# Magnet-Flux-Nulling Control of Interior PM Machine Drives for Improved Steady-State 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-based 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-based control results in a smaller induced current than when employing a synchronous-frame $dq0$ current regulator. The induced torque is also less than that when 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 current on the resulting phase currents is presented. Both simulation and experimental results are presented, verifying the operation of the proposed methods.**

***Index Terms*—Current regulation, inverter shutdown, magnet flux, short-circuit fault, variable-speed drive.**

## 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 linkage 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 originating in either the machine or the electronic drive, the magnets' location in the spinning rotor becomes a source of flux that 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 can induce elevated local temperatures inside the motor, and if sustained, can result in failure of the machine.

Several methods to handle short-circuit faults have been reported in the literature. One method incorporates major motor-design modifications so that the motor phases are electrically and magnetically isolated from one another [5]. While effective, the electronic-drive cost is increased significantly and the design changes in the motor will likely reduce its power density and increase its manufacturing cost compared to a more traditional three-phase motor. Incorporating fault-isolating devices within the inverter structure has also been proposed in [6]. Employing single-phase inverters powering each phase of the motor with an alternative control strategy has been shown to be effective for synchronous reluctance machines during short-circuit faults [7]. Overall, the inclusion of fault-isolating devices imposes a severe silicon overrating cost penalty, while employing a six-leg inverter imposes only a modest 15% increase in the required silicon kilovolt ampere rating [8]. Therefore, a fault-tolerant method based around a six-leg inverter represents a desirable alternative to more complex inverter circuits and motor designs.

In [9], a synchronous-frame control method to cancel the magnet-flux linkage was proposed so that the system fault response would be a zero-torque response. This paper proposes employing stationary-frame phase-based control to implement the magnet-flux-nulling-control method using a standard IPM motor and six-leg inverter. 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-circuited phase 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 current on the resulting phase currents is presented. Both simulation and experimental results are presented to verify the desired operating characteristics of the proposed methods.

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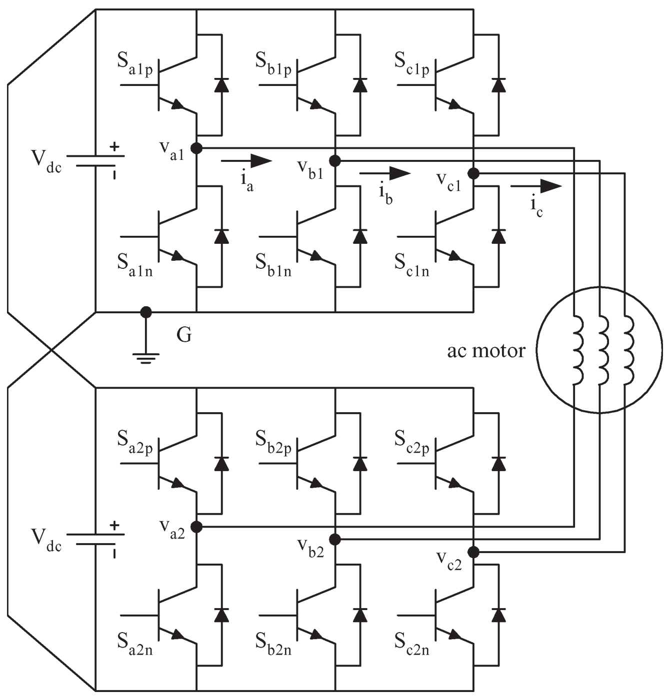


Fig. 1. Cascaded six-leg converter with connected dc links.

## 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 [9], [10] 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 if switches $S_{a1n}$ and $S_{a2n}$, or $S_{a1p}$ and $S_{a2p}$ are gated ON. The assumption of having one phase completely shorted 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.

### 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

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

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

$$\lambda_0 = L_0 i_0 \tag{3}$$

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

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

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

$$\lambda_0 = L_0 i_0. \tag{6}$$

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

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

The simplest case of a constant flux linkage in phase $a$ occurs when the flux linkage in the phase is 0. Using this, (7) can be rearranged as

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

Equation (8) indicates the conditions required to yield a phase $a$ flux linkage of 0. The zero-sequence inductance of the motor $L_0$ is typically small when compared to either the $q$- or $d$-axis inductance, and its value is often not conveniently available. In light of these circumstances, the control algorithm is developed under the simplifying assumption that $L_0 = 0$ (the impact of this assumption is explored later in this paper). Applying this assumption, (8) simplifies to

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

The asterisks $^*$ are included in the superscripts for the $dq$ current components to indicate that these are command (i.e., reference) values determined under the simplifying assumption of $L_0 = 0$. Setting the $q$-axis current to 0

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

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

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

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 ideally be 0. 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 produces a potentially significant amount of braking torque [4] at low speeds, while this proposed method ideally produces zero torque.

The solution given in (10) and (11) represents the ideal case since it assumes that $L_0 = 0$; this is typically not the

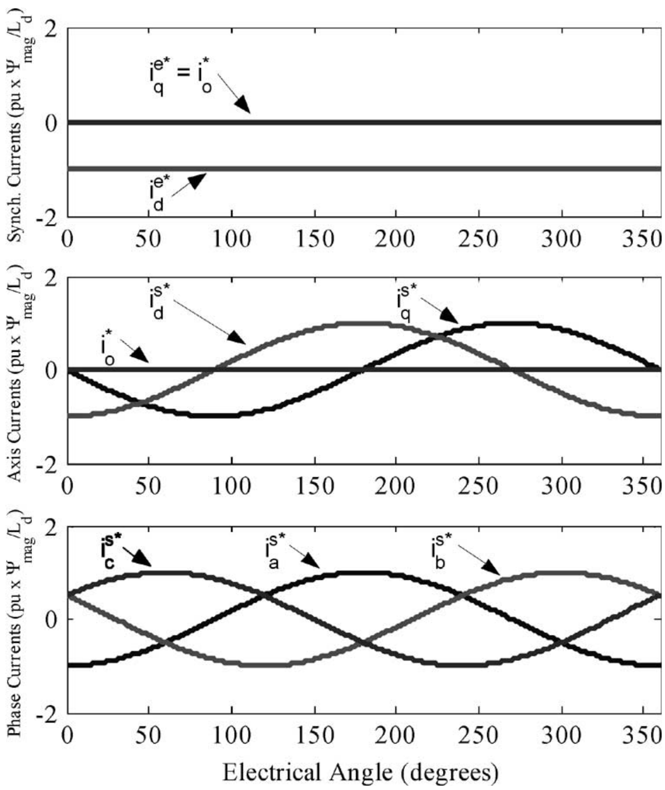


Fig. 2. Idealized flux-nulling current commands without a zero-sequence current command.

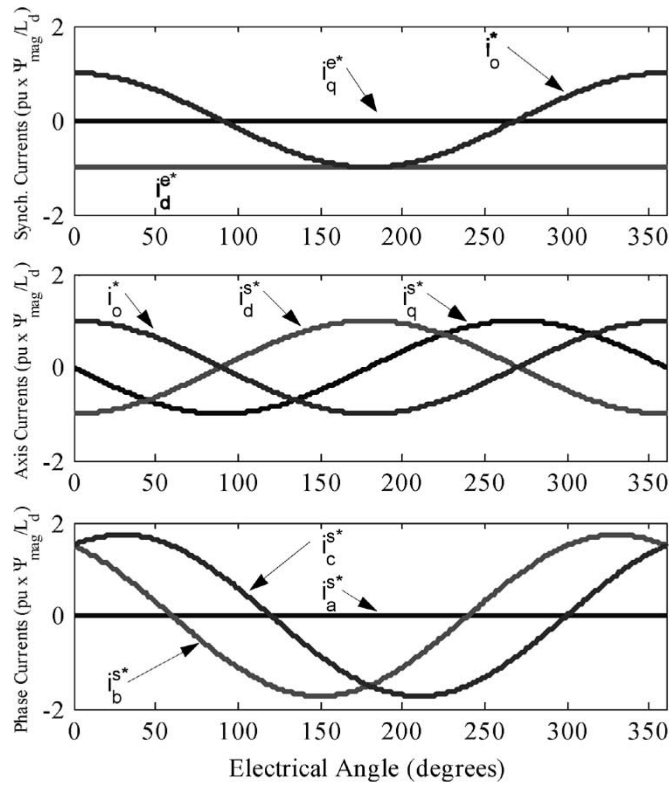


Fig. 3. Idealized flux-nulling current commands with a zero-sequence current command.

case for motors with a conventional distributed stator winding. Although useful as a simplification, the assumption introduces errors that cause the actual $dq$ currents to diverge from their command values in (10) and (11). The amplitudes of the resulting errors are quantified later in Section IV.

Consider the current in the shorted phase that results from employing the solutions given in (10) and (11). From the reference-frame transformations, the commanded stationary-frame current in the faulted phase is

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

Equation (12) indicates that the commanded current in the faulted phase is composed of two components. Only one of these components ($i_d^{s^*}$) is explicitly 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 $i_0^* = 0$. In this case, the resulting commanded current in the faulted phase is nonzero. More specifically, the commanded current in the faulted phase is sinusoidal, with amplitude equal to the motor's characteristic current $\Psi_{\text{mag}}/L_d$.

Another possibility is to utilize a zero-sequence current to null the current in the faulted phase. Setting (12) to 0 and solving yields

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

Utilizing the zero-sequence current command given by (13) results in a zero-amplitude current command for the faulted phase (i.e., $i_a^{s^*} = 0$). This is very beneficial in the case of a partially shorted stator winding, since any current may produce locally elevated temperatures near the short circuit.

Figs. 2 and 3 graphically illustrate the (idealized with $L_0 = 0$) resulting current commands for both methods. In particular, Fig. 2 shows the current waveforms for a zero-sequence current command of 0 (i.e., $i_0^* = 0$), while Fig. 3 shows the required waveforms when employing a zero-sequence current to drive the current in the shorted phase to 0.

When observing the figures, it is important to remember that a zero-sequence current will not, in general, be a dc quantity. The zero-sequence current is identical 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.

From the figures, it can be seen that when utilizing a zero-sequence current command, the remaining healthy phases will have to carry increased current. Overall, the current increases by $\sqrt{3}$ in the two healthy phases. As a result, utilizing a zero-sequence current command is only practical for systems where the characteristic current is less than $1/\sqrt{3}$ the value of the rated inverter current so that the overall inverter current rating is not exceeded. In systems with a characteristic current larger than $1/\sqrt{3}$ the value of the rated inverter current, a reduced zero-sequence command will still allow for zero commanded torque with all of the currents constrained to fall within their rated values. However, nonzero current will be induced in the shorted phase.

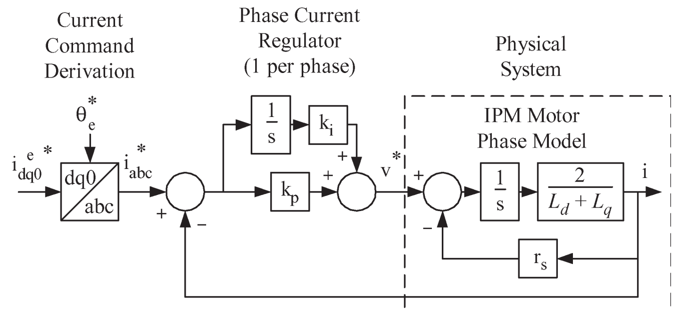


Fig. 4. Phase-current regulator.

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 |

The presence of a zero-sequence inductance in a practical system will cause some distortion from the idealized curves of Figs. 2 and 3, as will be shown and discussed in Section IV.

### B. Practical Considerations

The proposed control method to null the magnet flux following a short-circuit fault on one phase of the motor has the very desirable effect of also nulling the postfault torque. Some might consider elimination of the postfault torque to be the ultimate goal, as opposed to mitigating the magnet flux.

So why is nulling the magnet flux an important objective? If the $d$-axis current were controlled to be 0 (i.e., $i_d^e = 0$), large inverter output voltages would be necessary since the terminal voltage increases with speed due to the back electromotive force (EMF) generated by the magnet flux. Depending on the machine design and the required constant-power speed range, the magnet-flux linkage can cause the back-EMF voltage amplitude to significantly exceed the nominal dc-link voltage at high speeds.

Furthermore, a very large zero-sequence voltage, and hence, current, can be induced if a zero-sequence circuit path exists in the inverter topology, such as the one shown in Fig. 1. This condition is attributable to the fact that the current regulator in the faulted system has only two degrees of freedom when one of the phases is shorted, making it impossible to independently control all three $dq0$ current components.

In contrast, the magnet-flux-nulling technique uses $d$-axis current to cancel out the back EMF so that only a small nominal voltage must be applied by the inverter, independent of the motor speed.

## III. PHASE-CURRENT CONTROL

In order to control the current in each of the remaining healthy phases, individual proportional-plus-integral (PI) 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.

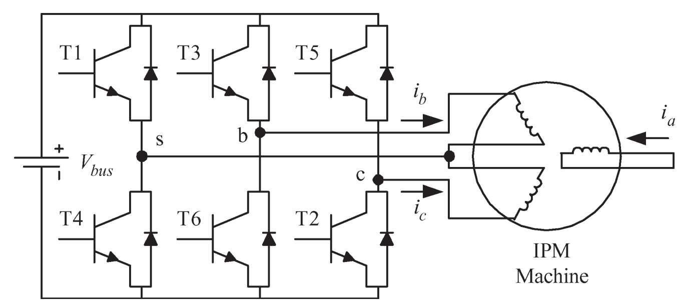


Fig. 5. Experimental drive configuration.

Employing individual regulators for each phase makes it possible for the controller to strive for the idealized current trajectories presented in Fig. 2 when the zero-sequence current is commanded to be 0. The two healthy phases are actively controlled in this situation and the phase coupling present in the machine will induce nearly sinusoidal currents in the shorted phase.

By delivering a zero-sequence current command to the regulators, the idealized current trajectories of Fig. 3 can nearly be achieved. Since only two of the three phase currents can be actively regulated when one of the phases is short circuited, the $d$- and $q$-axis currents are not directly controlled.

As a result of the simplifying assumption that $L_0 = 0$, the $q$-axis current is not controlled to be exactly 0, and parasitic torque will be developed. The amount of torque produced ultimately depends on the system parameters, and closed-form expressions to calculate this residual torque have not been developed for this paper. However, test results provided in Section IV show that the amplitude of this torque is rather modest.

## IV. SIMULATION AND EXPERIMENTAL RESULTS

The proposed control algorithm to null the magnet flux and suppress the braking torque following a short-circuit fault in phase $a$ was simulated using Simulink with data postprocessing in MATLAB. A 6-kW IPM machine developed for an automotive direct-drive starter/alternator application [11] was used in this simulation, and parameters for this machine are summarized in the Appendix. The proposed control method was also verified experimentally using the same machine. However, the proposed 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 the reconfigured experimental test setup that was used to test the flux-nulling-control method. The machine stator provides access to each end of the motor phase windings (six-wire connections), so the necessary changes could be accommodated without changing any internal machine connections.

The two leads of the phase $a$ stator winding were externally shorted together as shown to create the short-circuit conditions corresponding to a terminal winding fault, or the inverter's response to a single-switch short-circuit fault in one of the

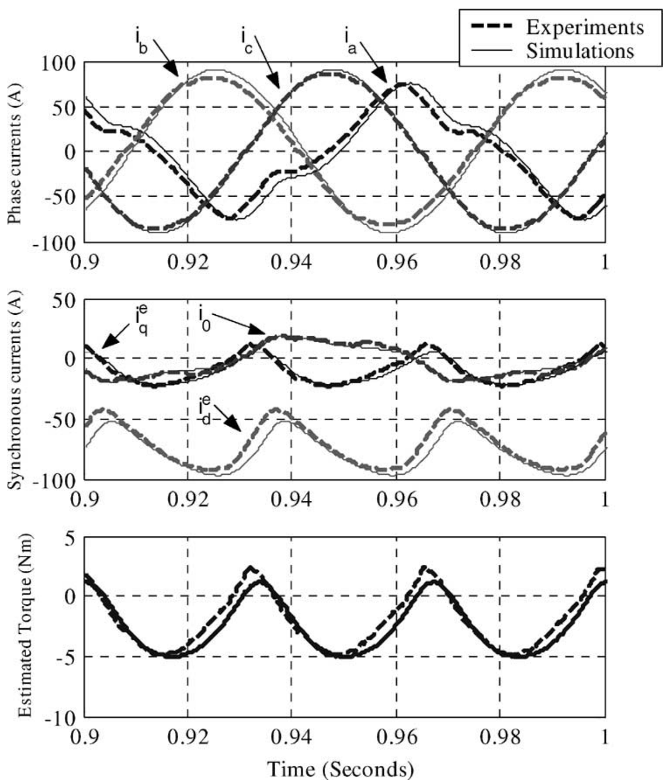


Fig. 6. Experimental and simulated results for the phase-based control method without a zero-sequence current command at $\omega_{\mathrm{r}} = 150$ r/min.

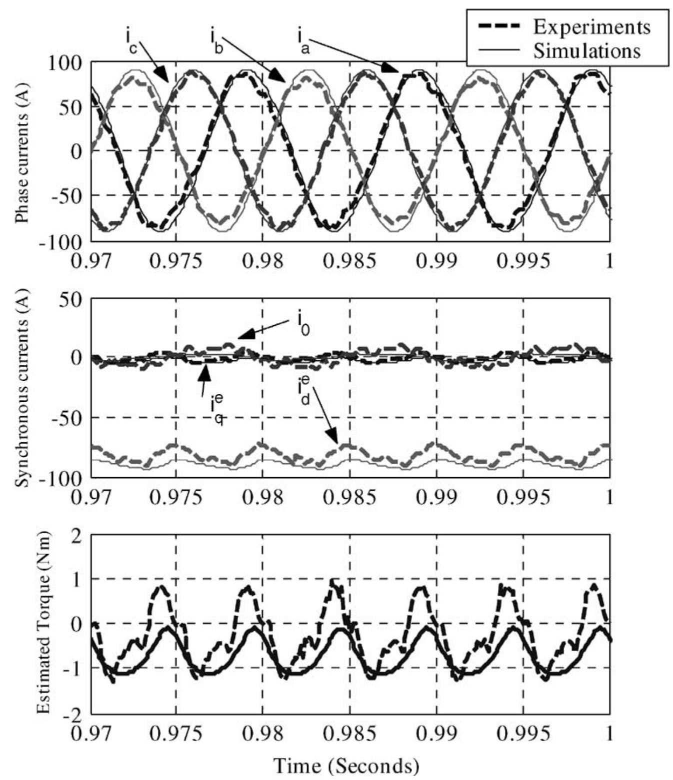


Fig. 7. Experimental and simulated results for the phase-based control method without a zero-sequence current command at $\omega_{\mathrm{r}} = 1000$ r/min.

six inverter phase legs. The center points $s$ of machine phases $b$ and $c$ were tied together and connected to the phase $a$ inverter output. This makes it possible for the inverter to provide independent control of the currents in phases $b$ and $c$.

For the tests, all three of the phase currents were measured as shown in Fig. 5 and used by the controller as needed. A traditional carrier-based pulsewidth-modulation (PWM) method was used for the active phases $b$ and $c$, while the $s$-leg of the inverter was controlled to deliver a fixed 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 operating characteristics of the proposed flux-nulling-control method. The speed was controlled externally by the dynamometer. The inverter control system was implemented on a dSPACE platform.

The phase-current regulators were implemented as described in Section III. A cross-coupling decoupling synchronous-frame $dq0$ current regulator tuned to a bandwidth of 700 Hz was employed when $dq0$ control results were obtained [9], [12].

Figs. 6 and 7 show the measured and simulated time-domain results for the flux-nulling control with a zero-sequence current command of $i_0^* = -i_d^{\mathrm{s}^*} = 0$ A. The estimated time-varying torque presented in the figures (Figs. 6–9) was calculated based on the measured synchronous-frame currents and estimated machine parameters. Low-speed operation at $\omega_{\mathrm{r}} = 150$ r/min is presented in Fig. 6, while higher speed operation at 1000 r/min is presented in Fig. 7.

With the zero-sequence current command set to 0, a current nearly equal in amplitude to the machine's characteristic current is induced in the shorted phase. At low speed, some distortion from an idealized sinusoid is clearly visible. At 1000 r/min, the current is nearly sinusoidal because the increased impedance of the zero-sequence circuit at elevated operating frequencies serves to smooth out the induced current.

The synchronous-frame $dq0$ currents are not well-regulated quantities, especially at 150 r/min. 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. The peak amplitude of this pulsating torque is 5 $\mathrm{N \cdot m}$ at 150 r/min, but only 1 $\mathrm{N \cdot m}$ at 1000 r/min. The average torque developed is a braking torque in both cases, reaching amplitudes that are only a few percent of the machine's torque capability of 150 $\mathrm{N \cdot m}$ under starting conditions (up to approx. 500 r/min) [11].

Figs. 8 and 9 show the measured and simulated results for the magnet-flux-nulling control using control of the individual phases and a zero-sequence current command of $i_0^* = -i_d^{\mathrm{s}^*} = -91$ $\mathrm{A_{peak}}$ in order to null the current in the shorted phase. The actual value of characteristic current for the tested machine is 91.3 A, but the test setup had a command resolution of 1 A.

The experiments verify the simulation results, demonstrating that the induced current in the shorted phase can be substantially reduced by the addition of the zero-sequence current command. Overall, the peak amplitude of the induced current in the shorted winding has been reduced to 44 and 60 $\mathrm{A_{peak}}$ compared to 75 and 87 $\mathrm{A_{peak}}$ without the zero-sequence command at 150 and 1000 r/min. The tested machine has a large value of zero-sequence inductance equal to 45% of the value of the

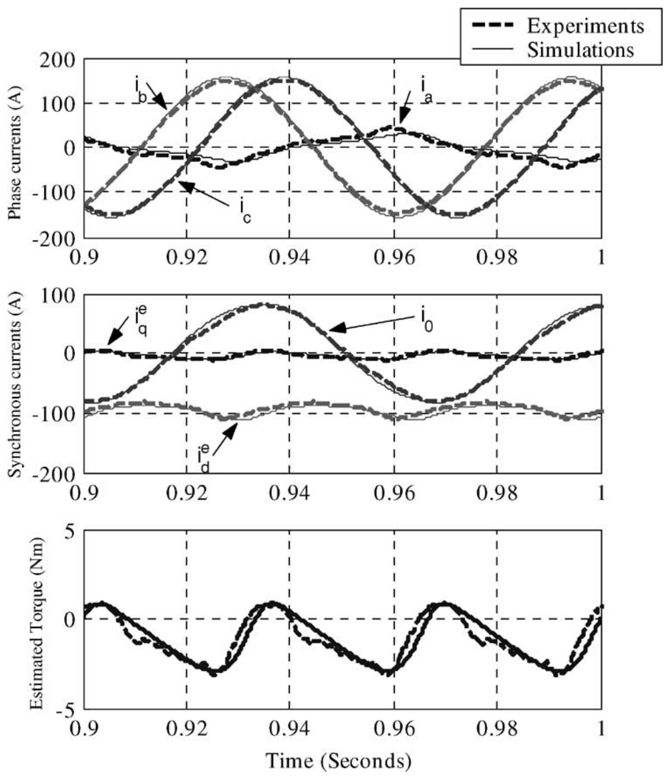


Fig. 8. Experimental and simulated results for the phase-based control method with an imposed zero-sequence current command at $\omega_\mathrm{r} = 150$ r/min.

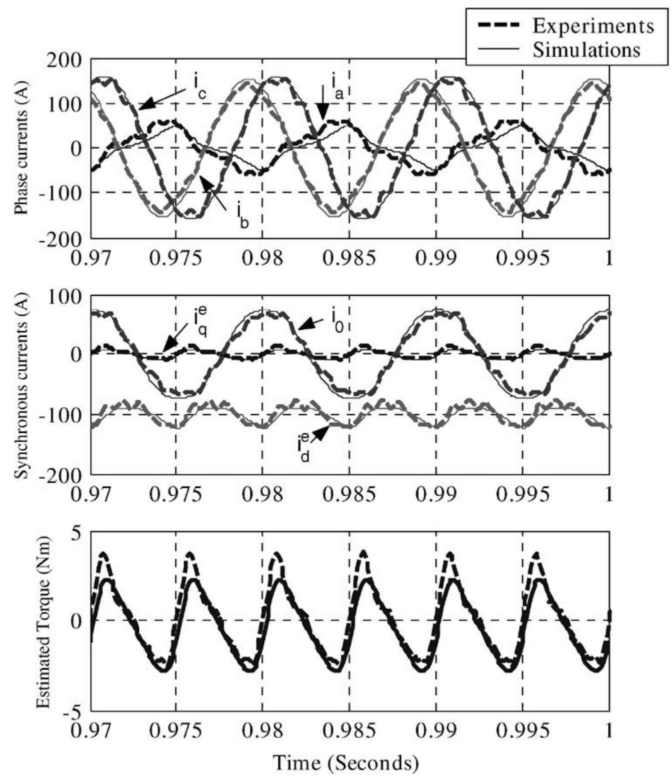


Fig. 9. Experimental and simulated results for the phase-based control method with an imposed zero-sequence current command at $\omega_\mathrm{r} = 1000$ r/min.

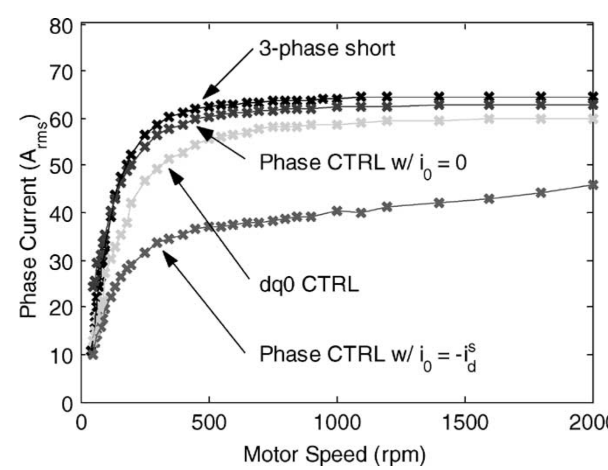


Fig. 10. Measured steady-state current in the shorted phase $a$ for different postfault control methods.

$d$-axis inductance. This relatively high value of zero-sequence inductance is a major contributing factor to the differences between the experimental results and the idealized waveforms given in Figs. 2 and 3.

The torque induced when a zero-sequence current is introduced is also pulsating in nature, although its value is still modest at less than 3 $\mathrm{N} \cdot \mathrm{m}$ peak. Overall, the experimental torque waveforms are in close agreement with the simulated results when considered in relation to the machine's torque capacity, plus the fact that slotting effects were neglected in the simulations. Taken together, these simulation and test results demonstrate the effectiveness of the proposed magnet-flux-nulling-control algorithm.

Figs. 10 and 11 provide experimental results comparing the current amplitude in the shorted phase and the average torque, respectively, for three alternative implementations of the proposed flux-nulling-control algorithm under short-circuit-fault conditions up to 2000 r/min. As a baseline, the corresponding curves for a symmetrical three-phase short circuit is also included. The measured currents in Fig. 10 are compared in terms of rms values since the induced fault currents are not perfectly sinusoidal due to nonlinear effects including magnetic saturation and slotting effects.

Fig. 10 shows that the flux-nulling method using phase-based control without a zero-sequence current command $(i_0^* = 0)$ produces approximately the same current amplitude in the shorted phase as the symmetrical three-phase short. That is, the current in the shorted phase asymptotes to the machine's characteristic current value as the speed increases in both cases.

In contrast, the flux-nulling method with synchronous-frame $dq0$ control [9] modestly reduces the current amplitude in the shorted phase, while the phase-based control with a zero-sequence command $\left(i_0^* = -i_d^{s^*}\right)$ results in the smallest induced current. For the tested system with phase-based control, the induced current in the shorted phase was approximately 60% of the value of the symmetrical three-phase short-circuit current. In general, the value of the induced current increases with the value of the zero-sequence inductance and the motor speed.

Fig. 11 plots the average steady-state postfault torque for the different control methods as measured by a torque meter. The curves in Fig. 11 show that any implementation of the

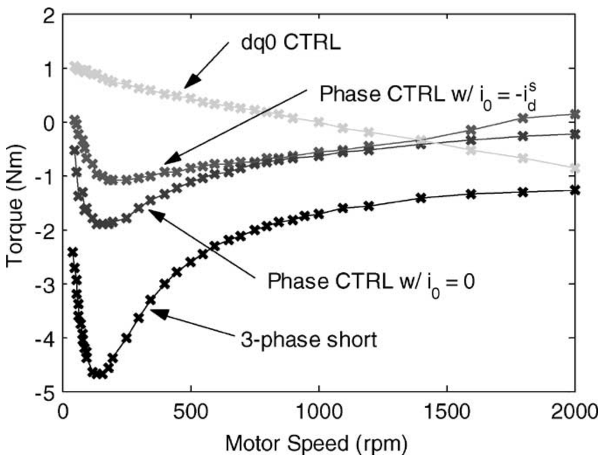


Fig. 11. Measured steady-state average motor torque for different postfault control methods.

flux-nulling-control method results in a smaller postfault-induced torque compared to the torque developed when a symmetrical three-phase short circuit is imposed as the postfault control action. Employing phase-based control with a zero-sequence current command $(i_0^* = -i_d^{s^*})$ produces a slightly smaller induced torque compared to the alternative control strategy without using a zero-sequence current command $(i_0^* = 0)$ over the tested speed range.

Applying a zero-sequence current does have the drawback of increasing the current required in the healthy phases. As a result, the strategy with $i_0^* = -i_d^{s^*}$ can only be implemented in systems where the characteristic current is less than $1/\sqrt{3}$ the value of the rated inverter current.

The phase-based control methods produce average torque envelopes with approximately the same shape as that of the symmetrical three-phase short circuit. The fact that the natural short-circuit behavior of the machine is not completely suppressed is due to the controller's restricted ability to control only two of the three phase currents combined with the inaccurate assumption of $L_0 = 0$. The $dq0$ synchronous-frame controller exhibits different characteristics, with the torque linearly decreasing due to increased iron losses as the speed increases.

## V. Conclusion

This paper has presented a new control method to null the magnet flux in an IPM motor following a short-circuit fault using individual PI phase-current regulators. The control action of a six-leg inverter is used to ensure that the short circuit is bidirectional in cases when the fault is caused by a single shorted inverter switch, creating a polarized fault.

The phase-current regulators are used to control the current in the remaining healthy phases to null the magnet flux in the machine. Taking advantage of these phase-current regulators, it is possible to purposely introduce a zero-sequence current to further suppress the current induced in the faulted phase. It has been experimentally demonstrated that the postfault-induced torque can be significantly reduced by employing the proposed method, as compared with the alternative strategy of purposely applying a symmetrical three-phase short circuit as the postfault control protection response.

A combination of simulation and experimental results has been used to show the value of this new short-circuit fault control strategy for reducing both the postfault average torque and the current in the shorted phase. The improvements are particularly apparent in the low to medium speed ranges where the braking torque from a symmetrical three-phase short circuit reaches its maximum value.

Despite this progress, the problem of short-circuit faults in PM synchronous machines continues to be a challenging one. Research efforts are continuing to search for fault-management techniques that minimize or eliminate the incremental cost burden associated with their implementation in practical drive systems.

## Appendix
## IPM Machine Parameters

Three-phase, 6-kW peak at 6000 r/min, and 12-pole machine with

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

where the $q$-axis inductance is approximated as

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

whichever is smaller.

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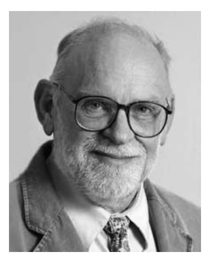

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