiency and high reliability are the main reasons of widely using induction motors in industrial applications. The tough environmental operating conditions of induction motor in industrial applications made it subject to different types of electrical and mechanical faults. Failure of stator/rotor windings insulation, and rotor broken bars /end-rings faults are the most common electrical faults. Failure of bearings and static/dynamic eccentricity are the most common mechanical faults. Operation of induction motor in the presence of a fault especially electrical asymmetry in the stator or rotor windings gives rise to space deformation in the air gap flux, consequently unbalanced supply line currents, increased losses, and increased torque pulsations. Since induction motor faults lead to unexpected motor failure and consequently production shutdown and financial loss so condition monitoring of induction motors is highly important.

Squirrel cage induction motors (SCIMs) had more attention from researchers than WRIMs, since SCIMs have robust construction that made it extensively used in industrial systems. Rotor broken bars and broken end-rings are the most common faults that can occur in the SCIMs. A lot of detailed mathematical models have been developed to study and analyze SCIMs under faulty conditions. These models have used different techniques such as multiple coupled circuit models, DQ models, magnetic equivalent circuit models and finite element models [1-5].

The capability of the WRIMs in developing a high starting torque at low starting currents by the means of inserting an external resistance in series with the rotor windings make them ideal for some applications. Besides limiting the starting current, this resistance can also be used in controlling the motor speed. These advantages made the WRIMs suitable for large power industrial application such as

cranes, pumps, conveyors and hoists [6]. Also the slip energy recovery WRIM drive is popular among variable speed AC drives due to its advantages such as higher efficiency, low converter cost and simple driving circuit.

WRIM is subjected to many types of faults such as stator/rotor windings asymmetry faults, open-circuit of one rotor windings, brushes and slip rings faults [7]. In [8], a complete magnetic equivalent circuit model has been developed to simulate a 3-phase WRIM under healthy and stator/rotor inter-turn short circuit winding fault conditions. The authors concluded that inter-turn short circuit fault in rotor windings is not as dangerous as stator winding faults because the current amplitude under rotor fault is the same as the rated rotor current and therefore it cannot damage the rotor windings. In [9], the performance of a WRIM under rotor inter turn short circuit fault is presented, using magnetic equivalent circuit and finite element method. The authors proved that the rotor inter-turn short circuit has no significant effect upon the developed torque, the stator and rotor currents. In [10], the performance of WRIM under resistance asymmetrical fault conditions in stator and rotor windings has been analyzed. The analysis showed that the performance of WRIM is more affected by asymmetrical rotor windings than asymmetrical stator windings. In [11] the authors used winding function approach to model an inter-turn short circuit in stator/rotor windings of WRIM and time-frequency analysis to detect these faults. From [8, 9, 11] it can be concluded that the rotor inter-turn short circuit has no significant effect on the motor performance. Another frequent rotor fault that occurs in WRIM is unbalanced rotor impedances. This fault has been analyzed to illustrate its effects on the motor performance in [12]. In [13] a dynamic model and an equivalent circuit at steady state for WRIM with the three rotor resistances differing from each other were developed to calculate the performance of the motor under these asymmetry conditions.

It was found that the WRIM could operate at a stable speed near to half its synchronous speed with one rotor phase open circuited which is called Gorges phenomenon [14-15]. It was shown that the motor efficiency with this fault is higher than that of the balanced motor operated at the same speed with external rotor resistances, but this method is hardly ever used in practice due to the current harmonics that injected into the supply, vibration and magnetic saturation which causes excessive currents [16].

Although theoretical and steady state analysis of WRIM performance with one rotor phase open circuited have been discussed and analyzed since 60 years, but no attempts have been made to examine the dynamic performance of the motor and its starting capability under these fault conditions. This paper presents the dynamic performance of the WRIM including the starting period in case of operation with opening one rotor phase. The stator currents, the rotor currents, the motor speed and the electromagnetic torque are analyzed with the aid of dynamic models for different four possible rotor connections. The simulated results are verified through experimental works with good agreement. The analysis shows that the stator and rotor currents have increased combined with increasing of the ripples of speed and torque. The paper suggests a delta connection with reversed one phase to improve motor performance under faulty conditions. Analysis of the motor performance with different rotor windings connections shows that the performance of the motor under asymmetry conditions depends on the type of connection of the rotor windings. The motor with star-connected rotor windings with isolated neutral has the worst performance while the suggested delta-connected rotor, with external open circuit has more acceptable performance.

2. Induction Motor Modeling.

The voltage differential equations and the mechanical equations of the 3-phase induction motor in healthy case can be written as functions of rotor position as follows.

$$\begin{bmatrix} V_s \\ V_r \end{bmatrix} = \begin{bmatrix} Z_{ss} & Z_{sr} \\ Z_{rs} & Z_{rr} \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \qquad (1)$$

Where:

$$[V_s] = \begin{bmatrix} v_{as} & v_{bs} & v_{cs} \end{bmatrix}^T, \qquad [V_r] = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T \qquad (2)$$

$$[I_s] = \begin{bmatrix} i_{as} & i_{bs} & i_{cs} \end{bmatrix}^T, \qquad [I_r] = \begin{bmatrix} i_{ar} & i_{br} & i_{cr} \end{bmatrix}^T \qquad (3)$$

$$[Z_{ss}] = \begin{bmatrix} R_s + L_s p & -0.5L_o p & -0.5L_o p \\ -0.5L_o p & R_s + L_s p & -0.5L_o \\ -0.5L_o p & -0.5L_o p & R_s + L_s p \end{bmatrix} \qquad (4)$$

$$[Z_{rr}] = \begin{bmatrix} R_r + L_r p & -0.5L_o p & -0.5L_o p \\ -0.5L_o p & R_r + L_r p & -0.5L_o p \\ -0.5L_o p & -0.5L_o p & R_r + L_r p \end{bmatrix} \qquad (5)$$

$$[\mathbf{Z}_{sr}]=L_o p\begin{bmatrix} \cos(\theta_r) & \cos(\theta_r-\frac{2\pi}{3}) & \cos(\theta_r+\frac{2\pi}{3}) \\ \cos(\theta_r+\frac{2\pi}{3}) & \cos(\theta_r) & \cos(\theta_r-\frac{2\pi}{3}) \\ \cos(\theta_r-\frac{2\pi}{3}) & \cos(\theta_r+\frac{2\pi}{3}) & \cos(\theta_r) \end{bmatrix} \quad (6)$$

$$[\mathbf{Z}_{rs}]=[\mathbf{Z}_{sr}]^T \quad (7)$$

$$L_s = L_{ls}+L_o, \qquad L_r = L_{lr}+L_o \quad (8)$$

$$T_{em}=\frac{P}{2}\begin{bmatrix}\mathbf{I}_s\\\mathbf{I}_r\end{bmatrix}^T \frac{d\mathbf{L}}{d\theta_r}\begin{bmatrix}\mathbf{I}_s\\\mathbf{I}_r\end{bmatrix} \quad (9)$$

$$p\omega_r=\frac{P}{J}(T_{em}-T_{load}) \quad (10)$$

$$p\theta_r=\omega_r=P\omega_m \quad (11)$$

$$p=\frac{d}{dt} \quad (12)$$

The equations of the WRIM are adjusted to represent the open rotor-phase cases. The stator windings of the studied motor have a star connection while the rotor windings could be star or delta connection. There are different four possible connections of rotor windings in case of open rotor phase, which are star with isolated neutral connection, normal delta connection with internal open circuit rotor phase, normal delta connection with external open circuit rotor phase and finally the suggested delta connection with reversed one phase with external open circuit rotor phase. These cases are shown in Fig. 1.

For star with isolated neutral connection, when one rotor phase is open circuited the other two phases are connected in series as shown in Fig. 1(a). So the voltage differential equations can be rewritten as in healthy case with the following changes:

$$[\mathbf{V}_r]=[0] \quad (13)$$

$$[\mathbf{I}_r]=[i_r], \qquad i_{ar}=-i_{br}=i_r \quad (14)$$

$$[\mathbf{Z}_{rr}]=[2R_r+(2L_{lr}+3L_o)p] \quad (15)$$

$$[\mathbf{Z}_{sr}]=L_o p\begin{bmatrix} \cos(\theta_r) & -\cos(\theta_r-\frac{2\pi}{3}) \\ \cos(\theta_r+\frac{2\pi}{3}) & -\cos(\theta_r) \\ \cos(\theta_r-\frac{2\pi}{3}) & -\cos(\theta_r+\frac{2\pi}{3}) \end{bmatrix} \quad (16)$$

For normal delta connection with internal open circuit rotor phase, when one rotor phase is open circuited each phase of the other two phases will be short circuited upon itself as shown in Fig. 1(b), the voltage differential equations can be rewritten with the following changes:

$$[\mathbf{V}_r]=\begin{bmatrix}0 & 0\end{bmatrix}^T \quad (17)$$

$$[\mathbf{I}_r]=\begin{bmatrix}i_{ar} & i_{br}\end{bmatrix}^T \quad (18)$$

$$[\mathbf{Z}_{rr}]=\begin{bmatrix} R_r+L_r p & -0.5L_o p \\ -0.5L_o p & R_r+L_r p \end{bmatrix} \quad (19)$$

$$[\mathbf{Z}_{sr}]=L_o p\begin{bmatrix} \cos(\theta_r) & \cos(\theta_r-\frac{2\pi}{3}) \\ \cos(\theta_r+\frac{2\pi}{3}) & \cos(\theta_r) \\ \cos(\theta_r-\frac{2\pi}{3}) & \cos(\theta_r+\frac{2\pi}{3}) \end{bmatrix} \quad (20)$$

For normal delta connection with external open circuit rotor phase, as shown in Fig. 1(c), where two of rotor phases are connected in series and the combination of them is connected in parallel with the third phase, the voltage differential equations of the this configuration can be rewritten as in healthy case with the following changes:

$$[\mathbf{V}_r]=\begin{bmatrix}0 & 0\end{bmatrix}^T \quad (21)$$

$$[\mathbf{I}_r]=\begin{bmatrix}i_{ar} & i_{br}\end{bmatrix}^T \quad (22)$$

$$[\mathbf{Z}_{rr}]=\begin{bmatrix} R_r+L_r p & -L_o p \\ -L_o p & 2R_r+(2L_r+L_o)p \end{bmatrix} \quad (23)$$

$$[\mathbf{Z}_{sr}]=L_o p\begin{bmatrix} \cos(\theta_r) & \cos(\theta_r+\frac{2\pi}{3})-\cos(\theta_r-\frac{2\pi}{3}) \\ \cos(\theta_r+\frac{2\pi}{3}) & \cos(\theta_r)-\cos(\theta_r+\frac{2\pi}{3}) \\ \cos(\theta_r-\frac{2\pi}{3}) & \cos(\theta_r-\frac{2\pi}{3})-\cos(\theta_r) \end{bmatrix} \quad (24)$$

For suggested delta connection with reversed one phase, as shown in Fig. 1(d), the voltage differential equations of this configuration can be rewritten as in healthy case with the following changes:

$$[V_r] = \begin{bmatrix} 0 & 0 \end{bmatrix}^T \quad (25)$$

$$[I_r] = \begin{bmatrix} i_{ar} & i_{br} \end{bmatrix}^T \quad (26)$$

$$[Z_{rr}] = \begin{bmatrix} R_r + L_r p & 0 \\ 0 & 2R_r + (2L_r + 3L_o)p \end{bmatrix} \quad (27)$$

$$[Z_{sr}] = L_o p \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r + \frac{2\pi}{3}) + \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r + \frac{2\pi}{3}) & \cos(\theta_r) + \cos(\theta_r + \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{2\pi}{3}) & \cos(\theta_r - \frac{2\pi}{3}) + \cos(\theta_r) \end{bmatrix} \quad (28)$$

3. Simulation Results

The experimental and simulation results have been carried out on a 4-pole, 175 W, 110 V, 1.9 A, 1370 rpm and 50 HZ 3-phase wound rotor induction motor. The fault is modeled by starting the motor with opening one phase of rotor circuit. The motor is loaded with its full load torque and the four possible connections of rotor are considered. Due to the asymmetry that occurs in rotor circuit the resultant magnetic flux in air gap is not a pure rotating field so it affects the performance of the motor as illustrated in the following figures for the different cases of rotor connections.

The motor speed, electromagnetic torque, stator current and the rotor currents are presented in Fig.2 for the case of star with isolated-neutral. As shown in Fig.2 (a) the motor operates at a speed near to half of its synchronous speed and the speed has noticeable ripples at steady state. Furthermore, the steady state torque is a pulsating torque as shown in Fig.2 (b) due to the backward component of the rotor MMF. Fig.2 (c) shows the current of phase A of the stator, it is clear that the stator current is oscillatory and reaches with harmonics. Additionally, the currents of the two phases of rotor are equal in magnitude but they are shifted by 180 electric degrees as shown in Fig. 2 (d).

Fig.3 shows the motor speed, electromagnetic torque, stator current and rotor currents in the case of normal delta connection with internal open circuit rotor phase. Similarly the motor operates at a speed near to half of its synchronous speed with noticeable ripples at steady state as shown in Fig.3 (a). Also the steady state torque is a pulsating torque as shown in Fig.3 (b). In this case the oscillatory stator current is shown in Fig.3 (c). Additionally, the currents of the two phases of rotor are not equal in magnitude but they are shifted by 120 electric as shown in Fig.3 (d).

Fig.4 shows the motor performance for the case of normal delta connection with external open circuit rotor phase. The motor operates at a speed near to half of its synchronous speed with noticeable ripples at steady state as shown in Fig.4 (a). The steady state torque is a pulsating torque as shown in Fig.4 (b). It is clear that the stator current is oscillatory and with harmonics content as shown in Fig.4 (c). Finally, the current of the two series connected phases of the rotor is equal to one half of the rms value of the third phase but they are shifted by 180 electric degrees as shown in Fig. 4 (d).

Fig.5 shows the motor performance for the case of delta connection with reversed one phase and external open circuit rotor phase. The motor operates at a speed slightly less than the full load speed with ripples as shown in Fig.5 (a). The motor torque has noticeable ripples as shown in Fig.5 (b). It is clear that the stator current has fewer oscillations compared to the previous connections as shown in Fig.5 (c). Finally, the currents of the (phase-br) and (phase-cr) of the rotor are the same since they are connected in series. While the current of (phase-ar) is different and, is shifted by 90 electric degrees from the other two phases as shown in Fig. 5 (d).

Fig. 6 shows the space phasors of rotor currents for all asymmetry cases, which could be taken as an indicator for the nature of the rotor field. It is clear that the rotor field is purely pulsating in the case of star with isolated neutral windings as shown in Fig. 6 (a), and the rotor field is an elliptic in the case of normal delta connection with internal open circuit rotor phase as shown in Fig. 6 (b), also in the case of normal delta rotor windings with external open circuit connection it is clear that the rotor field is purely pulsating as shown in Fig. 6 (c), while the rotor field is approximately pure rotating field since it almost has a constant magnitude and its axes coincide with the coordinates of the machine, in the case of delta connection with reversed one phase and external open circuit rotor phase as shown in Fig. 6 (d). That is because the magnetic axes of the rotor MMFs are perpendicular to each other's due to reversing one phase of rotor windings. The approximately pure rotating field of the rotor insures the normal operation of the motor in the case of delta connection with reversed one phase and external open circuit rotor phase.
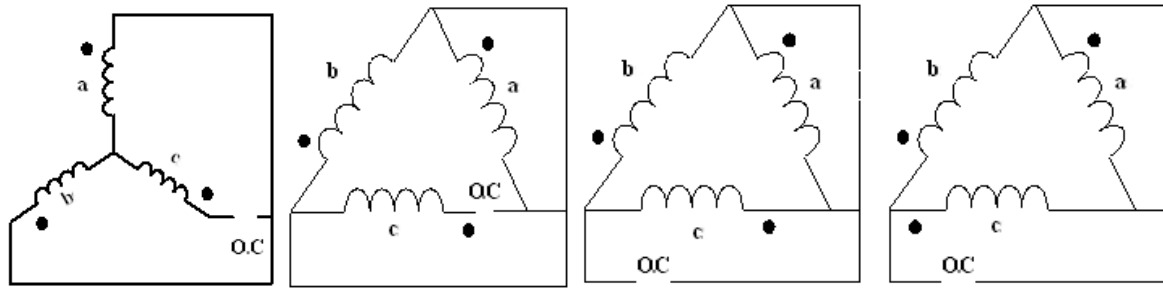
Fig. 1. Different connections of rotor windings: (a) Star with isolated-neutral (b) Normal delta connection with internal open circuit (c) Normal delta connection with external open circuit rotor phase (d) Suggested delta connection with reversed one phase
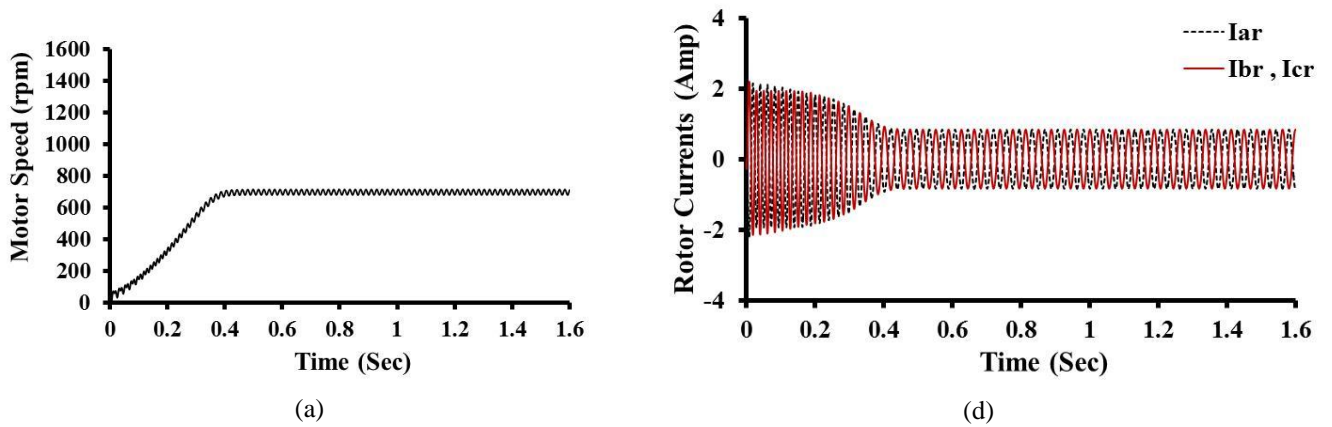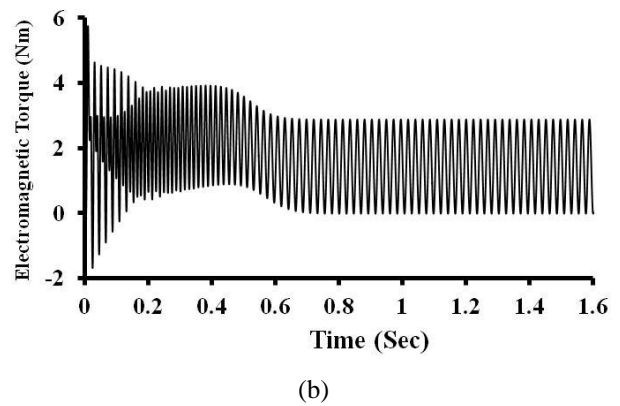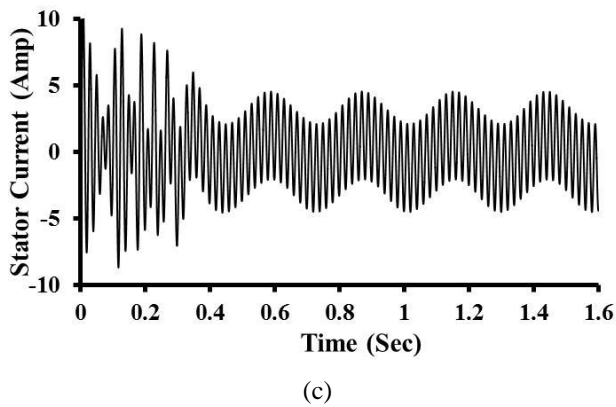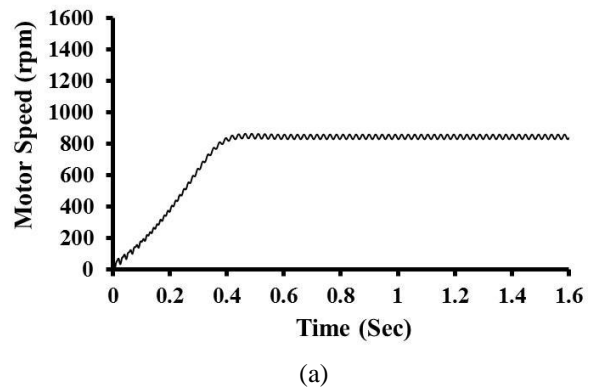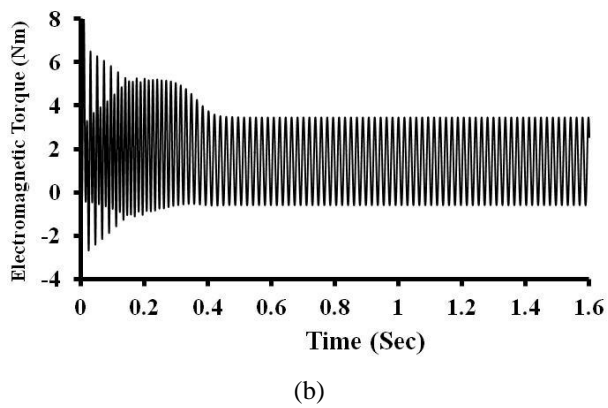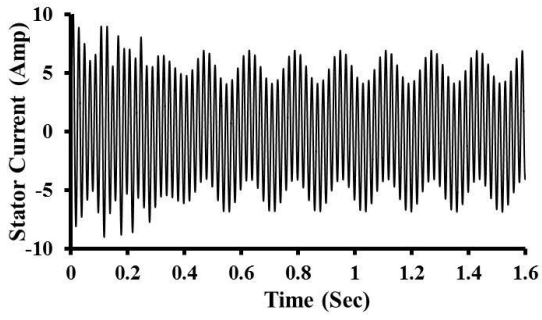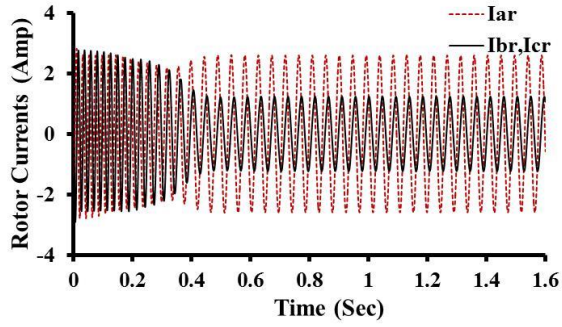

(a)

(d)

Fig.2 Motor performance for star with isolated neutral rotor windings connection, (a) Motor speed (b) Electromagnetic torque (c) Stator current (d) Rotor currents.
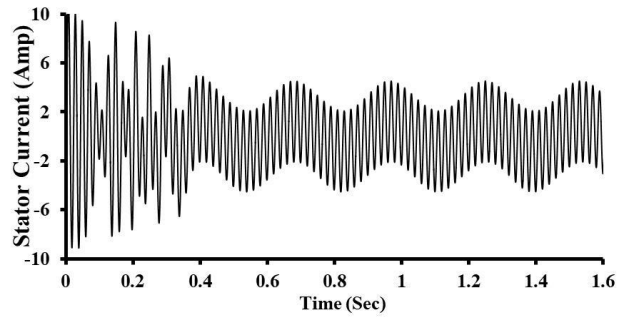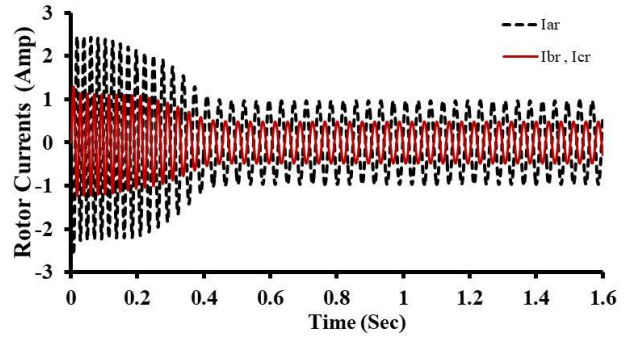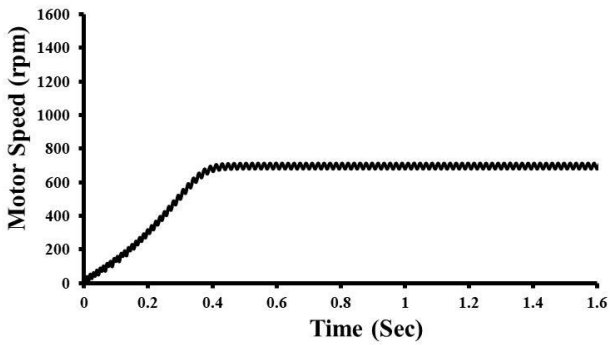

(b)

(a)

(c)

(b)

(c)

(c)

(d)

Fig.3 Motor performance for normal delta with internal open circuit connections, (a) Motor speed (b) Electromagnetic torque (c) Stator current (d) Rotor currents

(d)

Fig.4 Motor performance for normal delta with external open circuit connections, (a) Motor speed (b) Electromagnetic torque (c) Stator current (d) Rotor currents
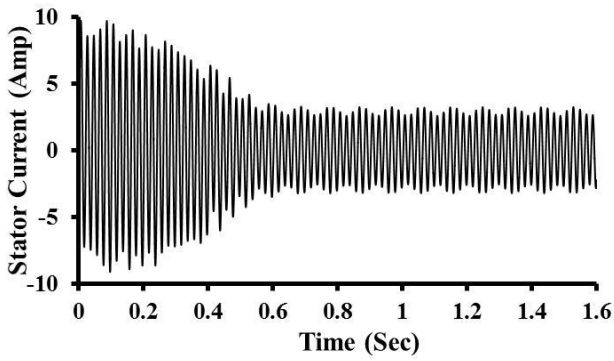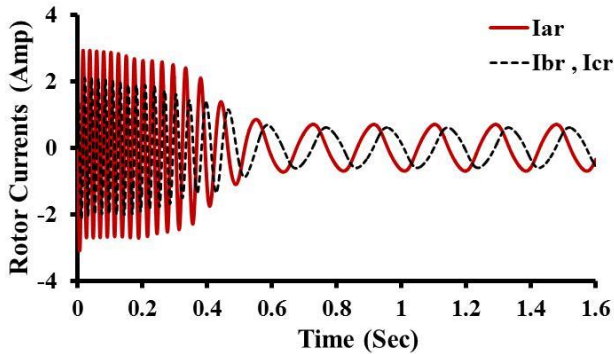

(a)

(a)

(b)
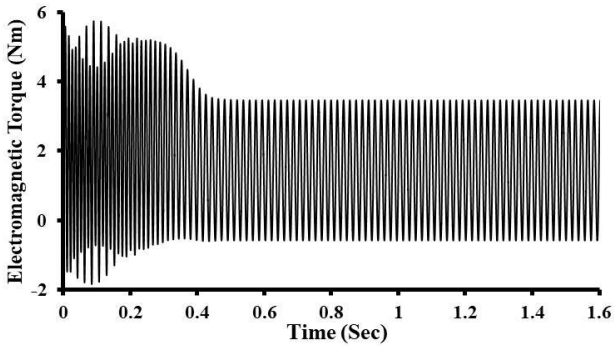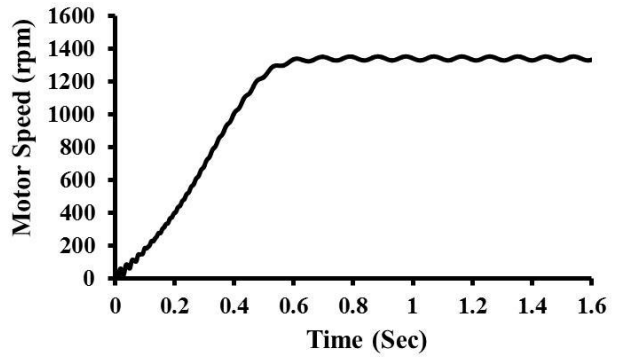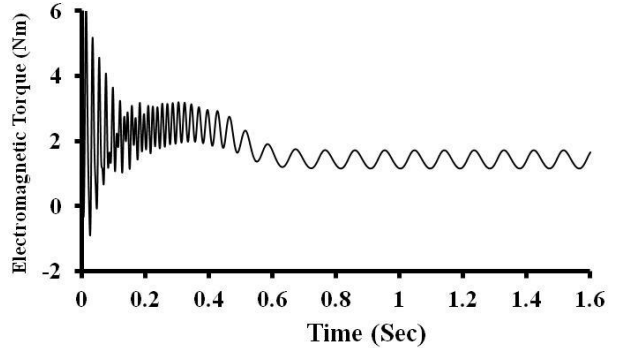
(b)

(c)

(d)

Fig.5 Motor performance for delta connection with reversed one phase and external open circuit, (a) Motor speed (b) Electromagnetic torque (c) Stator current (d) Rotor currents
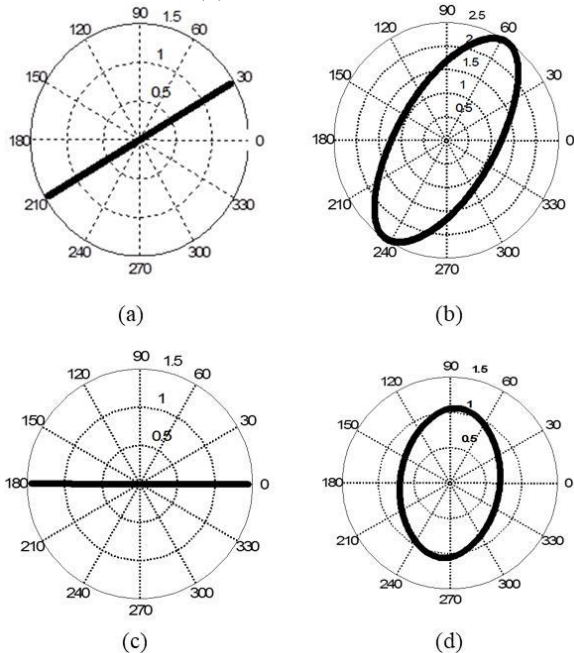

(a)

(b)

(c)

(d)

Fig.6 The space phasor of rotor currents, (a) Star with isolated neutral (b) Normal delta with internal open circuit (c) Normal delta with external open circuit (d) Delta with reversed one phase and external open circuit

4. Experimental Validation

In order to validate the simulation results a series of experiments were carried out for the case of starting the WRIM with opening one rotor phase and the four possible connections of rotor were considered. The picture of the experimental setup at the laboratory is shown in Fig. 7.

Fig. 8 shows the motor performance in the case of star connected rotor windings with isolated neutral. Fig. 9 shows that the motor speed, stator current and the currents of the two phases of rotor for the cases of rotor windings of delta connection with internal open circuit rotor phase. The motor performance in the case of normal delta connected rotor windings with external open circuit is shown in Fig. 10. Finally the motor performance in the case of delta connected rotor windings with reversed one phase and external open circuit is shown in Fig. 11. Table 1 gives a comparison between the simulation and experimental results. Good agreement has been achieved between the simulation and experimental results.
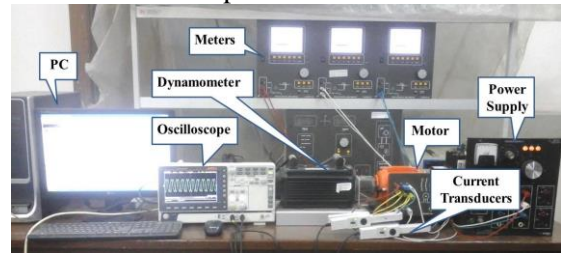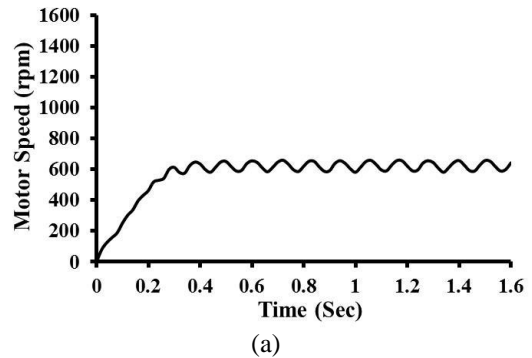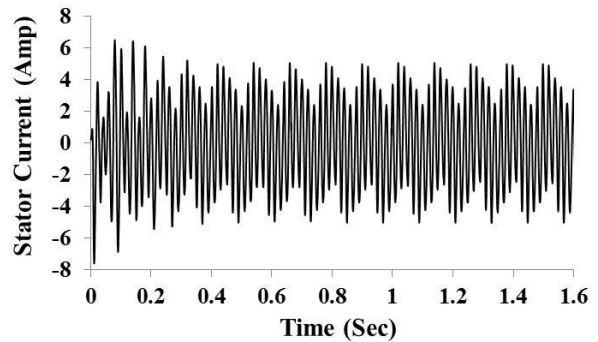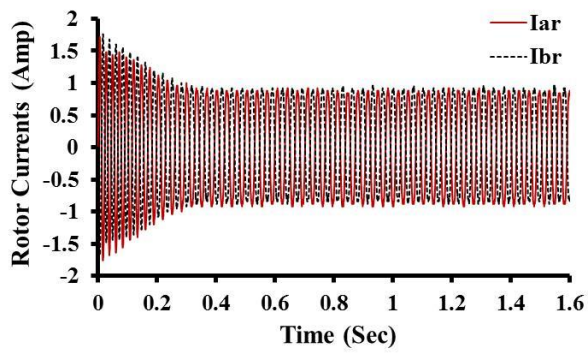

Fig. 7 The experimental setup at the laboratory
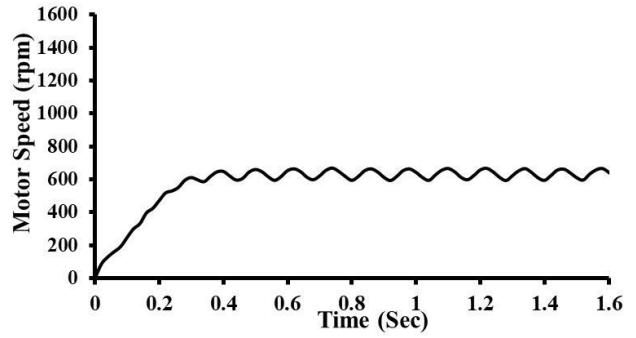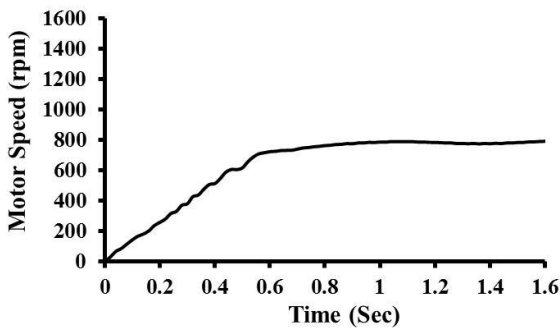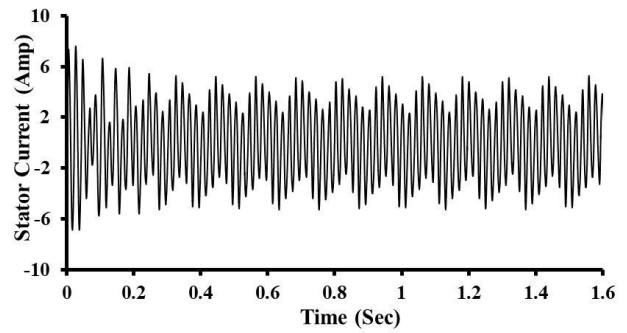

(a)

(b)

(c)

Fig. 8 Experimental results for star with isolated neutral connection, (a) Motor speed (b) Stator current (c) Rotor currents.

(a)

(a)

(b)

(b)
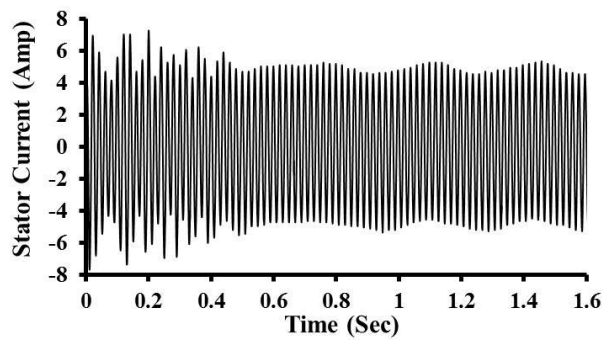
(c)

Fig. 9 Experimental results for normal delta connection with internal open circuit rotor phase, (a) Motor speed (b) Stator current (c) Rotor currents.
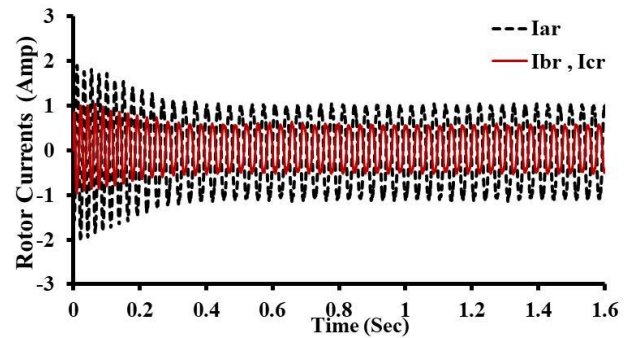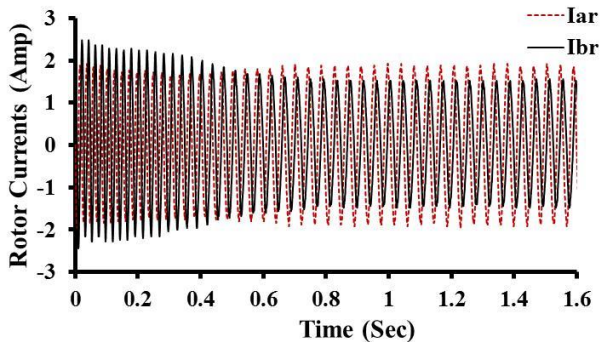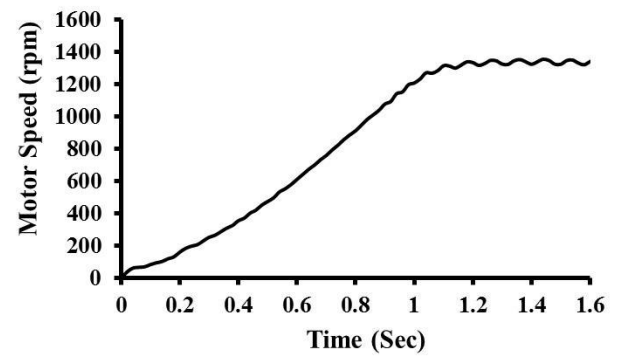

(c)

Fig. 10 Experimental results for normal delta connection with external open circuit, (a) Motor speed (b) Stator current (c) Rotor currents.
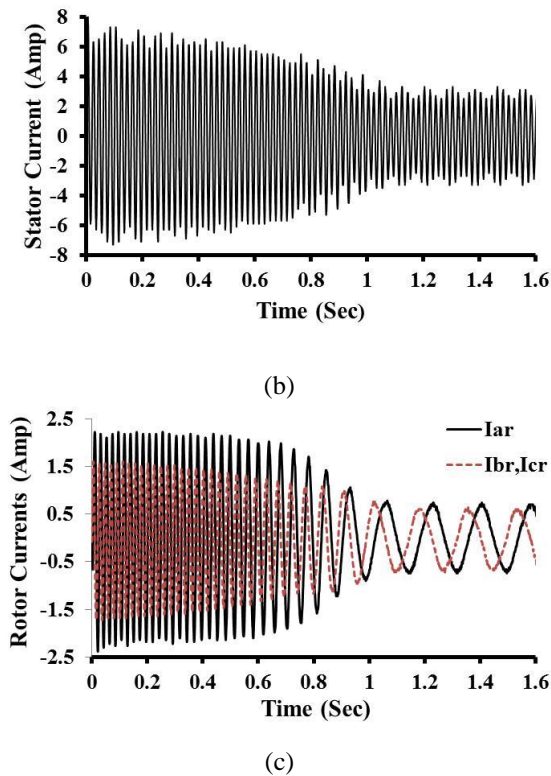

(a)

(b)

(c)

Fig. 11 Experimental results for delta connection with reversed one phase and external open circuit, (a) Motor speed (b) Stator current (c) Rotor currents

The observation of the simulation and experimental results yields the following relevant points:

• The performance of WRIM under the condition of opening of one phase of secondary circuit depends on the connection of rotor windings.

• The star rotor windings with isolated neutral and normal delta connection with internal open circuit have the worst performance because of occurrence of Gorges phenomenon, while the rotor delta connected windings with reversed one phase and external open circuit has an acceptable performance because of preventing Gorges phenomenon.

• Opening of one phase of rotor circuit causes oscillatory and high stator currents.

• The rotor MMFs of the star rotor windings with isolated neutral and normal delta with external open circuit connection have strong backward component, which affects the torque speed characteristic of the motor resulting in Gorges phenomenon.

• The motor torque is a pulsating torque due to the backward component of the rotor MMF.

• For all rotor connections under faulty cases the speed and torque ripples have a double rotor frequency.

• The acceleration of the delta connected rotor windings with reversed one phase and external open circuit is higher than that of the rotor with star connected windings.

• The rotor asymmetry results in unbalanced rotor currents combined with high values for all connections especially for star connection.

• In case of delta rotor connections with reversed one phase and external open circuit, the motor operates at a speed slightly less than its full load speed at any value of its loading in case of staring the motor wih opening one phase of rotor circuit.

• The rotor delta connected windings with reversed one phase and external open circuit insures the operation at a speed near to the full load speed of the motor if the externally open circuit is occurred at any terminal of the reversed phase so the motor will have good efficiency and power factor.

Table 1. Summarized simulation and experimental results

Case		n (rpm)	Ist (A)	Iar (A)	Ibr (A)	Icr (A)
Healthy case	Sim	1375	2.07	0.41	0.41	0.41
	Exp	1370	1.9	0.4	0.4	0.4
Star with isolated neutral	Sim	697	2.62	0.6	0.6	0
	Exp	620	2.8	0.68	0.68	0
Normal delta connection with internal open circuit	Sim	840	4.1	1.85	0.89	0
	Exp	780	3.4	1.3	0.99	0
Normal delta connection with external open circuit	Sim	697	2.63	0.67	0.34	0.34
	Exp	622	2.82	0.74	0.37	0.37
Delta with reversed one phase and external open circuit	Sim	1350	2.06	0.5	0.44	0.44
	Exp	1335	2.0	0.49	0.42	0.42

5. Conclusion

The paper introduces a dynamic model in the ABC frame to analyze the performance of WRIM under open circuit of one phase of rotor circuit. Four possible connections for rotor windings are considered; star with isolated neutral connection, normal delta connection with internal open circuit rotor phase , normal delta connection with external open circuit rotor phase and a suggested delta connection with reversed one phase. Motor speed, electromagnetic torque, stator and rotor currents have been investigated for all cases. The experimental results have good agreement with simulation results in all rotor windings possible connections. It is found that the WRIM suffers from operation at a speed near to the half of its synchronous speed, pulsating electromagnetic torque, high oscillatory stator currents and high unbalanced rotor currents for all connections except the suggested delta connected rotor windings with external open circuit rotor phase, where the WRIM operates at a speed near to its full load speed and approximately normal stator and rotor currents under condition that externally open circuit is occurred at any terminal of the reversed phase. So the suggested delta connected is recommended for the WRIM to insure normal motor performance at 67% of occurrence of open circuit of one rotor phase.

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