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RESEARCH PAPER

Performance Analysis of WRIM Drive System Operating under Distorted and Unbalanced Supply: A Survey

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ABSTRACT:

The development of technology in power semiconductor devices leads to the increasing use of a static switching device in wound rotor induction motor (WRIM) controller systems. Supply voltage and current always contain harmonics and in the same circumstances unbalanced supply voltages. The low power quality has detrimental effects on the motor characteristics in the form of derating the output power and increasing torque pulsation. The static rotor resistance chopper controller (SRRCC) and slip power recovery drive (SPRD) are used in many applications. This survey presents a comprehensive review of many studies of SRRCC and SPRD operating with distorted and unbalanced supply, and their effects on the wound rotor induction motor performance. Starting from various techniques of control methodologies of SRRCC, SPRD, harmonic analysis, unbalanced supply and distorted unbalance supply simultaneously. Contributions from various researchers in this field have been presented, reviewed, and assessed.

KEY WORDS: Wound Rotor Induction Motor (WRIM), Slip power Recovery Drive (SPRD), Static Rotor Resistance Chopper Control (SRRCC), Harmonic Analysis, Distorted Supply, Unbalance Supply, Performance Analysis of WRIM
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1. INTRODUCTION

Studies have shown that two-thirds of the global electricity is consumed by the electrical motors, about 8% is consumed by DC motors, the remaining 92% is consumed by the AC motors, and the majority of them that are used in industries are induction motors. In the past, induction motors were considered as a constant speed motor, but with the advanced development in power semiconductor technologies the variable speed induction motor drives have been developed.

These technologies made WRIM having a wide applications such as in mills, conveyors, cooling pumps, steel drives, paper drives, cranes, elevators, cement factories, ventilation pumps [(Von Jouanne and Banerjee 2001)].

The characteristic of speed control by the capability of inserting additional circuits to the rotor terminals makes WRIM superior to other commercial squirrel cages IMs [(Sen and Ma 1975)]. **Figure 1** shows a block diagram of the control scheme of WRIM. The improved starting characteristics are obtained by connecting an external resistance in series with the rotor windings as shown in **Figure 2**. The bridge rectifier can be connected through a DC link to the inverter and feedbacks slip power to the main as shown in **Figure 3**. The speed-torque curve of WRIM can be controlled by rotor resistance

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through the chopper circuit or by changing the firing angle of the inverter.

AC slip power of the rotor is converted to DC power through a bridge rectifier and consumed by the chopper resistance as depicted in **figure 2,** or this power can be recovered and return to the main through using inverter and transformer this is known as (SPRD). However, as slip power is taken from the rotor to the AC main in a unidirectional, the control of the speed will be in a sub-synchronous speed range. If a diode bridge rectifier is replaced by a controlled bridge, the slip power flow can be controlled in two directions (Scherbius Scheme), **figure 3**, and the speed can be controlled in both regions, sub-synchronous and super-synchronous speed.

Despite the increasing demand for using WRIM in the industries but the appearance of the disturbance, such as unbalance and voltage harmonic distortion, in the main causes the derating of its performance.

In general, most of the electrical devices are designed to operate under symmetrical and sinusoidal supply voltage conditions. However, voltages and currents in the electrical power system are infrequently sinusoidal and balanced. Induction motors like all other devices, they are designed to work under sinusoidal and balanced supply voltages. Any change in main or unbalanced supply voltage lead to deteriorated the characteristics of the induction machines (IM) [(El-Kharashi and Massoud 2017)].

There are many studies available in the literature review that have analyzed and evaluated these problems and proposed different types of solutions, in which this work is devoted to reviewing them. It has been noted that SPR drive system has replaced the conventional rotor resistance control, but the problem in the value of power factor and total harmonic distortion of the supply. Our work summarizes researches on the performance analysis of WRIMD, harmonic effect, unbalance supply effect, and harmonic with unbalance effect on the drive performance. Besides, more than ninety publications are reviewed and organized including WRIM mathematical model, static chopper resistance control, slip power recovery drive system, the effect of harmonic distortion, the effect of voltage unbalance on WRIM, and finally the conclusion and references.

This paper is organized as follows: following the introduction in section one, speed control techniques are presented in section two. Section three and four include the details of static rotor resistance chopper control and slip power recovery drive system. The effects of harmonics, unbalanced, and distorted supply voltage of the operation and performance for WRIM are given in sections five and six respectively. Finally, sections seven and eight are the latest trend and future development and conclude this survey paper.

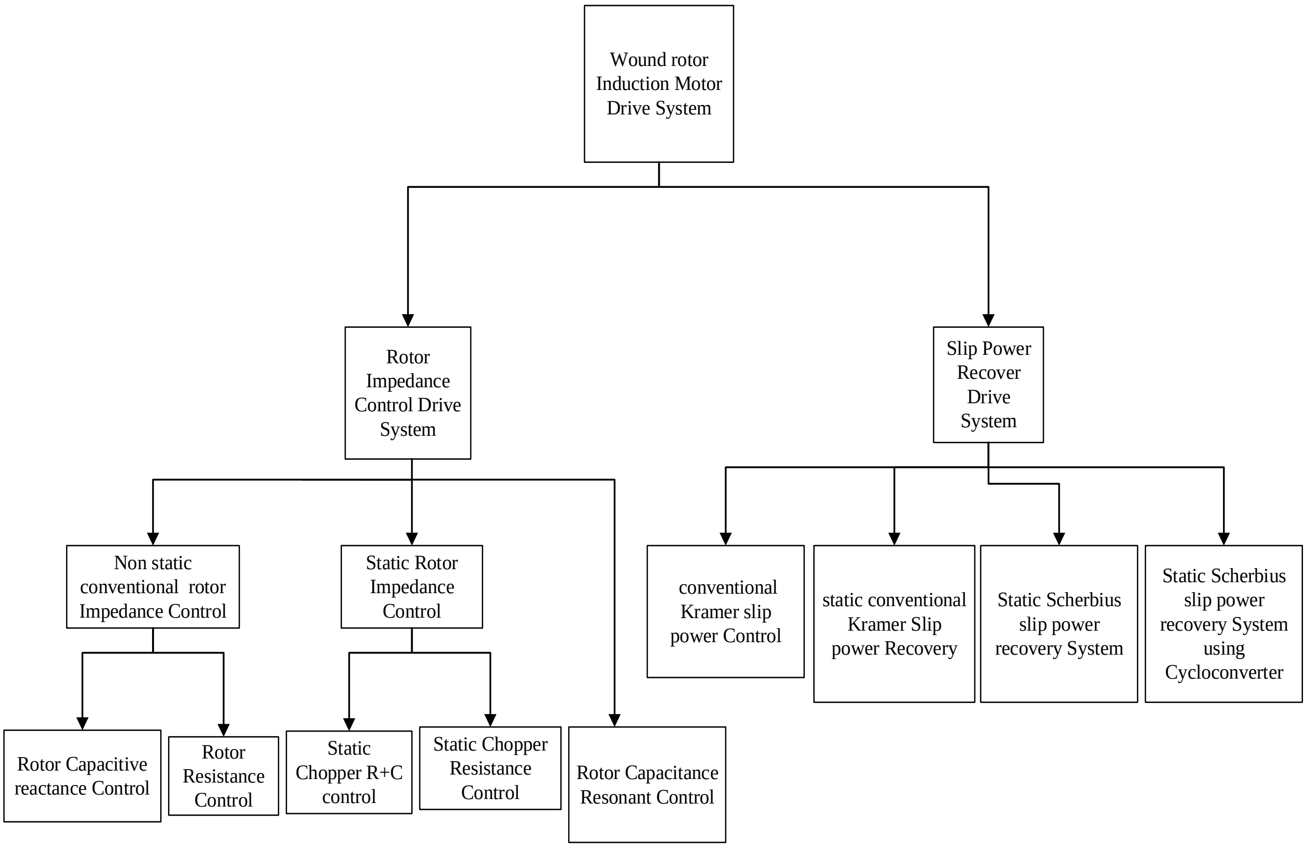


Figure 1: Control Scheme of Various WRIM Drive System

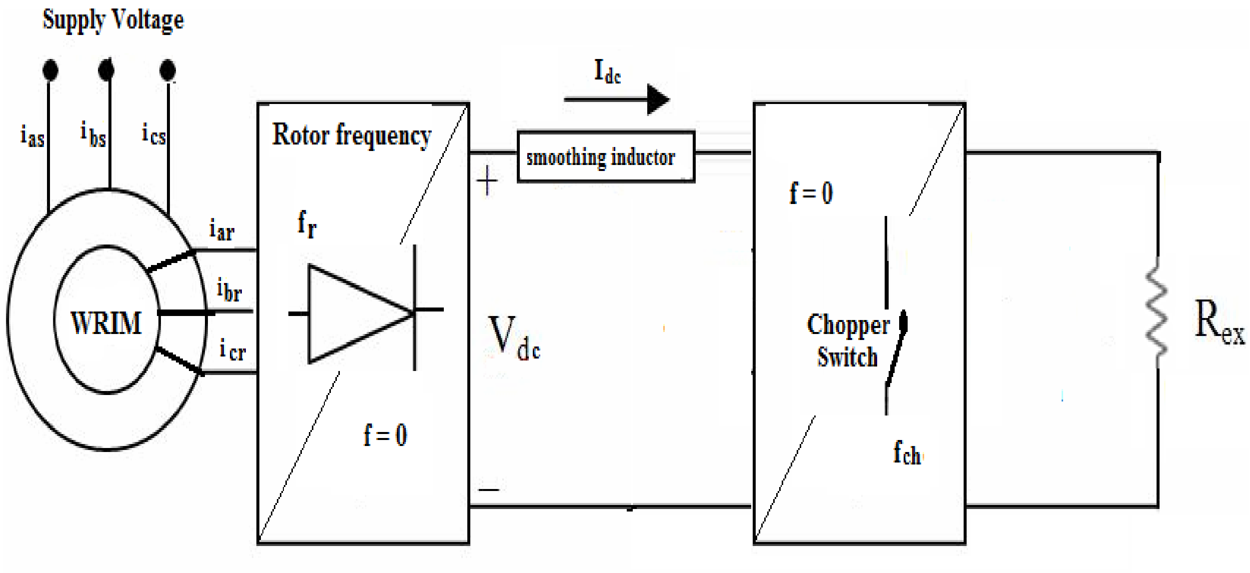


Figure 2: Static Rotor Resistance Chopper Control of WRIM [(Ameen 2011)]

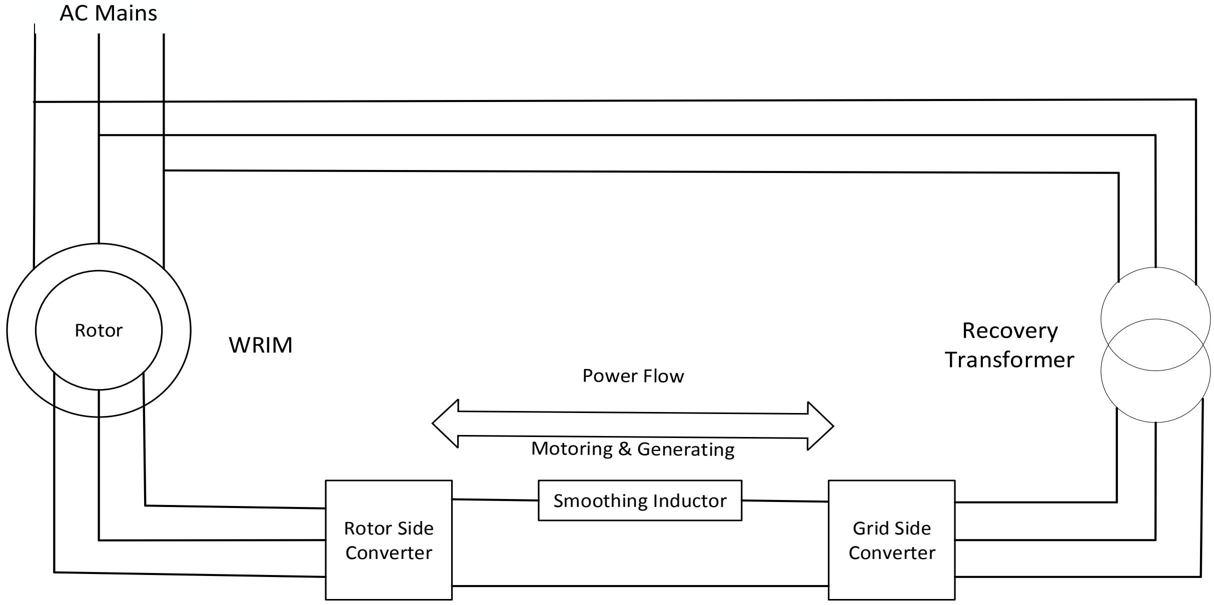


Figure 3: Static Scherbius SPR Scheme Block Diagram of WRIM [(Datta and Ranganathan 2013)]

2. WRIM Speed Control Techniques

A simple method of speed control of WRIM includes a mechanical variation of rotor circuit resistance as shown in **figure 4**. Based on the approximate equivalent circuit model of three phase induction motor, the electromagnetic torque developed can be written as

$$Te = \frac{3V^2\ R'/s}{\omega_s\left[\left(R_S+\frac{R'}{s}\right)^2+(X_S+X_r)^2\right]} \qquad (1)$$

Where $R' = R_{ex} + R_r'$, and V is the per phase voltage. The speed of WRIM is controlled by the variations of the external resistances at the rotor terminals. Since $Te \propto \frac{s}{R_r}$, therefore, the speed is decreased with increasing rotor resistance. The torque-speed characteristics for varying rotor resistance R_r of WRIM, as calculated in (1) is shown in **figure 5**. The drawbacks of this technique include the inherent disadvantage of the variations in the resistances and slip power energy is wasted in the rotor resistances. However, reducing the starting inrush current, high power factor, smooth and wide range speed-torque control without producing harmonics are major advantages of this technique.

3- Static Rotor Resistance Chopper Control (SRRCC)

3.1-Mathematical Model OF DC CIRCUIT

In basic SRRCC, the rotor slip power is rectified by a full bridge diode rectifier. A filter and an external resistance R_{ex} are connected with a diode bridge rectifier in different configurations as shown in **figure 6**. Assuming that the rotor rectified current I_{dc} is a ripple free and rotor phase current is a square pulse of (2π/3) duration, therefore, from both rectifications and chopping process the rms value of rotor phase current I_r is given by

$$I_r = \sqrt{\frac{2}{3}}\ I_{dc} \qquad (2)$$

The rotor rectified voltage of the rotor is

$$V_{dc} = \frac{3\sqrt{6}}{\pi}.s.\frac{V}{n} \tag{3}$$

From the DC equivalent circuit which is shown in **figure 7**, when either chopper frequency or smoothing inductor or both are high then the average DC current I_{dc} is given by the following expression[(Sen and Ma 1975)].

$$I_{dc} = \frac{V_{dc}}{R_s+R_{ex}(1-\delta)} \tag{4}$$

where δ is duty cycle of chopper circuit (on period/ chopper period), then the electromagnetic torque developed based from the dc model is given by

$$T_e = \frac{1}{s}\{\left[V_{dc} - \frac{3s\left(X_s^{'}+X_r\right)I_{dc}}{\pi}\right]I_{dc} - 2sR_s^{'}\,I_{dc}^2\} \tag{5}$$

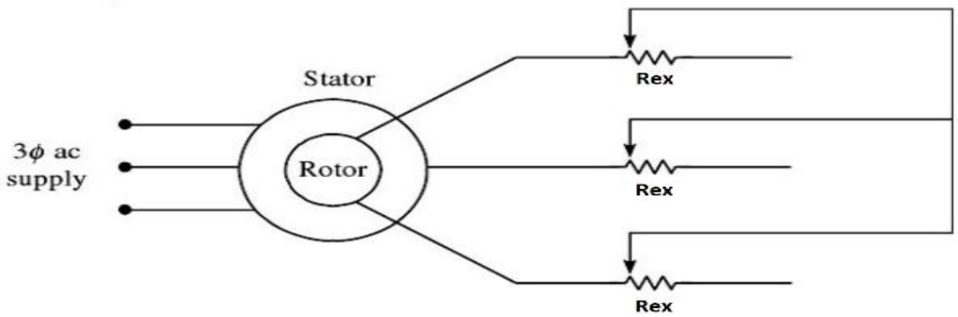


Figure (4): Conventional Rotor Resistance Control of WRIM

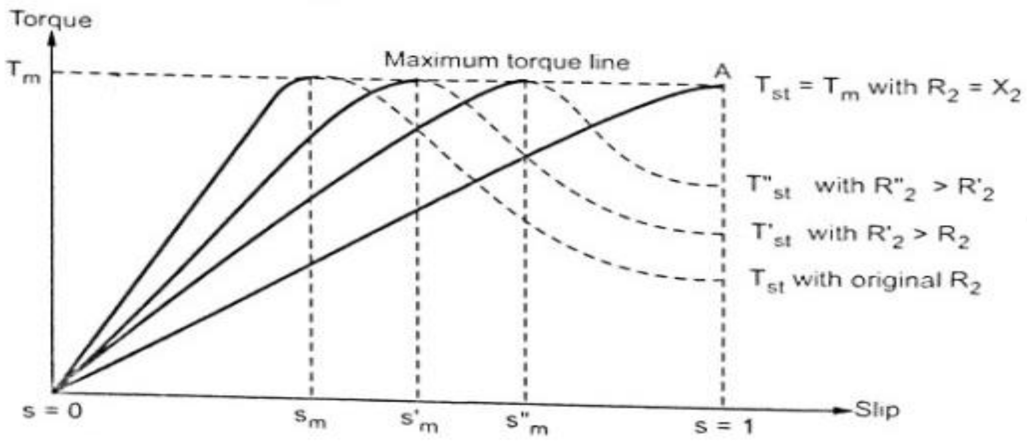


Figure (5): The Effect of Rotor Resistance on the Torque-Slip Characteristics of WRIM

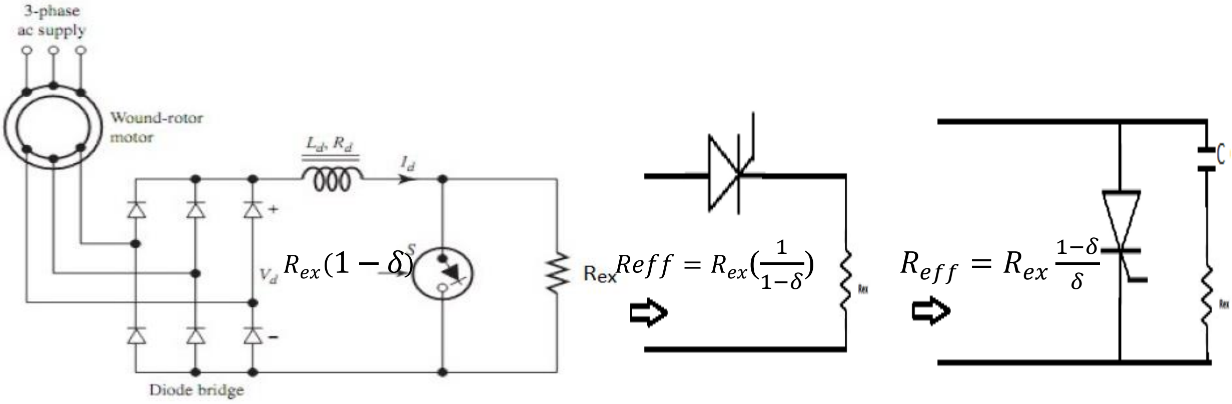


Figure 6: Different static chopper resistance control configuration

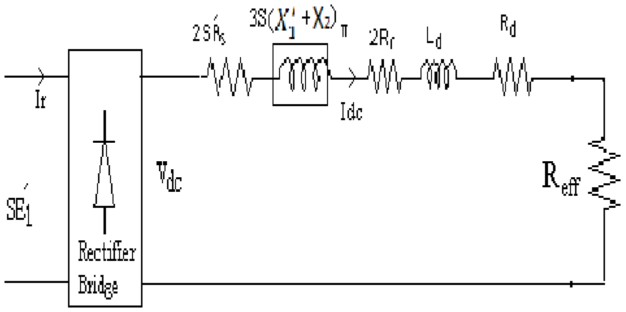


Figure 7 The dc circuit model of static chopper resistance control of WRIM

3.2 Mathematical Model of AC Circuit

By neglecting the commutation overlap of bridge rectifier due to motor leakage reactance, therefore, the total rotor resistance across the diode bridge rectifier is (R_d +R_{eff}) and the per phase power consumed, Pe is,

$$P_e = \frac{1}{3} I_{dc}^2 (R_d + R_{eff}) \tag{6}$$

This power is equivalent to the dissipated power which is caused by the flow of rotor current I_r in resistance and is equal to 0.5(R_d+R_{eff}) in each of the rotor phases. Hence the effective per phase value of AC resistance is given by [((Lavi and Polge 1966))].

$$R_{eff}^* = \frac{1}{2}(R_d + R_{eff}) \tag{7}$$

The per phase equivalent circuit is shown in **figure 8**, in which the drive circuit referred to the stator side and the mechanical power developed can be written as

$$E_1' \, I_{rf} cos\theta_r = (R_h + \frac{R_f}{s}) I_{rf}^2 \tag{8}$$

And the electromagnetic torque developed based on AC equivalent model is [(Sen and Ma 1975)]

$$T_e \cong 3I_{rf}^2 (R_h' + \frac{R_f'}{s}) / \omega_s \tag{9}$$

Where $R_h = \left(\frac{\pi^2}{9} - 1\right)\left(R_r + R^{*}_{eff}\right), R_f = \left(R_r + R^{*}_{eff}\right) and\ I_{rf} = (\frac{3}{\pi}) I_r$

(Sen and Ma 1975)] analyzed the SRRCC scheme using the time ratio technology, and derived the DC and AC equivalent model. while

[(Ramamoorty and Wani 1978)] have investigated a small signal dynamic model with a thyristorized chopper control closed loop and improving the speed and current feedback loops. The electromagnetic torque-speed characteristics and Torque against rotor rectified current of SRRC of WRIM with varying the chopper duty cycle for 2hp, 4-pole, 50Hz wound rotor IM are shown in **figure 9 and 10**, respectively.

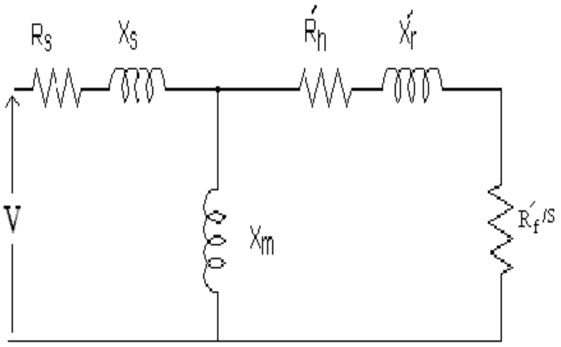


Figure 8 The AC circuit model of static chopper resistance control

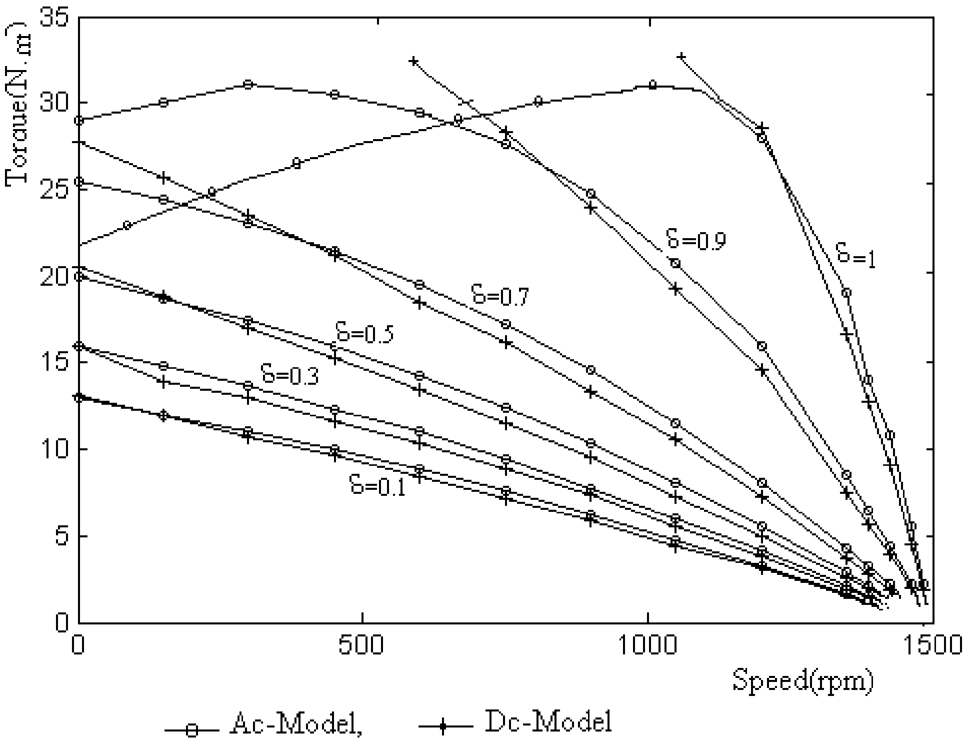


Figure 9: Torque-speed characteristics of SRRCC

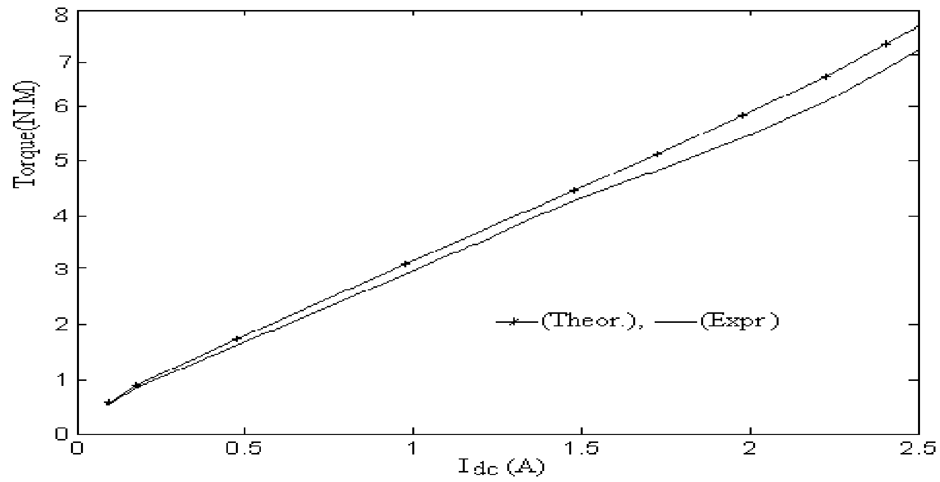


Figure10: Torque-rotor rectified current of of SRRCC

4. Slip Power Recovery Drive System (SPRDS)

4.1 Mathematical Model of SPRD

The slip power recovery provides the speed control for WRIM below and above the synchronous speed. There are two bridge rectifiers in the slip power recovery system, in which a portion of the power of the rotor is converted into DC by the first diode bridge rectifier, while the second converter works as an inverter that converts the slip power back to AC mains. In a slip power recovery system, the rotor slip power is feedback to mains unlike static chopper resistance control when is wasted in external resistors, such a method has higher efficiency than SRRCC.

The drive input power is equal to the difference between motor input power and the power returned back to the supply. The reactive input power is the sum of motor and inverter reactive powers. Therefore, the drive has a poor power factor during its operation.

Figures 11 and 12 show the static Kramer and Scherbius slip power recovery scheme of WRIM drive system, respectively. In the Kramer scheme, the speed will be controlled below the synchronous speed, while in the Scheribus scheme the speed will be controlled below and above synchronous speed and [(Taniguchi and Mori 1986) and (Al Zahawi, Jones, et al. 1987)].

In either scheme, the inverter terminal voltage Vi is given by

$$V_i = \frac{3\sqrt{6}\ V\ cos\alpha}{m\,\pi} \qquad (10)$$

In an ideal case, where the smoothing inductor resistance is neglected, the voltage equation in DC loop can be written as,

$$V_{dc} + V_i = 0 \qquad (11)$$

The slip as a function of inverter firing angle according to (3) and (11) can be written as,

$$s = -\frac{n}{m}\ cos\alpha \qquad (12)$$

If stator to rotor turn ratio (n) is equal to the grid side to inverter side turn ratio of recovery transformer (m), then the slip will be varying from 0 to 1, and the motor speed can be controlled from synchronous speed to the standstill. Thus, the motor speed can be controlled in the subsynchronous region by controlling the inverter firing angle. In Scherbius scheme the bridge 2 in **Figure 12** works as a rectifier while bridge 1 acts as an inverter and the speed can be controlled above the synchronous speed.

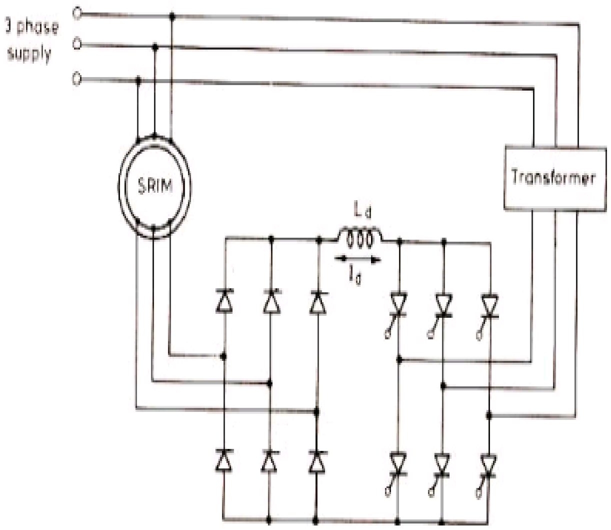


Figure 11: The Static Kramer Scheme

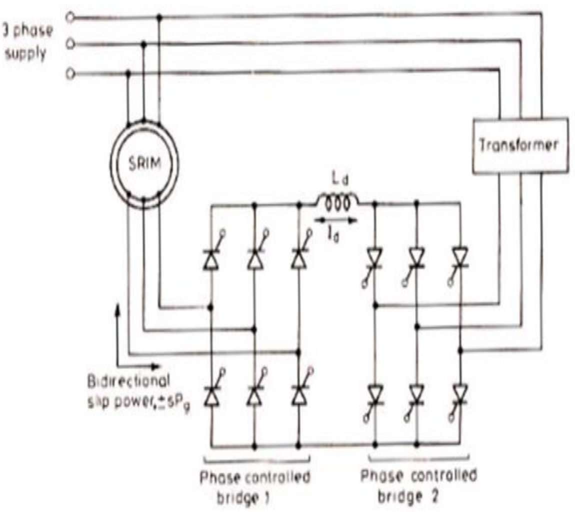


Figure 12: The Scherbius Scheme

4.2 DC Model of SPRD System

The rotor current of the SPRD ideally has six-stepped waves if the commutation effect of the rectifier is neglected and assuming that the link dc current is ripple free, and neglecting the rectifier and inverter bridge converter voltage drop. The DC equivalent circuit of the slip power recovery is shown in **figure 13**. The slip power (sp_g) of the slip power recovery drive system is given by

$$Slip\ power = (V_{dc} - sX_a\, I_{dc} - 2sR_s' I_{dc})I_{dc} \qquad (13)$$

where $X_a = 3\omega_s(L_s' + L_r)/\pi$, ω_s is synchronous speed, then the motor developed torque can be written as

$$T_e = [(V_{dc} - sI_{dc}(X_a + 2R_s')I_{dc})]I_{dc}/s\omega_s \qquad (14)$$

4.3 AC Equivalent Circuit Model of SPRDs

The slip power recovery drive is analyzed under the assumption that the rotor phase current is a square pulse of 2π/3 radians duration in six pulses, therefore the flux can be assumed sinusoidal. In the fundamental equivalent circuit, as shown in **figure 14**, the power transferred across the air gap is given by

$$P_g = 3E_{rf}I_{rf}'cos\theta_{rf} \qquad (15)$$

where θ_{rf} is the phase angle between $E_{rf}\ and\ I_{rf}'$. The total power consumed in the rotor circuit will be the sum of mechanical power (Pm), rotor copper loss (Pcr), and power feedback by the inverter (Pr).

$$P_r = -V_i I_d \ = -\frac{3VI_{rf}}{m}cos\alpha \qquad (16)$$

The electromagnetic torque developed based on AC model is given by [(Lavi and Polge 1966)]

$$T_e = \frac{3}{s\omega_s}[I_{rf}^2 R_d' + V_c' I_{rf}'] \qquad (17)$$

where $R_d' \ = n^2(R_r + 0.5R_f),\ R_h = \left(\frac{\pi^2}{9} - 1\right)(R_r + 0.5R_f) and\ V_c' = -\frac{n}{m}Vcos\alpha$

The AC equivalent circuit indicates that the speed and torque of the machine can be controlled by controlling the counter emf with the firing angle α as shown in **figure 15**.

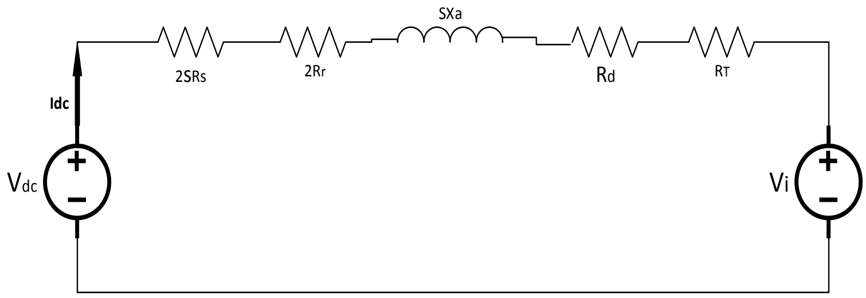


Figure 13: DC Equivalent circuit of the SPRD

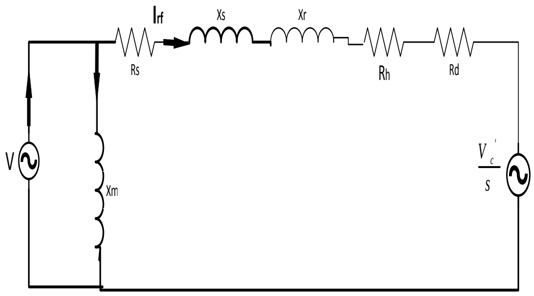


Figure 14: The AC Equivalent Circuit of SPRD

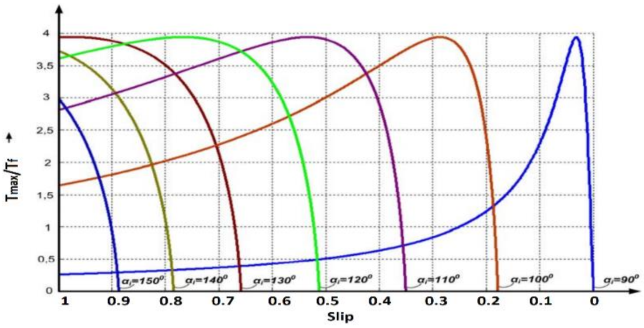


Figure 15: The torque slip characteristics of SPRD at Different Firing Angle

5. The Effect of Distorted Supply on the WRIM Operation and Performance

A chopper circuit, high-speed static semiconductor devices, is inserted between the diode and inverter bridge as shown in **figure 16**. This chopper converts the constant DC input voltage into variable DC output voltage directly. It controls the output of the inverter by duty cycle and fixing the inverter firing angle to take the minimum reactive power from the supply [(Kumar, Aggarwal et al. 2011)]. The chopper control technology also is used to improve the power factor of SPRDS and to improve the quality of power supply as well. Reducing harmonics in SPRDS is necessary for high power rating applications. Many researchers have contributed in the field of harmonic analysis and harmonic reduction techniques of SPRDS and chopper resistance of WRIM.

[(Mi 1968)] found that the inverter improves the power factor of WRIMDS by the time ratio control of inverter and provides smooth speed control. [(Pillai and Desai 1977) proposed the static sherbius with drive chopper circuit in which the required speed control was obtained by the duty cycle control of the chopper circuit. For constant firing angle inverter, they concluded that in the absence of the recovery transformer the current distortion in the supply system would increase.

More investigations using chopper power in SPRDS with improving the performance of the conventional system and improving power factor significantly had been presented by [(Doradla, Chakravorty et al. 1985) and (Taniguchi and Mori 1986)]. [(Al Zahawi, Jones et al. 1987)] investigated the effect of rotor rectifier on motor characteristics in SPRDS including the effect of overlap angle and diode voltage drop effect. In meantime [(Taniguchi, Takeda et al. 1987)] demonstrated the performance of static scherbius drive using DC and AC model circuits to improve the power factor and reducing the harmonic ripple current and the torque pulsation.

[(Akpinar, Pillay et al. 1992) and (Akpinar, Pillay et al. 1992)] presented and discussed in detail the starting transient in SPRD, by allowing the resistor develops maximum torque at starting, as well as the effect of overlap angle in rotor rectifier and harmonics reflected by the inverter. [(Baghzouz and Azam 1992)] proposed a technique using a hybrid d-q/abc model to evaluate harmonic distortion in SPRD, taking into account the commutation overlap and DC current ripple. Their technique predicted the voltage and current waveform accurately and computed the individual harmonic components.

The analytical technique to determine the overlap angle of rectifier voltage and the harmonic prediction was investigated by [(Akpinar, Pillay et al. 1993). (Pillay and Refoufi 1994) proposed two new circuit configurations for calculating the performance of the chopper controlled of SPRD. [(Refoufi and Pillay 1994)] compared the harmonic analysis of SPRD generated by rectifier and inverter as well as chopper control techniques to reducing it. [(Zakaria, Shaltout et al. 1996) and (Zakaria, Alwash et al. 1996)] developed the simulation model and carried out the harmonic analysis of a double rotor circuit WRIM to enhance the performance of SPRDS, but with the presence of two rotor circuits and their interaction have increased the complexity of the model.

[(Refoufi, Al Zahawi et al. 1999)] analyzed and compared the results obtained from the hybrid d-q model of DFIG using reference frame theory. [(Marques 1996) &(Marques 1999)] introduced a boost chopper control circuit to improve the performances and control the reactive power based on the rectifier theory. [(Marques and Verdelho 1996)] implemented the series resonant converter based SPRDS as a variable speed drive of WRIM and variable speed constant frequency in DFIG to maintain the rotor current sinusoidal with a unity power factor.

[(Marques and Verdelho 2000)] presented a simple method configuration for a slip power recovery system by connecting a boost chopper between the diode bridge rectifier to the DC link voltage. This method simplified the controller and minimized the cost in comparison with other configurations. [(Panda, Benedict et al. 2001)] described a novel machine side converter and control strategy of DFIM, which consists of a thyristor bridge and boost-buck-boost dc-to-dc converter. In this scheme, the speed is controlled in both region super and sub synchronous speed beside it works as an active filter to compensate any additional harmonics that are injected by the stator of the machine to the utility. The harmonic current of the stator and rotor, the electromagnetic torque pulsation of the SPRD considering harmonics produced by the bridge rectifier, and inverter have been examined by [(Papathanassiou and Papadopoulos 2001)].

[(Tunyasrirut, Kanchanathep et al. 1999, Tunyasrirut, Ngamwiwit et al. 2002)] presented various chopper control methods using fuzzy logic and voltage source inverter for SPRD. In addition to evaluation of the THD in stator current and, it reduced to less than the standard limit, Using the artificial neural network for controlling the speed and limiting the rotor current of static chopper resistance control of WRIM proposed by [(Abdelfattah and Ahmed 2002)].

[(Lee, Leeb et al. 2005)] proposed a voltage source drive power estimation method to find the relation between fundamental and high harmonic content in the stator current. [(Jarocha 2005)] studied the simulation and experimental test results base on the modified sub-synchronous speed and they found that the new model has a higher power factor and lower THD. [(El-Kholy, Mahmoud et al. 2006)] introduced a new technique for induction motor drive based on the current control space vector to get optimal voltage control and minimum THD.

The steady state analysis of SPRD using the microcontroller technique with increasing efficiency as shown in **figure 17** of the motor presented by [(Dalal, Syam et al. 2006). (Altun and Sunter 2007)] have developed the simulation model of slip power and matrix converter to improve the quality of power and conversion efficiency, while the current signal of SPRDS through discrete wavelet transform and harmonic reduction using active power filters have been investigated [(Alwash, Al-Chalabi et al. 2006)].

[(Ameen 2007)] analyzed the effect of duty cycle and switching frequency on the performance of WRIM and torque pulsation, and analyzed harmonics of stator and rotor current waveforms. [(Yang, Xi et al. 2008)] introduced a technique to improve the line power factor of a cascade speed control in WRIM drives by applying power factor correction into cascade speed control.

[(Ameen, K. et al. 2010) proposed a boost chopper in a static rotor resistance control system in which the stator and rotor current distortion have been reduced to about 2.9%. [(Joksimović 2010)] made the analysis expression of stator current harmonics frequencies in the spectrum of saturated cage and WRIM based on the mmf permeance wave approach. [(Tunyasrirut, Kinnares et al. 2010) and (Tunyasrirut and Kinnares 2013)] presented the line harmonic current reduction by the voltage source inverter and improving the power factor of the drive by applying a boost in which the THD is reduced to below the standard limits and power factor to about 0.85 at half of the rated speed. [(Ameen 2011)] analyzed the dynamic and steady state performance of SRRCC of WRIM using reference frame theory, further, he studied the effect of duty cycle on the performance of the motor. The injection of the third harmonic technique to the rotor circuit of chopper resistance control was done by [(Ameen 2011), it has been observed that the THD of the proposed technique and its power factor improved by 3.12% and 0.84 respectively.

[(Jaiswal, Joshi et al. 2012)] demonstrated the harmonic characteristics of currents and voltages of SPRDS with a comparison of harmonic contents of drive waveforms over a wide range of operating speed based on THD criteria. [(Hernández and Madrigal 2013)] developed a DFIM model for steady state harmonic analysis by taking into account the non-sinusoidal voltage source on the stator and rotor side of the machine, the results showed that harmonics of current exist on both sides of the machine depend on the slip and fundamental frequency of both voltage sources. [(Ajabi-Farshbaf and Azizian 2014)] introduced an SPRD consisting of a diode rectifier, a boost chopper, and three T-type converters to improve power factor and reducing the voltage output THD of WRIM in industrial applications.

[(Pardhi, Yadavalli et al. 2014),(Manoliu 2014) and (Ram, Rahi et al. 2015)] presented the study of SPRD with DC voltage intermediate circuit and the three types of PWM techniques. It has been observed that THD is reduced by 3.4%. [(Chen and Jiang 2015)] developed a double field model for steady state harmonic analysis taking into consideration the distorted supply source on the stator and rotor side of the machine. The effect of the stator supply harmonics of WRIM and DFIG on the pulsating torque and additional frame vibration have been investigated [(Djurović, Vilchis-Rodriguez et al. 2015)].

[(Lerch and Rad 2016)] demonstrated the power loss results in IM supplied with distorted voltage considering the effect of each of core losses, windage losses, and additional losses are resulting from distorted power supply conditions. [(Yao, Cosic et al. 2015)] studied the WRIM with a novel concept of the rotor fed by a converter, it has been obtained that the power factor and efficiency improved significantly. [(Yao and Sadarangani 2016)] proposed a novel idea of a rotating converter on the rotor of WRIM, and it is found that the efficiency and power factor improved significantly.

[(Sarma and Tuohy 2018)] studied the effect of voltage grid harmonics on the stator current of WRIMDS by using finite element time-stepping transient model and conductor distribution function. [(Bajjuri and Jain 2018) presented torque ripple estimation and reduction in a vector controlled double inverter fed of WRIM by employing different pulse width modulation techniques applied to both stator and rotor side voltage source inverter. [(Beleiu, Maier et al. 2020)] analyzed the effect of voltage waveform distortion on IM, mechanically and electrically, by applying the negative and positive sequence harmonics as a percentage of the fundamental, as well as the level of the stator current harmonics, and its effect on the electromagnetic torque, power factor and efficiency have been considered.

From the previous researches' results, it has been found that the different techniques of reducing harmonic distortion are used, depending on the slip and the fundamental frequency of the supply. Moreover, the negative effect of harmonics on the speed, torque, and power factor have been investigated.

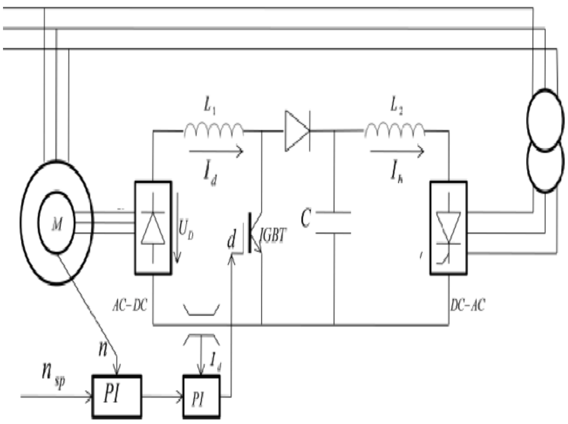


Figure 16 : Control scheme of SPR with chopper

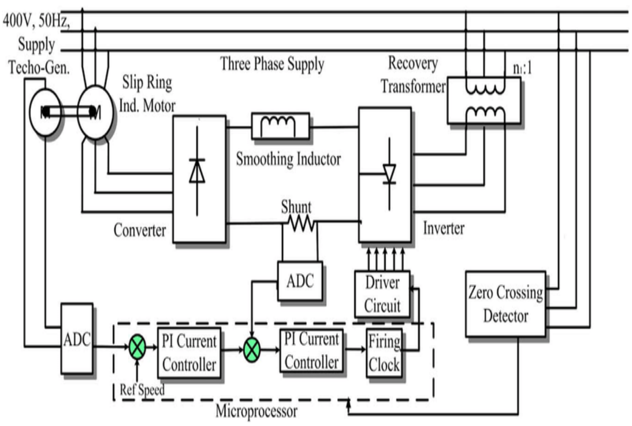


Figure 17: Closed loop SPRD

6. The Effect of Unbalance Supply Voltage on the performances of IM and WRIMD

The electrical machines are designed to operate under symmetrical and sinusoidal supply voltage conditions. However, voltage and current in the electrical power system are asymmetry and distorted by the effect of the non-linear loads. Induction motors like all other machines are designed to work under sinusoidal and balanced supply voltage. **Figures 18 and 19** show the derating of the efficiency and increase in the losses with increasing with a voltage unbalance factor [(Von Jouanne, 2001)]. Any quantities of unbalance will make the motor temperature rise and derating the power output. As per NEMA guidelines, operating a motor for any period of time at voltage unbalance above 5% is not recommended.

The general definition of voltage unbalance according to different principles are the IEC definition VUF, NEMA definition LVUR and IEEE definition PVUR [(Von Jouanne, 2001)].

$$\%\mathrm{VUF} = \frac{\mathrm{V_n}}{\mathrm{V_p}} \cdot 100 \qquad (18)$$

$$\%\mathrm{LVUR} = \frac{\text{Max Voltage Deviation from the Avg Line Voltage}}{\text{Avg Line Voltage}} \,.100 \qquad (19)$$

$$\%\mathrm{PVUR} = \frac{\text{Max Voltage Deviation from the Avg Phase Voltage}}{\text{Avg Phase Voltage}} \,.100 \qquad (20)$$

where V_n, V_p , and Avg are the negative sequence component, positive sequence component, and the average voltage, respectively.

In the literature review, many researchers have studied induction machines operating under an unbalanced voltage supply and its performance based on the positive and negative equivalent circuit as shown in **figure 20**. [(Woll 1975)] demonstrated that the effect of the unbalanced supply voltage is quite detrimental to successful motor operation, farther, it has been seen that an extremely serious loss of insulation life can be expected even with a voltage unbalance as low as 2%. [(Kersting 2000)] proposed a simple system using two transformers connections in order to find how these connections contribute to the voltage unbalance. [(Pillay, Hofmann et al. 2002) and (Wang 2001)] examined the proper application of IM in the presence of a combination of unbalance voltage and over voltage or under voltages and addressed the impact on the derating curve established.

[(Siddique, Yadava et al. 2004)] studied the effect of different voltage magnitude unbalance with the same voltage unbalance factor on the stator and rotor copper losses of three classes of three phase IM, while [(Pillay and Manyage 2006)] studied the loss of life of IM when supplied by unbalanced voltages, also, it has been estimated the motor life based on the thermal model parameters. [(Anwari and Hiendro 2010, Kostic and Nikolic 2010) studied the effect of unbalance supply on the IM performance considering the skin effect, and introducing the new unbalance factor for over and under rated voltage respectively. [(Singh, Singh et al. 2012)] proposed a new algorithm to determine the phase angle of voltage unbalance factor from the line voltage. Moreover, the presented the economic analysis for the different conditions of voltage index and it was shown that economical loss is more in the case under voltage condition in comparison to over voltage and equal voltage condition. [(Guasch-Pesquer, Youb et al. 2012) analyzed the effect of voltage unbalance on torque and current of IM at different unbalanced situations.

[(Youb 2014) and (Patil and Chaudari 2015)] investigated the negative effect of unbalance voltage on the performance parameters of IM, and verified their results by using MATLAB simulation. They concluded that the current unbalance factor is equal to 6 to 10 times the percent voltage unbalance factor. [(Quispe, Gomez et al. 2015)&(Kumar, Celliah et al. 2015)] presented the impact of unbalanced supply voltage on the energy-efficient of squirrel cage induction motors and on double field induction generators, respectively. [(Guasch-Pesquer, Jaramillo-Matta et al. 2017) and (Sudasinghe, Perera et al. 2018)] presented the effect of voltage unbalance in both complex current unbalance factor and torque ripple factor of three phase IM. From the simulation, they showed that only the voltage unbalance factor and positive voltage sequence parameters have a big influence in torque ripple factor and current unbalance factor. The detailed analysis of the impact of positive and negative sequence voltage components and the angle between them on the motor behavior has been presented by [(Quispe, López et al. 2018)].

[(Adekitan and Abdulkareem 2019) and (Adekitan, Ogunjuyigbe et al. 2019)] have revealed the significance of the manner of variation of the positive sequence voltage component on the motor losses, output power, and sensitivity of parameters of three phase IM. [(El-Kharashi, Massoud et al. 2019)] investigated and studied the performance and efficiency of two types of motors where they are mechanically combined and have been operated under balanced and unbalanced supply voltages. [(Donolo, Pezzani et al. 2020)] have presented the comparison of derating factor that has been provided by standards IEEE and NEMA to maintain the losses at rated value.

From the above, we can see that the voltage asymmetry appears to be much more harmful to the IM performance than distorted voltage. The effect of harming includes overheating, line current unbalance, derating of output power, torque pulsation, low efficiency (increasing losses), etc.

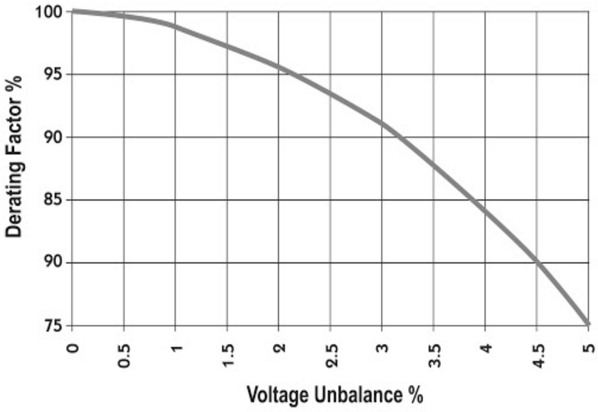


Figure 18: The Derating Factor against the voltage unbalance ratio

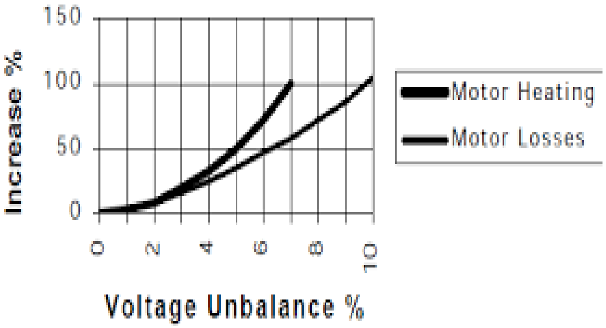
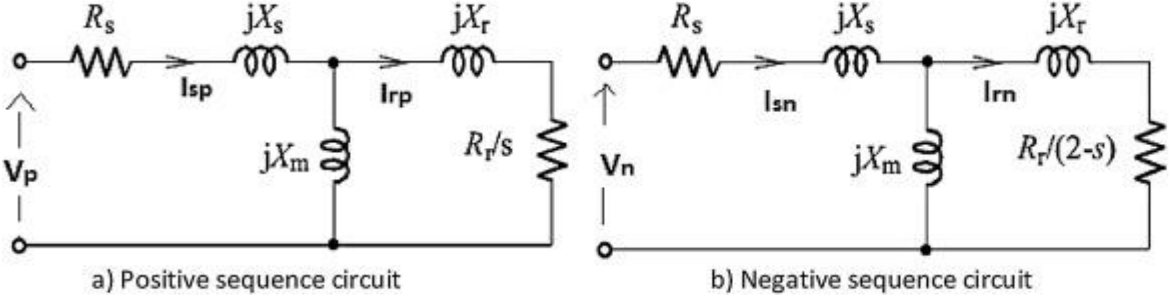


Figure 19: The Loss increasing with increasing the voltage unbalance ratio



a) Positive sequence circuit

b) Negative sequence circuit

Figure 20: The positive and negative sequence equivalent circuit of IM under unbalance supply

7. The Effect of Distorted and Unbalance Supply Voltage on The WRIM Performance

The three-phase WRIM is operated below rated power when it is supplied by voltage networks that are unbalanced and distorted, that is because of an increase in losses. **Figure 21** shows the distorted balanced supply while **figure 22** shows the distorted unbalanced supply waveforms applied on the same three phase IM.

(Eguiluz, Lavandero et al. 1999) presented the behavior of an induction motor supplied by non-sinusoidal and unbalanced networks, and they investigated those additional losses caused to induction motor when supplied by such systems.

[(de Abreu and Emanuel 2000) studied the effect of voltage unbalance and distortion upon thermal aging of IM insulation based on three dimensional modeling of heat transfer flow and monitored the temperature of hot spots of the insulation materials. [(Quispe, Gonzalez et al. 2004)] investigated the proper application of IM when subjected to unbalance and harmonic voltages, and they proposed a technique that showed a poor quality voltage have a bad impact on the motor characteristics, losses, temperature rise, derating of output power, efficiency, noise, current in bearing, and reliability of the machine.

A detailed analysis study on the effect of unbalance voltage in mains on the harmonic injected by three phase AC to DC rectifier with a new term named as phase total harmonic distortion unbalance factor (PTHDUF) have been introduced by [(Singh, Singh et al. 2006)]. [(Ramos, Martins et al. 2007)] presented and proposed a controller for minimizing the effect of unbalanced and distorted stator voltage on the rotor current and overall motor performance of the DFIG. [(Khoobroo, Fahimi et al. 2008)] investigated the combined effect of unbalance and harmonics on the electromagnetic performance of IM. They also studied in their work the relation between harmonics existence and unbalanced operating conditions to measurable parameters such as voltage, current, and harmonics.

[(Duarte and Kagan 2010) discussed the need for simultaneously monitoring voltage unbalance and harmonic distortion and a new power quality index has been proposed to combine the effect of voltage unbalance and harmonic distortion. [(Sousa, Viego et al. 2015)] proposed a new method based on the equivalent circuits of IM fed with harmonics and unbalanced supply voltages simultaneously and they calculated parameters by applying Bacterial Forging Algorithm as a technique of evolutionary search. The behavior of torque and efficiency of three phase IM when simultaneously supplied with imbalance voltage and harmonic distortion have been investigated by (Neves, de Mendonça et al. 2016)]. In meantime, [(Donolo, Bossio et al. 2016)] presented the effect of unbalance and harmonic voltage distortion on power factor, torque, and vibration of IM. Their results showed that vibrations are only presented during high level voltages' unbalance and harmonic distortion. [(Al-Badri, Pillay et al. 2017)] proposed an algorithm for in situ efficiency estimation of an induction motor operating under distorted unbalance voltages by using genetic algorithm procedures. Further proposed techniques to identify rotor harmonics from slip frequency, are determined by using the space time symmetrical characteristics of IM [(Zhang, An et al. 2017)].

[(Deleanu, Iordache et al. 2019)] studied the operation of the three phase IM when energized from an unbalanced voltage supply with the presence of harmonics with considering the skin effect due to the higher frequency harmonics on the overall motor performance. [(Donolo, Pezzani et al. 2020)] presented the voltage unbalance and harmonic distortion effect on the losses of IM in different efficiencies classes and it has been seen that IM losses due to voltage unbalance and harmonic distortion are greater in high efficiency class and derating factors are not enough to avoid overload on high efficiency class IMs.

From the above studies, we detected that analyzing the WRIM stator resistance chopper control and SPRDS when supplied by distorted and unbalanced supply voltage simultaneously require more investigations and researches. The presence of a rotor bridge rectifier and inverter, in addition to the low-quality supply, led to more power derating and loss of life of IM insulations.

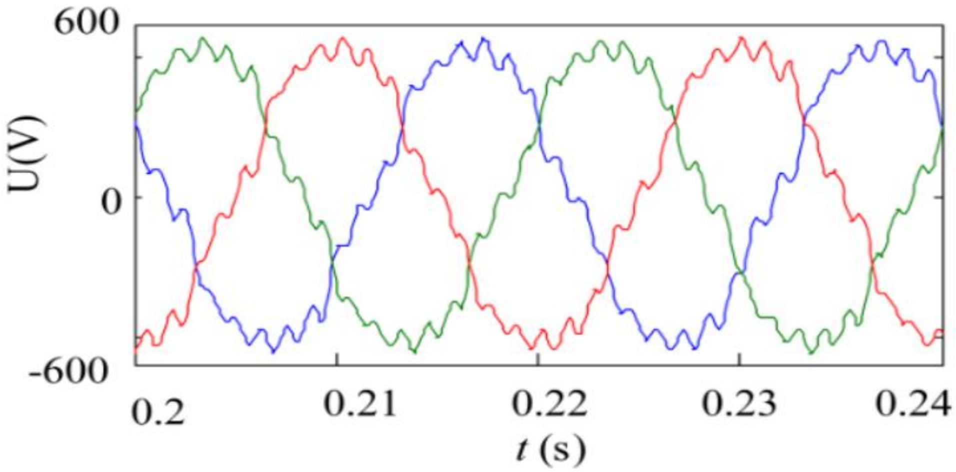


Figure 21: Voltage wave form with balance and THD of 10%

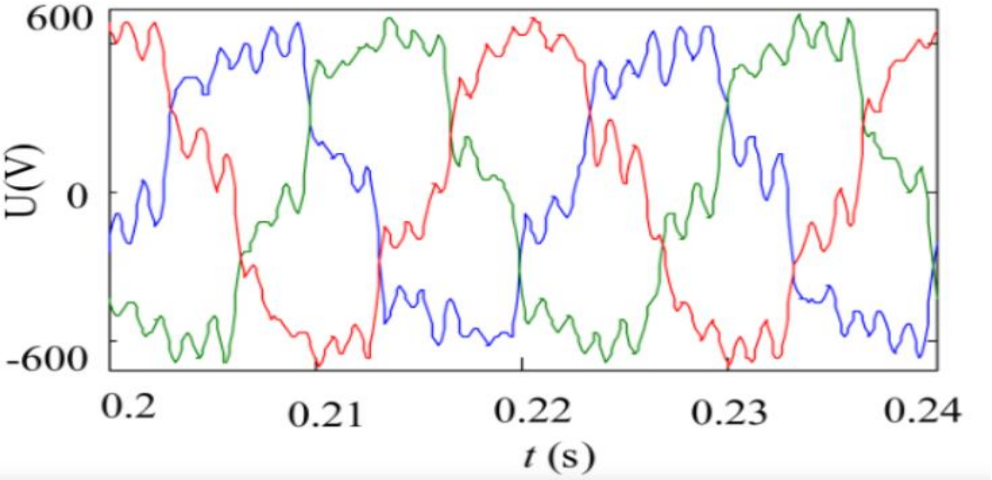


Figure 22: Voltage waveform with CVUF (5%) and THD of 20%

8- The Latest Trends and Future Developments in WRIM Drive System

The WRIM drive system specifically the SPRD system was developed and utilized in vast applications in the range of a few kilowatts to megawatt machine sizes. Such system adopts with advanced electronic subsystems such as converters, Rotor rectifier, DC link smoothing inductor, and recovery transformer. However, there are new developments in the ac-dc-ac converter for further improvements in their performance such as , increasing chopper frequency, boost chopper, buck boost chopper, multi-level inverter, PWM types inverter, and increasing the smoothing inductor value. These converters improvement provide improved power quality and WRIM drive system performance like a power factor, THD, efficiency of the system, speed, and torque pulsation.

The aim of this survey is to outline the study of the performance of WRIM drive system under unbalance supply voltage and combination of the unbalanced and distorted supply voltage simultaneously. The lake of researches in this field and low power quality in nowadays due to increasing in nonlinearity of loads, make the mains have distorted and unbalanced.

9. Conclusion

The intensive investigations spread in the last decades indicate the visibility of using adjustable speed drive to WRIM control in the rotor side with various methodologies and control techniques. Most of researches published in the harmonic analysis and performance improvement, static rotor resistance control, and SPRDS. A few papers have been presented the effects of the unbalanced supply of squirrel cage IM, and some papers have been dealt with the effect of distorted supply waveforms and unbalance supply voltage on the performance of IM.

It is found that the converters in the rotor side of WRIM drive system inject harmonic to the power supply, resulting in low power factor, and increasing the torque and speed pulsation. Various methods have been suggested by several authors to overcome these problems. Each technique has advantages and disadvantages with respect to power quality, complexity, cost, size, and applications. It is concluded that the multi-level inverters produce output voltage with very low distortion components in SPRD system. The brief history of beginning the speed control of WRIM during the last five decades has been outlined without taking into consideration the effect of unbalance supply voltage and unbalance supply voltage combined with distorted supply on the performance and operation of WRIM drive system.

This survey has focused on several areas and the current status of research of WRIMDS as well as an extension for the future work in the area of the impact of unbalanced supply voltage and distorted supply voltage simultaneously on the performance of SRRCC of and SPRD of WRIM. The objective and future outcome of this survey are to find out the effect of supply voltage asymmetry and distortion in separate and simultaneously on the performance of WRIM drive system.

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