A lot of major industrial applications use three-phase Wound Rotor Induction Motor Drive Systems (WRIMDS), particularly in cement mills because of their performance control capabilities. When a power supply is subjected to the unbalanced voltages, the motor performance is affected. The object of the study is the Wound Rotor Induction Motor Drive Systems under unbalanced supply voltage. The subject of this research is the effect of harmonics under unbalanced supply conditions on the rotor circuit of WRIM with the presence of rectifiers and the chopper circuit. The investigation assesses the stator current, the rotor current, and electromagnetic torque components using a mathematical equivalent circuit representation.

The analysis of this study presents the way for predicting the whole harmonic frequencies that belong to the currents of the stator, the rotor current, and the electromagnetic torque in terms of supply frequency and the rotor slip. The simulation and the proposed mathematical model results have shown good accuracy. The results show that the performance of WRIM, the variation of the motor currents, and the torque pulsation are dependent on the magnitude of the voltage unbalance factor and the duty cycle of the chopper circuit.

The results of this study demonstrate that the unbalanced supply voltage has a negative impact on the increase of stator harmonic currents injected from the rotor side, rotor harmonic currents, and torque pulsation; as a result, the performance of WRIMDS has been derated. It is noticed from the results that the obtained currents are accurate, excluding the currents at a slip of one sixth in which a noteworthy variance is observed. The speed ripple is increased by 0.38 %, and torque ripple by 16.6 % when the voltage supply unbalance factor varies from (0 to 10) %

Keywords: WRIMDS, rotor chopper circuit, voltage unbalance, harmonic analysis, torque pulsation

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IDENTIFYING OF ROTOR CONVERTER EFFECTS ON THE CHOPPER CONTROL SLIP RING INDUCTION MOTOR PERFORMANCES UNDER GRID VOLTAGE UNBALANCE

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1. Introduction

Induction machines, in general, play a key role in the field of electromechanical energy conversion systems. Most of the applications of WRIMs are in the industrial sector, due to their simplicity, efficiency, ruggedness in construction, low cost, and few maintenance requirements [1]. Unlike squirrel cage induction motor, which are constant-speed drives, WRIMs are variable speed drives in which their speed can be controlled by adding an external resistance in the rotor winding or recovery of rotor slip power to the main. Such techniques make WRIMs more able to maintain low starting current and high starting torque. Further, WRIM can rise the starting torque by reducing the required time for the motor to reach the nominal speed at a minimum time. Therefore, WRIMs are commonly used in industries for any applications that require rotating large mechanical loads and frequent starting and braking at the maximum motor torques.

Practically all the components in the power network have their distinctive performances and for some reason these components in the network cause distortion of the ideal sinusoidal waveform leading to unfavorable effects on the complete system and also on individual components in the network. The power system is subjected to harmonic distortions, the short-term voltage variation, the long-term voltage variation, the power factor variation, the voltage unbalance, voltage fluctuation, and frequency variation. These degrade the power quality and lead to reducing the efficiency and shortening the lifetime of IMs.

Unbalance in voltages occurs for two reasons in power systems. The first is structural, which is caused by unbalanced voltage in power distribution systems, such as AC generators, transmission system, transformers, and unbalanced bank of capacitors. Asymmetric voltage in the network impedance in three-phase systems such induction furnaces, X-ray devices, electrical welding machines, opening in a conductor in a power system, short circuits, and failure in equipment insulation cause the second reason.

The negative sequence component due to unbalance supply voltage in the electrical power system cannot carry energy to the motor shaft instead it dissipates energy as losses. As a result, the voltage unbalance reduces efficiency, life expectancy, speed of the rotating machine, output power, productivity, and profits at the consumption utilization level, and it contributes to reverse magnetic field, which is leading to increased temperature of windings. As a consequence, this motor should be derated to compensate for the extra heating which tends to increase the cost of relay coordination and cost of protection [2]. Because of the presence of power electronic converters in the rotor side of each of chopper resistance of WRIMDs, the harmonics are developed. These harmonics induce time harmonics in stator windings by transformation and further, they produce significant electromagnetic torque pulsation in industry applications, mainly due to concern that this torque pulsation leads to a mechanical problem that damages the machine shaft.

Rotor power semiconductor converters have an impact on the supply voltage asymmetry, which in turn affects the WRIMDS's performance. By modifying the resistance in the rotor circuit, the WRIMDS technique regulates motor speed while confirming the necessary performance. Conveyor belts, mills, crushers, mixers, agitators, and other devices are common uses for slip ring induction motor speed control [3]. For drives that need precise and quick speed response, and where slip power dissipation does not surpass a few kW, the use of a DC chopper to dissipate slip power in a constant external resistance offers a very appropriate alternative. This technology is quite easy and inexpensive so it is utilized for controlling the speed accurately and smoothly. At the same time, it causes greater losses, and inefficient operation. The insertion of a three-phase ac to dc converter and a dc-to-dc converter in the WRIM might degrade the operation quality. The presence of harmonics causes greater motor losses, resulting in decreased efficiency and a short lifetime. These harmonics causes also an electromagnetic interference, resulting in sensing reading and control troubles. Therefore, studies that are devoted investigate the effect of low power quality due to unbalance supply on the performance of WRIMDS are scientific relevance.

2. Literature review and problem statement

The paper [4] presents that the rectifier and chopper used in the configuration for speed control distort the current waveforms and consequently deteriorate WRIM operation and performance. In this way, the performance of WRIM with the occurrence of these abnormalities in the power system must be considered. It is necessary to provide a methodology that allows studying the WRIM performance when subjected to unbalanced and distorted voltages.

The paper [5] considered a reflection to stator through induction phenomenon; thus, the stator winding experiences induced currents of matching frequencies due to the three-phase rectifier bridge. A potential solution is reflected in [6] by utilizing MATLAB/Simulink automated state model generator, with a development of the rotor chopper for speed control of double-fed induction motors. However, the problem is partially solved at the start, but it is still open for running conditions.

The paper [7] presents the converting of a slip power in the outside side impedance as the most straightforward technique for regulating the speed. The study's results showed that the motor current and overall energy consumption are lowered. This approach was partially employed in [8], where it was found that by changing the resistance using the static resistance control technique, the third harmonic current injection has improved the power factor and decreased rotor current distortion; as a result, the THD of the current decreases significantly by 22 %. However, the amount of THD is still high and more than international voltage limits according to IEC and IEEE standards.

The article [9] demonstrated how to adjust the motor speed of a wound rotor type through varying the resistance of the rotor statically using MATLAB/Simulink for rotor resistance control by chopper circuit and slip power recovery technique to achieve low inrush current, high starting torque, lower starting current, high inertia application, and gradual build-up of torque, but the problem of torque pulsation stayed unsolved.

A significant advancement in [10] for WRIMDS operation was employed by using various PWMVSI and buck-boost dc to dc converter configurations, where the suggested settings reduced the power supply's THD and increased power factor and efficiency. The paper [11] presented the results of torque pulsation estimation and minimization in a vector that controlled the WRIM double inverter feed using various pulse width modulation approaches on both the stator and rotor side voltage source inverters. Though the effect of rotor harmonics on stator MMF remains unexplored.

The article [12] presents the results of the change occurrence in positive sequence components of the voltage that affected the three-phase induction motor sensitivity, output power, and motor losses. The results show that overheating, line current unbalance, output power derating, torque pulsation, and low efficiency are negative impacts on the squirrel cage induction motor performance and do not consider the performance of WRIMDS under such conditions.

The paper [13] considered the features and performance of two different kinds of mechanically connected motors that run on balanced and imbalanced voltages, where revealed to unbalanced voltages, and they proposed a technique that demonstrated the negative impact of a low-quality voltage on motor performances, losses, temperature rise, output power derating, efficiency, noise, and machine reliability. The comparison using the derating factors index provided by IEEE and NEMA standards for maintaining the losses at a specified rate has been presented in [14]. Nevertheless, consider the derating factor of WRIMDS under unbalanced supply and distorted supply voltage.

The results in paper [15] showed the effects of the three-phase bridge ac to dc converter and dc to dc converters, as well as the relationship between the fundamental component and the harmonics of the current flowing in the stator and rotor on the torque harmonics under various voltage types. Using a comprehensive mathematical model of slip power recovery, they have not explored this impact on the WRIMDS by static resistance variation.

The paper [16] presented a comparison between energy efficiency gain and low power quality through a detailed harmonic analysis of the effect of voltage harmonics and voltage unbalance with different efficient motor classes. Their result shows that the presence of voltage harmonics leads to magnification of current harmonics in electric motors for distortions of 8 % as well as in significant variations of other harmonic currents in electric motors, including negative and positive sequence harmonics, and consequently, lead to an increase in the THD of the network. Though the effect of rotor-induced harmonics of WRIMDS due to power electronic converters remains unexplored.

The issue of the negative impact of voltage unbalance and harmonics in electrical power system networks has been given considerable attention in [15–17]. Despite significant advancement in previous papers, there is pressing need for more investigation of WRIMDS performance under such conditions. However, new developments in ac-dc-ac converters are being made to increase their performance. Increased chopper frequency, boost chopper, buck-boost chopper, multi-level inverter, PWM inverter, and smoothing inductor value are some of the new trends that have been enhanced.

The aforementioned results demonstrate that assessing the WRIMDS when it is provided with distorted and unbalanced supply voltage at the same time needs additional research and analysis. In addition to the low-quality supply, the inclusion of a rotor bridge rectifier and inverter causes greater power derating and more IM insulation life loss.

Various studies in electrical power networks indicate an increase in unbalanced and distorted supply voltages. So, after reviewing the literature [4–17], it should be noted that the main attention has been paid to issues of researching the effect of unbalanced supply voltage on the performance of squirrel cage induction motors and slip power recovery. However, such studies are carried out only with unbalanced supply voltage, which does not take into account the static chopper resistance control of WRIM.

All these allow to assert that it is convenient to conduct a study of the effect of stator current harmonic analysis, rotor current harmonic analysis, and electromagnetic torque pulsation under unbalanced supply voltage conditions of WRIMDS.

3. The aim and objectives of the study

The aim of the study is to determine the effect of unbalanced voltage supply on the performance of WRIMDS when it is controlled by the chopper rotor resistance technique. A mathematical model based on an equivalent circuit including the low-order harmonics has been derived.

To achieve the aim, the following objectives were set:

– to analysis the stator harmonic current of WRIMDS under unbalanced voltage conditions;

– to analysis the rotor harmonic current of WRIMDS under unbalanced voltage conditions;

– to analysis torque pulsation analysis under different unbalanced voltage conditions.

4. Materials and methods

The object of the study is the Wound Rotor Induction Motor Drive Systems under unbalanced supply voltage.

The mathematical models are derived that are related to the behavior of WRIMDS under unbalanced supply voltage conditions. The performances are investigated under the effect of voltage unbalance factor (U) and duty cycle (D) of the chopper circuit. To overcome the difficulties in solving these equations analytically, a computer-aided simulation is used to solve the mentioned equations as well as verify of the predicting results. MATLAB/Simulink is implemented to examine the performance of the system models under different unbalance voltage levels, taking into account the effect of duty cycles.

An unbalanced power supply induces significantly unbalanced currents in IM and produces positive and negative sequence flux components. In addition, harmonics are sinusoidal voltages and currents with frequencies that are integer multiples of the fundamental electrical system frequency. When three-phase induction motors operate in networks with balanced voltages and without distortions, that are in a steady state, the directions of rotation of the rotating magnetic field and the rotor are the same.

Most semiconductor device switches produce harmonics in the DC side of the converter in the order of a multiple of an integer number (a) by converter pulses (p) and ($ap\pm1$) in the rotor AC side. In a robust machine drive system, the harmonic component cannot be neglected because it might produce noises and affect the reference speed or desired torque and performance of the drive system. In this drive system, the three-phase uncontrolled rectifier and chopper resistance control are joined as shown in Fig. 1. The existence of a 3-phase uncontrolled rectifier in the rotor circuit produces distorted currents in the windings of the rotor (I_{2h}), which are also harmonically induced in the stator winding currents (I_{1h}) by electromagnetic effect. These harmonics in stator and rotor windings increase the machine losses. An equivalent circuit of WRIM with rotor chopper resistance per phase with respect to the stator windings is shown in Fig. 2. Where R_1 is the stator winding resistance, $R_{eff}(D)$ is the effective AC resistance at the slip rings terminals, R_x is the additional resistance, R_{2h} is the rotor winding harmonic resistance, X_1 is the stator leakage reactance, X_2 is the rotor leakage reactance, and X_m is the mutual reactance.

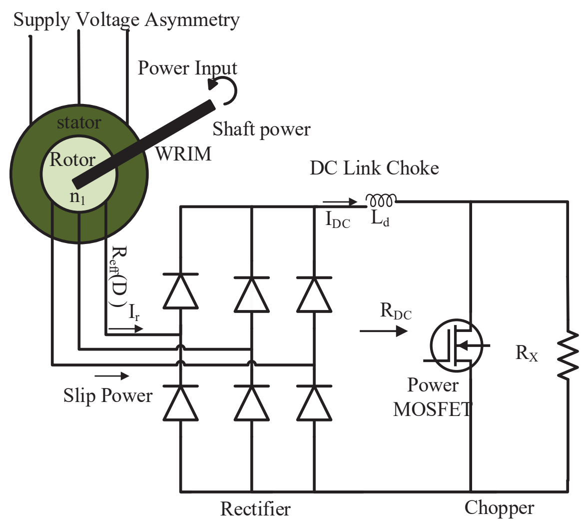

Fig. 1. The wound rotor induction motor drive system scheme

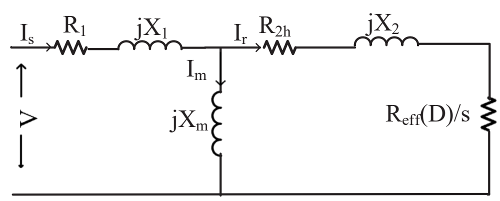

Fig. 2. The alternating current Model of static chopper resistance of wound rotor induction motor

The rotor current waveforms, which are in rectangular shape due to the commutation of power electronic switches, can be represented by Fourier series analysis as in (1):

$$i_s(\omega_s t) = 1.1 I_{DC} \sin(s\omega_s t + \theta_1) \pm \pm \frac{1.1 I_{DC}}{6q \pm 1} \sin((6q \pm 1) s\omega_s t + \theta(6q \pm 1)). \quad (1)$$

The nth rotor current's magnitude may be determined using:

$$I_{2n} = \frac{0.78}{n} I_{DC}, \quad (2)$$

where $a = 1, 2, 3, \ldots$

The root mean square (*rms*) rotor current of the harmonics order (n) is around (I_{2f}/n). These harmonics result in increasing copper losses, and the amount of current flowing relies on the motor's slip. The rotor's DC side has harmonic frequencies equal to $6f_2$, and a three-phase diode rectifier has 6 pulses. The rotor current frequency is (sf_1), while the slip is represented as s. The diode rectifier will cause the DC side's harmonic frequency to be:

$$f_{DC(h)} = 6asf_1. \tag{3}$$

The following are the harmonic components of rotor current produced by three-phase bridge rectifiers [1]:

$$f_{2(h)} = (1 \pm 6a)sf_1, \tag{4}$$

where $a=1, 2, 3, \ldots$

The rotor's foundational elements are represented by $a=0$ in (4), whereas the fifth and seventh harmonic orders are represented by $a=1$. The three-phase bridge rectifier causes the rotor circuit to suffer from harmonic currents. It is recognized that the ($6a+1$) order harmonics of the rotor current generate a magnetic field with a positive sequence rotate in the same direction as the frequency (f_1) magnetomotive force (*mmf*), whereas the ($6a–1$) harmonics generate a rotating magnetic field with a negative sequence. When operating in driving motor mode, the basic rotor *mmf* and rotor are rotates in the same direction, and their corresponding angular frequency is $(1 \pm 6a)sf_1$. Adding the effect of rotor speed $(1–s)f_s$, yields the speed of rotating *mmf* with respect to the stator, and therefore, the frequency of induced harmonic in stator current is given by:

$$f_{1h} = (1 \pm 6as) f_s, \tag{5}$$

where $a=1, 2, 3, \ldots$

The interplay of fundamental and harmonic currents with spinning field waves produced by the rotor and stator might be the reason for the torque involving electromagnetic harmonics components. When rotating *mmf* waves remain stationary relative to each other, a consistently non-zero average torque is produced. The frequency of the corresponding speed of every *mmf* is $(1 \pm 6as) \cdot f_1$. The following are the anticipated electromagnetic torque harmonics once the absolute value has been removed:

$$f_{T,h} = \pm 6asf_s, \tag{6}$$

where $a=0, 1, 2, \ldots$

Upon dividing the stator's frequency by $((1 \mp (n \pm 1)s)/[2])$, Fig. 3 displays a model of WRIM with chopper resistance control, When the rotor winding is referred to as the primary in this per-phase harmonic equivalent circuit, and it is supplying the stator winding circuit with voltage at slip (s_n).

The nth rotor current harmonic I_{2h} induces the harmonic stator current I1h, which can be found using the harmonic equivalent circuit in Fig. 3 and is given by:

$$I'_{1h} = I'_{2h} \frac{jhsX'_m}{\dfrac{R'_1}{sh} + jhs\left(X'_m + X'_1\right)}. \tag{7}$$

It is possible to determine the magnitude and phase angle of the stator harmonic currents for different slips, as demonstrated by (7). The 5th and 7th harmonics, which are low harmonic orders, will be quite valuable. The order of each harmonic component in the rotor winding determines the direction of the flux of magnitude that is induced. While the 7th harmonic sequence revolves in the same way at a frequency of $7sn_s$, the 5th harmonic current revolves in the reverse way of the rotor at a frequency of $5sn_s$. In the air-gap, a rotating field created by the 5th order rotor harmonic current rotates at ($–5sn_s$) in relation to the rotor ns ($1–s$). Consequently, the stator's 5th harmonic rotational field speed is ns ($1–6s$). Consequently, the frequency of the stator current harmonic induced by rotor harmonic current is $(1–6s)f_1$.

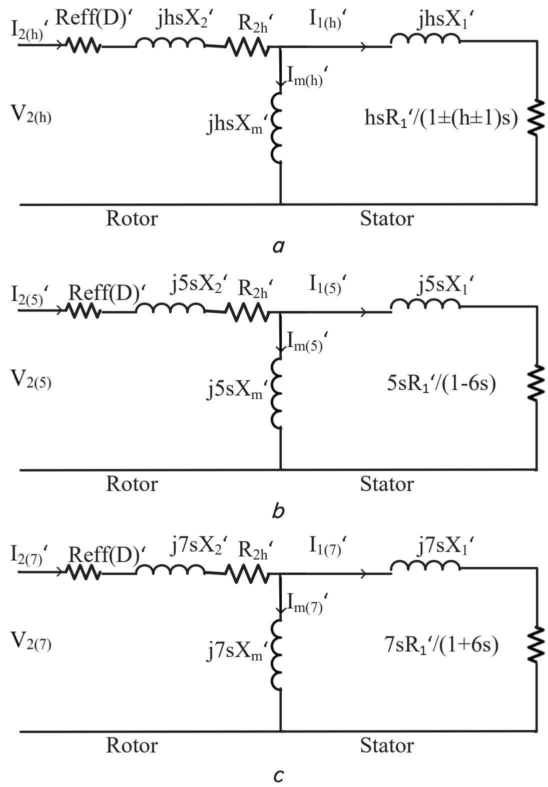

Fig. 3. The stator referred harmonic model per phase: *a* — *h* order harmonic; *b* — 5th order harmonic; *c* — 7th order harmonic

When the 5th and 7th harmonics of the rotor currents are induced into the stator, as shown in (7), the electromagnetic pulsing torque produced by the harmonics due to the rectification operation may be calculated. In this case, the slip can be written as:

$$s = \frac{n_1 \pi^2 I_{2f}\left(R_m(s) + R_d + R_X - f_{ch} R_X T_{on}\right)}{18V}, \tag{8}$$

where f_{ch} is the chopping frequency, T_{on} is the ON interval of the chopper cycle, and, n_1 is the stator to rotor turn proportional:

$$R_m(s) = \left(2R'_1 + \frac{3\left(X'_1 + X'_2\right)}{\pi} s + 2R_2\right), \tag{9}$$

$$T_{stator(5)} = 3\left(\frac{I_{r1}}{5}\right)^2 \frac{X'^2_m R'_s}{(1-6s)\omega_s\left[\left(\dfrac{R'_1}{(1-6s)}\right)^2 + \left(X'_m + X'_1\right)^2\right]} =$$

$$= 3\left(\frac{I'_{2f}}{5}\right)^2 \frac{X'^2_m R'_1}{c\omega_s\left[\left(\dfrac{R'_1}{c}\right)^2 + \left(X'_m + X'_1\right)^2\right]}. \tag{10}$$

$$T_{stator(7)}=3\left(\frac{I_{2f}}{7}\right)^2\frac{X_m'^2R_s'}{(1+6s)\omega_s\left[\left(\frac{R_1'}{(1+6s)}\right)^2+\left(X_m'+X_1'\right)^2\right]}=$$

$$=3\left(\frac{I_{2f}'}{7}\right)^2\frac{X_m'^2R_s'}{c\omega_s\left[\left(\frac{R_1'}{c}\right)^2+\left(X_m'+X_1'\right)^2\right]}, \quad (11)$$

$$C=\left(1-\frac{\pi^2I_{r1}\left[R_m(s)+R_d+R_X(1-D)\right]n_1}{3V}\right). \quad (12)$$

At $s<1/6$, the 5th harmonic electromagnetic torque to full load torque ratio is at its maximum; beyond that, it is negative. Since $R_1'\le R_d+R_{eff}(D)$, together with the other term, have values below one, the ratio is never more than 0.04. Likewise, the 7th harmonic torque to fundamental ratio is at its highest when $s=-1/6$, remains +ve as $s<1/6$, and becomes – ive when $s>1/6$. Furthermore, the ratio is never higher than 0.02 since $R_1'\le R_dR_d+R_{eff}(D)$, along with the other factors, are less than one. Although the torque generated by additional harmonics, such as the eleventh, thirteenth, seventeenth, nineteenth, twenty-three, and twenty-fifth, may be computed using the same approach, the results are extremely low.

Under unbalanced supply voltage, a 0.4 KV, 2.4 hp, four poles, WRIM has been employed for a range of voltage imbalance factor values as shown in Table 1. A three-phase ac to dc converter combined with the dc to dc converter in the circuit of the WRIM rotor result in the rotor harmonic current components, which transformation action has reflected to the stator. This leads to the development of harmonic pulsation and a rise in machine losses.

Table 1

The applied three phase voltage, +ve voltage, –ve voltage component regarding to percentage voltage imbalance

$U(V_2/V_1)$, %	$V_R(V)$	$V_S(V)$	$V_T(V)$	$V_1(V)$	$V_2(V)$
0	220∠0°	220∠–120°	220∠120°	220∠0°	0
5	220∠0°	211.282∠–124.3°	201.5∠120°	210.75∠–14°	10.58∠30°
10	220∠0°	204.52∠–128.5°	184.6∠120°	202.5∠–2.8°	20.31∠30°

Torque pulsations are developed when the angle between them varies with time. This occurs when the air gap rotating magnetic field of one frequency interacts with rotor currents of another frequency. The pulsating torque can be determined by superimposing the rotating flux and rotor current phasors of various frequencies on a single diagram as shown in Fig. 4.

In Fig. 4, the effects of only the fundamental, 5th, 7th, 11th, and 13th harmonic voltages are taken into account, and the flux phasors are assumed to be co-phasal at an instant of $t=0$. Each harmonic voltage will produce the corresponding flux and rotor current components.

The equivalent resistance of 5th, 7th, 11th, and 13th are neglected because, they are less than the corresponding leakage reactance of stator and rotor windings, therefore, harmonic currents will lag the respective flux component by an angle of 180°. The fundamental, 7th, and 13th harmonic phasor rotate in an anti-clockwise direction at a speed of ω_s, $7\omega_s$ and $13\omega_s$ respectively, whereas 5th and 11th harmonic phasor rotate in a clockwise direction at a speed of $5\omega_s$ and $11\omega_s$.

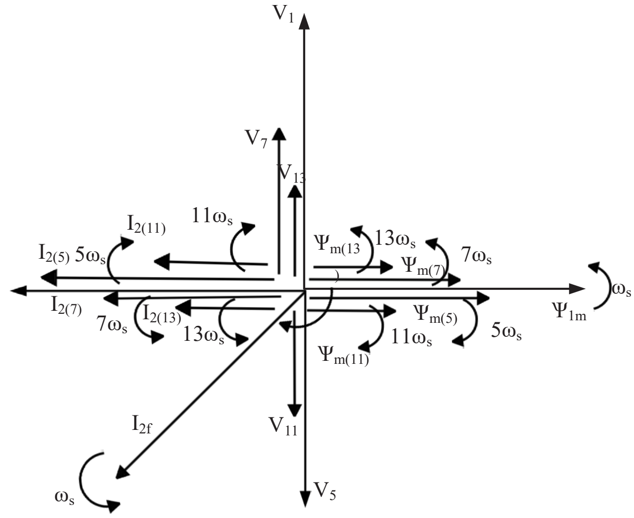

Fig. 4. The Phasor diagram of the fluxes and rotor currents for 5th, 7th, 11th, and 13th harmonic voltage frequency

The WRIMDS shows different performance under voltage asymmetry. The rise in temperature caused by increased cu losses is the most noticeable effect of voltage unbalance and harmonic voltages and currents on the WRIMDS. Overall, the outcomes of this study revealed that unbalanced supply voltages have a negative impact on WRIM performance. To evaluate the effects of the 5th, 7th, 11th, and 13th harmonic order voltages taking into account the flux phasors diagram which are presumed to be co-phasal initially. Each harmonic voltage will produce the corresponding flux and rotor current components. The fundamental, 7th, and 13th harmonic phasor rotate in an anti-clockwise direction at a speed of $7\omega_s$ and $13\omega_s$ respectively, whereas 5th and 11th harmonic phasor rotate in a clockwise direction at a speed of $5\omega_s$ and $11\omega_s$.

5. Results of the effect of harmonic distortion on wound rotor induction motor drive system

5. 1. The stator current harmonic analysis of wound rotor induction motor drive system

Based on the analytical calculation of the current harmonic magnitude, the rotor-injected stator current harmonic amplitude using (5) is displayed in Table 2 at different unbalance voltage factors for ($U=0$ %), (speed = 1200 rpm), ($U=5$ %), (speed = 1170 rpm), and ($U=10$ %), (speed = 1231 rpm) when the duty cycle of the dc to dc converter is set to 0.75.

Fig. 5 displays the harmonic spectrum for rotor injected stator currents based on the mathematical computation for a speed (1250 rpm) and (0, 5, 10) % of U, respectively. The dc to dc converter duty cycle may be changed to regulate the rotor speed. According to (7) ($n=5$), a specific situation pertaining to a particular combination of ($s=1/6$) appears. The stator windings do not experience a similar harmonic due to the revolving mmf generated by the rotor 5th harmonic component at stationary when $s=1/6$.

The rotor injected stator rms current for harmonic orders (5, 7, 11, 13) % is calculated analytically and by simulation versus the motor slip for U of (0, 5, 10) %, as shown in Fig. 6, 7.

Table 2

The magnitude of different stator current harmonics due to rotor harmonic orders

a	U=0 % (speed=1200 rpm)		U=5 % (speed=1170 rpm)		U=10 % (speed=1131 rpm)	
	/f/ (Hz)	I_1 (A)	/f/ (Hz)	I_1 (A)	/f/ (Hz)	I_1 (A)
0	50	6.06	50	6.1	50	6.3
1	10	0.6	16	0.65	23.8	0.7
	110	0.42	116	0.45	123.8	0.49
2	70	0.28	82	0.32	97.6	0.35
	170	0.22	182	0.23	197.6	0.27
3	130	0.18	148	0.21	171.4	0.24
	230	0.15	248	0.17	271.4	0.2
4	190	0.12	214	0.14	245.2	0.165
	290	0.1	314	0.13	345.2	0.15
5	250	0.11	280	0.12	319	0.14
	350	0.08	380	0.11	419	0.13

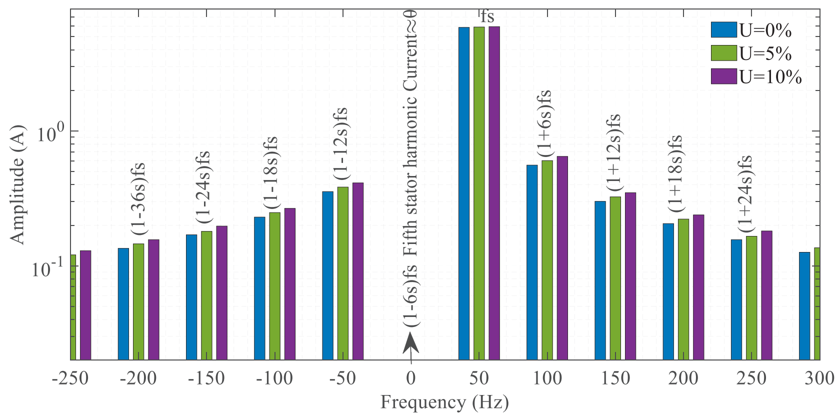

Fig. 5. Amplitude value at slip of 1/6 of the stator windings

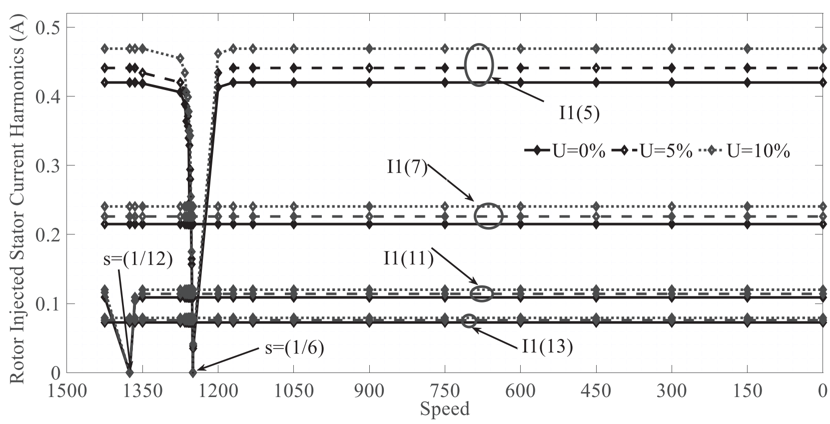

Fig. 6. Rotor injected stator current harmonics (D=0.75) (Analytically)

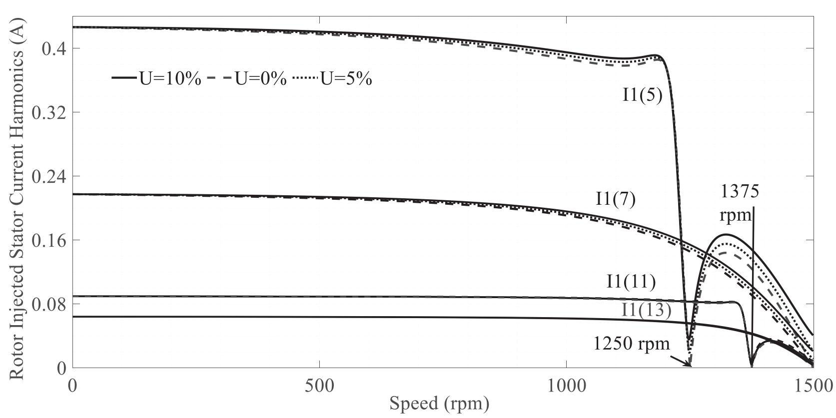

Fig. 7. Rotor injected stator current harmonics (D=0.75) (Simulation)

The 7th and 13th harmonic currents are roughly constant from standstill to roughly no-load slip, whereas the 5th component is zero when $s=1/6$. Similarly, as $U=(0, 5, 10)$ %, the 11th component is zero when $s=1/12$.

5. 2. The rotor current harmonic analysis of wound rotor induction motor drive system

Based on the analytical calculation of the current harmonic magnitude, the rotor current harmonic components are displayed in Table 3 at different unbalance voltage factors for ($U=0$ %), (speed=1200 rpm), ($U=5$ %) (speed=1170 rpm), and ($U=10$ %) (speed=1231 rpm) when the duty cycle of the dc to dc converter is set to 0.75.

Fig. 8 displays the rotor current harmonics spectrum generated by the rotor rectifier and chopper circuit for the same rotor winding slip based on the mathematical computation for a speed (1250 rpm) and (0, 5, 10) % of U, respectively.

The dc-to-dc converter duty cycle may be changed to regulate the rotor speed.

It has been shown from Table 3 and Fig. 8 that the rotor frequency and rotor harmonic currents are reduced with increasing the asymmetry of supply voltages.

5. 3. The pulsating harmonic torque analysis of wound rotor induction motor drive system

Applying the analytical calculation of the frequencies of electromagnetic torque developed and torque pulsation magnitude that are generated by rotor rectifier and chopper circuit for the same slip. are displayed in Table 4 at different unbalance voltage factors for ($U=0$ %) (speed=1200 rpm), ($U=5$ %) (speed=1170 rpm), and ($U=10$ %) (speed=1231 rpm) when the duty cycle of the dc-to-dc converter is set to 0.75. It also illustrates how the asymmetry of supply voltages affects these currents. Likewise, the system's electromagnetic torque is influenced by the supply voltage asymmetry, and as U increases, so does the torque pulsation, as seen in Fig. 9.

Fig. 10 shows the fundamental useful torque T_{e1}, T_{e5}, T_{e7}, T_{e11} and T_{e13} versus the slip for U variation between 0 % and 10 % for $D=0.75$.

Table 3

The magnitude of different rotor current harmonics

a	$U=0$ %, (speed=1200 rpm)		$U=5$ %, (speed=1170 rpm)		$U=10$ %, (speed=1131 rpm)	
	$/f/$ (Hz)	I_2 (A)	$/f/$ (Hz)	I_2 (A)	$/f/$ (Hz)	I_2 (A)
0	10	4.46	11	4.7	12.3	5.02
1	50	0.85	55	0.92	61.5	0.95
	70	0.62	77	0.64	86.1	0.74
2	110	0.39	121	0.4	135	0.43
	130	0.31	143	0.34	160	0.36
3	170	0.25	187	0.26	209	0.28
	190	0.22	209	0.23	234	0.25
4	230	0.15	253	0.19	283	0.21
	250	0.14	275	0.12	307	0.19
5	290	0.11	319	0.15	356	0.16
	310	0.09	341	0.14	381	0.12

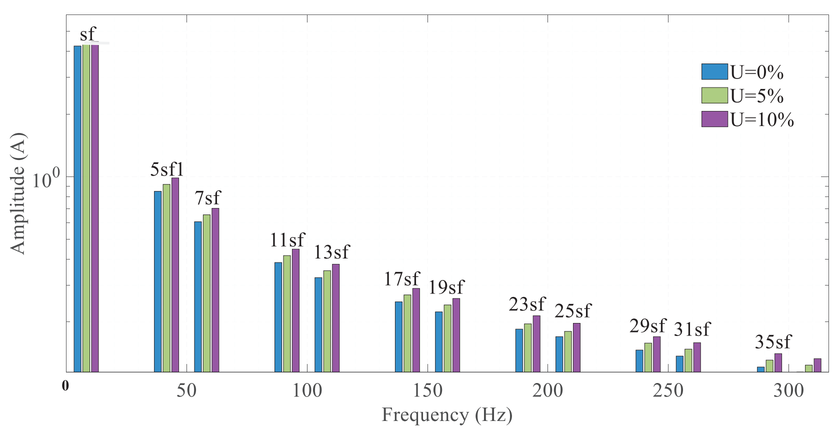

Fig. 8. Amplitude value at slip of 1/6 of the rotor windings current

Table 4

The magnitude of different developed torque due to different rotor harmonics

a	$U=0$ %, (speed=1200 rpm)		$U=5$ %, (speed=1170 rpm)		$U=10$ %, (speed=1131 rpm)	
	$/f/$ (Hz)	T_e (N·m)	$/f/$ (Hz)	T_e (N·m)	$/f/$ (Hz)	T_e (N·m)
0	0	12	0	11.99	0	11.98
1	60	0.95	66	0.96	73.8	1.02
2	120	0.22	132	0.235	147.6	0.251
3	180	0.1	198	0.106	221.4	0.109
4	240	0.05	264	0.058	295.2	0.064
5	300	0.03	330	0.037	369	0.04

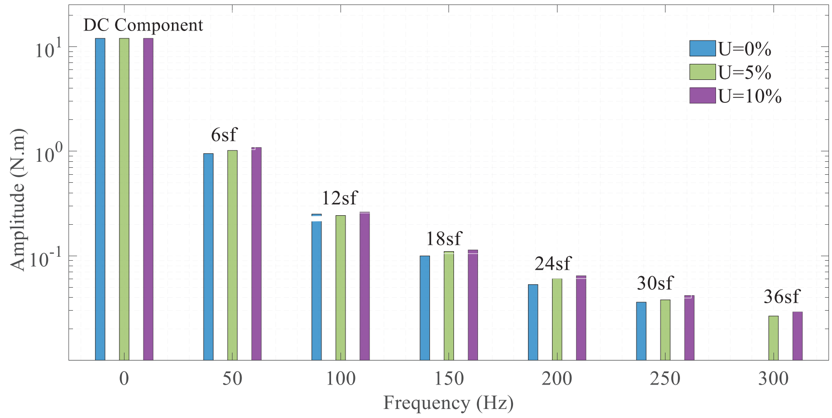

Fig. 9. Amplitude value at slip of 1/6 of the developed torque magnitude

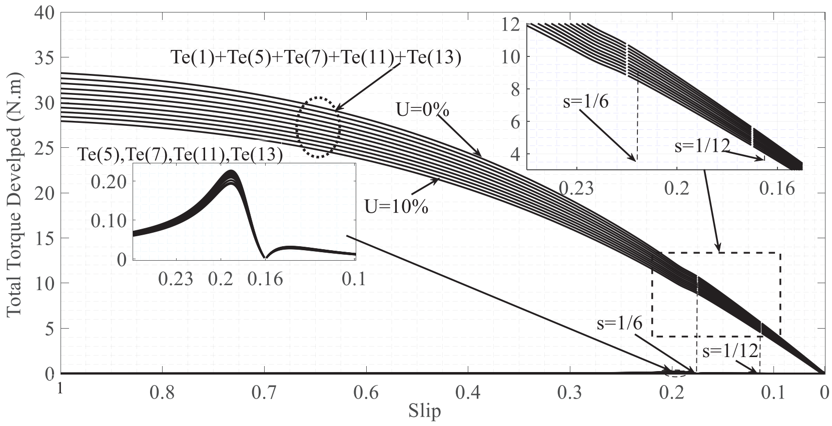

Fig. 10. The resultant torque against slip for U % vary from (0 to 10) and (D=0.75)

tion between 0 % to 10 when D=0.75 as it is clear in Fig. 10.

The electromagnetic developed torque response at s=1/6 for voltage imbalance factors of 0 %, 5 % and 10 %, respectively, is displayed in Fig. 11, *a–c*. The results obtained from Fig. 11 confirm that unbalanced supply voltage significantly increases the torque pulsation from peak to peak at a balanced supply voltage of 3 N·m, at U of 5 % is 4.5 N·m, and at U of 10 % is 5.5 N·m for a slip of 1/6.

Fig. 12, *a–c* show the response of the rotor speed for D=0.75 at U of 0 %, 5 %, and 10 %, respectively. Our study demonstrated that the ripple speed of the WRIMDS is 3 rpm for a balanced supply, 4.6 rpm for U of 5 %, and 7.5 rpm for U of 10 % at a duty cycle of chopper 0.75, as shown in Fig. 12.

It can be shown that the effect of rotor injected stator winding current is obvious but it is not notably as high to affect the WRIMDS characteristics. In contrast to $T_e(5)$, it is evident that $T_e(7)$, $T_e(11)$, and $T_e(13)$ are present in extremely modest concentrations. $T_e(1)$ and $T_e(5)$ as well as $T_e(7)$, $T_e(11)$, and $T_e(13)$ basic torques are shown against speed for U varia-

Fig. 13, *a–c* show the response of the torque pulsation for D=0.75 at U of 0 %, 5 %, and 10 %, respectively. It is noted that the ripple in motor torque for U of 0 % equals 2.5 N·m (speed=1200 rpm); for U of 5 %, it is 4.2 N·m (speed==1170 rpm); and for U of 10 %, it is 4.9 N·m (speed=1131 rpm), at D=0.75.

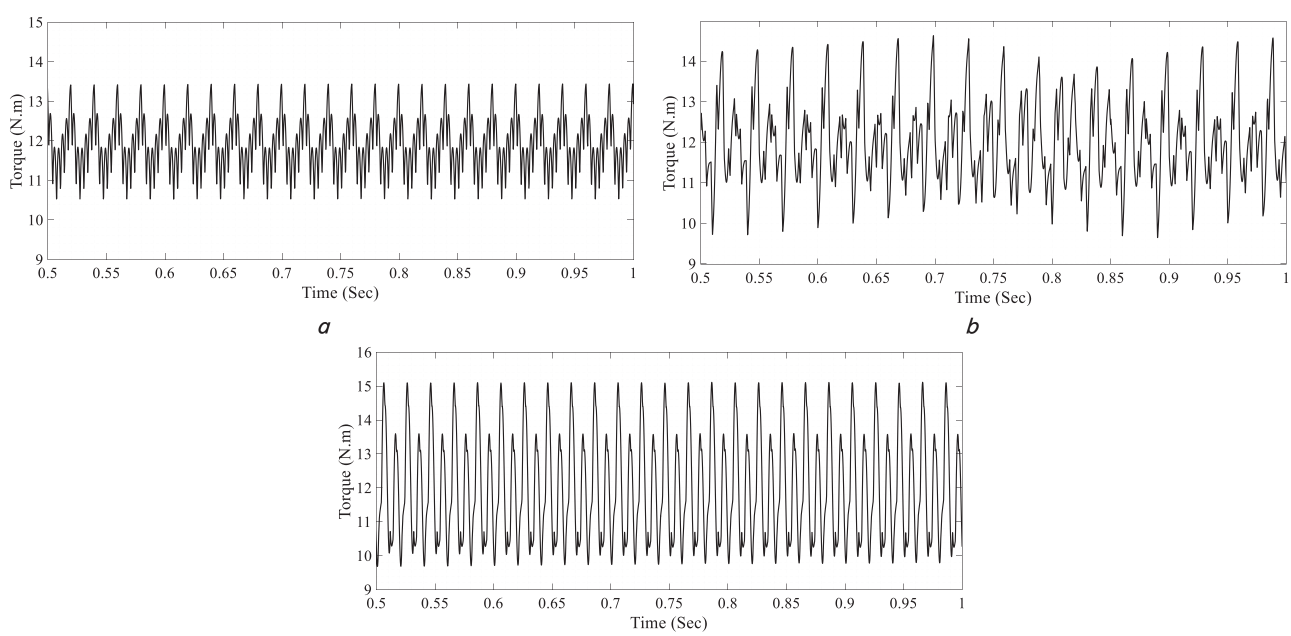

Fig. 11. The developed torque response at s=1/6: *a* – (U=0 %); *b* – (U=5 %); *c* – (U=10 %)

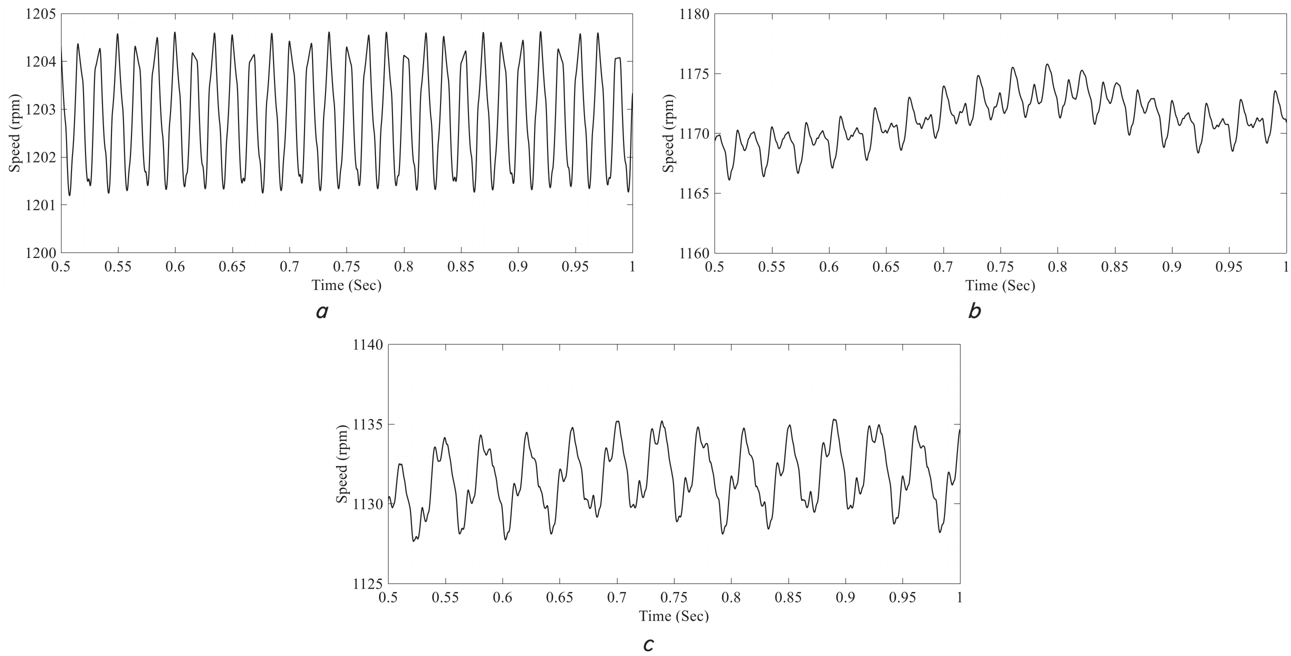

Fig. 12. The Rotor speed response at D=0.75: a – (U=0 %); b – (U=5 %); c – (U=10 %)

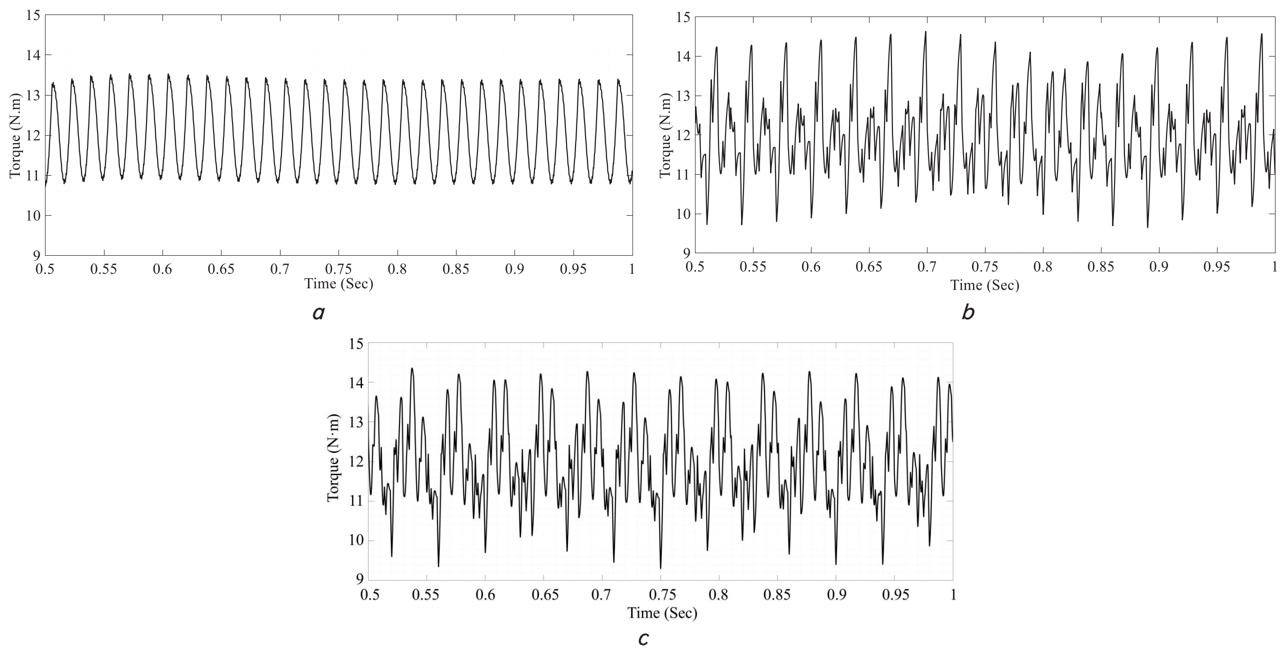

Fig. 13. The torque response at D=0.75: a – (U=0 %); b – (U=5 %); c – (U=10 %)

It has been investigated from Fig. 12, 13 that the ripple in rotor speeds and peak-to-peak torque variation increase directly with increasing the unbalance of supply voltage when the duty cycle is 0.75.

6. Discussion of results of unbalanced supply voltages effects on the performance of the wound rotor induction motor drive system

The results of this study demonstrate that the unbalanced supply voltage has a negative impact on the increasing of stator harmonic currents injected from the rotor side, rotor harmonic currents, and torque pulsation; as a result, the performance of WRIMDS has been derated.

The results obtained by derived mathematical models of WRIMDS show that the harmonic spectrum analysis of different unbalanced supplies voltage levels shows that the stator harmonic current spectrum (Table 2, Fig. 5), rotor harmonic current spectrum (Table 3, Fig. 8), and torque harmonic spectrum (Table 4, Fig. 9) are increased with U% for all harmonic orders.

In our study, the main efforts were focused on the evidence in this instance that the rotor harmonic mmf causes the 5^{th} and 11^{th} harmonics to be zero on the stator side (7). There are negligible harmonic components at this slip according to the stator current's Fourier transform and spectrum harmonic analysis. As U increases, it is possible to see that the injected stator current increases. Additionally, it is possible to see that this current is equal to zero when (s=1/6 and 1/12) and has not been impacted by the rotor current's 5th and 11th harmonic order. It can be seen that from Fig. 5–7, a special phenomenon relating to the motor space harmonic synchronization with the diode AC to DC converter commutation occurs once the speed value is a multiple of 1/6 and 1/12 due to this converter in the rotor circuit.

Further attention for this study involves the electromagnetic torque developed generated by the currents of the 7th and 13th components diminishes as the *U* % increases, it increases when the *D* increases. The impact of *U* is the same as that of $T_e(7)$ and $T_e(13)$, but the tendency of the *D* is to reduce $T_e(5)$ and $T_e(11)$ for harmonic torques of the 5th and 11th rising orders as shown in Fig. 10.

Unlike the study in [17, 18], in which the main attention is only on the slip of 1/6 of slip power recovery of torque ripple, which is (3–5) % of the average value, our study includes the slip of 1/6 and 1/12, and the torque ripple increased by 7 % (*U*=0 %) of the average value for balanced supply voltages. The torque ripple for (*U*=5 %) is 10.8 %, and it increased to 16.6 % when (*U*=10 %). Also, this study focuses on the speed ripple, which is increased by 0.375 % from 3 rpm (*U*=0 %) to 7.5 rpm (*U*=10 %).

Our study's findings demonstrated that excessive torsional oscillations in the motor shaft can occur from rotor harmonics under unbalanced supply conditions. To prevent drive system fatigue, extra attention must be given to the mechanical system in the design of WRIMDS.

One of the limitations of our research is that determining the commutation angle of a three-phase bridge rectifier by mathematical analysis assumes that the rotor rectified current is assumed to be ripple-free. The disadvantage of considered study is the lack of experimental validation. The validation between results obtained from the mathematical model and MATLAB/Simulink confirmed the impact of unbalanced supply voltage on WRIMDS performance.

Further prospects for this study involve determining experimentally the results of the effect of unbalanced supply voltage and taking into consideration the distortion supply voltage and low supply voltage WRIMDS.

7. Conclusions

1. Voltage unbalance causes a further increase in the stator harmonic currents, which leads to a reduction of resultant torque and the rotor speed for different duty cycles of WRIMDS chopper control resistance. The distortion currents have been independently determined using the equivalent circuit and mathematically derived equations, which are derived from the given rotor current harmonic components of the current flowing in the rotor. Rotor currents that are flowing in the stator cause distortion currents for the frequencies that are not integral multiples of the supply voltage frequency, particularly when $s=1/6$. The stator current waveform is created by summing these distortion currents. The increased heating brought on by extra losses is one of the most noticeable effects of an asymmetrical supply voltage.

2. The presence of a three-phase rectifier and chopper circuit in the rotor circuit produces the rotor harmonic currents, which are reflected to the stator side, and the distortion of the rotor current is increased by unbalanced supply voltage, duty cycle, and motor speed.

3. According to the obtained results, the torque pulsation magnitude increases with increasing VUF and THD. The generated torque and efficiency of WRIMDS are lowered as a result of these losses being dispersed in the stator and rotor windings.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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