# Remedial Operation of Brushless Permanent Magnet Synchronous Motors Derived by Field Oriented Control under Fault with Minimum Ripple

Hamdy Mohamed Soliman
General Manger in Cairo Metro Greater
Hamdysoliman123@gmail.com

S. M.EL. Hakim
Department of Electrical Power and Machines Engineering
Cairo University Egypt

**Abstract- In critical systems such as transportation, aerospace, medical, military and nuclear power plants, the faults are unwanted. They lead to loss of the human life and capital. In these systems, the reliability of the drive is very important. This paper is addressed this problem and suggested two models to solve it. The first model doesn't contain any special tools to improve the torque ripples and THD. The second model contains 2PI current controllers to improve the performance at fault and at 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 such as temperature and parameters variations. 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 (torque ripples). 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 second controller strong or weak. Matlab simulink is used to simulate the drive system.**

**Index terms- PMSM, FOC, Remedial Operation, PI Controller, Torque ripple.**

## I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used in many industrial applications due to have many advantages as: high efficiency, high power density and high-torque/inertia ratio. The method of motor control is very important in the drive system. This is because the operation of the PMSM under some methods of control is suffered from complicated coupling and nonlinear dynamic performance. This problem can be solved by field oriented control (FOC). PMSM with FOC emulates the separately excited DC motor. In this method of control, the stator current can be decupled into flux and torque current components. They can be controlled separately. The field oriented control 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 may be loss one phase or more which leads to fall the performance or damage part or totally drive system. In critical systems such as transportation, aerospace, medical, military and nuclear power plants, the faults are unwanted. They lead to loss of the human life and capital. In these systems, 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]. Separate phases are advised in [6]. Electrical separation allows controlling phases independently, which is possible with a full bridge since phases are electrically separated. Some compensation techniques for open-circuited fault were proposed to improve the fault-tolerant performance of multiphase rotor-PM brushless motor drives in [7-8]. 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. To solve this 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 isolated the faulty part and a second step is designing the reconfigurable inverter control.

## II. PMSM and MATHEMATICAL MODEL

Permanent magnet synchronous motor is similar to that of wound rotor synchronous motor. The rotor winding of synchronous motor is replaced with high resistivity permanent magnet material, hence, induced current in the rotor is negligible this means that, the rotor is lossless. The permanent magnets on the rotor are shaped in such a way as to produce sinusoidal back EMF in stator windings.

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 turn to turn or complete).
c) Position sensor (which can be also used to speed sensing) or current sensor failure.
d) Controller failure.
e) Combination of the above faults.

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

$$r_s = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix}, L = \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \qquad (2)$$

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:

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = -E_m \begin{pmatrix} \sin(\theta_e) \\ \sin(\theta_e - 120) \\ \sin(\theta_e - 240) \end{pmatrix} \qquad (3)$$

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

$$\begin{aligned} E_m &= K_t \omega_m \\ K_t &= \mathrm{P}\varphi_M \end{aligned} \qquad (4)$$

The electromagnetic torque can be expressed as:

$$\begin{aligned} T_e = -K_t(&i_a \sin(\theta_e) + i_b \sin(\theta_e - 120) \\ &+ i_c \sin(\theta_e - 240)) \end{aligned} \qquad (5)$$

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

$$T_e = T_L + \beta\omega_r + \frac{J}{P}\frac{d\omega_r}{dt} \qquad (6)$$

## III. H-BRIDGE is for RELIABILITY

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. It is used in the application requiring a high rate of reliability. It is the best choice for working in high voltage and high-power applications. It is operating with low switching frequency so its losses can be minimized. It offers maximum of redundancy. Each H-bridge consists of four power switches (with anti-parallel diodes). Fig. 1 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.

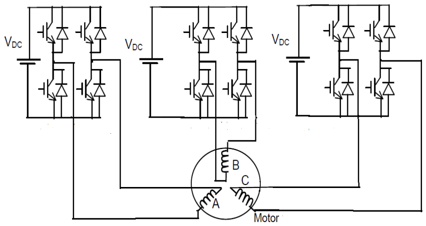

Fig.1 Feeding PMSM from separate phases

## IV. CURRENT CONTROLLER METHOD

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. Fig. 2 represents the hysteresis current controller. In this method each phase consists of comparator and hysteresis band. The switching signals are generated due to error in the current. The error comes from comparing between the reference current and actual 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.

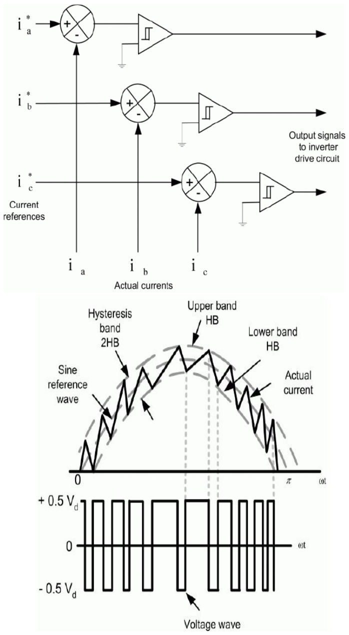

Fig. 2 Hysteresis current controller basic structure and concept

## V. 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

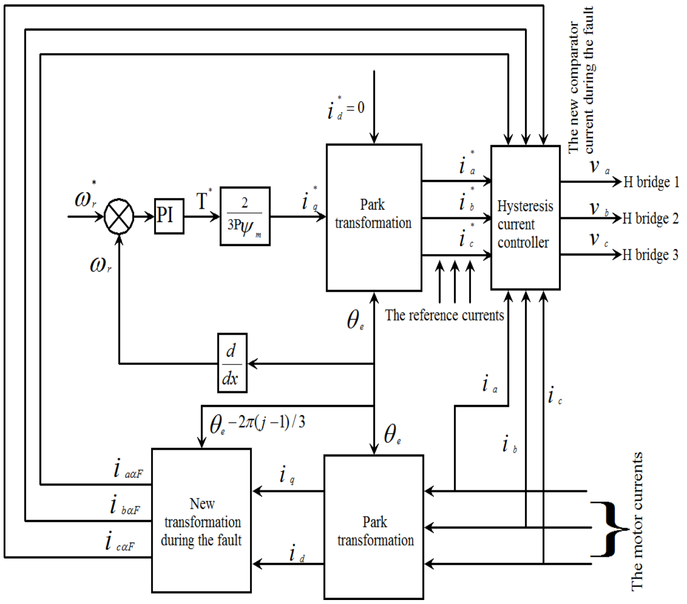

Fig.3 Remedial operation of PMSM at fault (first model)

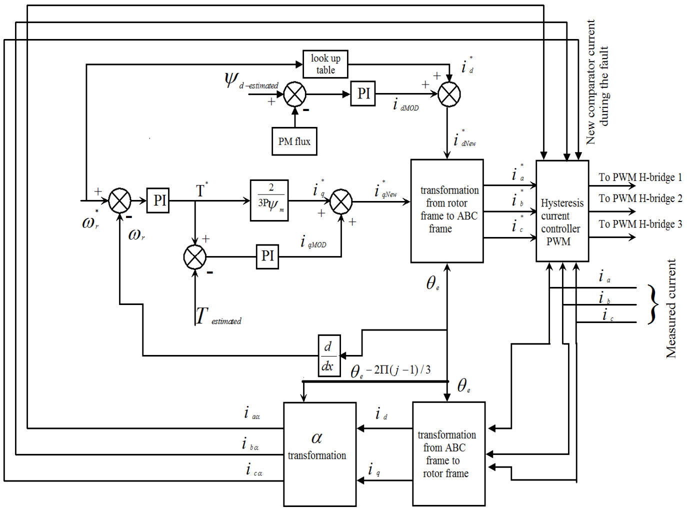

Fig.4 Remedial operation of PMSM at fault (second model)

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 ripples 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 ripples, 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. 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 $\alpha$ phase. Each phase can be built as;

$$i_{\alpha j} = i_d \cos(\theta_e - 2\pi(j-1)/3) - i_q \sin(\theta_e - 2\pi(j-1)/3) \qquad (7)$$

Where j = 1, 2, 3

This means that at fault, the faulty phase is isolated and the faulty signal which introduced to control became zero. The two healthy phase in the stationery reference frame will be transformed into two phase in synchronous reference frame ($i_d$, $i_q$). These currents ($i_d$, $i_q$) will be retransformed into three phase balanced currents using the block transformation during the fault as shown in Fig. 5. Inside the control, the faulty phase is isolated and the other phases which represented healthy phases are applied and compared to the reference current of the same these phases to get new currents inside the motor to verify the requirement of the load.

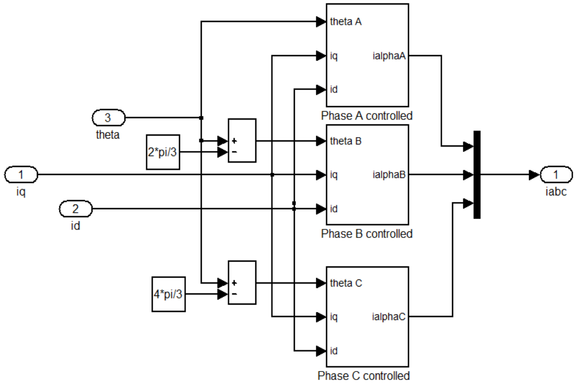

Fig. 5. New transformation during the fault

## VI. SIMULATION RESULTS

Here the following faults are study

1. One phase open circuit
2. One phase short circuit
3. Sensor failure.

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 0.25 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 ripples 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 ripples 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 ripples 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. Case One, the Open Circuit Fault*

It is a common motor fault. It can be detect by measuring the motor current and voltage. The motor torque when phase (a) is open can be calculated by putting the current in that phase equal zero in (5) then

$$T_e = -K_t\left[ i_b \sin(\theta_e - 120) + i_c \sin(\theta_e - 240)\right] \quad (8)$$

An effect of one phase open circuit (phase a) in the two models on the dq-axes currents is shown in Figs (6-7). When fault occurred, dq-axis currents are distorted. Highly distorted occurs with using model one as shown in Fig. 6 while in model two the distortion is decreasing as shown in Fig. 7. With applying the remedial strategies dq-axes currents are improved in two models but the best value occurred with model two.

The motor torque under fault is shown in Figs (8-9) where it is evident that, when phase (a) is open, the torque ripples increase and this is harmful for motor. It arises due to increase in harmonics, noise and electromagnet interface. In first model, the torque ripples increase as shown in Fig.8 these ripples are decreasing with second model as shown in Fig.9. With applying the remedial strategies, the oscillation is decaying and doesn't reach the best value with model one but in second model the oscillation is approximately vanish.

Some noise and oscillation in the speed with first model are shown in Fig.10. At fault, this noise and oscillation are approximately vanish with second model as shown in Fig.11. At remedial operation with two models, the oscillation can be neglected.

The stator currents become smoother with second model due to reduce the noise and suppress the harmonics as shown in Fig.13 if it is compared to model one this clears in Fig.12 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 rises in the current due to the motor with remedial strategies doesn't saturate.

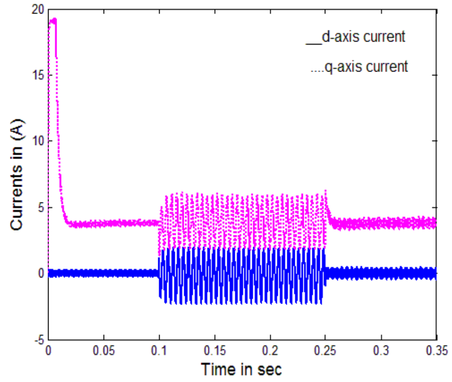

Fig. 6 Idq -axis current without modified PI controller for torque and flux

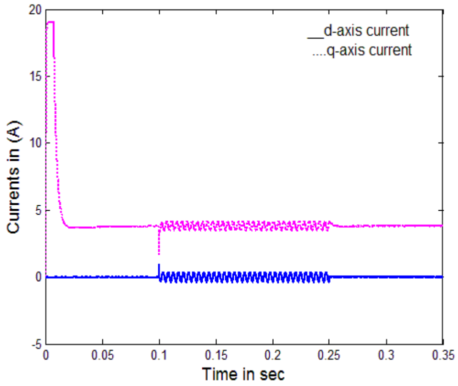

Fig. 7 Idq -axis current with modified PI controller for torque and flux

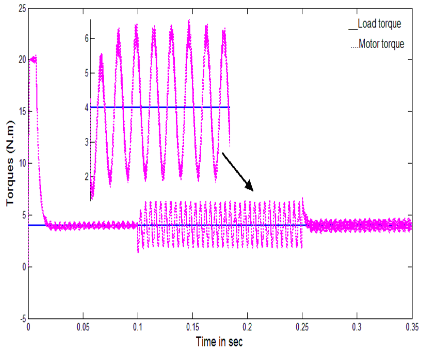

Fig. 8 Torque without modified PI controller for torque and flux

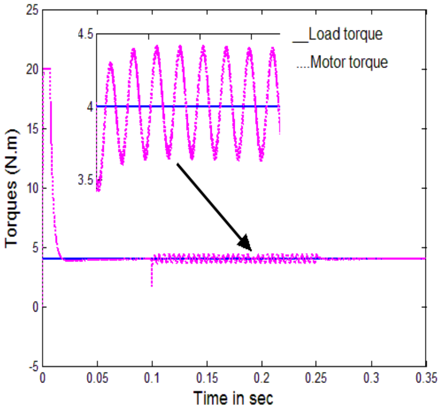

Fig. 9 Torque with modified PI controller for torque and flux

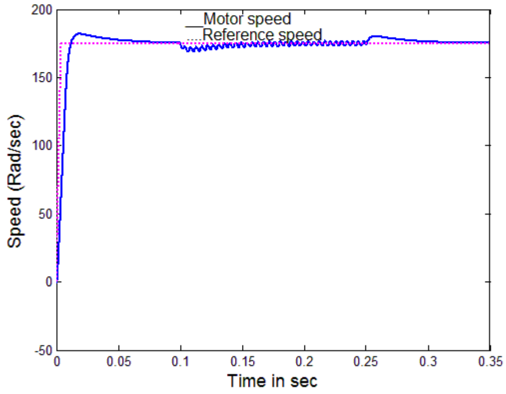

Fig. 10 Speed without modified PI controller for torque and flux

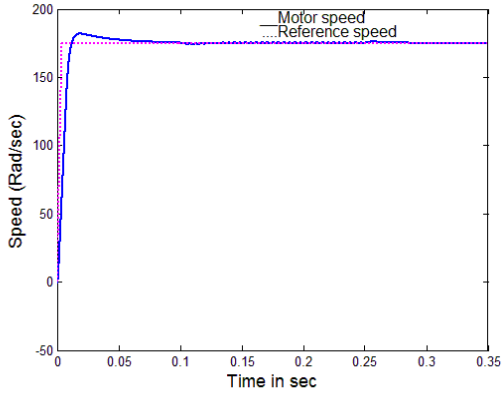

Fig. 11 Speed with modified PI controller for torque and flux

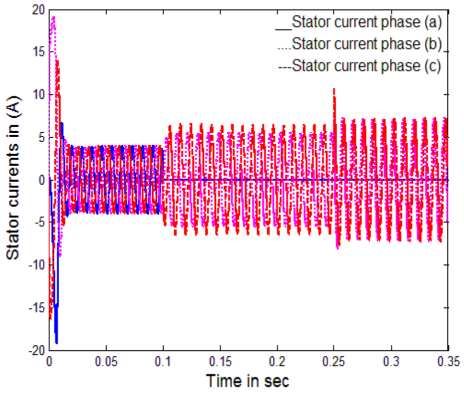

Fig.12 Stator current without modified PI controller for torque and flux

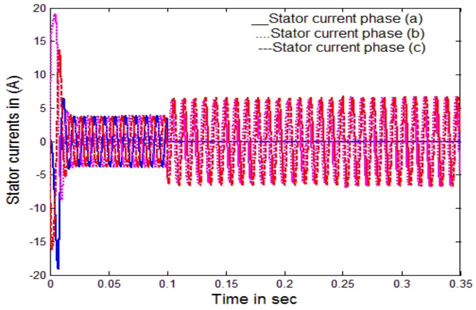

Fig.13 Stator current with modified PI controller for torque and flux

*B. Case Two, the Short Circuit Fault*

It is a critical motor fault so the faulty phase must be isolated. It is a very dangerous on the motor and causes serious problems on the motor and drive system. This fault can be avoided by impeded higher impedance in the fault phases circuit. The steady state short circuit current can be calculated as

$$I_{sc}=\frac{E_{m}}{\sqrt{r_{s}^{2}+(\omega_{e}L_{s})^{2}}} \qquad (9)$$

The effects of one phase short circuit (phase a) in the two models on the dq-axes currents are shown in Figs (14-15). At fault, dq-axis currents are highly distorted. With using model one a higher distortion in the dq-axes currents can be seen as Fig. 14 while the distortion decreases with model two Fig. 15. With applying the remedial strategies dq-axes currents are improved in two models but the best value occurred with model two.

In the first model, the torque ripples increase as shown in Fig.16 due to increase in harmonics, noise and electromagnet interface these ripples are a decrease with second model as shown in Fig.17. 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.

A highly noise and an oscillation in the speed with first model at fault can be seen in Fig.18. These noise and oscillation are approximately vanish with second model as shown in Fig.19. At remedial operation with two models, the oscillation can be neglected.

At fault, the short circuit current is too 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 reduce the noise and suppress the harmonics as shown in Fig.21 if it is compared to proposal one Fig.20 also at remedial strategies, the stator current with second model is less.

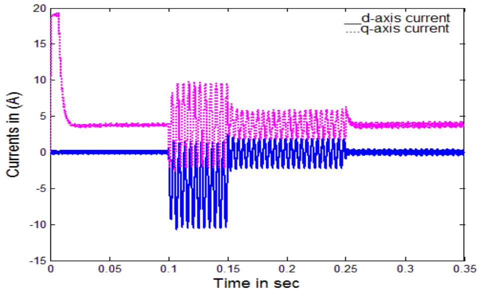

Fig. 14 Idq -axis current without modified PI controller for torque and flux

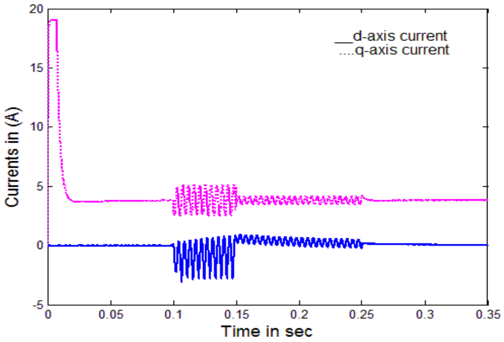

Fig. 15 Idq -axis current with modified PI controller for torque and flux

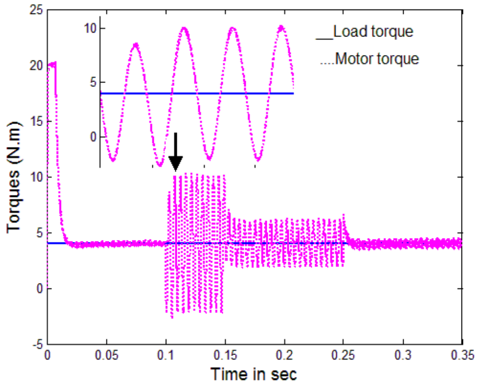

Fig. 16 Torque without modified PI controller for torque and flux

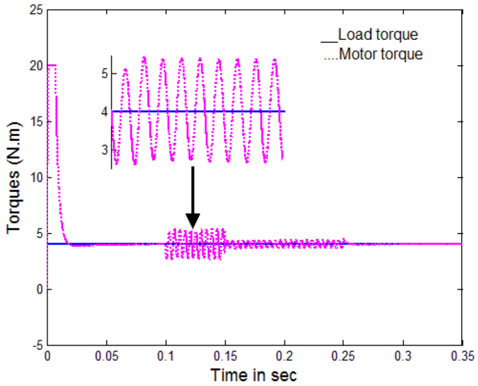

Fig. 17 Torque with modified PI controller for torque and flux

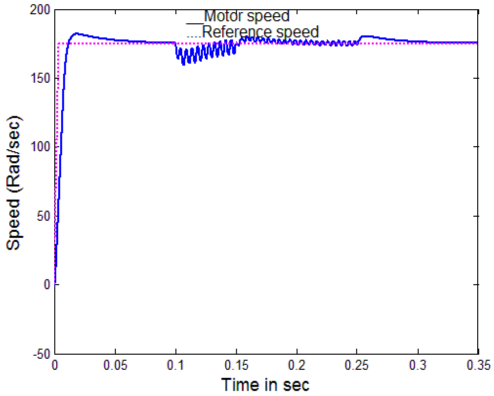

Fig. 18 Speed without modified PI controller for torque and flux

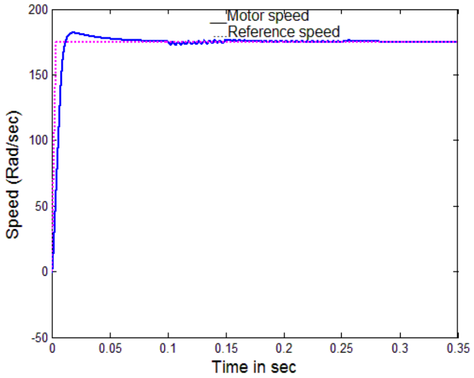

Fig. 19 Speed with modified PI controller for torque and flux

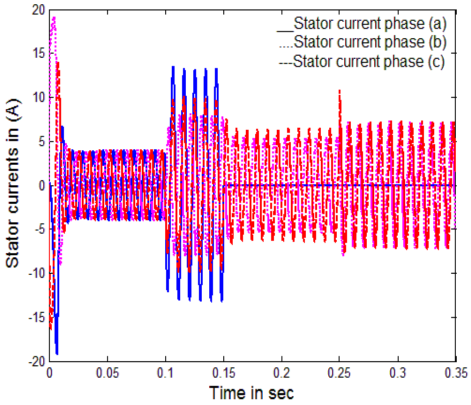

Fig. 20 Stator current without modified PI controller for torque and flux

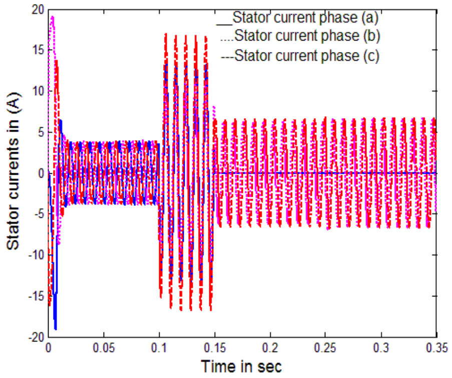

Fig. 21 Stator current with modified PI controller for torque and flux

### *C. Case Three, the Current Sensor Fault*

The dq-axes currents under one sensor fault (phase a) are shown in Figs (22-23). In first model, the ripples and oscillation increase as shown in Fig.22 but with second model the ripples and oscillation are decreased Fig.23. With applying the remedial strategies the oscillation and ripples are decayed and reach the best value with second model.

The motor torque is shown in Figs (24-25). Under fault, the torque ripples are to highly increasing and reshaped very harmful for the motor. This comes from highly increasing in harmonics, noise and electromagnet interface in first model. These ripples can be seen in Fig.24. With applying the remedial strategies the oscillation and ripple are decaying but doesn't reach the best value with model one. With second model, the oscillation and torque ripples are approximately vanish as shown in Fig.25.

Some highly noise and oscillation in the speed with first model at fault can be seen in Fig.26. These noise and oscillation are approximately vanish with second model as shown in Fig.27. At remedial operation the oscillation can be neglected.

The stator current is very dangerous at fault with model one this clears in Fig.28. With remedial strategies the current becomes acceptable but this current reaches the best value with model two as shown in Fig.29.

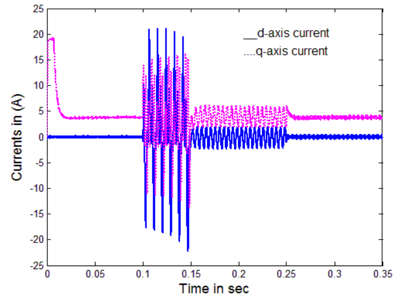

Fig. 22 Idq -axis current without modified PI controller for torque and flux

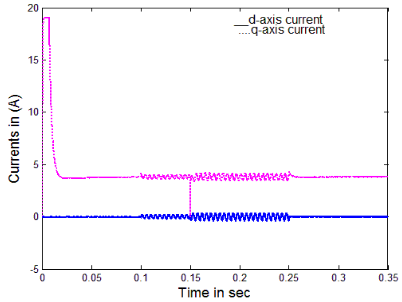

Fig. 23 Idq -axis current with modified PI controller for torque and flux

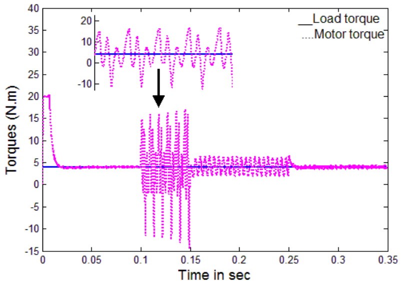

Fig. 24 Torque without modified PI controller for torque and flux

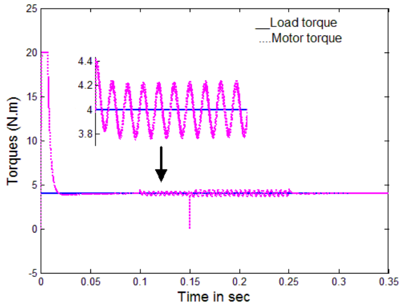

Fig. 25 Torque with modified PI controller for torque and flux

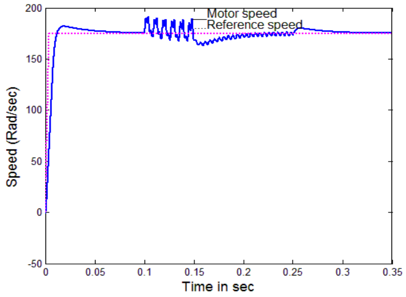

Fig. 26 Speed without modified PI controller for torque and flux

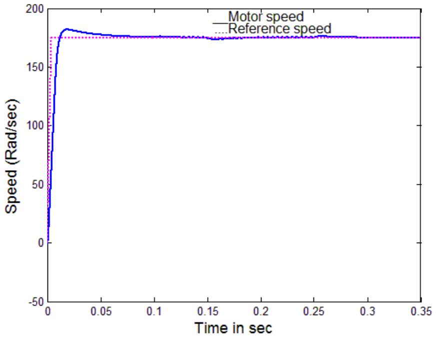

Fig. 27.Speed with modified PI controller for torque and flux

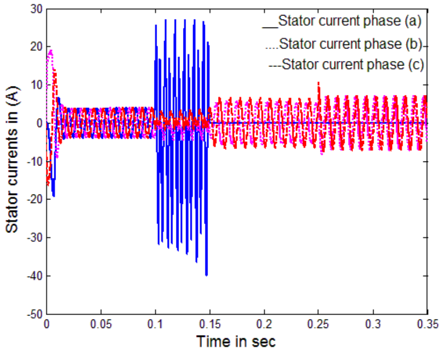

Fig. 28 Stator current without modified PI controller for torque and flux

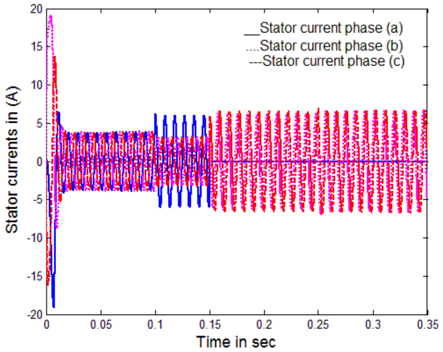

Fig. 29 Stator current with modified PI controller for torque and flux

## VII. CONCLUSION

The faults (open circuit, short circuit and current sensor failure) are discussed, two proposals method are used to verify remedial operation of PMSM at fault. One is for remedial operation only and the other is for remedial operation with improvement the torque ripples and THD. The simulation shows that, at remedial strategies, the results are acceptable for two models but with adding 2PI current controllers the performance becomes superior.

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 | 3.63 | 3.63 | 0.45 |
| One phase short circuit | 105 | 35 | 4.52 | 6.3 | 3.63 | 0.453 |
| One sensor current failure | 160 | 35 | 4.53 | 3.6 | 3.63 | 0.45 |

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 | 0.74 |
| One phase short circuit | 12.2 | 6.3 | 6.88 | 6 | 1.45 | 0.75 |
| One sensor current failure | 85 | 6.3 | 6.77 | 2.6 | 1.45 | 0.75 |

## 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$^2$

## REFERENCES

[1] B. C. Mecrow, A. G. Jack, J. A. Haylock, J. Coles, "Fault-tolerant permanent magnet machine drives", IEE Proceedings on Electric Power Applications, Vol. 143(6), Nov. 1996, pp. 437-442.

[2] J. A. Haylock, B. C. Mecrow, A. G. Jack, and D. J. Atkinson, "Operation of a fault tolerant PM drive for an aerospace fuel pump application", IEE Proceedings on Electric Power Applications, Vol. 145(5), September 1998, pp. 441-448.

[3] B. C. Mecrow, A. G. Jack, D. J. Atkinson and S. R. Green, "Design and testing of a four-phase fault-tolerant permanent-magnet machine for an engine fuel pump", IEEE Transactions on Energy Conversion, Vol. 19(4), Dec. 2004, pp. 671-678.

[4] N. Ertugrul, W. Soong, G. Dostal, and D. Saxon, "Fault tolerant motor drive system with redundancy for critical application", IEEE Power Electronics Specialists Conference, Cairns, June 2002.

[5] Dinyu Qin, Xiaogang **Luo,** and T. A. Lipo, " Reluctance Motor Control For Fault - Tolerant Capability", EEE IEMDC '97, Milwaukee, WI, USA, 1997.

[6] : Mecrow B.C., Jack A.G., Haylock J.A. and Coles J., "Fault tolerant permanent magnet machine drives", IEE Proceedings Electric Power Application; Vol 143, No. 6, pp 437-441

[7] L. Parsa and H. A. Toliyat, "Fault-tolerant interior-permanent-magnet machines for hybrid electric vehicle applications," *IEEE Trans. Veh. Technol.*, vol. 56, no. 4, pp. 1546–1552, Jul. 2007.

[8] N. Bianchi, S. Bolognani, and M. D. Pre, "Impact of stator winding of a five-phase permanent-magnet motor on postfault operations," *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 1978–1987, May 2008.

[9] Jahns, T. M. "Improved reliability in solid-state ac drives by means of multiple independent phase-drive units", In: IEEE Trans. on Ind. Appl., Vol. IA-16, No. 3, May/June 1980, pp. 321 – 331

[10] Mecrow, B. C. et al. "Fault-tolerant permanent magnet machine drives." In: IEE Proc. - Electr. Power Appl. Vol 143, No. 6, 1996, pp. 437 – 441

[11] Spée, R.; Wallace, A. K. "Remedial Strategies for brushless dc drive failures", In: IEEE Trans. on Ind. Appl., Vol. 26, No. 2, 1990

[12] Elch-Heb, T.; Fan, Y.; Hautier, J. P. "Reliability improvement of field-oriented controlled three-phase ac drives by means of two-phase remedial operation", In: Proc. Int. Conf. on Electric Machines (ICEM), Paris, 1994, vol. 2, pp. 194 - 198