Identification of Stator Winding Faults and Remedial Operation of Permanent Magnet Synchronous Motors with Suppress Noise and Ripple

Hamdy Mohamed Soliman, S. M. EL. Hakim

Abstract*—The reliability of the drive system is very important in critical systems. The faults in these systems are unwanted and the drive system must be operated under the fault conditions. If fault occurs this may be lead to loss of the human life and capital so the detection of this fault, separation the faulty part and method invention for remedial operation is very important. In this paper the performance of a permanent magnet synchronous motor drive under a stator winding fault is studied and a negative sequence is used to detect the different types of the faults in that winding. This paper is suggested two models for solving these faults. The control in these models depends upon the controlling in each phase separately. The first model doesn't contain any special tools to improve the torque ripple and THD. The second model contains 2PI current controllers to improvement the performance at fault and remedial operation. One is for the torque and the other is for the flux. The first PI controller is feeding from the torque error between the reference and estimated torques to get new q-axis current component representing modifier current arises from uncertain things inside the machine and drive system. This current will add to reference q-axis current to get robust new q-axis current to satisfy the drive requirement and solve the torque problem (ripple torque). With robust current, the total harmonic distortion is a decrease but doesn't reach the best value so the other PI controller is used to adjust the THD. In this PI controller, the d-axis flux is compared to rotor permanent magnet flux to solve this problem arises from non-sinusoidal of the magnetic flux. The output of the PI controller is introduced to the reference d-axis current. The new d-axis current will reach the best value of THD. The simulation of the second controller is compared to the simulation of first controller to show if the adding the 2 PI current controllers is profit or not. Here the matlab simulink is used to simulate the drive system.

***Index Terms*— fault detection, PI controller, remedial Operation, stator winding fault, Torque ripple.**

I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are excellent choices in many industrial applications for many reasons as: low cost, high efficiency, high power density and high-torque/inertia ratio. In the drive system the method of motor control is very important due to the motor under classical control is suffered from complicated coupling and nonlinear dynamic performance. This problem doesn't arise in separately excited DC motor due to decuple in flux and torque current components. With field oriented control (FOC), the PMSM emulates the separately excited DC motor. FOC is highly performance with healthy phases but when fault occurs, the control loop will influence the behavior of the variable speed drive during the fault. The fault in the drive system leads to fall the performance or damage part or totally drive system. The stator winding faults are the major fault of PMSM. Large portion of the stator windings comes from insulation failure. The insulation failure arises due to cyclic, over load and transient voltage stress. Here the faults studying are open phase, turn to turn fault and one phase short circuit. These faults can be detected by using the negative sequence current so it is necessary to monitor the phase currents. The phase currents give information about winding open circuit or windings partly or totally shorted. open circuit fault, it is a common fault of the motor, this fault can be detect by measuring the current, phase motor voltage and phase voltage of inverter. In this fault the current and that motor phase voltage is zero but phase voltage of inverter is exists. The short circuit in the stator windings often starts due to insulation failure between turns i.e. turn to turn fault, this faults must be detected this is because this fault continued causing deteriorate in the performance of the drive system and leads to loss of phase windings. The turn to turn fault causes circulating current in shorted windings, excessive heating, increasing the losses, negative torque and reducing the efficiency. The short circuit current is directly proportional to motor speed so this fault is very dangerous at high speed.

As soon as a fault is recognized the faulted phase is turned off and the operation mode of the drive is changed to two-phase operation. In critical systems such as transportation, aerospace, medical, military and nuclear power plants, the reliability of the drive is very important. It represents the primary selection in the pervious industrial applications. To improve it, the fault is detected, isolated and reconfiguration of control system is applied to verify the drive requirements. The critical systems must be continued to operate even in presence fault. A number of studies have been reported in the literature investigating fault-tolerant motor drives. Brushless permanent magnet (PM) motor drives can have the capability of fault tolerance by minimizing the electrical, magnetic and thermal interaction between phases and adopting H-bridge inverter circuits for each phase [1]-[3]. A dual fault-tolerant motor drive system has been proposed in [4]. The fault tolerant power electronic circuit topology to improve the reliability of the motors is studied in [5].

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Reference [6] advices to separate the phases. Mechanical separation, realized by having one slot per winding, prevents from having inter-phase short circuit. Electrical separation allows controlling phases independently, which is possible with a full bridge since phases are electrically separated. In references [7]-[8] some compensation techniques for open-circuited fault were proposed to improve the fault-tolerant performance of multiphase rotor-PM brushless motor drives. Reliability can be improved by special motor designs [9]-[10] or by means of remedial operation strategies [11]-[12]. This paper is proposed the remedial strategy of the PMSM in fault case. This occurs through two models, model one is used to remedial operation only but this model suffered from some ripples and noise. These noise and ripples are acceptable but the motor under fault doesn't reach the highest value. In model two 2PI current controllers are add to approximately vanish these problems. Here the second model is compared to first model to show the advantage of the second model. To solve the fault problem, the monitoring and fault detection of the all drive system is vital. This occurs by monitoring the phase currents i.e. an appropriate model is compared to the measured current to detect the abnormal operation. So the first step is detected the fault, second step is isolated the faulty part and a third step is designing the reconfigurable inverter control. This paper is organized as follows. Section I introduction. Section II Mathematical models of PMSM are discussed. Section III H-bridge is for reliability and current controller method is shown. Section IV shows the control structure. The simulation results are discussed in V. The conclusion is in VI.

II. MATHEMATICAL MODEL OF PMSM

The d-q equivalent circuit model is a perfect solution to analyze the multiphase machine because its simplicity and intuition. Conventionally, a two phase equivalent circuit model instead of complex three phase model has been used to analyze PMSM but now complex three phase model has been used to analyze PMSM. This is because this model must be able to deal with several types of fault such as:

a) Winding open-circuit.

b) Winding short circuit (partial or totally windings).

A. General Model of PMSM at Healthy and Faulty Case

The voltage equations PMSM can be simplified as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = r_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (1)$$

Where $\left[v_a v_b v_c\right]^T$ is stator a voltage, $\left[i_a i_b i_c\right]^T$ is a stator current and $\left[e_a e_b e_c\right]^T$ is a back-EMF

r_s = diagonal $\left[r_s \ \ r_s \ r_s\right]^T$ and $L = \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix}$

Where r_s is a stator resistance, L_s is a self inductance and M is mutual inductance between winding.

The ideal back-EMF waveforms for sinusoidal PM motor can be expressed as:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = -E_m \begin{pmatrix} \sin(\theta_e) \\ \sin(\theta_e - 120) \\ \sin(\theta_e - 240) \end{pmatrix} \qquad (2)$$

The peak value of induced voltage E_m is proportional to the mechanical angular speed and can be calculated as

$$E_m = K_t \omega_m$$
$$K_t = P\varphi_M \qquad (3)$$

The electromagnetic torque can be expressed as:

$$T_e = -K_t(i_a \sin(\theta_e) + i_b \sin(\theta_e - 120)$$
$$+ i_c \sin(\theta_e - 240)) \qquad (4)$$

Due to mechanical system, the dynamic model of rotor drive system can be given as

$$T_e = T_L + \beta\omega_r + \frac{J}{P}\frac{d\omega_r}{dt} \qquad (5)$$

This model is able to the lateral faults but when study the turn to turn fault this model must be had simple modified to deal with this fault. This can be discussed in the following section

B. Mathematical Model of PMSM under Turn to Turn Fault

A stator turn to turn fault occurs on one phase or between phases. Here turn to turn on one phase is studied due to each phase feeds from separate H-bridge. This fault can be represented as a transformer. The secondary winding is a shorted turns while the primary winding is an all winding of that phase. Fig.1 represented the faulty phase (transformer model), the short circuit current in the faulty part is very large and depends upon the number of short circuit turns. This current if it is continued would reshaped highly dangerous in that phase so this fault must be detected and isolate that part from the drive system.

Assume that the windings of phase (a) are spelt into healthy turns which has voltage (v_{ah}) and faulty turns which has voltage v_{af} . Assume that, δ_{scf} is fault percent

$$\delta_{scf} = \frac{N_{scf}}{N} \qquad (6)$$

Where N_{scf} is the number of shorted turn and N is the total number of turns in phase (a)

With turn to turn fault the new voltage equations PMSM can be simplified as follows:

$$\begin{bmatrix} v_{ah} \\ v_{af} \\ v_b \\ v_c \end{bmatrix} = r_{sf} \begin{bmatrix} i_{ah} \\ i_{scf} \\ i_b \\ i_c \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_{ah} \\ i_{scf} \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} (1-\delta_{scf}) e_a \\ \delta_{scf} e_a \\ e_b \\ e_c \end{bmatrix} \quad (7)$$

Where r_{sf} is diagonal

$$\left[(1-\delta_{scf}) r_s \quad \delta_{scf} r_s \quad r_s \quad r_s \right]^T$$

L_f is

$$\begin{bmatrix} (1-\delta_{scf})^2 L_s & \delta_{scf}(1-\delta_{scf}) M & (1-\delta_{scf}) M & (1-\delta_{scf}) M \\ \delta_{scf}(1-\delta_{scf}) M & \delta_{scf}^2 L_s & \delta_{scf} M & \delta_{scf} M \\ (1-\delta_{scf}) M & \delta_{scf} M & L_s & M \\ (1-\delta_{scf}) M & \delta_{scf} M & M & L_s \end{bmatrix}$$

The electromagnetic torque at turn to turn fault can be expressed as:

$$T_e = -K_t((1-\delta_{scf}) i_{ah} \sin(\theta_e) + \delta_{scf} i_{scf} \sin(\theta_e) + i_b \sin(\theta_e - 120) + i_c \sin(\theta_e - 240)) \quad (8)$$

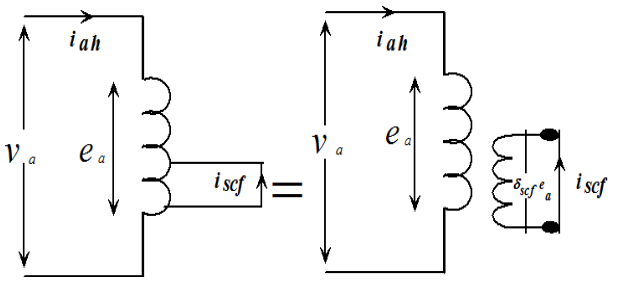

Fig.1 Represented the turn to turn fault

III. H-BRIDGE AND CURRENT CONTROL

An H-bridge inverter circuit is an electronic power circuit that allows motor speed and direction to be controlled. It is used to driving each motor winding separately so a failure in one winding will not affect the operation of the remaining windings. Each H-bridge consists of four power switches (with anti-parallel diodes). Fig. 2 shows the PMSM when fed from separate phases, each phase being fed by an H bridge. During the fault, the faulty H-bridge is isolated and the control can be configuration and the other H-bridges can be modified by gating signals. The disadvantages of these H-bridges are multiple switches.

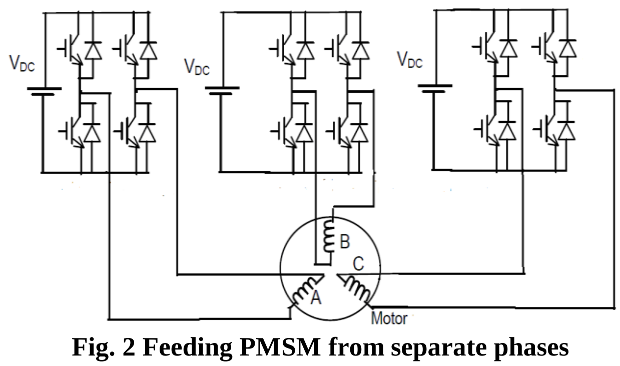

Fig. 2 Feeding PMSM from separate phases

In this work, the current control of converter is a hysteresis current controller. It is used due to simple, fast dynamic response and insensitive to load parameters. In this method each phase consists of comparator and hysteresis band. The switching signals are generated due to error in the current. The main task of this method of control is to force the input current to follow the reference current in each phase. The deviation of the current between the upper and lower in the hysteresis band is limited. The deviation of these currents (error current) represents the current distortion which can be calculated as

$$\text{distortion} = \frac{100}{I_{rms}} \sqrt{\frac{1}{T} \int (i_{act} - i_{ref})^2 dt} \ \% \quad (9)$$

In any phase, if the actual current becomes more than the upper limit of hysteresis band, the upper switch of the inverter arm is turned off, the lower switch is turned on and the current starts to decay. In contrast if the actual current reaches lower limit or less than of hysteresis band, the lower switch of the inverter arm is turned off, the upper switch is turned on and the current comes back into the hysteresis band. The band width calculates the switching frequency and current ripple. The band width is directly proportional to current ripple and inversely proportional to switching frequency so the selection of the band width means performance of inverter.

IV. THE CONTROL STRUCTURE

Here two proposals control are used for remedial operation of PMSM. The first control is shown in Fig. 3. where the second control is in Fig.4.

In the first control, the maximum torque can be performed by equating the q-axis current with the stator current so the regulation of this current is very important to get the desired torque. This can be done through the drive scheme. The drive is influenced by uncertainties, electromagnetic interface, non-sinusoidal of stator current and permanent magnet rotor flux or all of them. They reflect on the torque and current causing unwanted problems such as ripple and noise. So the PI speed controller which is used to generate the q-axis current isn't sufficient to overcome the noise and ripples in torque and current. To minimize the ripple, noise and harmonics in the torque another PI controllers are used; the input of the new PI controller is the error in the torque. This error comes from the output of comparator which comparing the reference torque to estimated torque. The output of the new PI controller is a new q-axis current (i_{qMOD}) which represents the torque problems. This current is adding to the reference of q-axes current to get robust current (i_{qNew}). The robust current satisfies requirements of the drive system. With this enhanced in the q-axis current component, the distortion of the current doesn't reach the best value. To reach the best value another PI controller is used. The input of this PI controller arises from comparing the estimated d-axis flux with permanent magnet flux. The output of this PI controller is added to the reference d-axis current which is forced to zero at constant flux region. The new d-axis current is reduced. So the first control (FOC) with adding 2PI current controllers (one for the torque and the other for the flux) is a good performance at healthy phases but when fault occurs the performance is deteriorate significantly unless proper remedial strategies are undertaken.

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So this controller is modified to verify highest performance in fault case. In the proposed control, the motor can be controlled phase by phase. This control is isolated the fault phase and reconfiguration the stator currents depending upon the fault case which is compared to the reference currents to apply new voltages on the healthy phases. This makes the motor with fault is able to drive the drive system without any problem. With fault, the sum of the phases current isn't equal to zero. This controller can be done by adding two blocks. One changes the stator current in the stationery reference frame (A,B,C) to rotor reference frame (d,q) and the other consists in building for each phase of motor into α phase. Each phase can be built as;

$$i_{\alpha i} = i_d \cos(\theta_e - 2\pi(j-1)/3) - i_q \sin(\theta_e - 2\pi(j-1)/3) \quad (10)$$

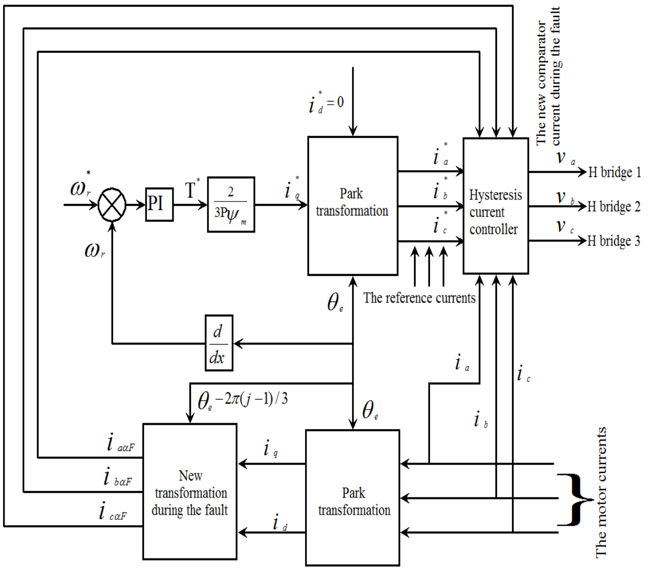

Fig.3. Remedial operation of PMSM at fault (first model)

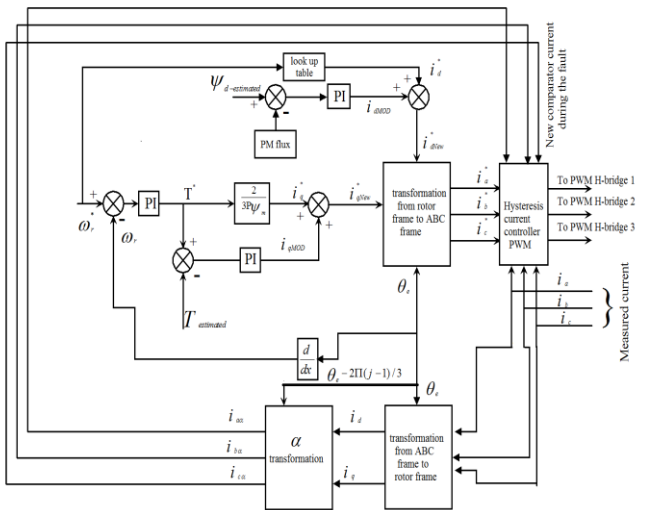

Fig.4. Remedial operation of PMSM at fault (second model)

V. SIMULATION RESULTES

Here the fault is occurred in phase (a) and the following faults are study

1. One phase open circuit
2. One phase short circuit
3. Turn to turn short circuit.

In all simulation cases, the motor start without fault, at 0.1 sec, the fault occurs without remedial strategies, at 0.15 sec, the faulty phases is isolated and at 0.2 sec, the remedial strategies are applied. This occurs to show the effect of remedial strategies on the performance of the motor during the fault. With remedial strategies the torque ripple and THD become improvement if it is compared to the fault case before applying it but when compared to the healthy case, it is found that, the torque ripple and THD must be get rid to reach the highest performance during the fault case. So they must be approximately vanish. This occurs through using 2PI controller one for the torque and the other for the flux. The proposal model is to verify the remedial strategies (model one) is acceptable but when adding the 2PI current controller the performance became highest (model two). Here the model two is compared to the model one to show the effectiveness of model two in the drive performance with fault case. The measured value of the torque ripple and THD at healthy phases, at faulty phases and remedial strategies in two models are shown in tables I, II, III and motor parameters in appendix I

A. One Phase Open Circuit

Motor phase open circuit, it is a common fault. This fault can be simulated by putting the current in that phase (faulty phase) is zero. The open phase fault is studied to show the effectiveness of this fault on the drive performance. The remedial operation phase by phase control (model one) through (10) is proposed. This model is acceptable but suffers from noise, ripple and THD. The model two is built to vanish these problems through adding two PI controllers one for the torque and the other for the flux. The fault can be detected through measure the negative sequence current. This is shown in Figs (5-6) where Fig. (5) shows the negative sequence current for model one while Fig. (6) shows the negative sequence current for model two. At healthy mode and at remedial strategy no negative sequence current measured but at fault mode the negative sequence current is detect in the two models. From these Figs it is found that, the negative sequence current with model one is higher than one with model two

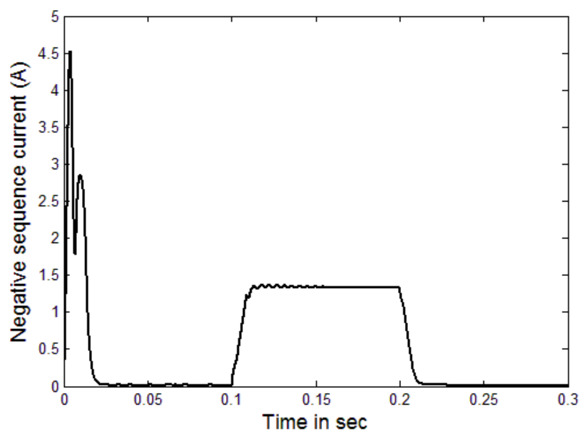

Fig. 5 detecting negative sequence current with model one

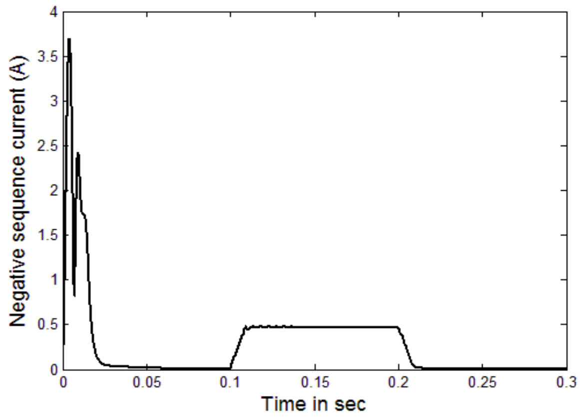

Fig. 6 detecting negative sequence current with model two

Figs (7-8) show the effect of one phase open circuit (phase a) in the two models on the dq-axes currents. From Fig. 7 it is found that, higher ripple when fault occurs (0.1 sec.) and these ripples are approximately decayed when applying the remedial strategy. In Fig. 8 it is found that the ripples decrease at fault if it is compared to the same ripples for Fig. 8 but these ripples are approximately vanish when remedial operation is applied with model two.

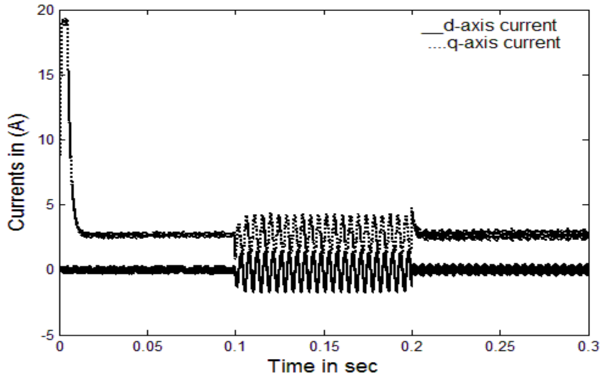

Fig. 7 Idq -axis current with model one

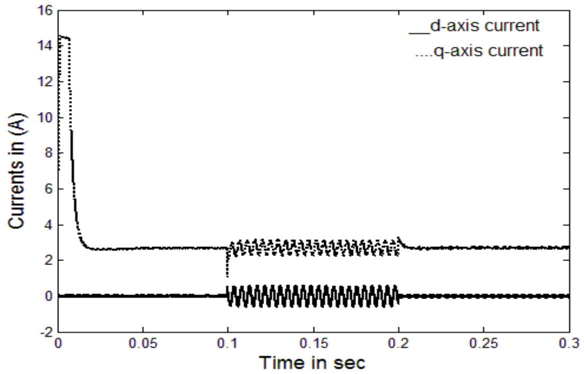

Fig. 8 Idq -axis current with model two

Figs (9-10) show the motor torque under fault where it is evident that, when phase (a) is open, the ripples torque increases and this is harmful for motor. It arises due to an increase in harmonics, noise and electromagnet interface. In first model, the ripple torque increases as shown in Fig.9 this ripple is decreasing with second model as shown in Fig.10. With applying the remedial strategies the oscillation is decaying but doesn't reach the best value with model one but in second model the oscillation is approximately vanish.

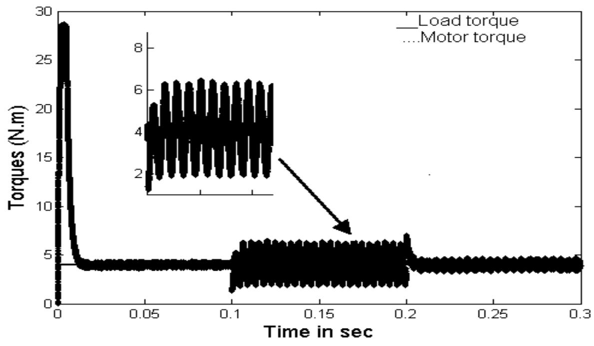

Fig. 9 Torque with model one

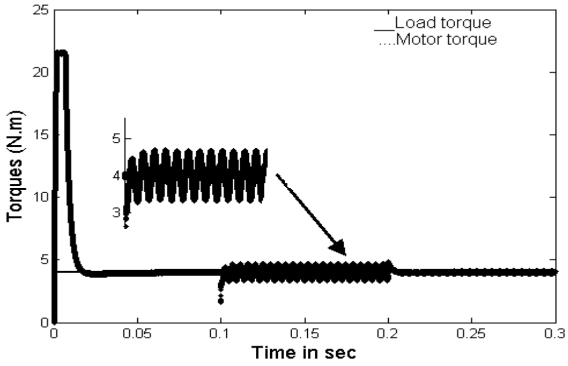

Fig. 10 Torque with model two

The speed is suffered from noise as the secondary problem of torque ripples. Fig. 11 shows some noise in the speed with model one these noise is vanish with model two (Fig. 12) this is because the torque ripple reaches the best value with modified methods.

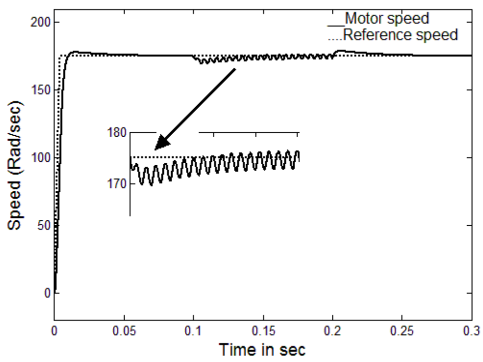

Fig. 11 Speed with model one

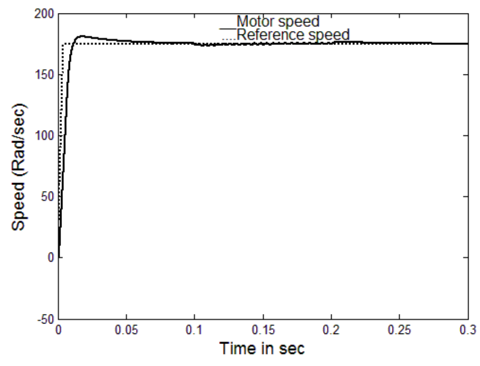

Fig. 12 Speed with model two

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The stator currents become smoother with second model due to reduction of the noise and suppress the harmonics (Fig.14) if it is compared to model one (Fig.13) also the stator current with second model is less. At remedial strategies the higher current in the remaining phases aren't quite dangerous add to that the windings don't affect by this rise in the current due to the motor with remedial strategies doesn't saturate.

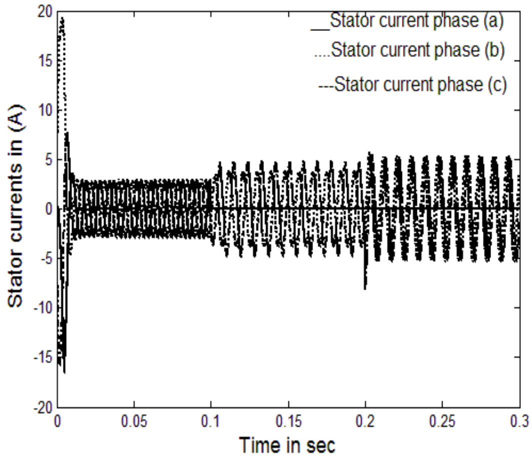

Fig. 13 Stator current with model one

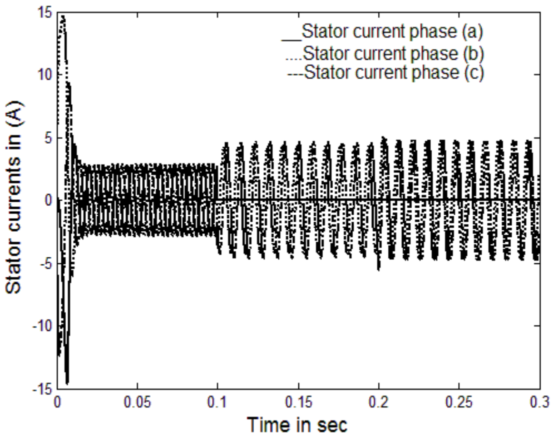

Fig. 14 Stator current with model two

B. One Phase Short Circuit

Stator windings short circuit, it is a most critical fault so when it detected must be quickly isolated this is because it causes serious problems such as: damage the winding, semiconductor device of the drive system may be damage, increase the torque ripples due to negative sequence torque and decrease the efficiency. The short circuit current depends up on the rotor permanent magnet and the motor speed at instant of short circuit as in (11) so the short circuit windings are to dangerous at high speed.

$$I_{sc} = \frac{E_m}{\sqrt{r_s^2 + p\omega_m L_s}} \qquad (11)$$

This fault can be simulated by putting the phase voltage at motor terminal of fault phase is zero. Here the effect of this fault on the drive performance is studied and the effect of remedial operation phase by phase control of two models is discussed. The fault can be detected by monitoring the current, the monitoring of the current at healthy operation, at fault, at isolated the fault and at remedial operation is shown in Figs (15-16) for two models. The fault can be detected by measuring the negative sequence current where it is found that, at healthy and remedial operations, the monitoring current doesn't record any negative sequence current but at fault and at isolated the faulty part, the negative sequence current is recorded. Here the monitoring of the current is adjustable to isolate the faulty part depends upon the magnitude of negative sequence current i.e. when negative sequence is high, the time isolation of faulty part is very small.

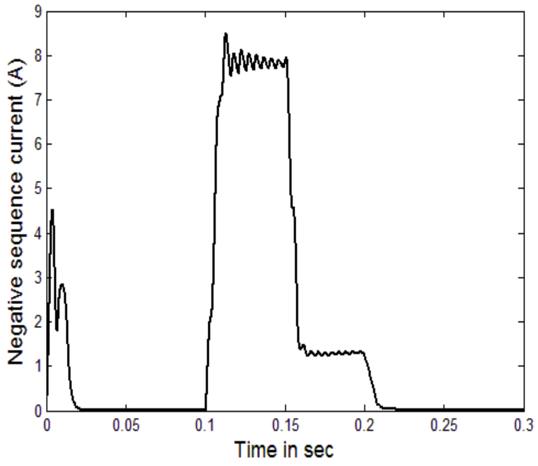

Fig. 15 detecting negative sequence current with model one

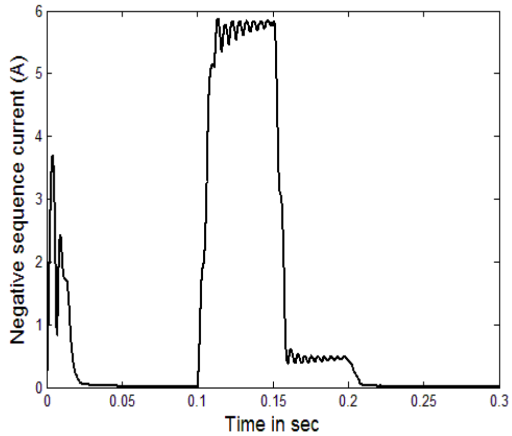

Fig. 16 detecting negative sequence current with model two

Figs (17-18) show the effect of one phase short circuit (phase a) in the two models on the dq-axes currents. Higher ripple and noise are occurred at fault (0.1 sec.) these ripples and noise are decreased when the faulty part is isolated and these ripples are approximately decayed when applying the remedial strategy. In model two, (Fig. 18) the ripples and noise are decreased at fault, at isolated the faulty part and at remedial operation if it is compared to the same cases for model one (Fig. 17) this means that the model two is very strong if it is compared to model one from side of suppers noise and ripples.

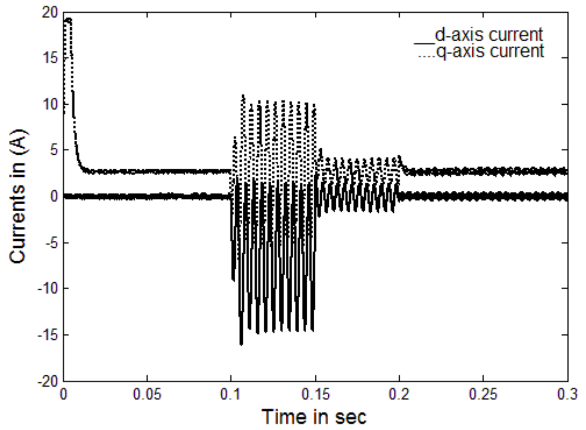

Fig. 17 Idq -axis current with model one

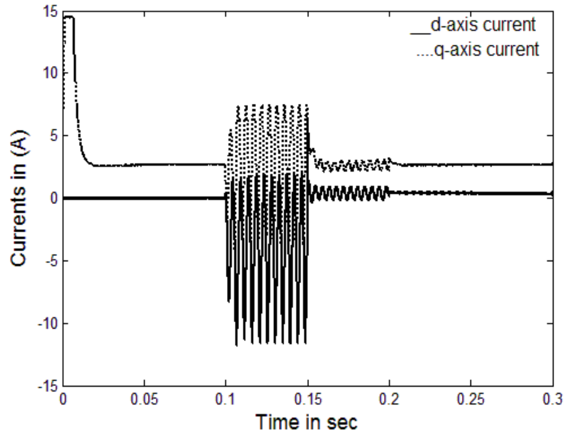

Fig. 18 Idq -axis current with model two

The motor torque under fault is shown in Figs (19-20) where it is evident that, in the first model, the ripple torque increases as shown in Fig.19 due to an increase in harmonics, noise and electromagnet interface this ripple is decreasing with second model as shown in Fig.20. With applying the remedial strategies the oscillation is decaying but doesn't reach the best value with model one. The oscillation is approximately vanish with second model.

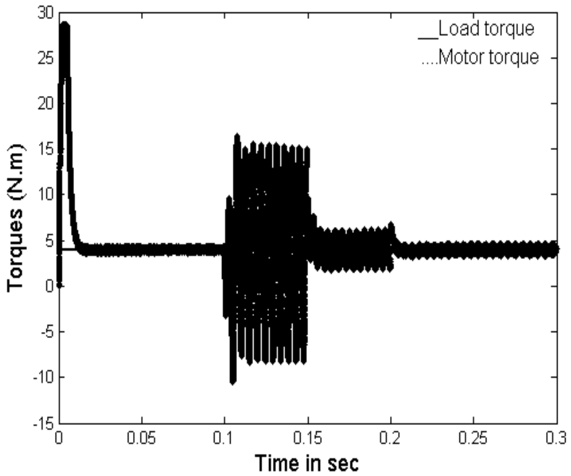

Fig. 19 Torque with model one

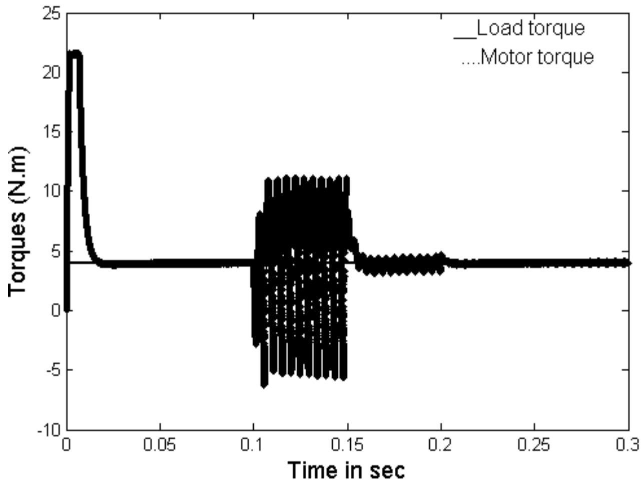

Fig. 20 Torque with model two

The speed is suffered from noise at fault as the secondary problem of torque ripples. Fig. 21 shows some noise in the speed with model one this noise is decreased with model two (Fig. 22). The noise reaches the best value with remedial strategy.

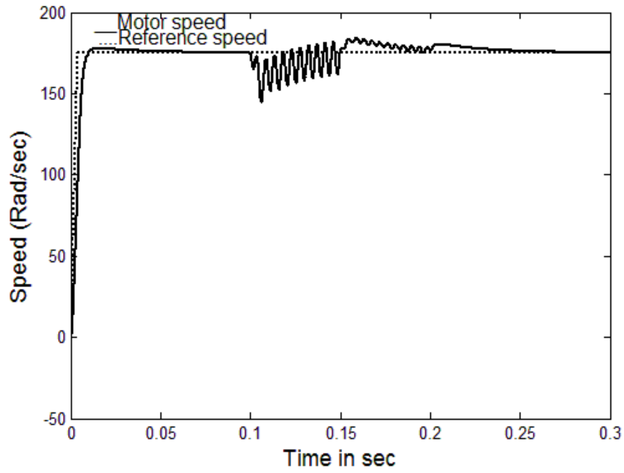

Fig. 21 Speed with model one

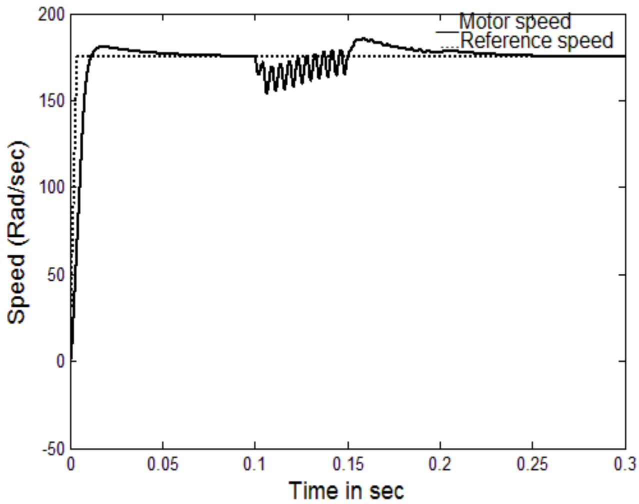

Fig. 22 Speed with model two

At fault, the short circuit current is to dangerous this fault can be damaged the motor so it very important isolated it quickly. The stator currents become smoother with second model due to reduction of the noise and suppress the harmonics Fig.24. if it is compared to proposal one Fig.23. at remedial strategies the stator current with second model is less.

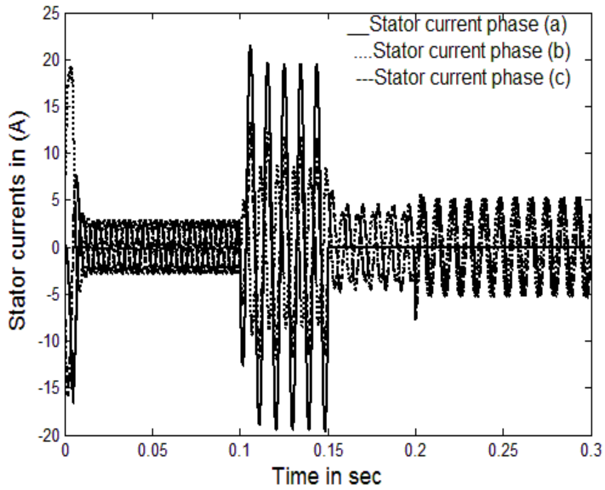

Fig. 23 Stator current with model one

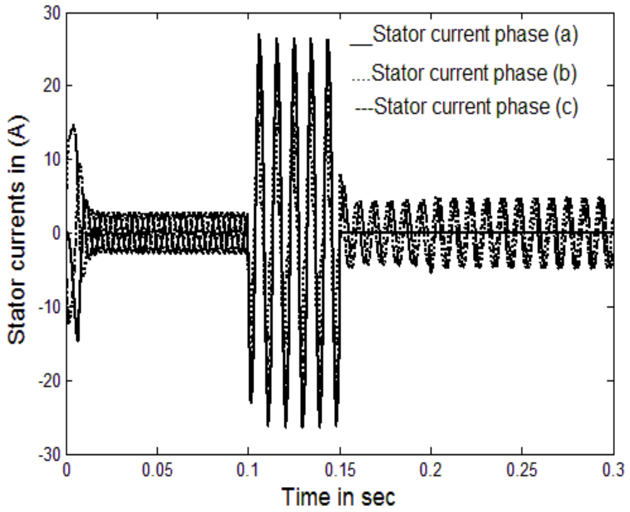

Fig. 24 Stator current with model two

C. Turn to Turn Short Circuit (25% Inter Turn Fault)

Turn to turn short circuit is one of most usual failures in the stator windings. This fault is generated due to problems in winding insulation. It induces a large circulating current and excessive heat in the shorted turns. An early detection of this fault is recommended this is because this fault has destructive nature. Here the effect of shorted turns in the stator winding on the performance of a PMSM is studied. This fault can be detected by monitoring the current. The negative sequence current component can be measured as shown in Figs (25-26) with two models to detect the fault the negative sequence current can be detected only at fault, at isolated the faulty part and vanish at remedial operation.

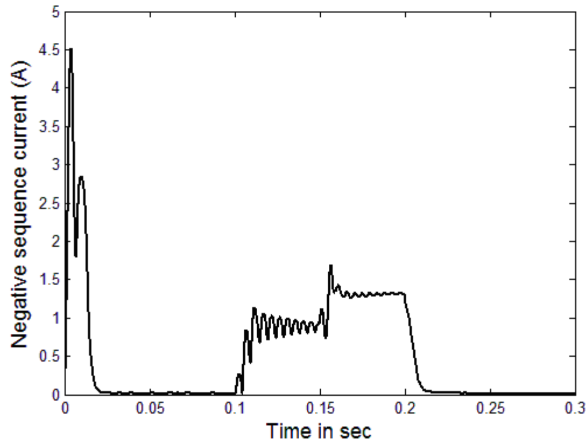

Fig. 25 detecting negative sequence current with model one

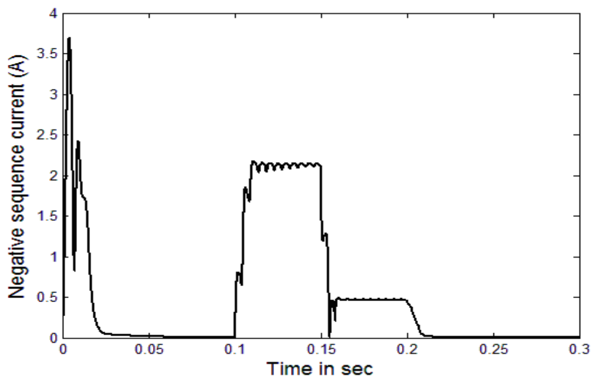

Fig. 26 detecting negative sequence current with model two

Response of dq-axes currents for turn to turn fault with two models respectively are shown in Figs. (27-28). at fault, the airgap flux is decreased due to the shorted turns so the q-axes current in two models must be increased to compensate the loss of air gap flux. In model two, (Fig. 28) the ripples and noise are decreased at isolated the faulty part and at remedial operation if it is compared to the same cases for model one (Fig. 27) this means that the model two is very strong if it is compared to model one from side of suppers noise and ripples.

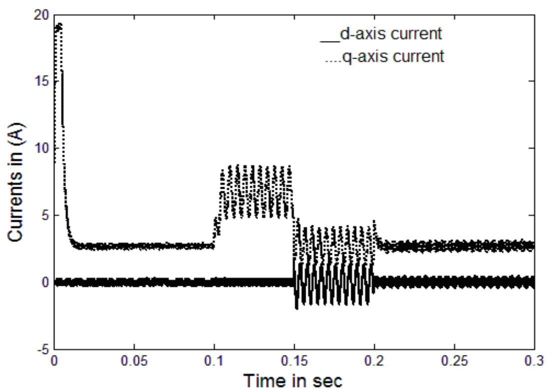

Fig. 27 Idq -axis current with model one

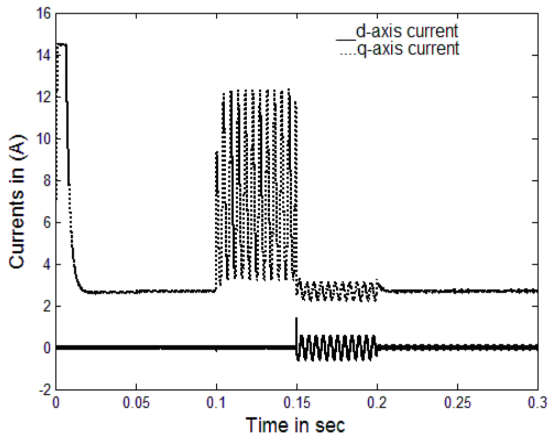

Fig. 28 Idq -axis current with model two

The motor torque under fault is shown in Figs (29-30) for model one and model two respectively when turn to turn fault occurs in phase (a), the ripples torque increases and the performance becomes poor. It arises due to an increase in harmonics, noise and electromagnet interface. In first model, the ripple torque increases as shown in Fig.29 this ripple is decreasing with second model as shown in Fig.30. With applying the remedial strategies the oscillation is decaying but doesn't reach the best value with model one but in second model the oscillation is approximately vanish.

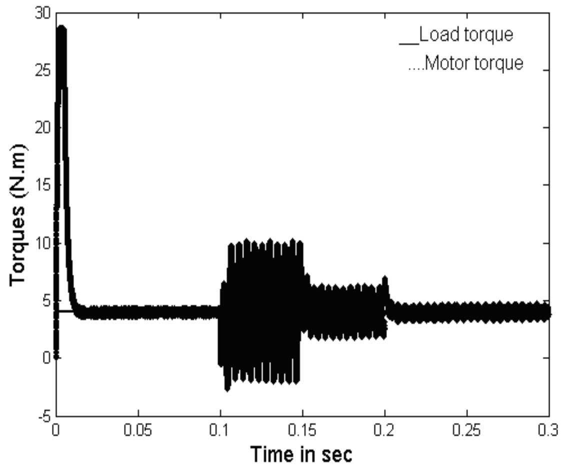

Fig. 29 Torque with model one

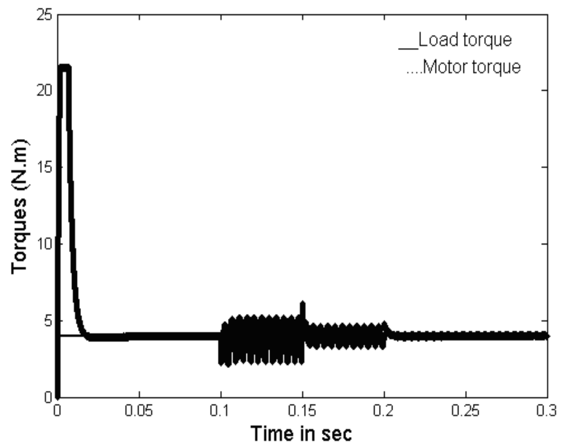

Fig. 30 Torque with model two

Under fault some noise in the speed with model one can be detected as shown in Fig. 31 these noise can be approximately neglected with model two as shown in Fig. 32. In two models at remedial operation, the noise in the speed is vanish.

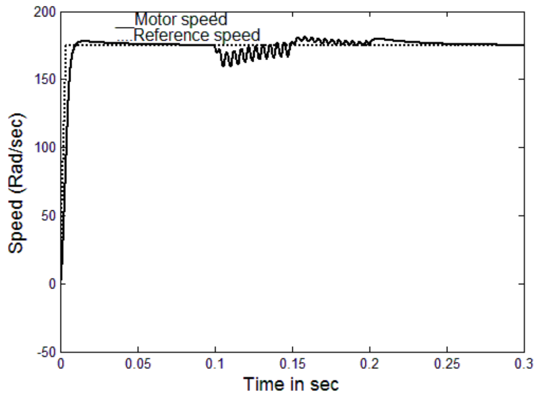

Fig. 31 Speed with model one

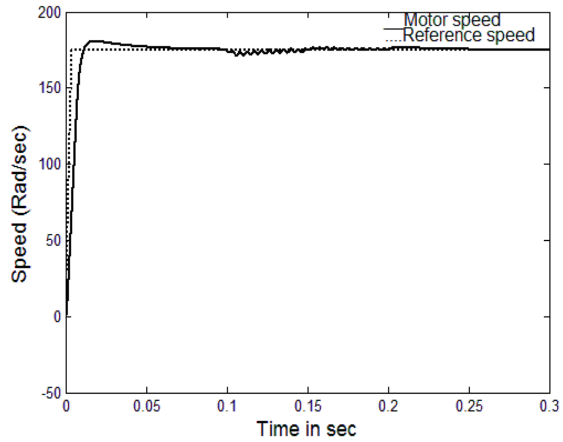

Fig. 32 Speed with model two

The stator currents become smoother with second model due to reduction of the noise and suppress the harmonics (Fig.34) if it is compared to model one (Fig.33) also the stator current with second model is less. At remedial strategies the higher current in the remaining phases aren't quite dangerous add to that the windings don't affect by this rise in the current due to the motor with remedial strategies doesn't saturate.

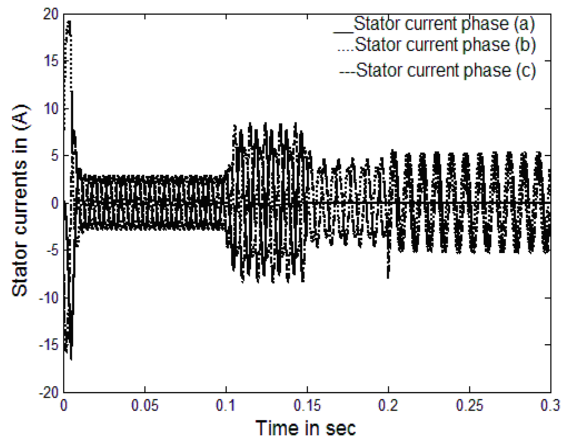

Fig. 33. Stator current with model one

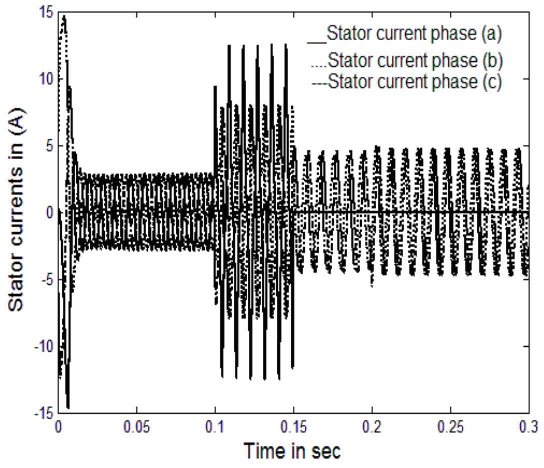

Fig. 34 Stator current with model two

VI. CONCLUSION

The stator winding faults (one open phase circuit, one phase short circuit and turn to turn shorted) are discussed, the general mathematical model and turn to turn mathematical model are built to deal with all motor fault. Two models are used to verify remedial operation of PMSM. One is for remedial operation only and the other for remedial operation with improvement the ripple torque and THD. The simulation shows that, at remedial strategies, the results are acceptable for two models. With adding 2PI current controllers the performance becomes superior. The torque ripples and THD are measured through simulated to show the effectiveness of the second model.

VII. TABLES

TABLE I. Torque Ripples and THD in Case of Healthy Phases for Model One and Model Two

Case of study	Torque ripples %		THD %	
	Model one	Model two	Model one	Model two
Healthy phases	3.1	0.45	5.49	0.7

TABLE II. TORQUE RIPPLES IN CASE OF FAULTY PHASES FOR MODEL ONE AND MODEL TWO

Fault case	Torque ripples %					
	Model one			Model two		
	At fault	At separation the faulty phase	Remedial operation	At fault	At separation the faulty phase	Remedial operation
One phase open circuit	35	35	4.5	6.3	6.3	0.53
One phase short circuit	105	35	4.5	23.6	6.3	0.53
Turn to turn fault	74.2	35	4.5	3.62	6.3	0.53

TABLE III THD IN CASE OF FAULTY PHASES FOR MODEL ONE AND MODEL TWO

Fault case	THD %					
	Model one			Model two		
	At fault	At separation the faulty phase	Remedial operation	At fault	At separation the faulty phase	Remedial operation
One phase open circuit	6.3	6.3	6.86	1.45	1.45	0.83
One phase short circuit	12.2	6.3	6.86	6	1.45	0.83
Turn to turn fault	9.8	6.3	6.86	4.6	1.45	0.83

APPENDIX I

Rated torque 4 N.M, Rated speed 175 Rad/Sec, Permanent magnet flux 0.175 Wb, phase stator resistance 2.875Ω, phase self inductance 12.5 mH, phase mutual inductance 4.5 mH, and rotor inertia 0.0008 Kg.m^2

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