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Disturbance Free Operation of a Multiphase Current Regulated Motor Drive with an Opened Phase

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Abstract—— **Although design of induction motor drives employing field oriented control has reached a relatively mature state, relatively little effort has been directed towards improving the reliability of these drives. In this paper a new, improved induction motor control strategy is proposed incorporating a multiphase machine which allows for continuous, disturbance free operation of the drive even with complete loss of one (or more) legs of the inverter or motor phase. A complete analysis of both even phase and odd phase machine utilizing this new control and circuit concept is included.**

I. INTRODUCTION

In the past several decades substantial progress has been made in the development of AC motor drives using both hard switched dc link and resonant-link power conversion. These converters typically utilize high speed switching devices such as fast recovery bi-polar junction transistors, insulated gate bi-polar transistors (IGBTs) and GTOs. Control strategies, particularly field oriented control strategies, have also greatly improved the performance of AC motor drives. These control strategies utilize almost exclusively pulse width modulated (PWM) switching strategies which exploit the low switching loss capability of these converters and seek to produce a precisely controlled current to the windings of the motor. In effect, the field oriented controller serves to convert the dc/ac inverter from a voltage to a current source thereby overcoming many of the inaccuracies involved in induction motor torque control.

While current regulation has greatly improved the torque response of ac drives, the use of this principle as a means of avoiding problems during system faults remains relatively unappreciated. One common type of fault is the loss of a transistor in one of the legs of the inverter, or alternatively, the loss of one of the phases of the motor. In this case one of the motor phases is suddenly open circuited, essentially single phasing the motor, resulting in a loss of field orientation and in high double line frequency pulsating torques. A topology for a three phase machine has recewntly been proposed to solve this problem [1]. By considering the drive circuit shown in Fig. 1, in the event that a transistor fails open in the inverter, a new current control strategy can be initiated by the converter which preserves the torque at its original value, or changes the torque to any desired value while eliminating the negative pulsating torque usually associated with operation with an open phase.

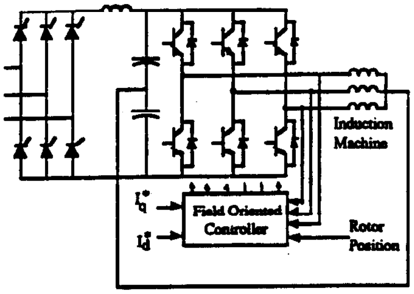


Fig. 1 Induction motor drive with machine neutral fed back to dc bus mid point.

In the case of a three phase machine, a neutral line connected between the motor neutral and the dc mid-point is required after one phase is open circuited so that the current in the remaining two phases can be individually controlled. In other words, a zero sequence component is required in a three phase machine to provide an undisturbed rotating MMF after one phase is open circuited. However, in a five phase or a seven phase machine, it is possible to take advantage of the additional degrees of freedom as a result of more phases. The current combination required to provide the same rotating MMF after one phase is open circuited is no longer unique. It can been shown that when one phase is open circuited, with appropriate control, the zero sequence current is no longer a necessary component as in a three phase machine. That is, it becomes possible to eliminate the use of a neutral line and still ensure that machine be controlled so as to produce a smooth non-pulsating torque. Figure 2 shows an example of an induction motor drive in which the machine has five rather than three phases.

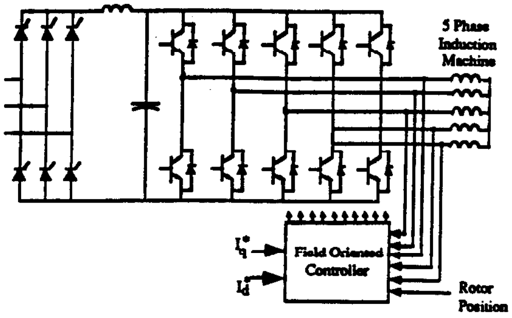


Fig. 2 Five phase current regulated PWM inverter drive.

II. ANALYSIS METHOD

The rotating MMF due to the currents in the winding of an induction motor, whatever the number of phases, can be developed by a two-winding system, if they are excited in an appropriate manner. By use of current-regulated pulse-width-modulation, the MMF is assumed to be sinusoidally distributed along the air gap, so that the combination of the direct-axis and quadrature-axis sinusoidal waves can represent this air-gap wave. Neglect of the higher space harmonics is normally an accepted practice to simplify the equations.

If one phase of a multiphase phase machine is open circuited, the combination of phase currents required to generate an undisturbed rotating MMF is no longer unique. The most important consideration then to establish an optimum set of currents that requires minimum current magnitudes (minimum I^2R loss). Whether a neutral line is required or not is also important. The phase angle of the current is not a concern as long as a rotating MMF can be generated. In this section, a general approach is introduced to find this optimum solution.

The open circuit analysis of a *n* phase machine can be approached as follows:

1. After one phase of an *n* phase machine is open circuited, the constraints required to maintain a rotating MMF are

$$\cos(2\pi/n)I_2 + \cos(4\pi/n)I_3 + \cos(6\pi/n)I_4 + \cos(8\pi/n)I_5 + \ldots\ldots\cos[2(n-1)\pi/n]I_n = (n/2)I\cos\theta \quad (1)$$

$$\sin(2\pi/n)I_2 + \sin(4\pi/n)I_3 + \sin(6\pi/n)I_4 + \sin(8\pi/n)I_5 + \ldots\ldots\sin[2(n-1)\pi/n]I_n = (n/2)I\sin\theta \quad (2)$$

From the phasor point of view, a current phasor can be obtained by the sum of two other phasors. So it can be assumed that

$$\begin{aligned} I_n &= \mathbf{i}x_n - \mathbf{j}y_n \\ &= x_n\cos\theta + y_n\sin\theta \end{aligned} \quad (3)$$

where $n = 2,3,4,5,\ldots.n$

Separating the $\cos\theta$ and $\sin\theta$ components and take *I* as per unit value, we have following 4 equations

$$a_2x_2+a_3x_3+a_4x_4+a_5x_5+\ldots..+a_nx_n = n/2 \quad (4)$$

$$a_2y_2+a_3y_3+a_4y_4+a_5y_5+\ldots..+a_ny_n = 0 \quad (5)$$

$$b_2x_2+b_3x_3+b_4x_4+b_5x_5+\ldots..+b_nx_n = 0 \quad (6)$$

$$b_2y_2+b_3y_3+b_4y_4+b_5y_5+\ldots..+b_ny_n = n/2 \quad (7)$$

where $a_n = \cos[2(n-1)\pi/n]$
$b_n = \sin[2(n-1)\pi/n]$

The goal is to find I_n so that the maximum of $\sqrt{x_n^2+y_n^2}$ is minimum.

2. Additional reasonable assumptions are

(1) no neutral is required, so that

$$x_2+x_3+x_4+x_5+\ldots\ldots+x_n = 0 \quad (8)$$

$$y_2+y_3+y_4+y_5+\ldots\ldots+y_n = 0 \quad (9)$$

(2) for minimum stator copper loss is expected that each winding should have the same current magnitude, so that

$$x_2^2+y_2^2 = x_3^2+y_3^2 \quad (10)$$

$$x_32+y_32 = x_4^2+y_4^2 \quad (11)$$

$$x_4^2+y_4^2 = x_5^2+y_5^2 \quad (12)$$

$$x_5^2+y_5^2 = x_6^2+y_6^2 \quad (13)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots$$

$$x_{n-1}^2+y_{n-1}^2 = x_n^2+y_n^2 \quad (14)$$

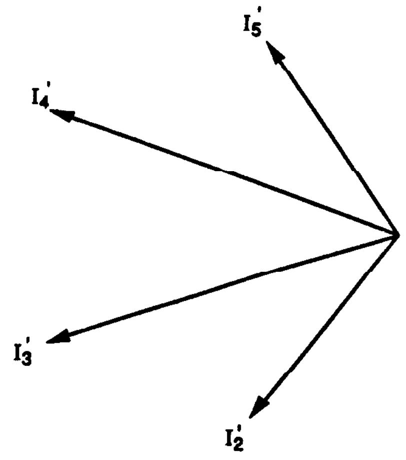
With the above assumptions, the original problem becomes a set of $n+4$ equations with $2(n-1)$ unknowns.

This approach can also be used in the cases of machines with any phase number. However, in the case of a three-phase machine, it can be noted that their exists 4 unknowns and 7 equations. Hence, there is no additional freedom to allow the neutral current to be zero. Hence, a neutral connection is required in the case of a three phase machine[1].

III. ANALYSIS OF MACHINE WITH ODD NUMBER OF PHASES

A. Five-Phase Motor

A simple means for realizing a uniformly rotating wave with four of the five phases under control can be accomplished by consideration of the zero-sequence component. Since a zero-sequence component of armature current will not produce net air-gap flux and hence no net flux linking the rotor, a zero-sequence component can be added to all of the remaining four phases, and the rotating MMF of the machine will not be changed. To maintain the rotating MMF after one phase is open circuited, a zero sequence component with magnitude the same as and phase angle opposite to the interrupted phase is introduced. A zero-sequence component can be added to a balanced five-phase current set to achieve an open circuit condition. The phasor diagram of the remaining four phases which will maintain the rotating MMF unchanged after phase *a* is open circuited is shown in Fig. 3.



$$I_2' = 1.176\,I\cos(\theta - 7\pi/10)$$
$$I_3' = 1.902\,I\cos(\theta - 9\pi/10)$$
$$I_4' = 1.902\,I\cos(\theta + 9\pi/10)$$
$$I_5' = 1.176\,I\cos(\theta + 7\pi/10)$$

Fig. 3 Phasor diagram of the remaining four phases that will keep the rotating MMF unchanged after phase *a* is open circuited

The current phasors shown in Fig. 3, if appropriately applied to the remaining four phases of a five-phase machine, will also produce a rotating MMF the same amplitude and phase as the one produced by a balanced five-phase current set. However, while simple to implement it is unfortunately not a good choice. In particular, can be noticed that this choice of current implies the necessity of increasing the current of two phases to values as high as 1.9 times their original values. Furthermore, the current magnitudes in the remaining phases are not all the same. Fortunately, the solution for generating the same rotating MMF is not unique. From the analysis in section II, it can be determined that there are two constraints on the rotating field in the real and imaginary components respectively. In the three-phase case, with two equations and two unknowns, the solution is unique. However, in a five-phase machine, there are still four remaining stator currents that can be individually controlled. With two equations and now four unknowns, it is clear that the solution is not unique. For an optimum solution it is desirable to have a set of currents which will generate the same rotating MMF with the minimum possible current magnitude for all phases. The following shows an approach to achieve this result.

The MMF in a five-phase machine can be depicted by the equation

$$\mathrm{MMF} = NI_a + aNI_b + a^2NI_c + a^3NI_d + a^4NI_e \qquad (15)$$

where, in this case $\mathbf{a} = 1\angle 72°$.

It is readily shown that if the five currents form a balanced, positively rotating set, then, under normal balanced operation,

$$\mathrm{MMF} = \frac{5NI}{2}e^{j\theta} \qquad (16)$$

where $\theta = \omega t + \phi$. Assuming that phase *a* suddenly becomes open circuited, then ,after the open circuit, the real and imaginary parts of Eq. (16) are

$$\frac{5NI}{2}\cos\theta = N(I_b' + I_e')\cos 72° - N(I_c' + I_d')\cos 36° \qquad (17)$$

$$\frac{5NI}{2}\sin\theta = N(I_b' - I_e')\sin 72° + N(I_c' - I_d')\sin 36° \qquad (18)$$

In order to eliminate the two degrees of freedom remaining in Eqs. (17) and (18) it is useful to assume that

$$I_b' = -I_d' \qquad (19)$$

$$I_c' = -I_e' \qquad (20)$$

whereupon, it can be determined that

$$I_b' = -I_d' = \frac{5I}{4}\left(\frac{\sin\theta}{\sin 72° + \sin 36°} + \frac{\cos\theta}{\cos 72° + \cos 36°}\right)$$
$$= 1.38I\cos(\omega t + \phi - 36°) \qquad (21)$$

$$I_c' = -I_e' = \frac{5I}{4}\left(\frac{\sin\theta}{\sin 72° + \sin 36°} - \frac{\cos\theta}{\cos 72° + \cos 36°}\right)$$
$$= 1.38I\cos(\omega t + \phi - 144°) \qquad (22)$$

Hence, if an open circuit occurs in a five-phase machine, the current in the remaining four phases can be used to control the torque of the machine without the presence of a negative sequence or zero sequence current (i.e current in the neutral wire of the machine). Figure 4 shows the phasor diagram of the desired currents for the four remaining healthy phases required to maintain the undisturbed rotating MMF. In this case the current amplitude of the healthy phases needs to be increased to a value only 38 percent greater than when all five phases are functional. Similar control algorithms can be worked out for an open circuit in any of the other four motor phases.

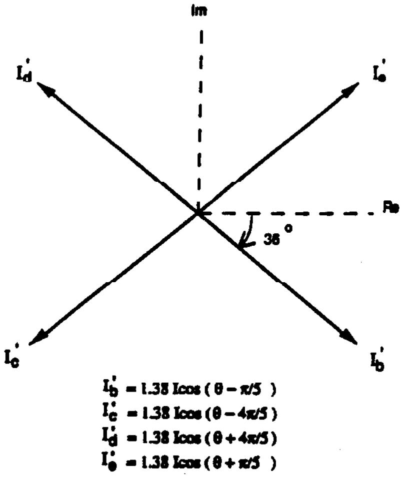


Fig. 4 Phasor diagram of the desired currents for the remaining four healthy phases when phase *a* of a five-phase motor is open circuited

B. Seven-Phase Motor

After one phase of a seven phase machine is open circuited, the constraints for producing a smooth, rotating MMF are

$$\cos(2\pi/7)I_2 + \cos(4\pi/7)I_3 + \cos(6\pi/7)I_4 + \cos(8\pi/7)I_5 + \cos(10\pi/7)I_6 + \cos(12\pi/7)I_7 = (7/2)\cos\theta \qquad (23)$$

$$\sin(2\pi/7)I_2 + \sin(4\pi/7)I_3 + \sin(6\pi/7)I_4 + \sin(8\pi/7)I_5 + \sin(10\pi/7)I_6 + \sin(12\pi/7)I_7 = (7/2)\sin\theta \qquad (24)$$

In order to eliminate the three degrees of freedom remaining in Eqs.(23) and (24), it is useful to assume that

$$I_2' = -I_5' \qquad (25)$$

$$I_3' = -I_6' \qquad (26)$$

$$I_4' = -I_7' \qquad (27)$$

These assumptions actually specify the relationship of the current magnitude and the phase angle of the three pairs of the current. The remaining degrees of freedom can be used to constrain the magnitudes of the phase currents so that all the phase currents have the same magnitude. That is

$$|I_2'| = |I_3'| \qquad (28)$$

$$|I_3'| = |I_4'| \qquad (29)$$

whereupon, it can be determined that

$$I_2' = -I_5' = 1.233I\cos(\omega t + \phi - 21.4°) \qquad (30)$$

$$I_3' = -I_6' = 1.233I\cos(\omega t + \phi - 90°) \qquad (31)$$

$$I_4' = -I_7' = 1.233I\cos(\omega t + \phi - 158.6°) \qquad (32)$$

Figure 5 shows the phasor diagram of the desired currents required to maintain the undisturbed rotating MMF for the six remaining healthy phases after one phase of a seven-phase motor is open circuited.

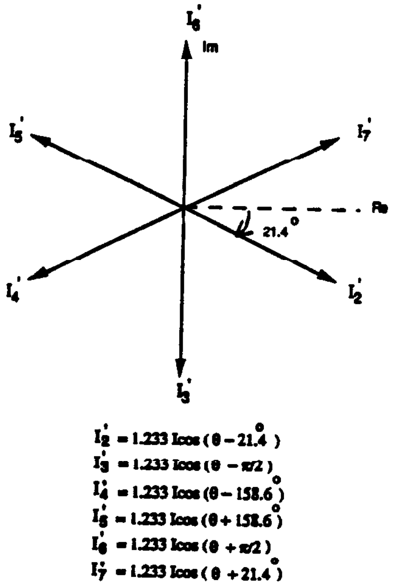
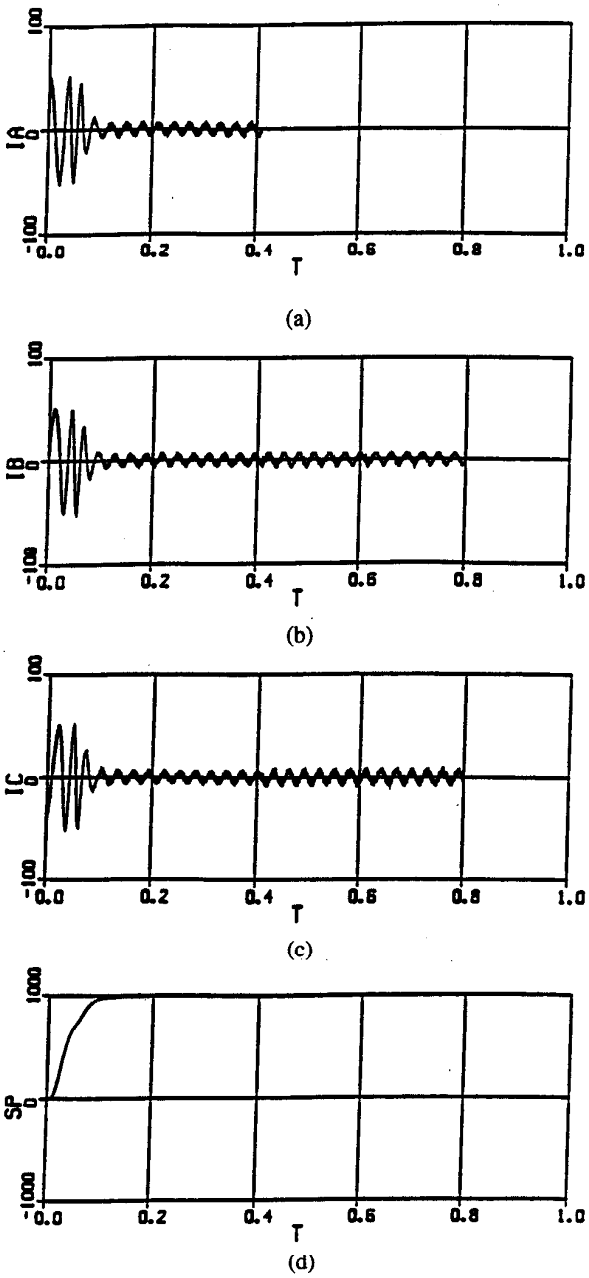


Fig. 5 Phasor diagram of the desired currents for the remaining six healthy phases when phase *a* of a seven-phase motor is open circuited

IV. SIMULATION RESULTS

The simulation of a five-phase induction motor operated with the proposed strategy when one of its phases is open circuited has been implemented to demonstrate the feasibility of the approach. In this case, phase *a* is open circuited. The current commands of the four healthy phases after phase *a* is open circuited are controlled to be the values as shown in Fig. 4. Figure 6 shows the simulation results in which the machine is first accelerated to synchronous speed from rest. A sudden changeover from balanced five phase to asymmetric four phase operation occurs at t = 0.4 sec. at which point the current amplitudes of the remaining four phases has been increased to 1.38 times its original value as indicated in Eq. 22. No disturbance in the speed trace can be noted.



(a)

(b)

(c)

(d)

Fig. 6 Computer simulation of current variation after phase *a* of a five-phase machine is open circuited (a) phase *a* current I_{as}, (b) phase *b* current I_{bs}, (c) phase *c* current I_{cs}, (d) speed.

V. ANALYSIS OF MACHINE WITH EVEN NUMBER OF PHASES

A. Four-Phase Motor

For a balanced four-phase motor, it is assumed that the stator currents are controlled to be a balanced positive sequence. From the space phasor point of view as

$$I_a = \frac{I}{2}(e^{j\theta} + e^{-j\theta}) \qquad (33)$$

$$I_b = \frac{I}{2}(a^{-1} e^{j\theta} + a\, e^{-j\theta}) \qquad (34)$$

$$I_c = \frac{I}{2}(a^{-2} e^{j\theta} + a^2 e^{-j\theta}) \qquad (35)$$

$$I_d = \frac{I}{2}(a^{-3} e^{j\theta} + a^3 e^{-j\theta}) \qquad (36)$$

where $a = e^{\pi/2}$
$\theta = \omega t$

Hence,

$$\begin{aligned} MMF &= MMF_a + MMF_b + MMF_c + MMF_d \\ &= NI_a + aNI_b + a^2NI_c + a^3NI_d \\ &= 2NIe^{j\theta} \qquad (37) \end{aligned}$$

The above expression shows that the air gap flux in the four-phase motor is a forward traveling wave. It can be shown that any multi-phase machine energized with balanced currents produces only one unidirectional rotating field. When one phase of a four-phase machine is open circuited, the rotating MMF will be provided by the remaining three phases. In case phase *a* is open circuited and the same rotating MMF is to be maintained, then

$$\begin{aligned} MMF &= N(aI_b' + a^2I_c' + a^3I_d') \\ &= N[-I_c' + j(I_b' - I_d')] \qquad (38) \end{aligned}$$

The equation results in two constraints for the three remaining currents, i.e.

$$I_c' = -2I\cos\theta \qquad (39)$$

$$I_b' - I_d' = 2I\sin\theta \qquad (40)$$

It is clear that I_c now needs to be twice its original current value after phase *a* is open circuited. Currents I_b and I_d can be randomly determined provided that the relation in Eq (40) is satisfied. A third constraint, requiring minimum amplitude for both the *b* and *d* phases can be introduced to obtain a unique solution for I_b and I_d. Currents I_b and I_d can also be controlled to cancel the neutral current as shown in Fig. 7. Thus, to maintain zero neutral current, I_b and I_d must increase to $\sqrt{2}$ times their original values.

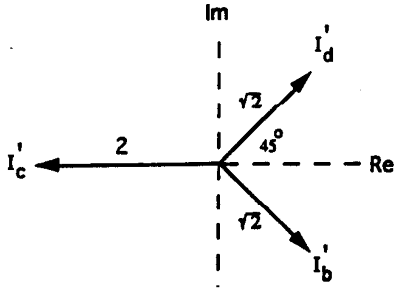


Fig. 7 Phasor diagram of the remaining three phases for zero neutral current when phase *a* of a four-phase machine is open circuited

B. Six-Phase Motor

For a six-phase machine, two types of magnetic field structures are common, and, hence, are considered here. One type has six magnetic field directions evenly separated (60 degree electrical phase shift between windings). The other type consists of two sets of three-phase windings, having a 30 degree electrical phase shift with respect to each other ("dual three-phase" winding).

B.1 Evenly separated six-phase machine

The field produced by the six-phase machine is also a rotating field. It can be considered as two sets of three-phase windings with a 180-degree phase shift. Phases 1,3 and 5 are one set. Phases 2, 4 and 6 are the other set. Hence, the analysis performed in the three-phase motor for one phase open circuited can be applied immediately. If phase 1 is open circuited, one means to keep the rotating MMF the same is to control the current amplitudes and phase angles of phases 3 and 5 as in the three phase case.

Since the currents are very unbalanced, one can take advantage of having a second set of stator windings to improve the current distribution. From the previous discussion it can be determined that one unit of current increase in set 2-4-6 can be used to reduce, by $\sqrt{3}$ times, the current in set 3-5. Hence it is possible to increase the current in set 2-4-6 and decrease the current in set 3-5 until the currents in both sets are equal.

A set of currents with equal magnitude of 1.268 is now achieved as shown by the phasors in Fig. 8.

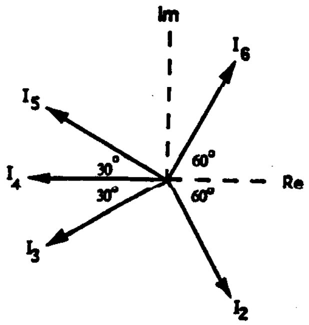
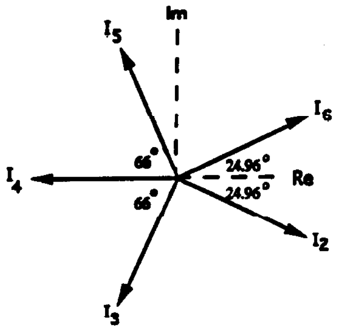


Fig. 8 Phasor diagram of the remaining five phases, which have the same magnitude and will maintain a rotating MMF as unchanged after phase *1* is open circuited

Unfortunately, this equal magnitude current set will result in a neutral current with a magnitude of 2.2 times its rated value. The general approach discussed in Sec. II can alternatively be used to achieved a solution without a neutral current.

The solution of the equations as discussed in section II is a required set of currents for the remaining five phases of a six-phase machine after phase *1* is open circuited. Solution of these equations can again be solved by means of a computer. This solution has the same magnitude for each phase of current and no neutral connection required. Figure 9 shows the phasor diagram for this solution. It is noted that the current magnitude is increased slightly, from 1.268 to 1.297.



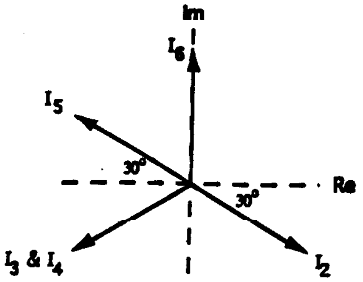
$$
\begin{aligned}
I_1 &= 0\\
I_2 &= 1.297\,I\cos(\theta - 24.96^\circ)\\
I_3 &= 1.297\,I\cos(\theta - 114^\circ)\\
I_4 &= 1.297\,I\cos(\theta + \pi)\\
I_5 &= 1.297\,I\cos(\theta + 114^\circ)\\
I_6 &= 1.297\,I\cos(\theta + 24.96^\circ)
\end{aligned}
$$

Fig. 9 Desired phasor diagram of the remaining five phases of a six phase machine that will maintain the same MMF after phase *1* is open circuited and will result in zero neutral current

B.2 Thirty degree displaced six-phase machine

It is well known that the sixth harmonic pulsating torque associated with conventional three-phase six-step CSI induction motor drives can be eliminated by a thirty-degree displaced six-phase motor winding configuration, or "dual three-phase" arrangement. If the neutrals of these two three-phase sets are not connected, and the voltage of the 2-4-6 set lags behind the voltage of the 1-3-5 set by 30 degrees, all the air gap flux components of orders 6n ± 1 (n = 1,3,5,....) contributed by the six stator phases cancel each other. Hence, such machines are popular for high horsepower applications.

By using CRPWM control, the neutrals of the two three-phase sets need not be separated. In contrast, they should be connected together so that the neutral current can be eliminated when one or more of the stator windings is open circuited. The analysis in Section II can be applied directly to this situation. If a minimum current in the remaining windings is desired, a neutral connection is required. The current phasor in this case is shown in Fig. 10



$$
\begin{aligned}
I_1 &= 0\\
I_2 &= 1.268\,I\cos(\theta - \pi/6)\\
I_3 &= 1.268\,I\cos(\theta - 5\pi/6)\\
I_4 &= 1.268\,I\cos(\theta - 5\pi/6)\\
I_5 &= 1.268\,I\cos(\theta + 5\pi/6)\\
I_6 &= 1.268\,I\cos(\theta + \pi/2)
\end{aligned}
$$

Fig. 10 Minimum current phasor diagram of the remaining five phases which have the same magnitude and will keep the rotating MMF unchanged after phase *1* of a thirty-degree displaced six-phase motor is open circuited

If no neutral connection is desired, the solution can be solved by the general approach described in Sec. 5.3.1. The constraints needed to realize an unchanged rotating MMF are now

$$0.866x_2 - 0.5x_3 - 0.866x_4 - 0.5x_5 = 3 \tag{41}$$

$$0.866y_2 - 0.5y_3 - 0.866y_4 - 0.5y_5 = 0 \tag{42}$$

$$0.5x_2 + 0.866x_3 + 0.5x_4 - 0.866x_5 - x_6 = 0 \tag{43}$$

$$0.5y_2 + 0.866y_3 + 0.5y_4 - 0.866y_5 - y_6 = 3 \tag{44}$$

$$x_2 + x_3 + x_4 + x_5 + x_6 + x_7 = 0 \tag{45}$$

$$y_2 + y_3 + y_4 + y_5 + y_6 + y_7 = 0 \tag{46}$$

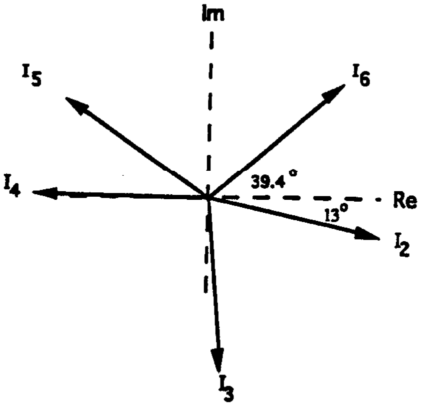
$$x_2^2 + y_2^2 = x_3^2 + y_3^2 \tag{47}$$

$$x_3^2 + y_3^2 = x_4^2 + y_4^2 \tag{48}$$

$$x_4^2 + y_4^2 = x_5^2 + y_5^2 \tag{49}$$

$$x_5^2 + y_5^2 = x_6^2 + y_6^2 \tag{50}$$

The computer solution of the above equations results in a set of currents for the remaining five healthy phases. This solution again has the same magnitude for each current and no neutral connection is required. Figure 11 shows the phasor diagram of this solution. It is noted that the current magnitude has been increased from 1.268 to 1.44.



$$
\begin{aligned}
I_1 &= 0\\
I_2 &= 1.44\,I\cos(\theta - 13^\circ)\\
I_3 &= 1.44\,I\cos(\theta - 85.4^\circ)\\
I_4 &= 1.44\,I\cos(\theta + 178.5^\circ)\\
I_5 &= 1.44\,I\cos(\theta + 145.8^\circ)\\
I_6 &= 1.44\,I\cos(\theta + 39.4^\circ)
\end{aligned}
$$

Fig. 11 Phasor diagram of the remaining five phases which will keep the rotating MMF unchanged after phase *1* of a thirty degree displaced six-phase motor is open circuited

VI. COMPARISON OF CURRENT REQUIREMENTS

From the previous analysis, it can be seen that the current requirement for maintaining the same rotation MMF after one phase is open circuited depends not only on the phase number but also on the construction of the stator. The neutral connection also has effects on the magnitude of required currents. Table 1 summarizes the results from the previous analysis. Generally speaking, the current is decreased with an increase of the phase number. For a three-phase machine, a neutral connection is necessary. For a four-phase machine , a desired current set of equal magnitude cannot be obtained because of its symmetric construction. In effect, the lost MMF caused by the open-circuited phase cannot be compensated by those windings that are orthogonal to it. Hence, a asymmetrical current is required in a four-phase machine after one phase is open circuited. For a dual three-phase machine, a neutral connection could reduce the current from 1.44 pu to 1.268 pu. Figure 12 shows the trend of current magnitude and stator copper loss for multi-phase machines.

Table 1 The current comparison of multi-phase machines

Pnase Numbers	w/o Neutral (pu)	w/ Neutral (pu)	Neutral Currents (pu)
3ϕ	NA	1.732	3
4ϕ	$2:\sqrt{2}:\sqrt{2}$	2 : 1 : 1	2
5ϕ	1.382	NA	NA
6ϕ	1.297	1.268	2.2
6ϕ (dual 3 ϕ)	1.44	1.268	2.2
7ϕ	1.23	NA	NA

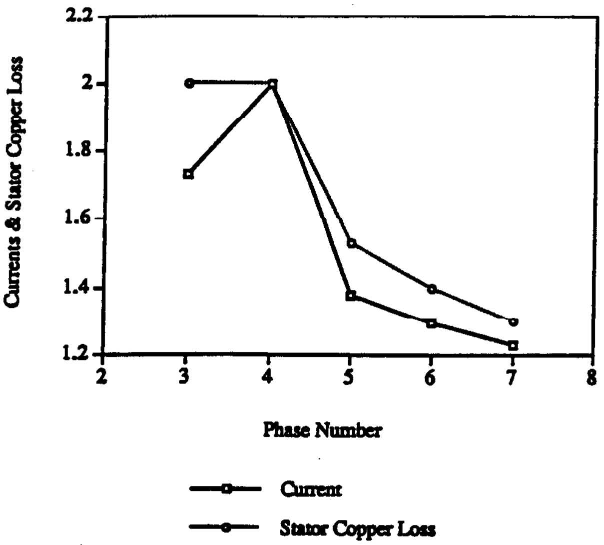


Fig. 12 The trend of current magnitude and stator copper loss for multi-phase machines NA=Not Applicable (i.e. not practical).

VII. CONCLUSION

A neutral line connected between the motor neutral and the dc mid-point of a three-phase machine is required after one phase is open circuited if it is desired that the current in the remaining two phases be individually controlled. Hence, a zero sequence component is required in a three-phase machine to provide for an undisturbed rotating MMF after one phase is open circuited. However, it has been shown in this paper that by using a five-phase or a seven-phase machine, it is possible to take advantage of the additional degrees of freedom as a result of more phases. The current combination required to provide the same rotating MMF after one phase is open circuited is no longer unique. It has been shown that when one phase is open circuited, with appropriate control, the zero sequence current is no longer a necessary component as in a three-phase machine. That is, one can eliminate the need for a neutral line and the machine can still be controlled so as to produce a smooth non-pulsating torque.

It has also been determined that the rating of motor and inverter will both benefit by the use of extra phases. In a three phase machine, after one phase is open circuited, the motor can continue to operate at the rated torque provided that the current phase angle of the remaining two phases are appropriately controlled and the current magnitude are increased to 1.732 times of the rated current. However, in a five phase machine, the magnitude of the phase current required to provide the same torque can now be only 1.382 times of its rated value. In a seven phase machine, the ratio can be reduced to 1.233. With this reduced current rating, the proposed one open phase control strategy becomes quite feasible.

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