Production of Circular Stator Current Trajectory in Multi-Phase Induction Drive Under Open Phase Fault Condition

A. Pitrėnas, D. Uznys, and D. Beištaras

Abstract—**In this paper multi-phase induction drive with a frequency converter is researched under open phase fault condition. Control strategy of stator voltage phase shift is proposed for dealing with over-currents during steady state. Symmetry of stator current trajectory is achieved. Experiments with six-phase induction motor without a neutral wire under one open phase condition were carried out.**

Index Terms—**Current trajectory, induction motor, frequency inverter, multi-phase drive, open phase fault, scalar control.**

I. INTRODUCTION

MULTI-PHASE induction motors have numerous advantages compared to three-phase induction motors such as reduced torque pulsations, magnetic flux harmonic reduction, reduction on the rotor harmonic current losses, dc link current harmonics and higher reliability under the loss of one or more stator phases [1-4].

Multi-phase induction motors are used in wind power systems, electrical and hybrid vehicles [5], electric ship propulsion [6], in ‘more electric aircraft’ actuators and in safety-critical applications, such as aerospace or military naval drives, where fault tolerance is a desirable feature [7].

Induction motor failures can be divided into the following categories: bearing faults, stator and rotor faults, eccentricity and vibration faults. The most common failures occur in the stator and rotor.

Stator faults are open circuit or short-circuit of one or more stator windings, coil-to-coil, phase to phase and coil to ground. These kinds of faults can be caused by local damage to insulation, extreme electrical operating conditions or extreme ambient conditions, leading to different phase winding short circuit, which may result in further open phase faults of one or more phase windings [8, 9].

Open phase fault is the most common fault that increases peak values of currents in the rest of the phases significantly. Under these conditions trajectory of rotating magnetic field becomes elliptical.

It is important to find appropriate methods to obtain circular currents trajectories in six-phase motors for single-phase fault. Therefore, a control strategy of stator voltage phase shift is proposed for dealing with over-currents during steady state.

II. STATOR OPEN-PHASE FAULT

Induction motor torque depends on the generated stator magnetic flux. Ideally, the magnetic flux trajectory is circular.

A six-phase squirrel-cage induction motor with isolated neutral point is investigated. Measuring the magnetic flux directly is complicated, therefore stator phase currents are measured and the trajectory of magnetic flux is calculated instead. Current trajectory in stationary frame is calculated by the following expressions:

$$i_{sd} = 0 \cdot i_{sA} + \left(\sin\left(\frac{\pi}{3}\right)\cdot i_{sB}\right) + \left(\sin\left(\frac{2\pi}{3}\right)\cdot i_{sC}\right) + \\ + \left(\sin(\pi)\cdot i_{sD}\right) + \left(\sin\left(\frac{4\pi}{3}\right)\cdot i_{sE}\right) + \left(\sin\left(\frac{5\pi}{3}\right)\cdot i_{sF}\right) \quad (1)$$

$$i_{sq} = i_{sA} + \left(\cos\left(\frac{\pi}{3}\right)\cdot i_{sB}\right) + \left(\cos\left(\frac{2\pi}{3}\right)\cdot i_{sC}\right) + \\ + \left(\cos(\pi)\cdot i_{sD}\right) + \left(\cos\left(\frac{4\pi}{3}\right)\cdot i_{sE}\right) + \left(\cos\left(\frac{5\pi}{3}\right)\cdot i_{sF}\right) \quad (2)$$

Where: i_{sd} – is d component of stator current of stationary frame; i_{sq} – is q component of stator current of stationary frame; $i_{sA} \ldots i_{sF}$ – are instantaneous stator phase currents.

Stator current trajectory in healthy mode is circular as all instantaneous currents have the same peak values and are shifted 60 electrical degrees. Upon loss of a phase, adjacent phases share the load on the missing phase and current peak values increase significantly. As this is not a three-phase machine, it does not stop and continues producing torque. Stator current trajectory shows a current drop in the direction of the lost phase and increment in orthogonal direction.

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Experimental results of steady state stator currents are shown in Fig. 1 and Fig. 2. Here stator phase F is open.

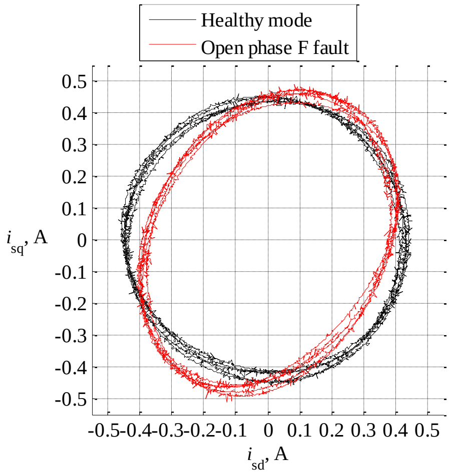

Fig.1. Stator current trajectory in healthy mode and under open phase F fault condition without adjustments

While the mean power consumption stays the same, stator current trajectory and, therefore, the flux trajectory becomes elliptical (Fig. 1) in faulty mode.

Effective stator phase current values in healthy mode are equal and in faulty mode (Fig.2) they are all different in an induction motor with an isolated neutral point. The effective value in the greatest phase current is 40 % greater in faulty mode (correspondingly 92,4 mA and 129 mA).

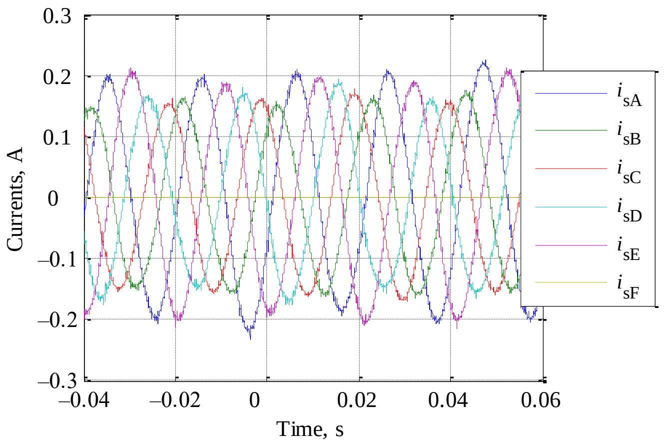

Fig.2. Steady state currents under open phase F fault condition without adjustments

III. CONTROL OF STATOR CURRENTS BY ADJUSTING STATOR VOLTAGE ANGLES

Adjusting the angles of voltage phases generated by inverter is proposed as a method for control of current trajectory in stator phase fault mode. This way meeting the minimum copper loss criterion is expected.

In healthy mode the six stator voltage phase angles are 0°, 60°, 120°, 180°, 240°, 300°. In faulty mode F phase (the 300°) is open and, therefore, adjustments to adjacent phases are made.

Drawing the adjacent voltages closer to the lost F, 10° and 20° are tried and the results are shown in Fig. 3. Here the angles of phases A to E are 350°, 60°, 120°, 180°, 250° and 340°, 60°, 120°, 180°, 260° for 10° and 20° shifts correspondingly.

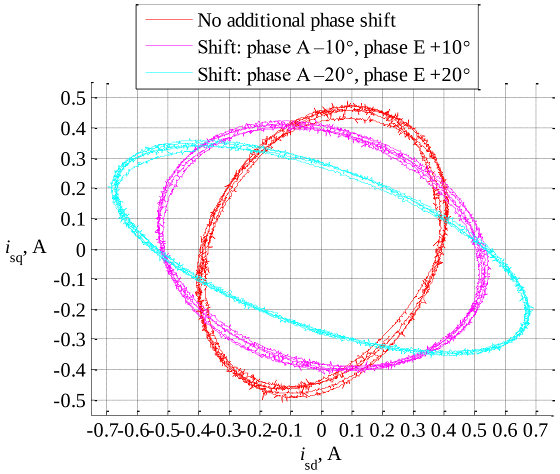

Fig.3. Stator current trajectory under open phase F fault condition with adjustments: additional phase A shift of -10° and phase E shift of +10; and additional phase A shift of -20° and phase E shift of +20°

Based on trajectories presented in Fig. 3, it is obvious that a more circular stator current trajectory could be achieved using the proposed method. Although there is a 60° angle between stator current vectors, a 10° voltage angle shift of two phases is two phases is too great.

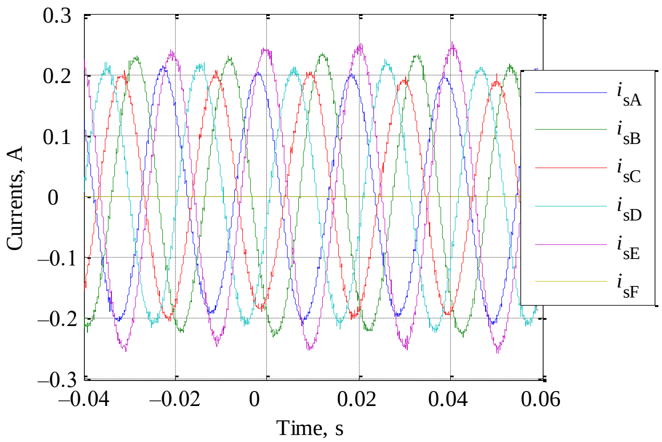

Fig.4. Steady state currents under open phase F fault condition with additional phase A shift of -10° and phase E shift of +10°

Voltage phase adjustments in both cases had a negative effect on instantaneous currents: peak values increased significantly in most phases. Note that shift in current phase angles does not match voltage angles. Current phase angle shifts in A and E phases are 40–50° instead of 10°. This effect would not be present in an induction machine with a grounded neutral point.

IV. REDISTRIBUTION OF STATOR CURRENTS

By running multiple experiments with various stator voltage angle shifts, a near circular current trajectory was achieved (Fig. 5).

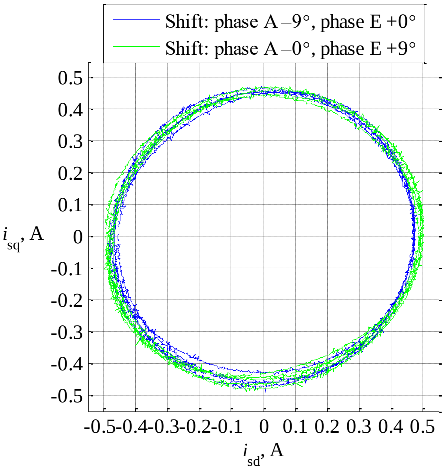

Fig.5. Stator current trajectory under open phase F fault condition with adjustments: additional phase A shift of -9° and phase E shift of +0°; and additional phase A shift of -0° and phase E shift of +9°

The most important conclusion to be made is that optimal (circular) trajectory can be achieved with numerous phase shifts and does not have a sole solution. Analysis of instantaneous stator phase currents is in order.

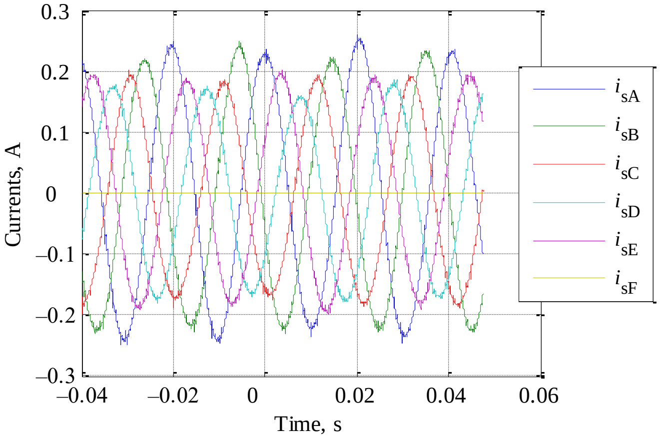

Fig.6. Steady state currents under open phase F fault condition with additional phase A shift of -9°

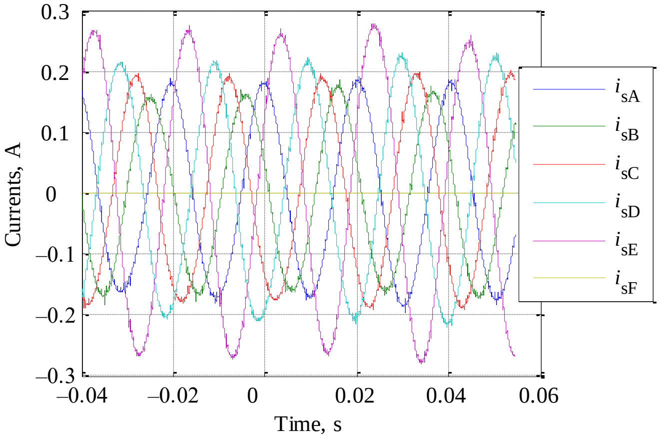

Fig.7. Steady state currents under open phase F fault condition with additional phase E shift of +9°

In Fig. 6 and Fig. 7 instantaneous stator phase currents are presented for both angle shifts. Both cases show worse results compared to unadjusted open-phase fault mode as peak values are significantly greater in some phases (Fig. 2): 62% and 81% correspondingly compared to 40% of unadjusted faulty mode. This would cause a significant strain on all of the system as it might result in further damage.

Note that greatest currents flow in different phases (Fig. 6 and Fig. 7). This means our method allows any distribution of power to all phases. The optimal redistribution would uniform currents of all the stator phases. This way minimum copper loss criterion would also be met.

The best result was achieved by changing 4 phase angles (Fig. 8). Note that the minimum stator voltage angle shift increment is 1°.

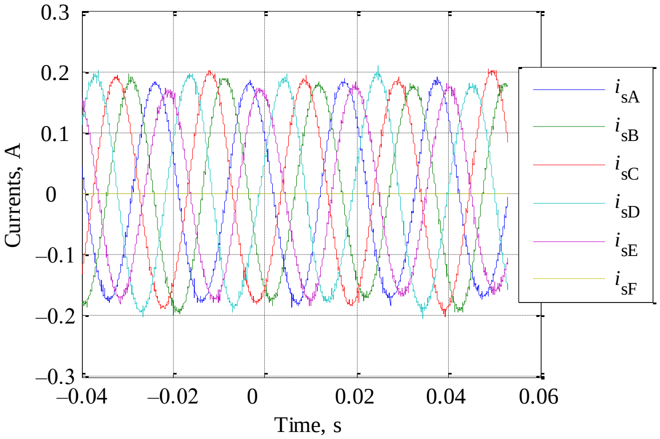

Fig.8. Steady state currents under open phase F fault condition with additional phase A shift of -6°, phase B shift of -1°, phase D shift of +4° and phase E shift of +6°

The achieved effective value in the greatest phase current is 31 % greater in adjusted faulty mode while in the unadjusted mode it is 40 % (Fig. 8).

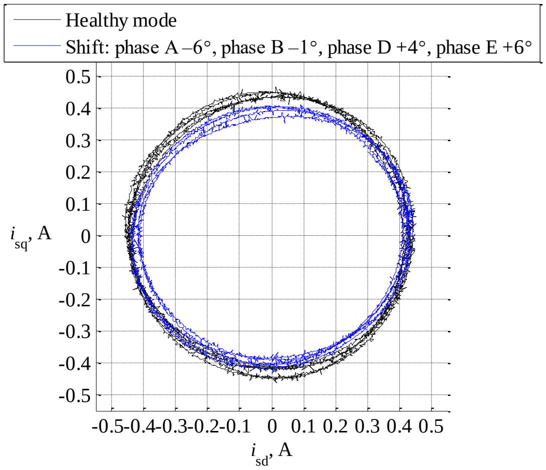

Fig.9. Stator current trajectory under open phase F fault condition with additional phase A shift of -6°, phase B shift of -1°, phase D shift of +4° and phase E shift of +6°

The stator current trajectory is slightly more elliptical compared to results presented in Fig. 5. This is considered to be the best result as the over-all quality was increased.

Mathematical model of an asymmetric induction machine is not accurate enough to reproduce experimental results. Stator phase voltage angles are adjusted by 10% to achieve near circular current trajectories. This degree of accuracy could not be guaranteed.

V. CONCLUSION

A compensation method for stator open-phase fault is presented. It allows control of stator current amplitudes by adjustment of stator voltage phase angles without reducing voltage amplitudes. This way maximum potential is drawn from the power source and no investments or changes to the hardware are required.

Using proposed method circular stator trajectory can be achieved. Experiments show that slight adjustments to voltage phase angles (up to 10% of spatial displacement of adjacent stator windings) has great impact on the trajectory in an induction motor with isolated neutral point. Currently mathematical models are not accurate enough to calculate optimal stator voltage phase angles with required accuracy.

Individual stator phase currents can also be controlled. One of the currents increases 40% during open-phase fault compared to healthy mode which may cause damage to the machine. With a minimal stator phase angle shift increment of one degree the greatest current was reduced to 31%. In theory, equal effective stator current values of all phases may be achieved with optimal stator voltage phase angles and, therefore, the greatest current value could go down to 20%.

In all modes, including the healthy mode, power consumption is almost the same.

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