Magnet Flux Nulling Control of Interior PM Machine Drives for Improved Response to Short-Circuit Faults

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Abstract – **This paper proposes a control method to null the magnet flux in an Interior Permanent Magnet (IPM) motor following short-circuit type faults in either the inverter drive or motor stator windings. Phase control is employed to implement the flux nulling control method so that it is possible to take advantage of a zero sequence current in order to minimize the current in the shorted phase. It is shown that phase control results in a smaller induced current than employing a synchronous frame *dq0* current regulator. The induced torque is also less than employing a purposely commanded symmetrical short-circuit in response to a short-circuit type fault. In the paper, the complete magnet flux nulling control algorithm is derived with reference to the proposed phase current control method. The impact of controlling the zero sequence on the resulting phase currents is presented. Both simulation and experimental results are presented verifying operation of the proposed methods.**

I. INTRODUCTION

INTERIOR PERMANENT MAGNET (IPM) synchronous machines are attractive for a variety of applications because of their high power density, wide constant power speed range, and excellent efficiency [1], [2]. However, their adoption in applications such as electric propulsion has been hindered by concerns about faults. During normal operation, the magnets provide an inherent flux in the machine so that a larger percentage of the applied current can be used to produce torque. In the presence of any type of system fault, either originating in the machine or the electronic drive, the magnets' location in the spinning rotor becomes a source of flux which cannot be turned off at will.

Short-circuit type faults are problematic as they induce sustained currents regardless of speed for both symmetrical and asymmetrical short-circuit conditions resulting from an inverter-based fault [3], [4]. Partial or full short-circuit faults located in the stator windings also exhibit similar fault responses. These winding faults are of a particular concern because even a single shorted coil could induce elevated local temperatures within the motor, and if sustained, could result in failure of the machine.

Methods to handle short-circuit faults typically incorporate major motor design modifications [5], an alternative control strategy [6], or, a combination of both hardware and software changes [7]. In [8], a synchronous frame control method to cancel the magnet flux was proposed so that the system fault response would be a zero-torque response. This paper proposes employing stationary frame phase control to implement the magnet flux nulling control method. By employing phase current control, it is possible to take advantage of a zero sequence current in order to minimize the current that is present in the short-circuit when compared to synchronous frame *dq0* control. In the paper, the complete magnet flux nulling control algorithm is derived with reference to the proposed phase current control method. The impact of controlling the zero sequence on the resulting phase currents is presented. Both simulation and experimental results are presented verifying operation of the proposed methods.

II. MAGNET FLUX NULLING CONTROL

One requirement of fault tolerant PM machine drives is the necessity of having individual control of the phase currents. In effect, this requires that each phase be driven by an H-bridge inverter, or alternatively employing a six-leg inverter. A cascaded converter consisting of two standard three-phase, six-switch inverters with connected dc links as shown in Fig. 1, allows for the individual control of the phase currents while simplifying the dc link structure of the system.

The magnet flux nulling control method, [8], [9], assumes that one phase of the motor is fully shorted. This is equivalent to having either the upper or lower set of switches in one phase each gated on. For example, phase *a* is shorted out if switches S_{a1n} and S_{a2n}, or S_{a1p} and S_{a2p} are gated on. The assumption of having one phase completely shorted out is useful as it covers several different short-circuit fault conditions. In the event of a single switch short-circuit fault, the control could turn on the complementary switch in the phase to emulate a fully shorted phase. For the case of a partial stator winding short-circuit, closing either the upper or lower pairs of switches in the phase makes the phase appear fully shorted.

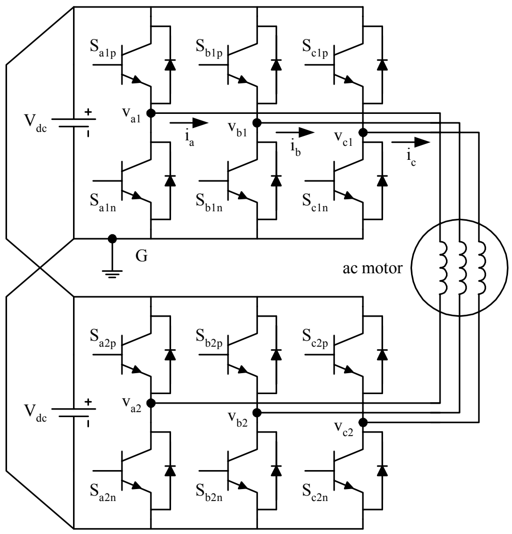

Fig. 1. Cascaded converter with connected dc links.

A. Control Method Derivation

In the presence of a short-circuit fault, it is desirable to make the current in the faulted phase as small as possible. Therefore, it is required to make the flux linkage in the shorted phase as constant as possible. From the machine model of an IPM motor, the flux linkages are given as

$$\lambda_d^e = L_d\, i_d^e + \Psi_{mag} \tag{1}$$

$$\lambda_q^e = L_q\, i_q^e \tag{2}$$

$$\lambda_0^e = L_0\, i_0^e\,, \tag{3}$$

where the superscript e indicates the synchronous reference frame.

Since the fault occurs in the stationary frame, it is necessary to transform the synchronous fluxes back to the stationary reference frame, indicated by the superscript, s. Applying the transformation gives

$$\lambda_d^s = -\left(\sin\theta_e\right)L_q\, i_q^e + \left(\cos\theta_e\right)\left(L_d\, i_d^e + \Psi_{mag}\right) \tag{4}$$

$$\lambda_q^s = \left(\cos\theta_e\right)L_q\, i_q^e + \left(\sin\theta_e\right)\left(L_d\, i_d^e + \Psi_{mag}\right) \tag{5}$$

$$\lambda_0^s = L_0\, i_0^e\,. \tag{6}$$

It will be assumed that the fault occurs in phase a. From the reference frame definitions and (4) − (6), the phase a flux linkage is given as

$$\lambda_a = -\left(\sin\theta_e\right)L_q\, i_q^e + \left(\cos\theta_e\right)\left(L_d\, i_d^e + \Psi_{mag}\right) + L_0\, i_0^e\,. \tag{7}$$

The simplest case of a constant flux linkage in phase a occurs when the flux in the phase is zero. Using this, (7) can be rearranged as

$$\Psi_{mag}\cos\theta_e = L_q\, i_q^e\sin\theta_e - L_d\, i_d^e\cos\theta_e - L_0\, i_0^e\,. \tag{8}$$

Equation (8) indicates the conditions required to yield a phase a flux linkage of zero. Since the zero sequence inductance of the motor is typically quite small when compared to either the q- or d-axis inductance, it can momentarily be neglected for the proceeding control method. As a result, (8) simplifies to

$$\Psi_{mag}\cos\theta_e = L_q\, i_q^e\sin\theta_e - L_d\, i_d^e\cos\theta_e\,. \tag{9}$$

Setting the q-axis current to zero,

$$i_q^e = 0, \tag{10}$$

and solving (9) for the d-axis current yields

$$i_d^e = -\frac{\Psi_{mag}}{L_d}\,. \tag{11}$$

Equation (11) indicates that setting the d-axis current to the motor's characteristic current will null the magnet flux. Without a q-axis current (10), the net torque of the motor will be zero. This result is a significant improvement over the previously proposed method of creating a symmetrical three-phase short-circuit as a response to short-circuit type faults. The symmetrical three-phase short-circuit produced a potentially significant amount of braking torque [4], while this proposed method produces zero torque.

The solution given in (10) and (11) represents the ideal case since it was assumed that L_0 was negligible. Consider the current in the shorted phase which results from employing the solutions given in (10) and (11). From the reference frame transformations, the stationary frame current in the faulted phase is

$$i_a^{s*} = i_d^{s*} + i_0^{s*}\,. \tag{12}$$

where the * superscript indicates a desired or reference quantity. Equation (12) indicates that current in the faulted phase is composed of two components. Only one of these components, i_d^{s*}, is given by the proposed control algorithm. As a result, the flexibility afforded by the zero sequence current command can be utilized. One possibility is to set $i_0^{s*} = 0$. In this case, the resulting current in the faulted phase would be non-zero. In particular, the current in the faulted phase would be sinusoidal, with amplitude equal to the motor's characteristic current, Ψ_{mag}/L_d. Another possibility is to utilize a zero sequence current to null the current in the faulted phase. Setting (12) to zero and solving yields

$$i_0^{s*} = -\,i_d^{s*}\,. \tag{13}$$

Utilizing the zero sequence current command given by (13) will result in an effective zero current command for the faulted phase. This is very beneficial in the case of a partially shorted stator winding, as any current could produce locally elevated temperatures near the short-circuit. A drawback is that the remaining healthy phases will have to carry an increase in current. Overall, the current increases by $\sqrt{3}$ in the two

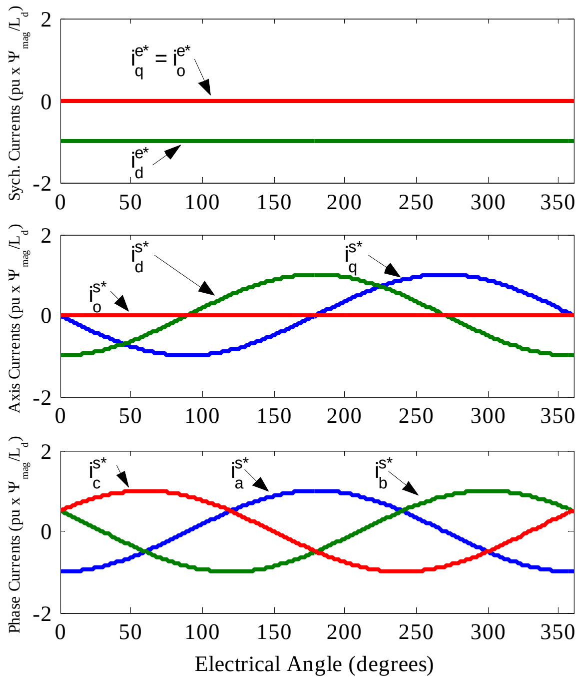

Fig. 2. Idealized flux nulling current commands without a zero sequence current command.

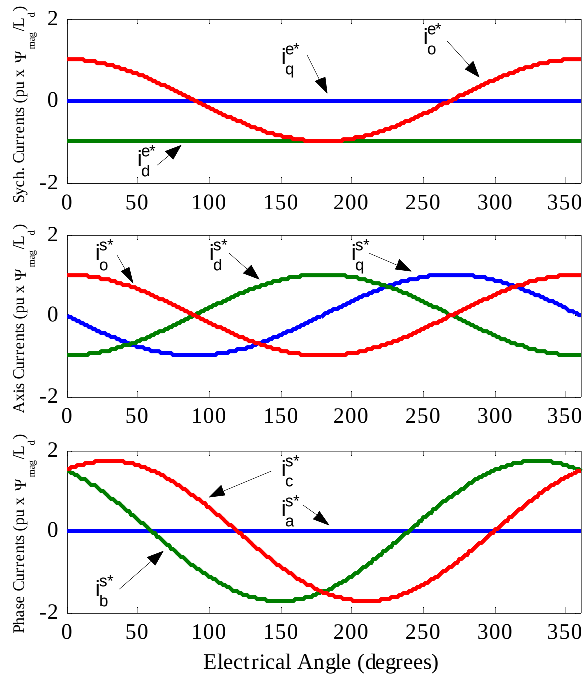

Fig. 3. Idealized flux nulling current commands with a zero sequence current command.

healthy phases. Fig. 2 and Fig. 3 graphically illustrate the (idealized with $L_0 = 0$) required current commands for both methods. In particular, Fig. 2 shows the current waveforms for a zero sequence current command of zero, while Fig. 3 shows the required waveforms when employing a zero sequence current, in order to zero out the current in the shorted phase. When observing the figures, it is important to remember that a zero sequence current in the synchronous frame will not, in general, be a dc quantity. The zero sequence current is mathematically the same in both the stationary and synchronous frames. As a result, it would only be possible to have a constant zero sequence current (in both stationary and synchronous frames) if a dc offset current were added to each phase.

B. Practical Considerations

The proposed control method to null the magnet flux following a short-circuit fault on one phase of the motor, had the very desirable effect of also nulling the post-fault torque. It could be considered that eliminating the post-fault torque is the ultimate goal as opposed to mitigating the magnet flux. So why is nulling the magnet flux the preferred solution? In order to null the torque, it is necessary to control the *d*- and *q*-axis currents to zero. While possible to control both axis currents to zero, large voltages would be necessary, since the required terminal voltage would increase with speed due to the magnet flux. As a result, it is not possible to control the currents to zero if the magnet content of the motor would place the motor's back-emf voltage above what could be generated by the dc link. Furthermore, a very large zero sequence voltage, and hence, current, would be induced if a zero sequence path exists in the inverter topology employed, such as the one shown in Fig. 1. Since the magnet flux nulling technique cancels out the back-emf, only a small nominal applied voltage is needed, which is independent of the motor's speed.

III. PHASE CURRENT CONTROL

In order to control the current in each of the remaining healthy phases, individual proportional plus integral (PI) type current regulators were employed as shown in Fig. 4. The current regulators were tuned to a bandwidth of 550 Hz and employed the gains indicated in TABLE I. Employing individual regulators on each phase will allow the current trajectories presented in Fig. 2 to be achieved when the zero sequence current is commanded to be zero. The two healthy phases will be controlled in this situation and the phase coupling present in the machine will induce nearly sinusoidal currents in the shorted phase. By including a zero sequence current command to the regulators, the current trajectories of Fig. 3 can be achieved. Since the phase current regulators act independently, the *d*- and *q*-axis currents are not directly controlled. As a result, a transient voltage will appear across the machine inductances and a parasitic torque will be developed.

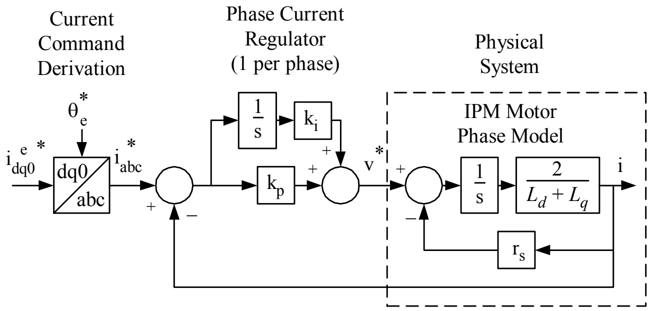

Fig. 4. Phase current regulator.

TABLE I
PHASE CURRENT REGULATOR GAINS

Current Regulator	Proportional Gain k_p (Ohms)	Integral Gain k_i (Ohms/second)
b- and *c*-axis	0.69	36

IV. SIMULATION AND EXPERIMENTAL RESULTS

The proposed control algorithm to null the magnet flux and torque following a short-circuit fault in phase *a*, was simulated in Simulink® with data post-processing in MATLAB®. The IPM motor of [10] was used, and parameters for this motor are given in the Appendix. The proposed control method was also verified experimentally using the same motor whose parameters were used for the simulations. However, as proposed, the flux nulling control method employs a six-leg inverter. The available experimental dynamometer setup employed a standard three-phase, three-leg inverter. As a result, it was necessary to reconfigure the system in order to test the flux nulling control method.

Fig. 5 shows how the experimental test setup was configured to test the flux nulling control method. The motor has access to each end of the motor phases (six-wire connections) so the necessary changes could be accommodated without affecting anything internal to the motor. Phase *a* of the motor was externally shorted together as shown, which represents purposeful commanding of a single-phase short-circuit by the inverter in response to a single-switch short-circuit or detection of a stator winding short-circuit fault. The center points, *s*, of phases *b* and *c*, were tied together and connected to the traditional phase *a* output of the inverter. This allows for independent control of the currents in phases *b* and *c*. For the tests, all three of the phase currents were measured as shown in the figure, and used by the controller as needed. A traditional carrier based PWM method was used for the active phases *b* and *c*, while the *s*-leg of the inverter was set for a 50% duty cycle to emulate that phase being connected to the center point of the dc link. Due to the modified connection of the test setup, it was only possible to test the steady-state characteristics of the proposed flux-nulling control method. The speed was controlled externally by the dynamometer.

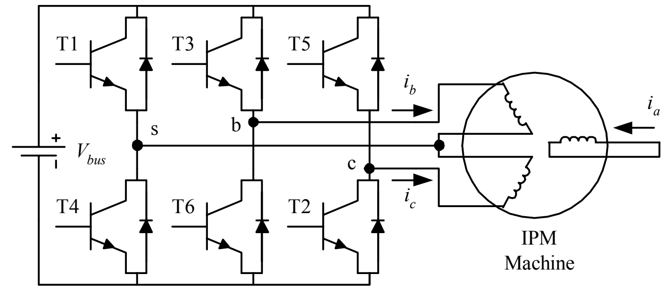

Fig. 5. Experimental drive configuration.

Fig. 6 and Fig. 7 show the measured and simulated time domain results for the flux nulling control with a zero sequence current command of $i_0^{s*} = -\, i_d^{s*} = 0$ A. The estimated torque presented in the figures was calculated based on the measured synchronous frame currents and estimated motor parameters. Low speed operation at $\omega_r = 150$ rpm is presented in Fig. 6 while higher speed operation at 1000 rpm is presented in Fig. 7. With the zero sequence current set to zero, a current nearly equal in amplitude to the characteristic current is induced in the shorted phase. At low speed, some distortion from an idealized sinusoid is clearly visible. At 1000 rpm, the current is nearly sinusoidal as the increased impedance of the zero sequence at elevated operating frequencies serves to smooth out the induced current.

The synchronous frame *dq0* currents are not well regulated quantities, especially at 150 rpm. However, this is expected as they are only indirectly controlled. Since the *d* and *q* currents are not constant, a pulsating torque is produced by the motor. This varies up to 5 Nm at 150 rpm, but only up to 1 Nm at 1000 rpm. The torque developed is a breaking torque in both cases.

Fig. 8 and Fig. 9 show the measured and simulated results of the magnet flux nulling control using phase control and a zero sequence command of $i_0^{s*} = -\, i_d^{s*} = -91$ A_{peak} in order to null the current in the shorted phase. The actual value of characteristic current for the tested system is 91.3 A, but the test setup had a command resolution of 1 A. The experiments verify the simulations which show the induced current in the shorted phase can be substantially reduced by the addition of the zero sequence current command. Overall, the peak induced current has been reduced to 44 and 60 A_{peak} compared to 75 and 87 A_{peak} without the zero sequence command at 150 and 1000 rpm. The tested machine had a large value of zero sequence inductance, 45% of the value of the *d*-axis inductance. This relatively high value of zero sequence inductance is the reason for the difference from the idealized waveforms given in Fig. 2 and Fig. 3.

The torque induced when a zero sequence is utilized is also pulsating in nature, although its value is still modest at less than 3 Nm peak. Overall, the experimental waveforms are in close agreement with the simulated results, verifying the proposed magnet flux nulling control algorithm.

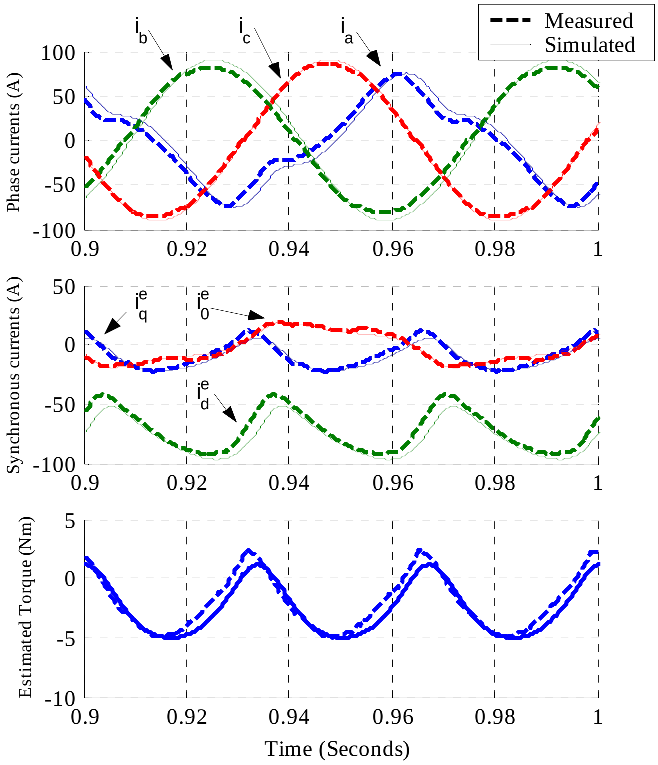

Fig. 6. Experimental and simulated results without a zero sequence at ω_r = 150 rpm.

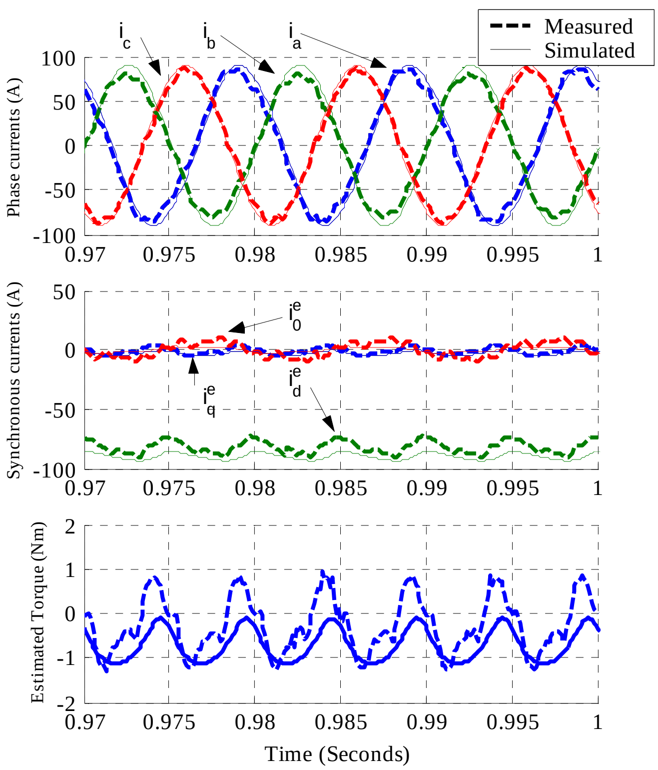

Fig. 7. Experimental and simulated results without a zero sequence at ω_r = 1000 rpm.

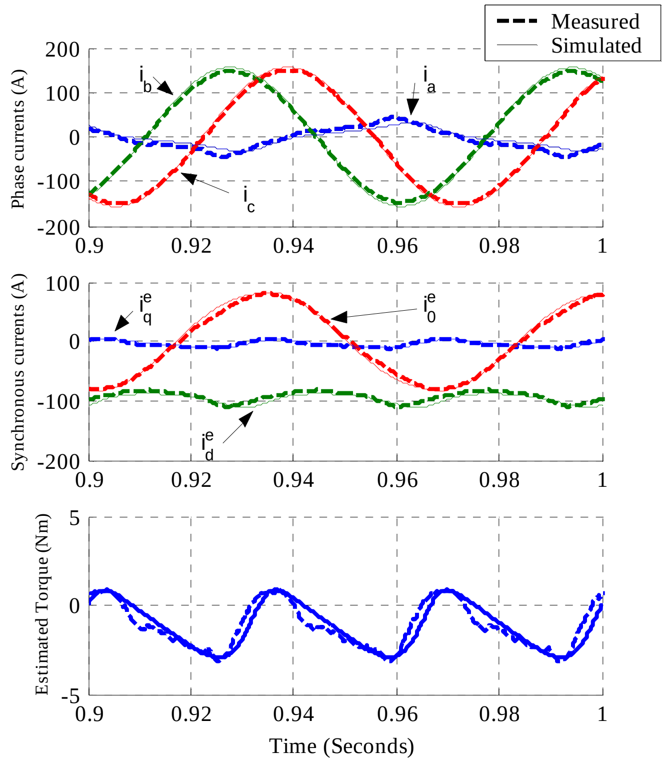

Fig. 8. Experimental and simulated results with a zero sequence at ω_r = 150 rpm.

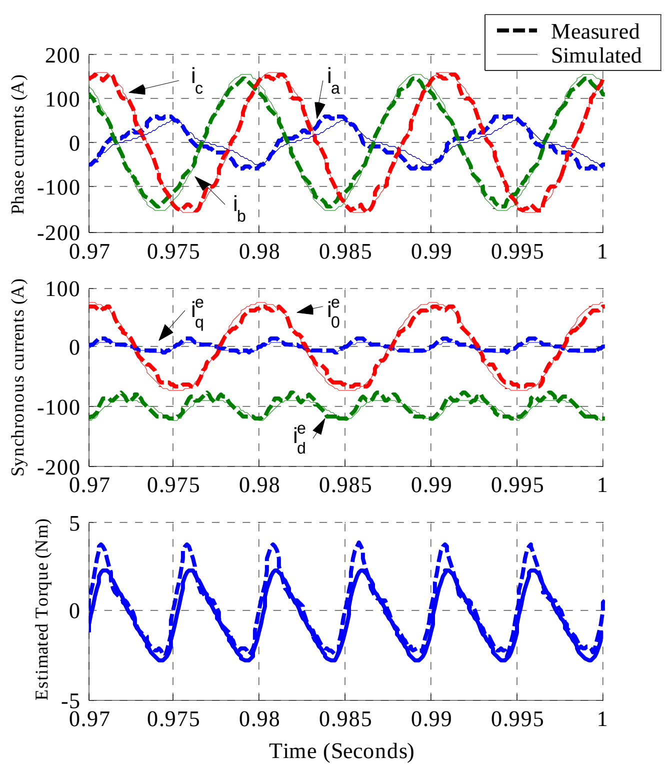

Fig. 9. Experimental and simulated results with a zero sequence at ω_r = 1000 rpm.

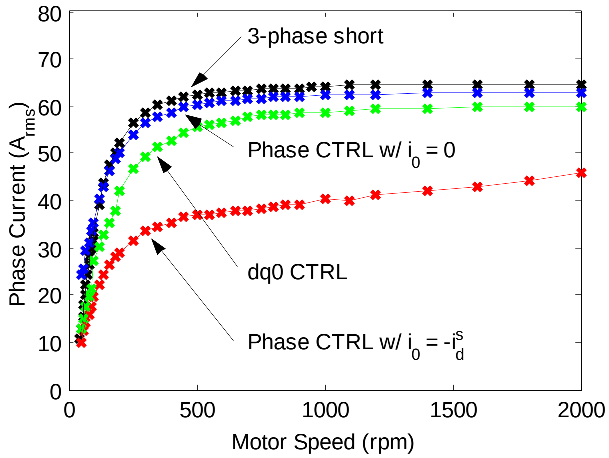

Fig. 10. Measured steady-state current in the shorted phase *a* for different post-fault control methods.

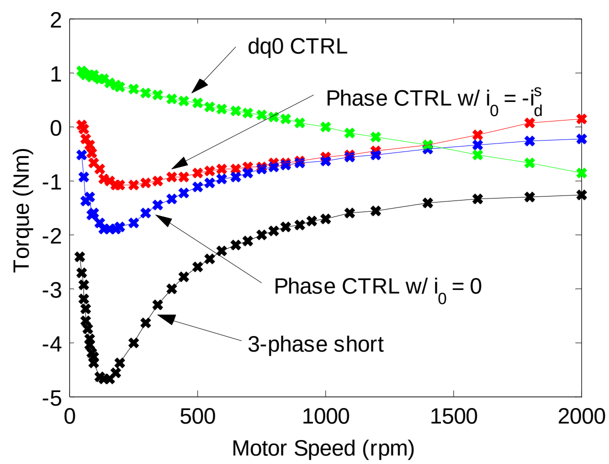

Fig. 11. Measured steady-state motor torque for different post-fault control methods.

Fig. 10 and Fig. 11 compare the three different possible implementations of the proposed flux nulling control algorithm in response to short-circuit type faults. As a baseline, the response from creating a symmetrical three-phase short-circuit is also included. Fig. 10 shows that the measured current induced in the shorted phase, employing the flux nulling method using phase control without a zero sequence command produces about the same response as the symmetrical three-phase short. That is, the current in the shorted phase asymptotes out to the characteristic current as the speed increases. In contrast, implementing the flux nulling method with synchronous frame *dq0* control [8] and phase control with a zero sequence command results in a smaller induced current. Using phase control with a zero sequence results in the smallest induced current in the shorted phase. For the tested system, this current was approximately 60% of the value of the symmetrical three-phase short-circuit response. In general, this value is proportional to the value of zero sequence inductance. It should be noted that the measured values are being compared in terms of rms values since the induced fault currents are not perfectly sinusoidal due to the slotting effects from both the stator winding and rotor magnet cavities.

In terms of post-fault induced torque, Fig. 11 shows that any implementation of the flux nulling control method results in a smaller post-fault induced torque when compared to creating a symmetrical three-phase short-circuit as a post-fault control action. Employing phase control with a zero sequence current command produced a slightly smaller induced toque compared without using a zero sequence command. Employing a zero sequence current does have the drawback of increasing the current required in the healthy phases. As a result, it can only be employed in systems where the characteristic current is less than $1/\sqrt{3}$ the value of the rated inverter current. In general, the phase control methods produced a torque envelope with approximately the same shape as that of the symmetrical short-circuit. This is likely due to the difficulty in controlling a time varying command with traditional proportional plus integral controllers as were employed in this paper. The synchronous frame controller produced more consistent results, with the torque linearly decreasing due to increased iron losses as the speed increased.

V. Conclusions

This paper has proposed implementing a control method to null the magnet flux in an interior permanent magnet motor following a short-circuit type fault using individual PI type phase current regulators. The control method creates a short-circuit in the faulted phase via control action of a six-leg inverter. Using the remaining two healthy phases, the phase current regulators control the current to null the magnet flux in the motor. Due to the nature of the phase current regulators, it is possible to employ a zero sequence current command to further reduce the current induced in the faulted phase due to the inherent zero sequence inductance in the machine. Control of the zero sequence with the flux nulling control algorithm was previously not possible when synchronous *dq0* current regulators were used. It was also experimentally demonstrated that the post-fault induced torque could be significantly reduced employing the proposed method compared with previous techniques of applying a symmetrical three-phase short-circuit in the post fault condition.

Overall, this paper has demonstrated an improved method to handle short-circuit type faults in permanent magnet motors as it has shown the post-fault induced torque and current could be reduced. However, the area of short-circuits remains a difficult subject as the methods highlighted here impose a cost burden due to the inverter structure which was required.

Appendix
Interior PM Machine Parameters

3 phase, 6 kW peak at 6000 rpm, 12 pole machine with

$r_s \approx 0.0103\ \Omega$ $\quad \Psi_{mag} \approx 5.91$ mW$_{rms}$ $\quad L_d \approx 91.5\ \mu$H
$L_{qmax} \approx 305\ \mu$H $\quad L_0 \approx 41.2\ \mu$H
$C_1 \approx 0.0058$ H/A $\quad C_2 \approx -0.605$

where the *q*-axis inductance is approximated as

$$L_q \approx L_{qmax} \text{ or } C_1 \left| i_q^e \right|^{C_2}$$

whichever is smaller.

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REFERENCES

[1] W. L. Soong, *"Design and modeling of axially-laminated interior permanent magnet motor drives for field-weakening applications,"* Ph.D. Dissertation, Dept. of Electronics and Elec. Eng., Univ. of Glasgow, Glasgow, U.K., Sept. 1993.

[2] T. M. Jahns, G. B. Kliman, and T. W. Neuman, "Interior PM synchronous motors for adjustable speed drives," *IEEE Trans. Ind. Applicat.*, vol. IA-22, no. 4, pp. 738-747, July/August 1986.

[3] N. Bianchi, S. Bolognani, and M. Zigliotto, "Analysis of PM synchronous motor drive failures during flux weakening operation," in *Conf. Rec. IEEE PESC*, 1996. pp. 1542-1548.

[4] B. A. Welchko, T. M. Jahns, W. L. Soong, and J. M. Nagashima, IPM synchronous machine drive response to symmetrical and asymmetrical short circuit faults," *IEEE Trans. Energy Conversion*, vol. 18, no. 2, pp. 291-298, June 2003.

[5] J. A. Haylock, B. C. Mecrow, A. G. Jack, and D. J. Atkinson, "Operation of fault tolerant machines with winding failures," *IEEE Trans. Energy Conversion*, vol. 14, no. 4, pp. 1490-1495. Dec. 1999.

[6] D. Qin, X. Lua, and T. A. Lipo, "Reluctance motor control for fault-tolerant capability," in *Conf. Rec. IEEE IEMDC*, 1997, pp. WA1-1.1-WA1-1.6.

[7] S. Bolognani, M. Zordan, and M. Zigliotto, "Experimental fault-tolerant control of a PMSM drive," *IEEE Trans. Ind. Electronics*, vol. 47, pp. 1134–1141, Oct. 2000.

[8] B. A. Welchko, T. M. Jahns, and T. A. Lipo, "Short-circuit fault mitigation methods for interior PM synchronous machine drives using six-leg inverters," in *Conf. Rec. IEEE PESC*, 2004, June 20-25, Aachen, Germany.

[9] B. A. Welchko, *"Contributions to the reduced cost and increased reliability of permanent magnet synchronous machine drives,"* Ph.D. Dissertation, Dept. Elec. Comp. Engineering, Univ. of Wisconsin, Madison, WI, 2003.

[10] E. C. Lovelace, T. M. Jahns, J. Wai, T. Keim, J. H. Lang, D. D. Wentzloff, F. Leonardi, J. M. Miller, and P. J. McCleer, "Design and experimental verification of a direct-drive interior PM synchronous machine using a saturable lumped-parameter model," in *Conf. Rec. IEEE IAS Annual Meeting*, 2002, vol. 4, pp. 2486-2492.