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Research Article

Performance Prediction of Multi-Phase Induction Motor

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Abstract

Performance prediction of an asymmetrically wound multi-phase (6-phase) induction motor under various phase loss conditions on the basis of comparative analysis is presented. The captured scopes are accompanied by a magnified (zoom) in order to obtain a better sense of the consequences on the torque-ripple content in the resulting time-domain torque profile. The phase loss scenarios analyzed in this paper are based on the simulated result of an AWSP-IM a modeled using MATLAB/SIMULINK platform. The analysis of ripple contents in the torque profiles under various phase loss conditions reflects the deterioration of the torque-profile quality in each case. Further its comparison with result of three phase counterpart shows that AWSP-IM exhibits better performance than the Three Phase Induction Motor (TPIM) under the phase loss without any external control techniques. Moreover, some of the cases gave results, which were very close to the healthy operation of TPIM.

Keywords: *AWSP-IM, Comparative analysis, Phase loss conditions, TPIM*

1. Introduction

Very early Induction motors had two phases, but in all performance aspects three-phase version very soon replaced these, and resulted in a motor that was generally better Increasing the number of phases beyond three, though may be costly, has the advantages which might be worth considering for certain special applications. Multi-phase motors (more than three) find their application in areas which require high reliability, power density and high efficiency. Although multi-phase motor drives have been around for more than 35 years, it is in the last five years or so that one sees a substantial increase in the volume of research related to these motor drive systems. For multiphase induction machines, as in three phase induction machines, the constant volts/hertz (V/f) control was extensively studied in the 1970's and 1980's , whereas in recent times the emphasis has shifted to vector (field-oriented) control and direct torque control of induction motors . A most important area of research is the development of fault-tolerant control techniques for multi-phase motors. Control algorithms used for continuous disturbance free operation of multi-phase induction and permanent magnet machines can be found in the literature in references.

For a three-phase motor to continue operating under loss of one phase, a divided dc bus and neutral connection are required. In other words, a zero sequence component is necessary to provide an undisturbed rotating MMF after a phase is lost. Due to their additional degrees of freedom, multi-phase (more than three) motors are potentially more fault tolerant than their three-phase counterparts. This also eliminates the need for accessibility to the neutral line. If one phase of a multi-phase machine is open circuited, the combination of phase currents required to generate an undisturbed forward rotating MMF is no longer unique. The most important consideration then is to establish on optimum set of currents which would produce the same value of MMF as under the healthy conditions. Therefore, with proper current control, an undisturbed forward rotating MMF can be maintained, which can be used to control the electromagnetic torque.

Similar control algorithms can be worked out for any other multi-phase machine, in the case of an open-circuit. Due to additional degrees of freedom, the current in the remaining phases can be used to control the torque of the machine without the presence of negative-sequence or zero-sequence current. Some of the other areas of research include modeling of multi-phase induction machine with structural unbalance, influence of the loss of a stator phase /phases on the stator current spectrum. This is done through studying the behavior of some of the frequency components which depend on the speed/slip of the motor. The fluctuation of these frequencies was examined to evaluate the effect of torque ripples generated by the negative sequence component in the stator current which is associated with loss of phase/phases .

One of their main advantages is an inherent higher reliability at a system level and this is because, a multi-phase machine can operate with an asymmetrical winding

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configuration in the case of loss of more than one inverter leg/a machine phase .

Thus, on the basis of literature survey it has been found that the conventional three-phase induction motors have an inherent drawback in so far as performance under loss of phase conditions. The two-phase operation of a three-phase induction motor doesn't provide the necessary performance such as torque and output power under applications which require high reliability such as in electric traction applications, electric ship propulsion, etc. Therefore one of the means to overcome this drawback is by the addition of more phases. The detailed investigation particularly in survivability aspects of machine under faulty conditions is quite essential from design points of view and hence the work is on improving reliability of operation of induction motors in case of phase-loss scenarios by incorporating the multi-phase (more than three) design concept.

2. Mathematical model

A schematic representation of the stator and rotor windings for a two pole, six phase induction machine is given in figure 1.

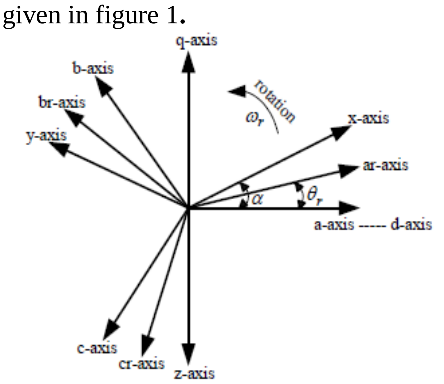

Fig.1 A two-pole six-phase induction machine with displacement between two stator winding set

6-phase stator are divided into two Y connected three phase sets, abc and xyz, whose magnetic axes are displaced by an arbitrary angle α. The windings of each 3 -phase set are uniformly distributed and have axes that are displaced 120° apart.

3-ph rotor windings ar, **br,** cr are also sinusoidal distributed and have axes that are displaced by 120° apart. Equations are developed, which describe the behavior of a multi-phase machine.

The following voltage equations of a multi-phase induction machine in arbitrary reference frame are:

$$v_{q1} = r_1 i_{q1} + \omega_k \lambda_{d1} + p\lambda_{q1} \quad (1)$$

$$v_{d1} = r_1 i_{d1} - \omega_k \lambda_{q1} + p\lambda_{d1} \quad (2)$$

$$v_{q2} = r_2 i_{q2} + \omega_k \lambda_{d2} + p\lambda_{q2} \quad (3)$$

$$v_{d2} = r_2 i_{d2} - \omega_k \lambda_{q2} + p\lambda_{d2} \quad (4)$$

$$0 = r_r i_{dr} - (\omega_k - \omega_r)\lambda_{qr} + p\lambda_{dr} \quad (5)$$

$$0 = r_r i_{qr} + (\omega_k - \omega_r)\lambda_{dr} + p\lambda_{qr} \quad (6)$$

The torque and rotor dynamics equations can be expressed as:

$$T_{em} = (3/2)(P/2)[(i_{q1} + i_{q2})\lambda_{md} - (i_{d1} + i_{d2})\lambda_{mq}] \quad (7)$$

i_m is given by

$$i_m = \sqrt{[(-i_{q1} - i_{q2} + i_{qr})^2 + (-i_{d1} - i_{d2} + i_{dr})^2]} \quad (8)$$

where,
ω_k = the speed of the reference frame,
P = *differentiation* w.r.t. time,
ω_r = the rotor speed,

All other symbols have their usual meaning rotor quantities are referred to stator.

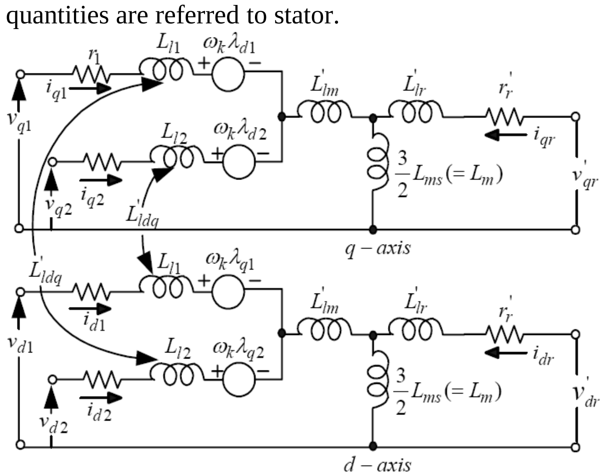

Fig.2 The q-and d-axis equivalent circuit of a six- phase induction m/c in arbitrary reference frame

3. Simulation of the 6-phase induction motor under various phase loss scenarios

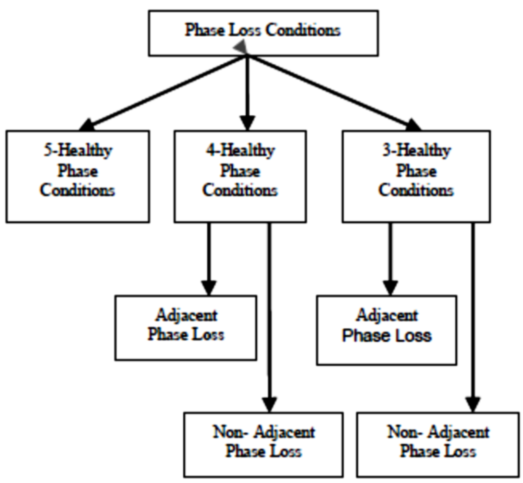

Fig.3 Flow-Chart of types of phase-loss scenarios

As depicted in Fig 3, the phase loss scenarios studied in this work are, 5-phase operation where there is a loss of one phase, 4-phase operation where there is a loss of two phases and 3-phase operation where there is a loss of three phases. Furthermore, the 4-phase and 3-phase operations, in which two or three phases have been taken out of service, were studied under conditions where there is a loss of adjacent phases that is a loss of phases which are located adjacent to each other or alternately a loss of two or more phases which are non-adjacent to each other, that is the loss of phases separated by one or two other healthy phases were also studied in this work.

3.1 6-healthy phase conditions

Fig.4 shows the phasor representation of voltages in the 6-phase healthy case. In Fig 5 the torque profiles of the 6-phase healthy is shown.

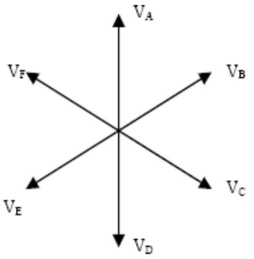

Fig.4 Voltage phasors in healthy six-phase operation

Fig.5 show magnified (zoom), portion of the steady-state torque profiles, in order to obtain a better sense of the torque-ripple content in the time-domain torque profile.

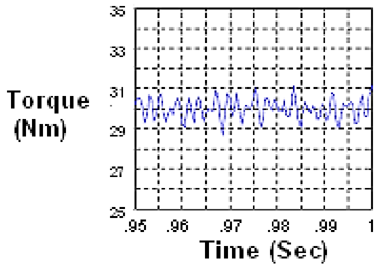

Fig.5 Torque profile of the healthy 6-phase case under full- load (Ripple content: 6.67 **%**)

3.2.5-healthy phase conditions and one faulty phase operation

Fig.6 shows voltage phasors the five-phase healthy and one faulty phase case, under the loss of phase A. In Fig 7 and Fig 5, the torque profiles of the faulty case with 5 healthy phases are compared with the 6-phase healthy.

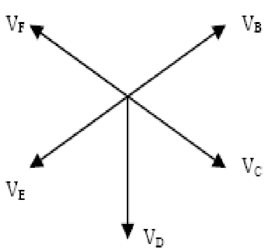

Fig.6 Voltage phasors in the five-phase operation with loss of phase A

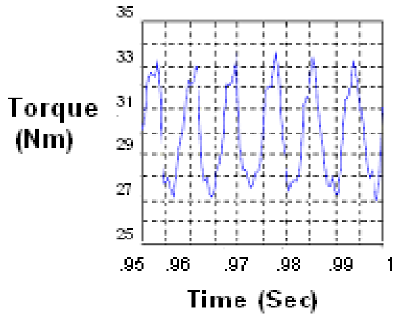

Fig.7 Torque profile of the 5-healthy phase case with loss of phase A (Ripple content: 18.33%)

These figures show magnified (zoom), portion of the steady-state torque profiles, in order to obtain a better sense of the consequences of the loss of one phase on the torque-ripple content in the resulting time-domain torque profile.

From these analysis , the torque ripple content in the resulting torque is 18.33% with the 5-healthy phases and one faulty phase case, in comparison with 6.67% torque ripple content in the healthy six-phase case.

3.3 The four healthy phases–two faulty phase operation

Here two cases are considered, one case is the loss of two adjacent phases and the other case is the loss of two non-adjacent phases.

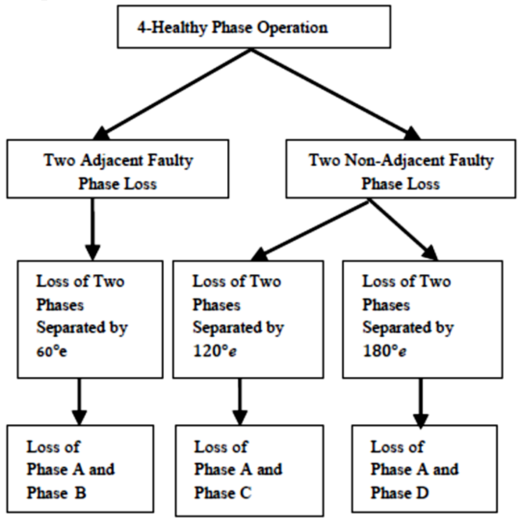

Fig.8 Flow chart of 4-phase operations

Fig 8 summarizes the four-healthy phase and two faulty phase operations

3.1.1 Loss of two adjacent phases

In this case, the 6-phase motor is simulated under loss of two adjacent phases namely Phase A and Phase B. Fig 9 shows the phasor representation of voltages in the four-healthy phase faulty two-phase case under loss of phase A and phase B. In Fig 10 and Fig 5, the torque profiles of the 4-healthy phase and two faulty phases case are compared with the 6-healthy phase case. These figures show magnified (zoom) portion of the steady-state torque profiles.

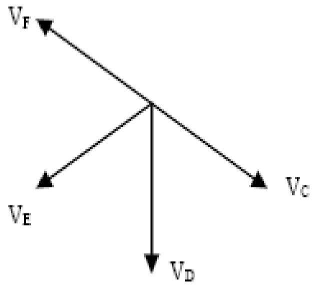

Fig.9 Phasor representation of the voltages in the four-healthy phase operation with loss of adjacent phases A and B

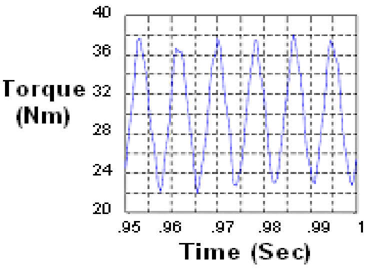

Fig.10 Torque profile of the 4-healthy phase case with loss of two adjacent phases A and B (Ripple content: 49.67 %)

From the above analysis , the torque ripple content in the resulting torque is 49.667 % with the 4-healthy phases and two faulty phase adjacent to each other, in comparison with 6.67% torque ripple content in the healthy six-phase case. This is significant, and some applications may constitute an unacceptable performance.

3.1.2 Loss of two non-adjacent phases

Here, the two non-adjacent faulty phase cases are considered, In the first case, the 6-phase motor is simulated under loss of two non-adjacent phases separated by 120°e i.e., loss of phase A and phase C are considered. Fig 11 shows the phasor representation of the voltages in the four-healthy phase faulty two-phase case such as under loss of phase A and phase C. In Fig 12 and Fig 5, the torque profile of the 4-healthy phase with two faulty phases separated by 120° e is compared with the 6-phase healthy case. These figures show magnified (zoom) portion of the steady-state torque profiles

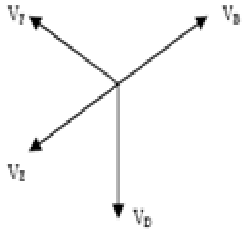

Fig.11 Phasor representation of the voltages in the four-healthy phases with two non-adjacent faulty phase with loss of phases A and C

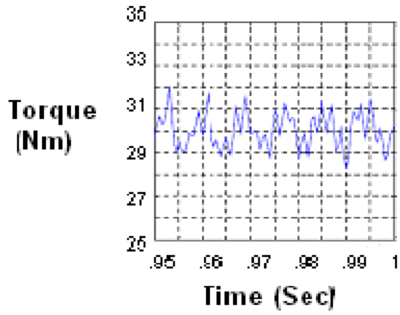

Fig.12 Torque profile of the 4-healthy phase case with loss of non- adjacent phases A and C (Ripple content: 10.33 %)

In the second case, the six-phase motor is simulated under loss of two non-adjacent Phases separated by 180°e, i.e., the loss of phase A and phase D are considered. Fig 13 show the phasor representation of voltages in the four phase healthy case with two non-adjacent faulty phases separated by 180°e under loss of phase A and phase D. In Fig 14 and Fig 5, the torque profile of the four-phase healthy case with two non-adjacent faulty phases separated by 180°e is compared with the 6-phase healthy case.

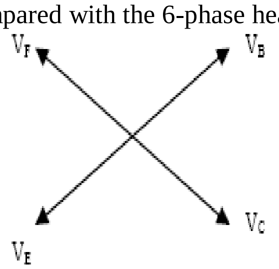

Fig.13 Phasor representation of the voltages in the 4-healthy phase with two non-adjacent faulty phase with loss of phases A and D

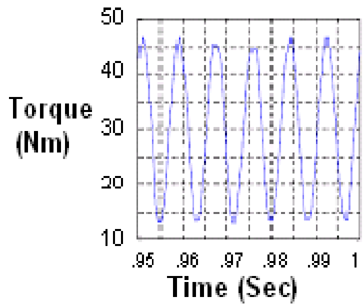

Fig.14 Torque profile of the4-healthy phase case with loss of two non-adjacent phases A and D (Ripple content: 111%)

The torque ripple content in the resulting torque is 10.33 % with the 4-healthy phases and two non-adjacent faulty phase separated by 120°e, in comparison with 6.67% torque ripple content in the healthy 6-phase case whereas, the torque ripple content in the 4-healthy phases and two non-adjacent faulty phase separated by 180°e is 111% in comparison with 6.67% torque ripple content in the healthy 6-phase case. It should be observed that for the two non-adjacent faulty phase cases there is a marked difference between the 120°e separation and the 180°e separation cases in so far as the adverse effect on the ripple content in the time-domain torque profile. The 120°e separation is far less severe.

4. The 3-healthy phase and 3-faulty phase operation

When there is loss of three adjacent phases each separated by 60°e and when there is loss of three non-adjacent phases each separated by 120°e.

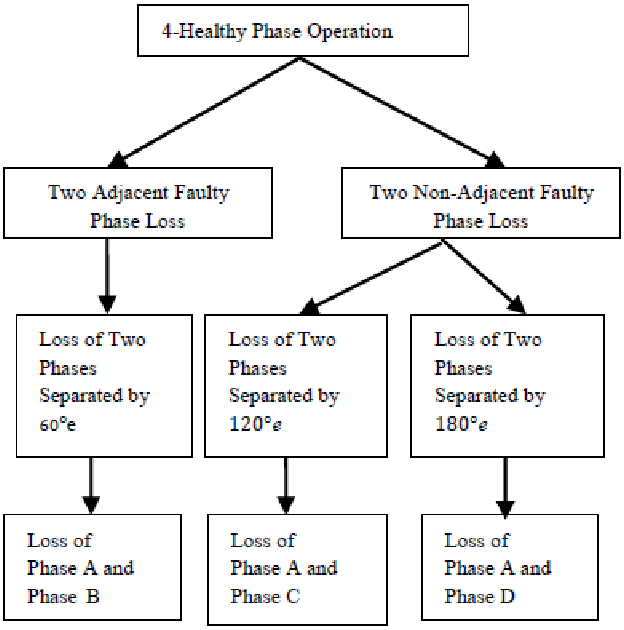

Fig.15. Flow chart summarizing the various cases of 3-phase operations.

Fig.15 summarizes the phase loss scenarios of the three-healthy phase and three faulty phase operations.

4.1 Loss of three adjacent phases

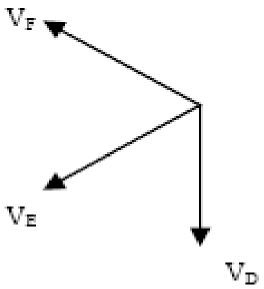

Fig.16 Voltage phasors in the 3- healthy phase operation with 3-adjacent faulty phase loss operation with loss of phases A, B

The six-phase motor is simulated under loss of three phases adjacent to each other such as when phases A, B and C become faulty and are taken out of operation. Fig 16 show the phasor representation of voltages in the three-healthy phase and three adjacent faulty phase case under loss of phases A, B and C. In Fig 17 and 5, the torque profile of the three-healthy phase and three adjacent faulty phase case is compared with the 6-phase healthy case

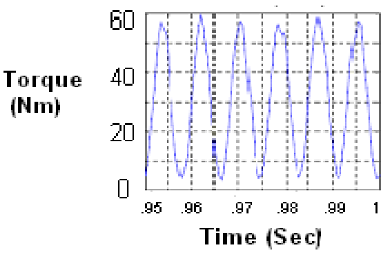

Fig .17 Torque profile of healthy phase case with loss of three adjacent phases A, B and C (Ripple content: 178%)

From the above analysis, the torque ripple content in the resulting torque is 178 % with the 3-healthy phases and three adjacent faulty phases, in comparison with 6.67% torque ripple content in the healthy six-phase case. This is a very significant amount of torque ripple and is not suitable.

4.2 Loss of three non adjacent phases

Here, the two non-adjacent faulty phase cases shown in Fig 18 are considered , **In the first case** , the six-phase motor is simulated under loss of three non-adjacent phases each separated by 120°e , such as the loss of phase A and phase C and phase E. Fig 18 show the phasor representation of the voltages in the three-healthy phase and three non-adjacent faulty phase separated by 120°e case such as under loss of phase A , phase C and phase E. In Fig 19 and Fig 5, the torque profile of the 3-healthy phase with three faulty phases each separated by 120°e is compared with the 6-phase healthy case.

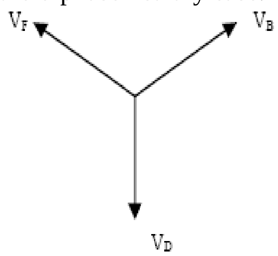

Fig.18 Voltage phasor operation of three healthy phase with three non-adjacent phase loss operation with loss of phases A, C and E

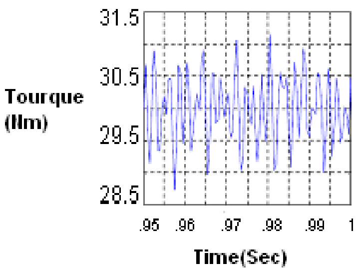

Fig.19 Torque profile of the 3-healthy phase case with loss of three non- adjacent phases phases A, C and E (Ripple content: 7.13 %)

In the second case, the six-phase motor is simulated under loss of three non-adjacent phases, two of which are separated by 60°e and the other is separated by 120°e, i.e. the loss of phase A, phase B and phase D are considered.

Fig 20 shows the phasor representation of voltages in the three-phase healthy case with three non-adjacent faulty phases separated by 60°e and 120°e under loss of phase A, phase B and phase D. In Fig 21 and Fig 5, the torque profile of the three-phase healthy case with three non-adjacent faulty phases separated by 60°e and 120°e is compared with the 6-phase healthy case.

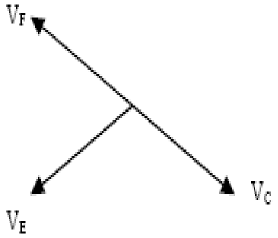

Fig.20 Voltage in phasor in the three healthy phases with three non-adjacent faulty phase los operation with loss of phases A, B and D

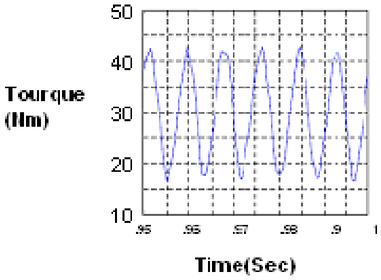

Fig.21 Torque profile of the 3-healthyphase case with loss of three non- adjacent phases phases A, B and D (Ripple content: 83.6 %)

From the above analysis, the torque ripple content in the resulting torque is 7.13 % with the 3-healthy phases and three non-adjacent faulty phases each separated by 120°e, in comparison with 6.67% torque ripple content in the healthy six-phase case whereas, the torque ripple content in the 3-healthy phases and three non-adjacent faulty phase separated by 120°e and 60°e is 83.6 % in comparison with 6.67% torque ripple content in the healthy six-phase case. It should be observed that for the three non-adjacent faulty phase cases there is a marked difference between the 120°e separation and the phases separated by 120°e and 60°e cases in so far as the adverse effect on the ripple content in the time-domain torque profile. The 120°e separation is far less severe. It should also be observed that the ripple content in the three healthy phase and three non-adjacent faulty phase separated by 120°e and 60°e is far less when compared to the three phase healthy and three adjacent faulty phase operation. This would be acceptable in certain applications.

5. Simulation of the two-phase healthy operation with one faulty phase in a 3-phase motor

Here, the case-study 5HP, 3-phase induction motor was simulated with the loss of one phase. Fig.22 and Fig.23 show the phasor representation of voltages in the 3-phase healthy case and the two-phase healthy and one-phase faulty case under the loss of phase A. In Fig 24 the torque profiles of the two-phase faulty operation is shown.

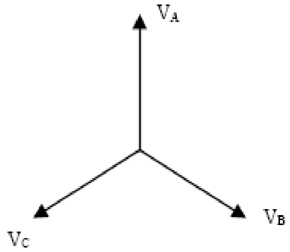

Fig.22 Voltages phasor of the 3-healthy phase case

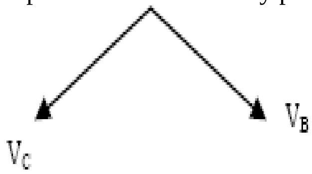

Fig.23 Voltages phasor of the 2-healthy phase case with loss of phase A

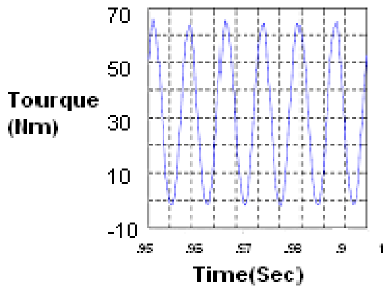

Fig.24 Torque profile of the 2-healthy phase case with loss of phase A (Ripple content: 213%)

From the above analysis, the torque ripple content in the resulting torque is 213 % with the 2- healthy phase operation, in comparison with 6.67% torque ripple content in the healthy 3-phase case. This case yields the highest and has the most adverse effect on the torque ripple content when compared to any of the cases discussed earlier.

Table-1: Showing the torque ripple content under different phase loss cases

	Phases Condition	% age Torque
Cases	Phases Condition	Ripple Content
1	Healthy	6.67
2	5 Healthy Phase with loss of Phase(A)	18.33
3	4 Healthy Phase with loss of Adj phases (A,B)	49.667
4	4 Healthy Phase with loss of Non Adj phases (A and C)	10.33
5	4 Healthy Phase with loss of Non Adj phases (A and D)	111
6	3 Healthy Phase with loss of Adj phases (A,B, C)	178
7	3 Healthy Phase with loss of Non Adj phases (A,C,E)	7.13
8	3 Healthy Phase with loss of Non Adj phases (A,B,D)	83.6
9	2-healthy phases and one faulty phase of a 3-phase motor	213

A summary representing by a table and the chart percentage torque ripple content for various faults considered in percent of the developed average torque is shown in Table-1 and Fig 25

Conclusion

A comparative analysis of the various phase-loss conditions with respect to the healthy case was presented. The analysis of the ripple content in the torque under various loss of phase / phases conditions were presented. These analyses effectively reflect the deterioration of the quality of the torque-profile under the different cases. Overall, it is shown that the six-phase motor exhibits better performance under the loss of phases than the three-phase motor without any external control techniques. Moreover, some of the cases gave results which were very close to the healthy operation.

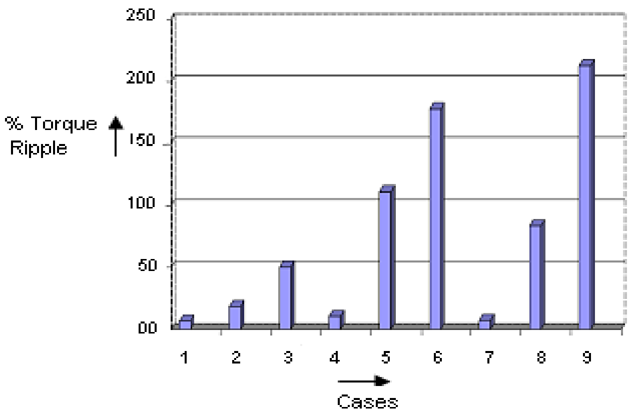

Fig.25 Summarized chart showing the torque ripple content under different cases.

Table-1 clearly indicates that the 5-healthy phase operation with one faulty phase, 3-healthy phase and three non-adjacent faulty phase operation and 4-healthy phase and two nonadjacent faulty phase operation considering loss of phases separated by 120° *e* yields the least amount of torque ripple and are almost equal in ripple content, to the healthy case. The current space vector locus diagrams affirm these results in being closest in shape to a circle. Even the 4-healthy phase non-adjacent operation considering loss of phases separated by 180 ^{O} *e* , the 4-healthy phase adjacent phase-loss operation and the 3-healthy phase non-adjacent phase-loss operation exhibit relatively lower amount of torque ripple content when compared to the standard two-phase operation of a three-phase motor.

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