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Inter turn Fault Analysis on Wound Rotor Induction Machine

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Abstract. Prevention of industrial machineries against internal and external faults is mandatory for uninterrupted operation. Identifying the exact faults or anomalies in the system and predicting the machine's health continuously is an essential preventive measure. To realize the protection system, pre-analysis of various faults under different load conditions is mandatory and hence, paper analysis a critical fault "Inter turn fault" in the wound rotor induction machine (WRIM). Inter turn fault is developed experimentally in 2.2 kW WRIM with 20 percent of internal windings shorted under different load conditions (0 to 1 per unit load). Obtained results are analysed for various electrical and mechanical parameters, and the faulty effects are revealed.

*Index Terms***:** Wound Rotor Induction motor, inter turn fault, power analyser

1. Introduction

Induction motor is a vital device for most of the industries and comprises magnetic circuit interlink between two circuits which are important parts of induction machine i.e. stator and rotor [1]. The stationary part is stator and rotational part is rotor. Through electromagnetic induction power is transferred. Preventive maintenance of electrical motors for condition monitoring of abnormal electrical and mechanical condition of the motor has been done for anomaly detection and protect the motor from failure [2]. Continuous monitoring of electrical parts of the motor helps to reduce the maintenance cost, save the energy, make the system more energy efficient. Online monitoring of induction motor helps to save the machine from major failure which is expensive for recovering. Condition monitoring technology can detect incipient fault [3]. There are various faults can be occurred in induction motor for various reasons like stator fault, rotor fault, winding faults, rotor inter turn faults, stator inter turn faults, broken rotor bar, unbalanced stator and rotor windings etc. Several fault detection methods have been introduced to identify these faults like vibration monitoring, current monitoring, temperature monitoring, chemical monitoring, acoustic emission monitoring etc. All these monitoring technique needs specialized tools, various sensors, data acquisition system. Verities of sensors can be used to analysis the critical damage of the system. These sensors measure stator voltage and currents, magnetic flux densities, output torque, speed, external temperature, rotor position and speed, internal and external temperature, case vibrations etc. A variety of motor failures can be monitored by system. The failures include opens, bearing failure, conductor shorts etc. It is seen that in a consisting manner failure monitoring is possible and different sensors can physically measure the failures.

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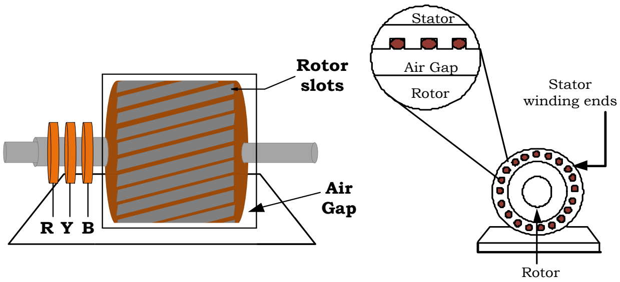

Figure 1 Schematic diagram of Induction motor

In Figure 1, the schematic diagram of wound rotor induction motor where three phases R, Y, B are shown and rotor slots are highlighted. Separately front view of stator and rotor are shown in the figure. With the help of wound rotor induction motor the experiment has been done here (Figure 1).

This paper is present the stator fault detection of WRIM and specially inter turn fault has been described here which is vital problem in industrial sector. As the main aim of the industry is to reduce operational and maintenance cost so condition monitoring of the machine is highly important to them. The failure of whole machine leads to cost of the additional equipment and maintenance cost for every time is also sometimes leads to loss for industry. So continuous monitoring of the winding is very much essential. Once in a six month the testing of winding, lubrication, insulation, resistance checking is needed. Inter turn fault causes degradation of winding, stator rotor failure etc. So overall stator winding fault has been described in this article.

2. Faults in induction motor

Among various faults Induction motor is highly affected by electrical faults and mechanical fault and mainly bearing faults. The induction motor faults are recognized as bearing fault (69%), stator winding fault (21%), rotor bar (7%), shaft/ coupling fault on the basis of IEEE standard 3004.8 the statistics have been shown in the figure. There are mainly two types of faults one is electrical fault another is mechanical fault. Under electrical fault stator, rotor fault and under mechanical fault eccentricity, bearing and broken rotor bar are seen. Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.

2.1. Mechanical Fault

Mechanical faults are such types of faults which are generally occurred in internal housing of three phase induction motor. This fault is subdivided into various categories.

- *Bearing Fault*

Bearing failure is progressive but ultimately machine has a catastrophic effect for this fault. Improper forcing of bearing shaft or housing causes premature failure and physical damage of the system [5]-[10].

- *Eccentricity Fault*

Unbalanced air gap between rotor and stator of induction motor causes eccentricity and this leads for incorrect position of stator and rotor [13].

- *Broken Rotor Bar*

Squirrel cage induction motor belongs to rotor bars and shorted end ring. Any time bars will damage or partially also cracked then this broken rotor bar has been seen [11].

2.2. Electrical Fault

In induction motor very crucial fault is electrical fault which can damage the whole system within very short time period. This research is based on mainly on electrical fault detection and focuses more on inter turn fault. Induction motor cannot be break down suddenly but due to overheating or over running causes severe damage. This electrical fault has four categories.

- *Single Phasing Fault (External Fault)*

General working of three phase induction motor three phases voltage supply is must, if in case one of the phases is damaged only two phases will be available which will lead to burned or causes excessive heating of the motor.

- *Reverse Phase Sequencing Fault (External Fault)*

Reverse phase sequencing fault is occurred when any one phase of three phase voltage supply is reversed which leads to change in the direction of the motor.

- *Under Voltage and Over Voltage (External Fault)*

Due to load variations the over and under voltage phenomenon occur in the induction motor. When the circuit is overloaded this causes over voltages and under voltage fault causes due to reduced voltage supply. The rated mechanical load supplies reduced voltage and that moment under voltage problem happen [17]. Under voltage causes increased current and excess heating of machine and increased stator rotor losses. Load switching, capacitor bank switching off these are the examples of under voltage causes.

- *Unbalanced supply voltage (External Fault)*

Normal balanced operating condition positive sequence voltage is developed. Negative sequence voltage is developed when supply voltage is unbalanced. Motor behaves like a super position of two separate motors due to neglecting of non-linearity and saturation and when one is running at slip s with terminal voltage Vp and other slip is (2-s) with terminal voltage Vn [19].

- *Internal Faults*

Inter turn fault is most common electrical fault in induction motor. It is recognized as inter turn short circuit fault in stator or rotor side. The phase to phase and phase to ground fault occurs due to increase heat and short circuit condition which leads to stator circuit breakdown. Several different phenomena can be seen for short circuit faults. Mechanical stress also a reason behind short circuit fault. This fault creates a big impact in stator fault. Due to moisture flow of current from scratch to scratch causes hot spot and thereby insulation also will destroy. When stator is supplied by a PWM voltage source partial discharge can happen to destroy the insulation which causes short circuit fault. Moisture causes flow of current which leads to make hot spot and destroy the insulation. Between turns high alternating voltage causes partial discharge when PWM voltage source is supplied by stator. Various faults in induction motor and its effects has been described (Table 1).

Table 1: Various faults of Induction motor and its cause and effects

Name of the faults		Causes of faults	Percentage of faults	Effects of faults	Ref
Mechanical Faults					
	a) Bearing Fault	The external causes of bearing faults are contamination, corrosion, improper lubrication, improper installation or brine-ling. Defective bearing installation	40-50%	The rolling elements of the machine may generate vibrations and noise. Continuous break causes local fragments of the materials and causes break loss. These excessive vibrations cause physical damage of the machine.	[1], 2005
	b) Eccentricity	Static air gap between stator and rotor causes eccentricity.	10-20%	Serious damage of stator core and winding for which dynamic electricity can damage.	[5], 2016
	c) Broken rotor bar	Manufacturing defect, hotspot, thermal unbalance, mechanical stress leads to create bearing fault and metal fatigue. This is mainly happening in squirrel cage induction motor.	7-10%	Rotor bar can break and fundamental frequency increases	[8], 2011
Electrical Faults					
External Faults	**a) Single phasing faults**	In the motor if winding is open	33%	Stator can induce more current causes winding failure, for creation of vibration rotor winding can fail.	[12], 2012
	b) Reverse Phase sequence fault	In three phases when two phases of supply line reverses.	23%	Major winding failure	[8], 2011
	c) Under voltage and Over voltage	Load variation or fluctuation in the system	10-15%	Harmful effects on machine insulation	[20], 2014
	d) Unbalance supply voltage	Unbalance loading and supply voltage, unequal tap settings, unbalance primary voltage, High resistance connections	21-25%	Motor efficiency will reduce and winding will fail prematurely.	[23], 2010
Internal Faults	**Inter turn fault (stator and rotor inter turn fault)**	Unbalance supply voltage, fluctuation of voltage within a very short time repeatedly.	33-35%	High current will flow within the short circuit area causes total winding failure.	[15] [16], 2010, 2010

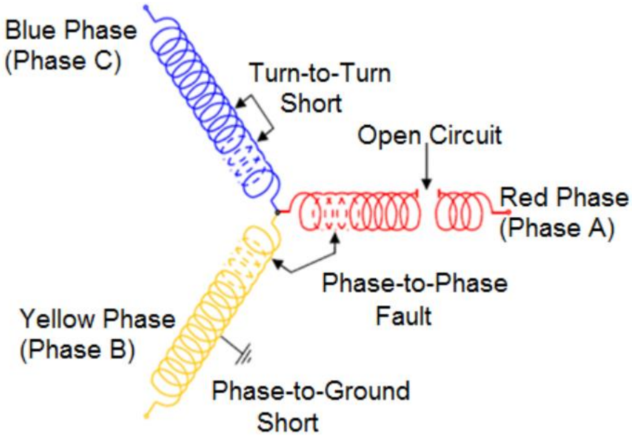

Figure 2: Different types of Stator Winding faults

An induction motor various stator winding faults are shown in Figure2.

Stator and rotor equation in the induction machine is described [6] The voltage, current, flux of stator and rotor has been expressed [1-6]

$$V_S = R_S I_S + P\lambda_S \tag{1}$$

$$0 = R_r I_r + p\lambda_S \tag{2}$$

Where

$$V_S = [V_{as1} \quad V_{as2} \quad V_{bs} \quad V_{cs}]^T \tag{3}$$

$$I_S = [I_{as} \quad (I_{as} - I_f) \quad I_{bs} \quad I_{cs}]^T \tag{4}$$

$$I_r = [I_{ar} \quad I_{br} \quad I_{cr}]^T \tag{5}$$

$$\lambda_S = [\lambda_{as1} \quad \lambda_{as2} \quad \lambda_{bs} \quad \lambda_{cs}]^T \tag{6}$$

Voltage is shown as V, current is I, λ is recognized as flux here, and stator, rotor are represented as s and r respectively, three phases are denoted as a,b,c as_1, as_2 are denoted as unfaulty and faulty part of stator.

$$V_{as2} = turn \;\; R_s\left(I_{as} - I_f + \rho\,\lambda_{as2}\right) = R_f I_f \tag{7}$$

$$\lambda_s = \mathrm{L}_s I_s + L_{sr}\mathrm{I}_r \tag{8}$$

$$\lambda_r = [L_{sr}]^T I_s + L_r \mathrm{I}_r \tag{9}$$

These equations show the shorted part of stator winding voltage.

The resistance matrix is shown as

$$R_s = R_s\, diag[(1 - turn) \quad turn1 \quad 1] \tag{10}$$

$$R_r = R_r\,[I]_{3\times 3} \tag{11}$$

The stator winding's self and mutual inductance has been shown here [12-14].

$$+\begin{bmatrix} (1-turn)^2 & turn*(1-turn) & -\dfrac{(1-turn)}{2} & -\dfrac{(1-turn)}{2} \\ turn*(1-turn) & (turn)^2 & -\dfrac{turn}{2} & -\dfrac{turn}{2} \\ -\dfrac{(1-turn)}{2} & -\dfrac{turn}{2} & 1 & -\dfrac{1}{2} \\ -\dfrac{(1-turn)}{2} & -\dfrac{turn}{2} & -\dfrac{1}{2} & 1 \end{bmatrix} \tag{12}$$

$$L_{sr} = L_{ms} \begin{matrix} (1-turn)*\cos(\theta_r) & (1-turn)*\cos(\theta_r + {2\pi}/{3}) & (1-turn)*\cos(\theta_r - {2\pi}/{3}) \\ turn*\cos(\theta_r) & turn*\cos(\theta_r + {2\pi}/{3}) & turn*\cos(\theta_r - {2\pi}/{3}) \\ \cos(\theta_r - {2\pi}/{3}) & \cos(\theta_r) & \cos(\theta_r + {2\pi}/{3}) \\ \cos(\theta_r + {2\pi}/{3}) & \cos(\theta_r - {2\pi}/{3}) & \cos(\theta_r) \end{matrix} \quad (13)$$

$$L_r = \begin{bmatrix} L_{lr} + L_{RM} & -\frac{L_{RM}}{2} & -\frac{L_{RM}}{2} \\ -\frac{L_{RM}}{2} & L_{lr} + L_{RM} & -\frac{L_{RM}}{2} \\ -\frac{L_{RM}}{2} & -\frac{L_{RM}}{2} & L_{lr} + L_{RM} \end{bmatrix} \quad (14)$$

Turn is denoted as pu for phase a, θ_r represented as rotor position, self-inductance is shown as L_S rotor self-inductance is shown as L_r Stator to rotor mutual inductance is represented as L_{Sr}.

3. Experimental procedure

The experiment is carried out with the help of wound rotor induction motor whose rotor windings are in star connection. The purpose of this research is to find out intern turn short circuit fault's effect by creating intern turn fault in the machine. The interesting current signature can be shown by stator current and harmonics are shown by rotor current. An experimental setup has been formed for three phase wound rotor machines with 5hp, 220V, 50Hz, 4.7A (stator side), 7.5 A (rotor side), 1500 RPM. In WRIM both the stator and rotor are accessible. The DC generator is coupled with WRIM for excitation purpose. One protection circuit has been connected through current sensor with the WRIM R phase to protect the circuit when fault has been created. One circuit breaker has been connected as a protection purpose to trip the circuit when it exceeds rated current of the machine. Here the process has been limited in up to 6 amp as the resistance value is higher. If 6-amp current exceeds then winding can be burnt out. But if resistance value will less current can be increased.

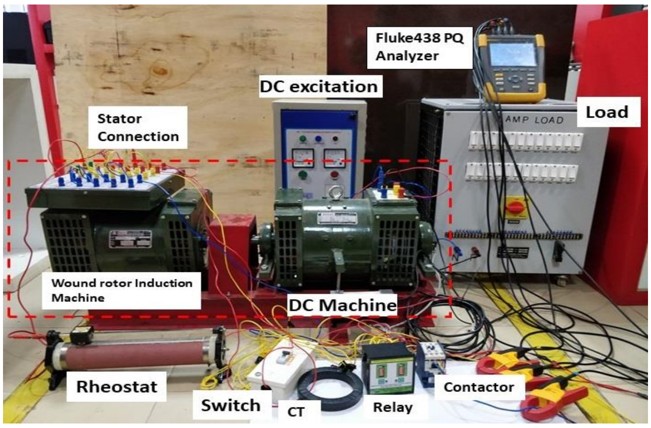

Figure. 3. Experimental Setup

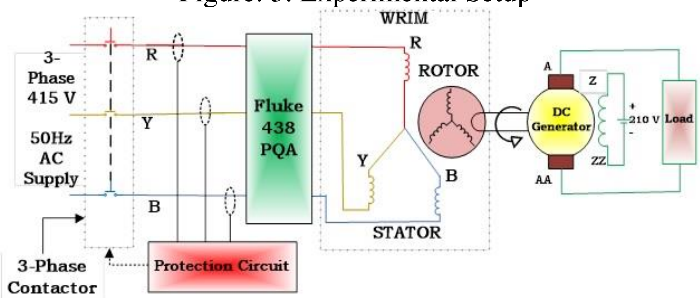

Figure. 4a. Circuit diagram of the experiment

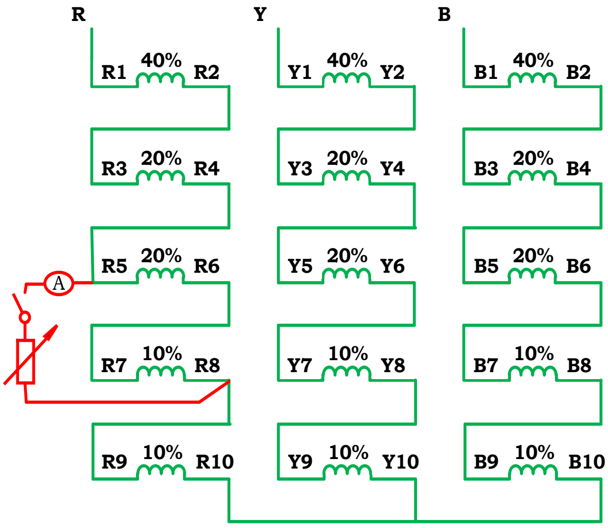

Figure .4b. Faulty winding connection

The WRIM machine three phase supply is not directly connected to the supply as in the experiment voltage is varied slowly. So, in this experiment the three phases of the induction machine stator side are connected to the supply through auto transformer. The Fluke 438 PQA is connected in between auto transformer and three phase supply of the induction machine. One protection circuit through current sensor is connected with WRIM for protection purpose. The circuit is made with relay coil, single phase switch and rheostat. One DC excitation is connected with the rotor of the induction machine. The rotor is coupled with the stator by shaft. A lamp load is connected with rotor armature. First experiment has been done with the no fault condition from 0 to full load with the 12 loads approximately. Then with same loads R6 to R7 sorted (Figure4a, Figure4b). So, 20% of the inter turn fault created to check the experiment. Now after 6 A the circuit breaker isolates the circuit as it exceeds the rated current. In the result maximum current, power is higher in the faulty condition rather than no faulty condition. Figure 4 shows the circuit diagram of the experiment and Figure3 shows the experimental hardware setup. Experimental results are shown in Figure 5.

4. Experimental results

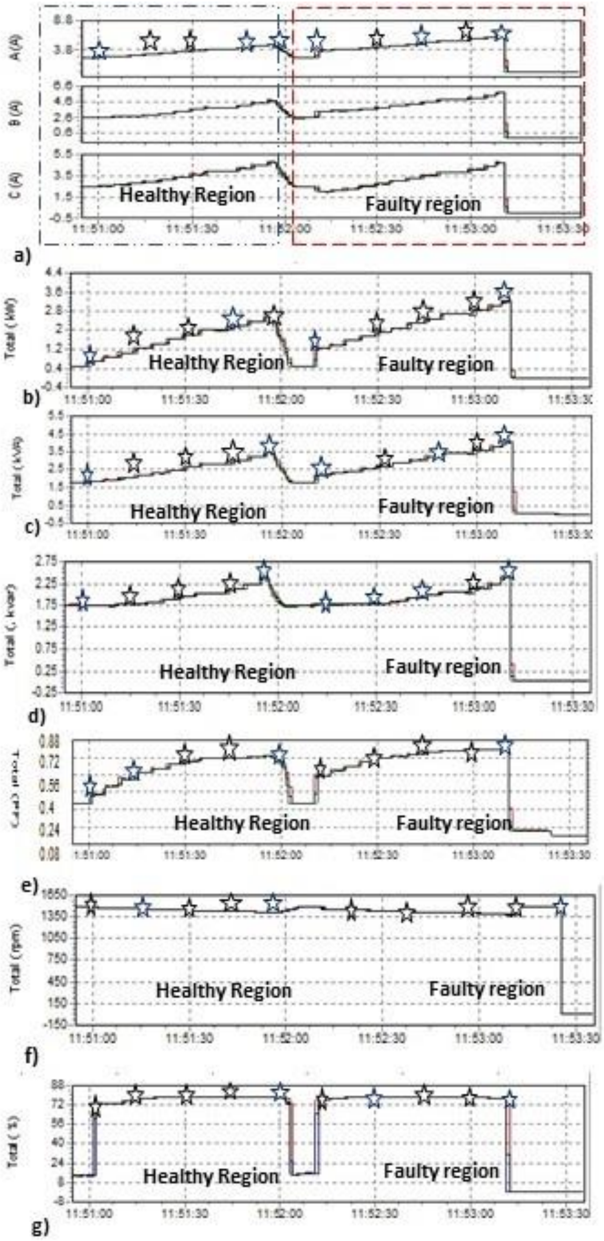

Figure 5. Experimental results

a) For 0 load healthy to faulty condition current change is 17.03%. For 0.25 load healthy to faulty region current change is 47.33%. For 0.5 load healthy to faulty region change of current is 58.77%. For 0.75 load healthy to faulty region current change is 60.68%. For 1 load healthy to faulty region current change is 61.98%.
b) For 0 load healthy to faulty condition power change is 47.03%. For 0.25 load healthy to faulty region power change is 63.15%. For 0.5 load healthy to faulty region power change is 63.15%. For 0.75 load healthy to faultyregion power change is 66.07%. For 1 load healthy to faulty region power change is 68.25%.
c) For 0 load healthy to faulty condition apparent power change is 8.3%. For 0.25 load healthy to faulty condition apparent power change is 28.03%. For 0.5 load healthy to faulty region apparent power change

is 35.70%. For 0.75 load healthy to faulty condition apparent power change is 46.34%. For 1 load healthy to faulty condition apparent power change is 48.31%.

d) For 0 load healthy to faulty condition reactive power change is 1.72%. For 0.25 load healthy to faulty condition reactive power change is 1.8%. For 0.5 load healthy to faulty region reactive power change is 2.76%. For 0.75 load healthy to faulty region reactive power change is 12.34%. For 1 load healthy to faulty region reactive power change is 14.38%.

e) For 0 load healthy to faulty region power factor change is 31.03%. For 0.25 load healthy to faulty region power factor change is 33.68%. For 0.5 load healthy to faulty region power factor change is 36.98%. For 0.75 load healthy to faulty region power factor change is 40.03%. For 1 load healthy to faulty region power factor change is 41.35%.

f) For 0 load healthy to faulty region speed change is 1.5%. For 0.25 load healthy to faulty region speed change is 2.67%. For 0.5 load healthy to faulty region speed change is 2.7%. For 0.75 load healthy to faulty region speed change is 2.7%. For 1 load healthy to faulty region speed change is 6.74%.

g) For 0 load efficiency change of healthy to faulty region is 13.80%. For 0.25 load efficiency change of healthy to faulty region is 13.96%. For 0.5 load efficiency change in healthy to faulty region is 15.69%. For 0.75 load efficiency change of healthy to faulty region is 14.01%. For 1 load healthy to faulty region efficiency change is 14.38%. Table 2 describes the overall analysis of the results.

Table 2: Analysis of the results

Parameters	Load (p.u)				
	0	0.25	0.5	0.75	1
Current (A)	17.03% ↑	47.33% ↑	58.77%↑	60.68% ↑	61.98% ↑
Power (kw)	47.03% ↑	63.15% ↑	48.21%↓	66.07% ↑	68.25% ↑
Apparent power (kva)	8.3% ↑	28.03% ↑	35.7%↑	46.34% ↓	48.31% ↑
Reactive power (kvar)	1.72% ↑	1.8% ↑	2.76%↑	12.34% ↓	14.38% ↑
Power factor	31.03% ↑	33.68% ↓	36.98%↑	40.03% ↓	41.35% ↑
Speed (rpm)	1.5% ↓	2.67% ↓	2.84%↓	2.7% ↓	6.74% ↓
Efficiency (%)	13.8% ↓	13.96% ↓	15.69%↓	14.01% ↓	14.38% ↓
	↑ Increase in percentage ↓ decrease in percentage				

5. Conclusion

The paper is on inter turn fault in WRIM. Different experimental techniques can be implemented for stator and rotor short circuit fault and stator rotor voltage, current, flux can be shown as different signals here. Here machine is used as motor and it can be used as generator also. Stator can provide interesting power signature module and rotor current can show new harmonics also. The use of current sensor in the rotor side detect the electrical fault very prominently in the system. It is seen from the curves that when fault occurs current is higher than the normal condition and it affects the other two phases where fault not created also. Total power, apparent power, reactive power, power factor is higher than the normal condition in faulty condition.

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