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# FAULT DETECTION OF A THREE PHASE INDUCTION MOTOR

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## ABSTRACT

The use of induction motors in industry is extensive. These motors are exposed to a wide variety of environments and conditions, which age the motor and make it subject to inter-turn faults. One major cause of these faults is breakdown of the turn insulation leading to damage the ground insulation wall. Early detection of inter turn shorts during motor operation would eliminate consequential damage to adjacent coils and the stator core reducing repair costs and motor outage time. This paper deals a modeling simulation and detection of induction motor inter turn short circuit faults. A new detection method for inter-turn short circuit faults in stator windings using sum of stator currents was presented. The simulation and experimental results are reported to demonstrate the effectiveness of the proposed technique.

تستخدم المحركات التأثيرية في الصناعة على نطاق واسع وتتعرض هذه المحركات الى ظروف بيئية مختلفة ، التي تعمل على تقادم المحرك وجعله عرضة لأعطال مختلفة منها كسر العازل وقد يصل إلى قصر الدائرة. الاكتشاف المبكر لعطل كسر العازل خلال فترة تشغيل المحرك يقضى بدوره على الأضرار التى تتزايد مع حدوث مثل هذه الأعطال ويعمل على خفض تكاليف الإصلاح وبالتالي خفض وقت انقطاع تشغيل المحرك. هذا البحث يعرض تمثيل ومحاكاة واكتشاف أعطال كسر العازل وقصر الدائرة بين اللفات والتى يتعرض لها المحرك التأثيرى ثلاثى الأوجه. وقدم طريقة جديدة لاكتشاف هذه الأعطال باستخدام مجموع تيارات العضو الثابت. وتم إجراء النتائج العملية ومحاكاتها بالنتائج النظرية للتدليل على فعالية هذه الطريقة المقترحة.

***Keywords:*** Simulation, inter turn short circuit, fault detection, three phase induction motor.

## 1. INTRODUCTION

Induction motors are electro-mechanical devices utilized in most industrial applications for the conversion of power from electrical to mechanical form. Induction motors are used worldwide as the workhorse in industrial applications. Such motors are robust machines used not only for general purposes, but also in hazardous locations and severe environments. Additionally, induction motors are highly reliable, require low maintenance, and have relatively high efficiency. Moreover, the wide range of power of induction motors, which is from hundreds of watts to megawatts, satisfies the production needs of most industrial processes [1].

A motor failure that is not identified in an initial stage may become catastrophic and the induction motor may suffer severe damage. Thus, undetected motor faults may cascade into motor failure, which in turn may cause production shutdowns. Such shutdowns are costly in terms of lost production time, maintenance costs, and wasted raw materials. The common faults in the stator of an induction motor include: turn-to-turn short-circuit, coil-to coil short-circuit, phase-to-phase short-circuit, phase-to ground short-circuit, open-circuit of stator windings, deficit of insulation, and core laminations short-circuit. The common faults in the rotor of an induction motor include broken rotor bars and broken end-rings [2, 3]. This paper is focused on only one type of electrically detectable induction motor faults, namely: inter-turn short circuits in stator windings.

Inter-turn short circuits in stator windings constitute a category of faults that is most common in induction motors. Typically, short circuits in stator windings occur between turns of one phase, or between turns of two phases, or between turns of all phases. Moreover, short circuits between winding conductors and the stator core also occur [1, 5]. Short circuits between the stator windings can occur only with degradation of the stator insulation. It is known that stator faults account for 30-40 % of motor failures and between half and two-thirds of these are stator failures due to winding short-circuits[4].

## 2. MODELING OF INDUCTION MOTOR UNDER INTER-TURN SHORT CIRCUIT CONDITION

An inter-turn fault denotes an insulation failure between two windings in the same phase of the stator. The Insulation failure is modeled by a resistance, where its value depends on the fault severity [6, 7]. The stator winding of an induction machine with inter-turn fault is represented in Fig.1. In this figure, the fault is occurred in the phase *a* and $r_f$ represents the fault insulation resistance. The sub-windings ($as_1$) and ($as_2$) represent the healthy and faulty part of the winding of phase *a* respectively. When fault resistance ($r_f$) decreases toward zero, the insulation fault evaluates toward an inter-turn full short-circuit. The evolution of fault resistance from infinite to zero is very fast in most insulation materials.

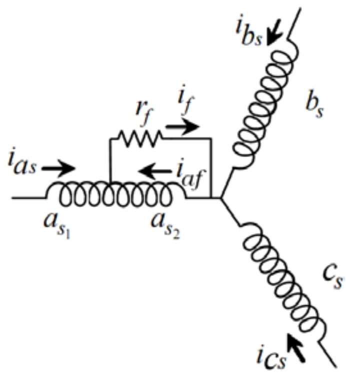


**Fig.1** Stator circuit of induction motor with inter-turn fault in the phase a.

The voltage equations of a three-phase induction machine under inter-turn short circuit condition can be expressed as follow:-

$$\mathbf{V}^s_{abcf} = \mathbf{R}^s_{abcf}\mathbf{i}^s_{abcf} + \mathbf{L}^{ss}_{abcf}\frac{d}{dt}\mathbf{i}^s_{abcf} + \frac{d}{dt}\left(\mathbf{L}^{sr}_{abcf}\,\mathbf{i}^r_{abc}\right)$$

$$\mathbf{V}^r_{abc} = \mathbf{R}^r_{abc}\mathbf{i}^r_{abc} + \mathbf{L}^{rr}_{abc}\frac{d}{dt}\mathbf{i}^r_{abc} + \frac{d}{dt}\left(\mathbf{L}^{rs}_{abcf}\,\mathbf{i}^{rs}_{abcf}\right)$$

Where:

$$\mathbf{V}^s_{abcf} = \begin{bmatrix} v_{as} & v_{bs} & v_{cs} & 0 \end{bmatrix}^T \quad , \quad \mathbf{i}^s_{abcf} = \begin{bmatrix} i_{as} & i_{bs} & i_{cs} & i_f \end{bmatrix}^T$$

$$\mathbf{R}^s_{abcf} = \begin{bmatrix} R_s & 0 & 0 & -R_{as_2} \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ -R_{as_2} & 0 & 0 & (R_{as_2}+r_f) \end{bmatrix}$$

$$\mathbf{L}^{ss}_{abcf} = \begin{bmatrix} L_s & M_{as_1bs}+M_{as_2bs} & M_{as_1cs}+M_{as_2cs} & -(L_{as_2}+M_{as_1as_2}) \\ M_{as_1bs}+M_{as_2bs} & L_s & M_s & -M_{as_2bs} \\ M_{as_1cs}+M_{as_2cs} & M_s & L_s & -M_{as_2cs} \\ -(L_{as_2}+M_{as_1as_2}) & -M_{as_2bs} & -M_{as_2cs} & L_{as_2} \end{bmatrix}$$

$$\mathbf{R}^r_{abc} = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \qquad \mathbf{L}^{rr}_{abc} = \begin{bmatrix} L_r & M_r & M_r \\ M_r & L_r & M_r \\ M_r & M_r & L_r \end{bmatrix}$$

$$\mathbf{L}^{sr}_{abcf} = \begin{bmatrix} M_{sr}\cos(\theta) & M_{sr}\cos(\theta+2\pi/3) & M_{sr}\cos(\theta-2\pi/3) \\ M_{sr}\cos(\theta-2\pi/3) & M_{sr}\cos(\theta) & M_{sr}\cos(\theta+2\pi/3) \\ M_{sr}\cos(\theta+2\pi/3) & M_{sr}\cos(\theta-2\pi/3) & M_{sr}\cos(\theta) \\ -M_{sr_2}\cos(\theta+\gamma) & -M_{sr_2}\cos(\theta+\gamma+2\pi/3) & -M_{sr_2}\cos(\theta+\gamma-2\pi/3) \end{bmatrix}$$

$$M_{as_1bs} = M_{as_1cs} = M_{bsas_1} = M_{csas_1} = \frac{N_s^2}{R_m}(1-k_f)\cos\varphi_s = \frac{N_s^2}{R_m}(1-k_f)\cos\frac{2\pi}{3} = -\frac{1}{2}M_s(1-k_f)$$

$$M_{as_1as_2} = M_{as_2as_1} = \frac{N_s^2}{R_m}k_f(1-k_f)\cos(\gamma) = M_s k_f(1-k_f)\cos(\gamma)$$

$$M_{as_2bs} = M_{bsas_2} = \frac{N_s^2}{R_m}k_f\cos(\gamma-120^\circ) = M_s k_f\cos(\gamma-\frac{2\pi}{3})$$

$$M_{as_2cs} = M_{csas_2} = \frac{N_s^2}{R_m}k_f\cos(\gamma-240^\circ) = M_s k_f\cos(\gamma+\frac{2\pi}{3})$$

$$R_{as_2} = \left(1-k_f\right)R_s \quad , \quad L_{as_2} = \left(1-k_f\right)^2 L_s$$

$R_s$, $L_s$ and $M_s$ are the stator phase resistance, self and mutual inductances of the healthy machine and $M_{sr}$ is the mutual inductance between stator and rotor phases. $R_{a2}$ and $L_{a2}$ are the resistance and the self-inductance of the faulty winding $as_2$. $M_{as1b}$ and $M_{as1c}$ are mutual inductances between $as_1$ and the windings *bs* and *cs*. In addition, $M_{as1as2}$, $M_{as2b}$ and $M_{as2c}$ are respectively the mutual inductances between $as_2$ and the windings $as_1$, *bs* and *cs* and also $M_{sr}$, $M_{sr2}$ are the mutual inductances between $as_1$, $as_2$ and rotor. $\gamma$ is the angle of faulty winding $as_2$ after occurring inter- turn fault and its value depends on the location and faulty turns concerned in the fault. $k_f$ is the fault ratio and it equals to the number of faulted turns divided by the total stator phase turns.

The expression of electromagnetic torque for the induction motor with inter-turn fault can be written as follows:-

$$T_e = \left[i^s_{abcf}\right]^T \frac{\partial L_{sr}}{\partial \theta}\left[i^r_{abc}\right]$$

$$T_e - T_l = J\frac{d\omega_m}{dt}$$

Where J is the moment inertia, $T_l$ is the load torque and $w_m$ is the mechanical angular speed.

## 3. SIMULATION RESULTS

The previous simulation of the model achieved by m-file under MATLAB toolbox. The short circuit assumes to be solidly shorted ($r_f=0$) of turn-turn fault at phase A to the ground. The figures from 2 to 4 show the model results for stator and faulty phase currents (in RMS values) against the supply voltage at 25%, 50% and 75% fault percentage of phase winding respectively.

## 4. EXPERIMENTAL WORK

Experimental work is implemented to verify and validate the model results represent the motor under healthy and faulty conditions. The schematic diagram of the experimental connection is shown in Fig.5.

The experimental work has to be done at low values of voltage, to avoid the break down of stator winding insulation due to high current passing during the actual faults occurrence. The motor in the experimental work is a three phase motor, 4-poles, Each phase consist of four series coils with taps to a connection board that short turns per any phase can be applied. The results in this section are taken by using HIOKI 9624 PQA power quality analyzer. This set can capture ten cycles every one press in its START button. These ten cycles can be stored as a numerical data in HIOKI 9624 PQA flash compact disk and travel to pc easily.

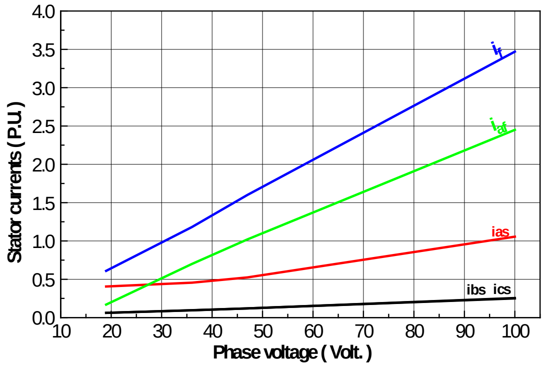


**Fig.2** Stator currents against voltage at 25% fault ratio in phase A

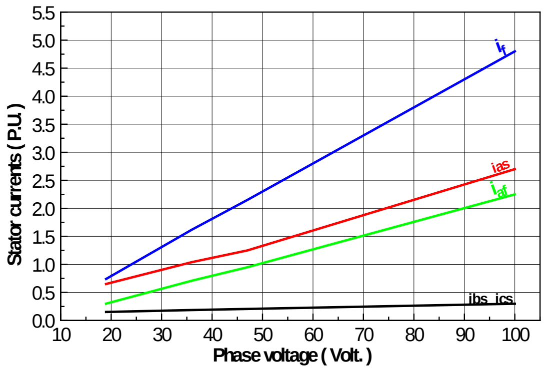


**Fig.3** Stator currents against voltage at 50% fault ratio in phase A

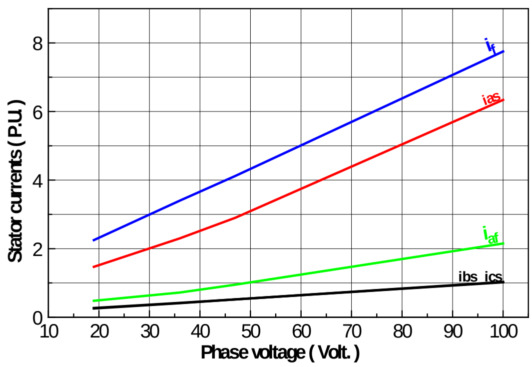


**Fig.4** Stator currents against voltage at 75% fault ratio in phase A

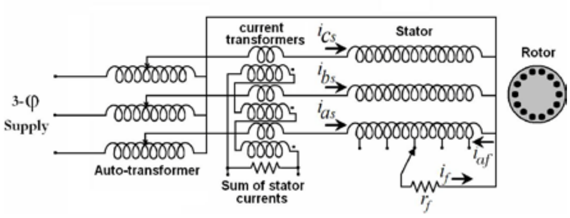


**Fig.5** Schematic diagram of the experimental connections

## 5. EXPERIMENTAL RESULTS

Figures from 6 to 8 show the experimental results for stator and faulty phase currents (in RMS values) against the supply voltage at 25%, 50% and 75% fault percentage of phase winding respectively. As shown in figures the faulty phase current $i_{as}$ is so sensitive with the fault ratio. While the two healthy phases currents are slightly affected with the fault ratio.

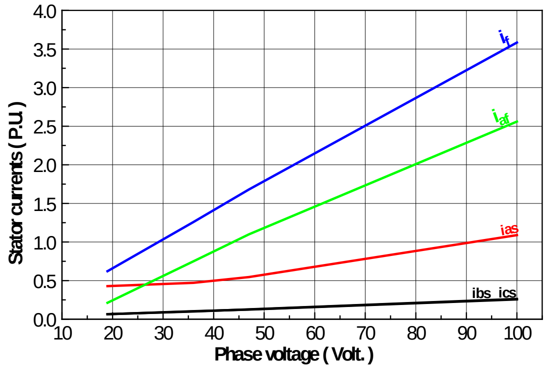


**Fig.6** Stator currents against voltage at 25% fault ratio in phase A

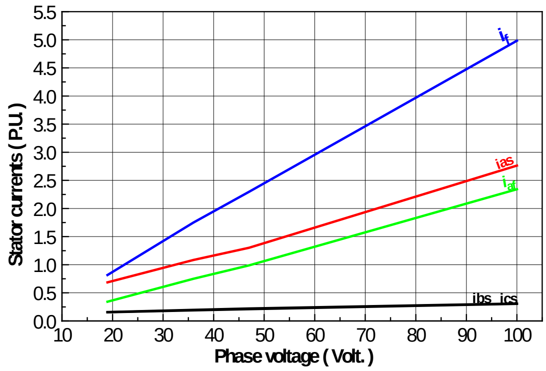


**Fig.7** Stator currents against voltage at 50% fault ratio in phase A

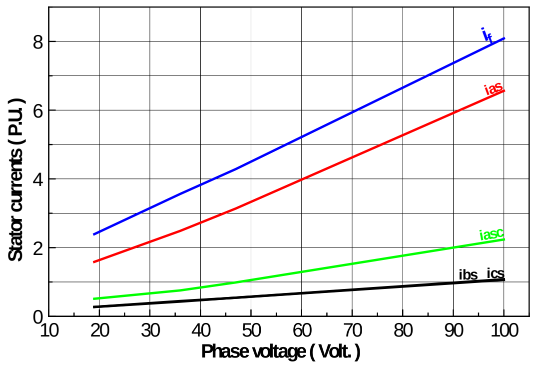


**Fig.8** Stator currents against voltage at 75% fault ratio in phase A.

## 6. MODEL VERIFICATION

It is very important to verify the mathematical model results with the experimental work results to check that the model represents the motor behavior under turn-turn fault efficiently. Figures from 9 to 20 show the comparison between measured and computed currents at different values of stator voltage. It is clear that, the model results are agreed with the actual experimental work results and the model is applicable to be used for turn-turn fault detection.

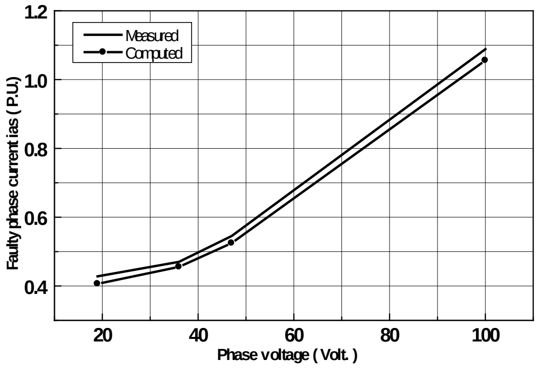


**Fig.9** Measured and computed faulty phase current against phase voltage at 25% fault ratio.

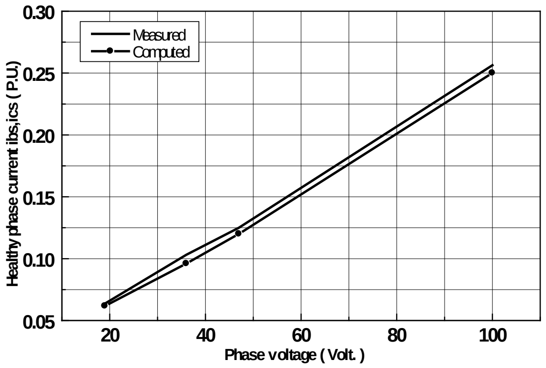


**Fig.10** Measured and computed healthy phase currents against phase voltage at 25% fault ratio.

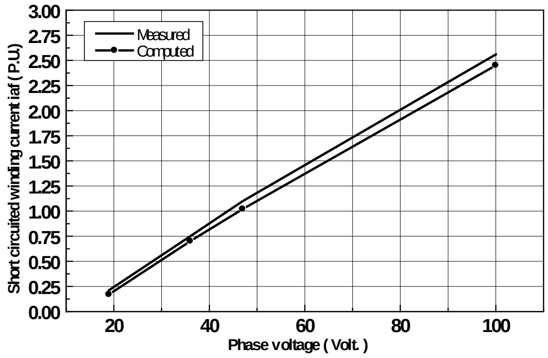


**Fig.11** Measured and computed short circuited winding current against phase voltage at 25% fault ratio.

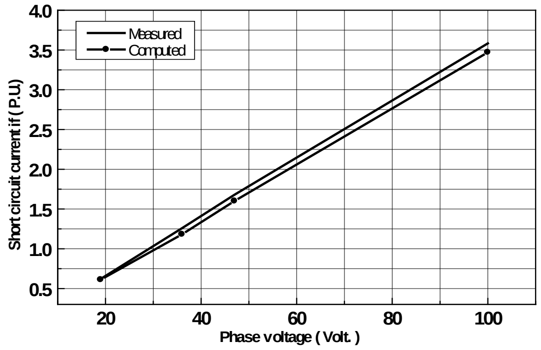


**Fig.12** Measured and computed short circuit current against phase voltage at 25% fault ratio.

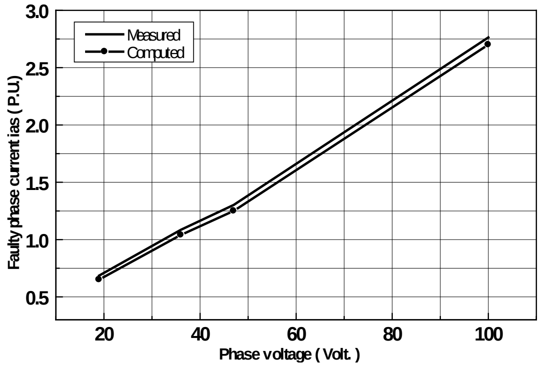


**Fig.13** Measured and computed faulty phase current against phase voltage at 50% fault ratio.

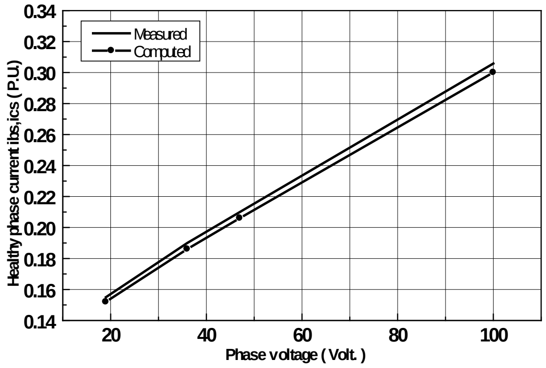


**Fig.14** Measured and computed healthy phase currents against phase voltage at 50% fault ratio.

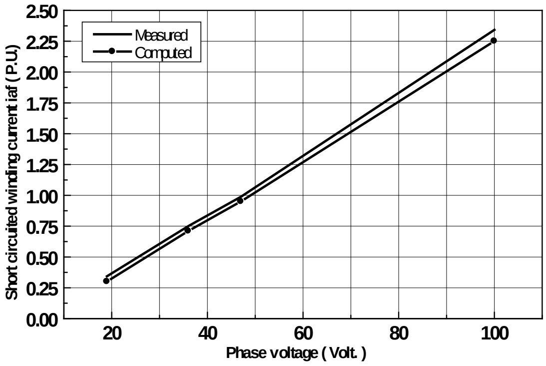


**Fig.15** Measured and computed short circuited winding current against phase voltage at 50% fault ratio**.**

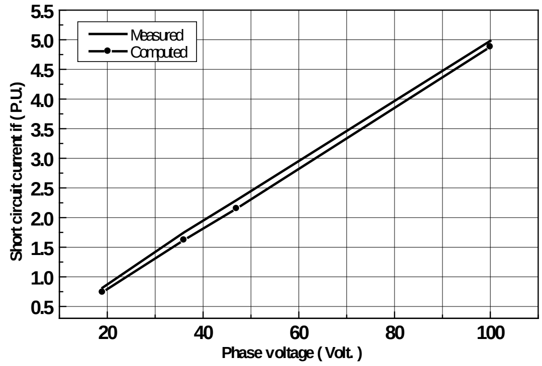


**Fig.16** Measured and computed short circuit current against phase voltage at 50% fault ratio**.**

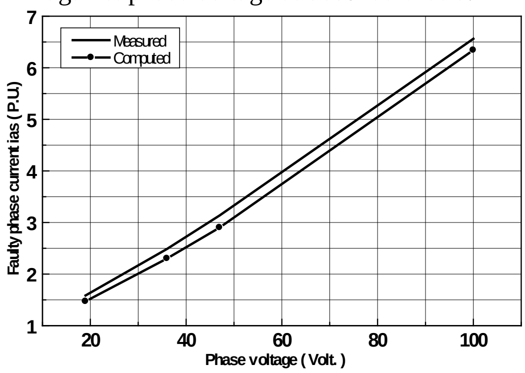


**Fig.17** Measured and computed faulty phase current against phase voltage at 75% fault ratio.

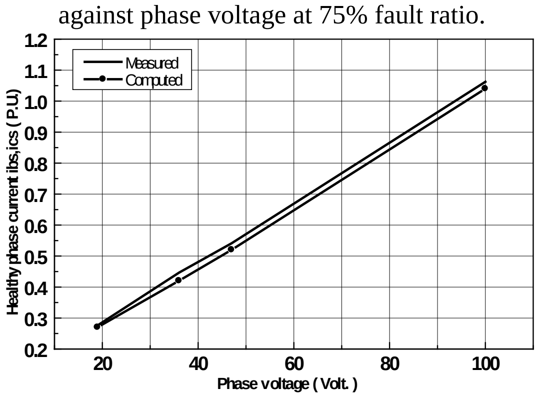


**Fig.18** Measured and computed healthy phase currents against phase voltage at 75% fault ratio.

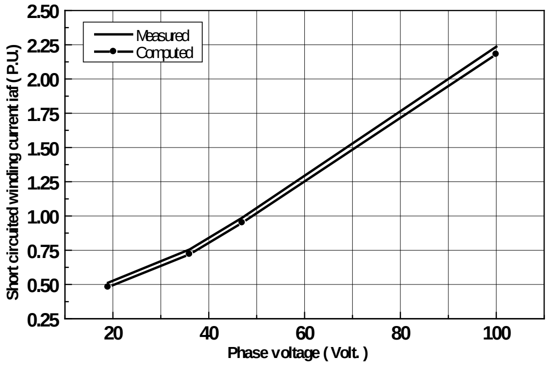


**Fig.19** Measured and computed short circuited winding current against phase voltage at 75% fault ratio**.**

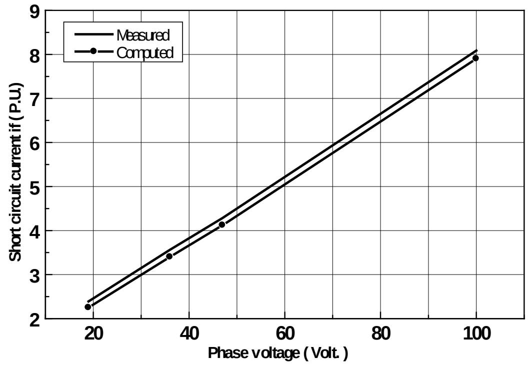


**Fig.20** Measured and computed short circuit current against phase voltage at 75% fault ratio**.**

## 7. THE PROPOSED DETECTION METHOD BASED ON SUM OF STATOR CURRENTS

As shown in Schematic diagram of the experimental connections **(**Fig.5**)**, the faulty phase current and sum of stator currents are the only signal that can measure compared with short circuit current and short circuited windings current. But the faulty phase current varies with the load torque and sum of stator currents depends only on the difference between the three phase stator currents. This makes the usage of sum of stator currents as a feature is a very successful detection method.

The experimental work results were used to confirm the efficiency of using sum of stator currents as a feature to detect the fault. The schematic diagram of the experimental connection used for the proposed detection method based on sum of stator currents is shown in Fig.5. Signal of the sum of stator currents can measured by using three typical current transformers connected as shown in Fig. 5. Figure 21 shows the measured Sum of stator currents against supply voltage at 25%, 50%, 75% fault ratio. In order to confirm the efficiency of using sum of stator currents as a feature to detect the fault, the verification between the experimental work results and the simulation results has been done. Figures from 22 to 25 show the measured and computed Sum of stator currents against fault ratio at supply voltage=19, 36, 47,100 volt respectively.

The results showed that, the theoretical results are closely to the experimental results. This method can be successfully used as a fault detection method.

Figure 26 shows the sum of stator currents at different values of load torque at rated voltage.

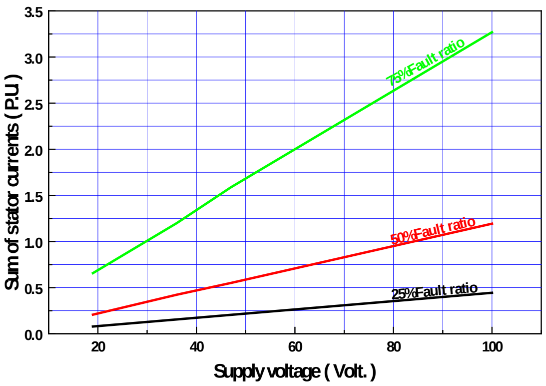


**Fig.21** Sum of stator currents against supply voltage at 25%, 50%, 75% fault ratio

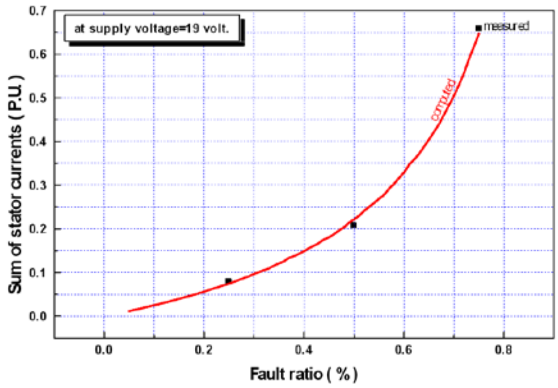


**Fig.22** Sum of stator currents against fault ratio at supply voltage=19 volt.

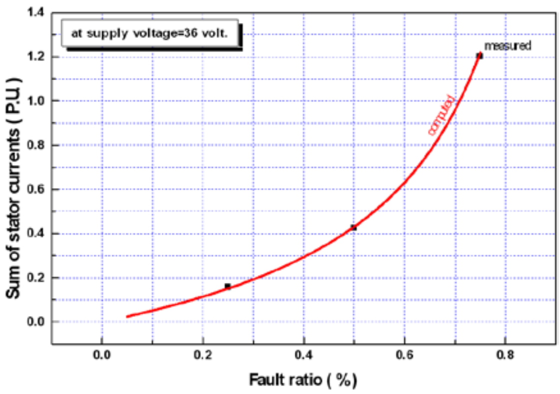


**Fig.23** Sum of stator currents against fault ratio at supply voltage=36 volt.

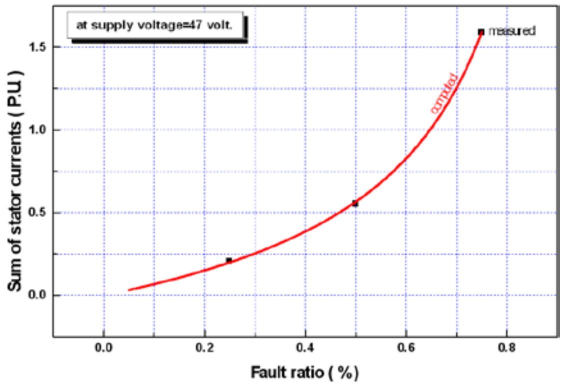


**Fig.24** Sum of stator currents against fault ratio at supply voltage=47 volt.

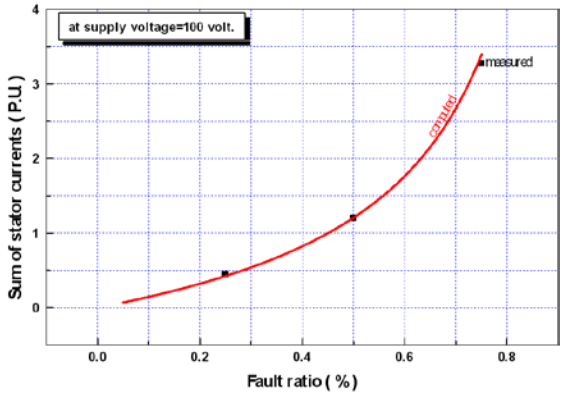


**Fig.25** Sum of stator currents against fault ratio at supply voltage=100 volt.

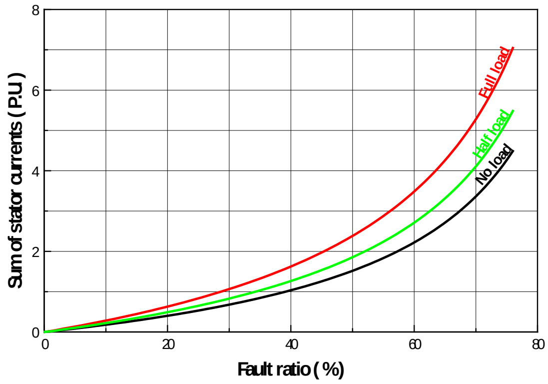


**Fig.26** Sum of stator currents at different values of load torque at rated voltage.

## 8. CONCLUSIONS

Fault detection for squirrel cage induction motors is the main concern of this paper, which is an essential tool for the predictive maintenances programs. Predictive maintenance becomes the new trend in the industrial maintenances schedules. A proposed model for the induction motor under turn-to-turn fault in the stator windings is developed. Experimental results are occurred on the proposed motor to give the actual and real values of the motor characteristics under turn-to-turn fault. In order to verify the proposed analysis a comparison between the theoretical and experimental results has been obtained. The theoretical results are closely to the experimental results for turn-to-turn fault.

The proposed fault detection method is based on the summation of stator currents. This method can be successfully used as a fault detection method.

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