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Self-Healing Control with Multifunctional Gate Drive Circuits for Power Converters

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Abstract— **Many commercial and military transport systems have fault diagnostic functions implemented to help protect the device when a severe fault occurs. However, most present systems do not contain prognostics capability which would allow operators to observe an unhealthy system component in its pre-fault condition. In industry applications, scheduled downtime can result in considerable cost avoidance. The next technology step is self-healing system components which observe not only potential problems, but can also take steps to continue operation under abnormal conditions – whether due to long-term normal wear-and-tear or sudden combat damage. In this paper, current and voltage information using the double-layer gate drive concept is fed to intelligent networks to identify the type of fault and its location. These intelligent networks are based on unsupervised and supervised learning networks (self-organizing maps and learning vector quantization networks respectively). The proposed concept allows the reconfiguration of the electric machinery system for continued normal operation of the machine. This paper presents an intelligent health monitoring and self-healing control strategy for a multi-phase multilevel motor drive under various types of faults.**

Keywords-fault diagnosis; fault prognosis; power converters; computational intelligence; motor drives

I. INTRODUCTION

As commercial and military transport systems become more complex and software-intensive, the need for dependable onboard electric power increases [1-8]. The machinery must be reliable, available, and safe to use. In the past, false alarms, missed failures, mishandled preventive maintenance scheduling, and underutilized resources have resulted in poor operational performance. Recent advances in information systems technology use intelligent monitoring of these many measurement points along with decision support algorithms to provide an increase in fault detection and isolation. New emerging capabilities are partial recovery, forecast of impending problems, as well as increased operational use during abnormal operations. Many navy and industrial power system components (power converters, motor drives, etc.) have diagnostic capability. These components have the capability to record fault events and provide post-fault information to engineers which is helpful for maintenance. However, the present systems do not contain prognostics capability which would allow operators to observe an unhealthy system component in a pre-fault condition. This capability would allow scheduled downtime as opposed to unscheduled downtime. In industry applications, scheduled downtime can result in considerable cost avoidance. The next technology step is self-healing system components which observe not only potential problems, but can also take steps to continue operation under abnormal conditions - whether due to long-term normal wear-and-tear or sudden combat damage.

This paper focuses on three important components to achieve these goals. Firstly, advanced sensor technologies are needed to gather enough information from the system so that its operational status can be continuously monitored. Existing sensor technology that is employed in most motor drive systems lend themselves to single point failure. If the sensor fails, or even more costly, if the lead between the sensor and monitoring component fails, then there exists no redundancy to render the component operational. This paper introduces a power converter gate drive technology which provides more voltage and current information for prognostic control.

Secondly, an intelligent health monitoring strategy is also presented for a multi-phase motor drive system using a learning vector quantization (LVQ) network [9] under various fault types. This monitoring component continuously processes the data gathered by the gate drive circuitry to identify any unhealthy operating conditions that might evolve into severe faults.

Thirdly, a self-healing control strategy is proposed to ensure that the system can continue operating when a pre-fault condition is detected or when a severe fault has occurred. In the first case, the unhealthy component can be isolated to avoid further deterioration. In the second case, the faulted component can operate in a reduced capacity mode through reconfiguration, which provides an opportunity for scheduled downtime and maintenance without abruptly affecting the operation of the whole system. For naval electric machinery systems, this control strategy improves war-fighting effectiveness and ensures a "limp home" capability.

II. MULTIFUNCTIONAL GATE DRIVES

In power converter systems, a gate drive circuit serves as an interface between the controller and the power transistors such as MOSFETs and IGBTs. The main purpose of the circuit is to translate the digital switching signals from the controller into gate signals to trigger the transistors. These gate signals not

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only need to meet the voltage requirement of the switching devices, they must also be able to supply a large gate current to charge the gate capacitance so that fast transition can be achieved.

Modern commercial-off-the-shelf (COTS) gate drivers often provide a variety of protection features to prevent the switching devices from being damaged. The most commonly addressed faults types include driver power supply under-voltage, transistor short-circuit and overcurrent. The gate drive can perform some fault handling such as applying a gate signal to snub an over-voltage at turn-off or softly removing a gate signal in the case of an over-current. Although these protection features are essential for the safe and reliable operation of the drive system, they provide very limited diagnostic and prognostic functions.

Fig. 1 shows an example power converter circuit using conventional gate drive technology; an active rectifier in this case. The digital signal processor (DSP) control sends gate commands to the gate drives (GDs). The gate drives have local IGBT fault handling capability to shut down after a short-circuit or an over-current fault in the switching devices and may communicate to the DSP that a fault occurred. Several researchers have shown that the rectifier control can operate without ac side voltage sensors [10]. However, ac current sensors and the dc voltage sensor are still needed for the control in most designs.

The gate drive protection circuitry generally contains considerable sensor information about the status of the switching devices. To utilize these sensor information for diagnostic and prognostic purposes, the concept of advanced gate drives (AGDs) is proposed. Fig. 2 shows the active rectifier with advanced gate drives. The idea behind the AGD is that, in addition to transistor gating, it sends back samples of the collector current and collector-to-emitter voltage to the DSP. In a fully developed application the AGD could perform some local analog sampling functions. For example, the AGD could sample the collector current or collector-to-emitter voltage (depending on the switch state of the IGBT at the time) at a high rate. A number of samples can then be locally processed on the AGD in a way which throws out outlying samples and averages reasonable samples. This feature would eliminate problems that plague power converter circuits; namely sensor non-linearity [2] and analog circuit noise in the presence of high power IGBT switching [3]. The conditioned samples could be sent back to the DSP through the use of digital fiber-optic cables using serial communication. This would further eliminate noise from running analog sensor cables. Although the serial communication process will take additional time, it should be noted that the voltage and current samples need to be known only on the time scale of the DSP clock cycle (typically 50 to 100 microseconds). The ripple current and certainly the MHz level switching noise do not need to be known by the DSP.

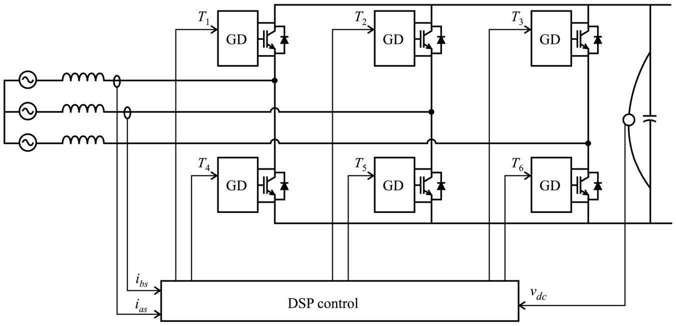

Figure 1. Active rectifier circuit using conventional gate drives.

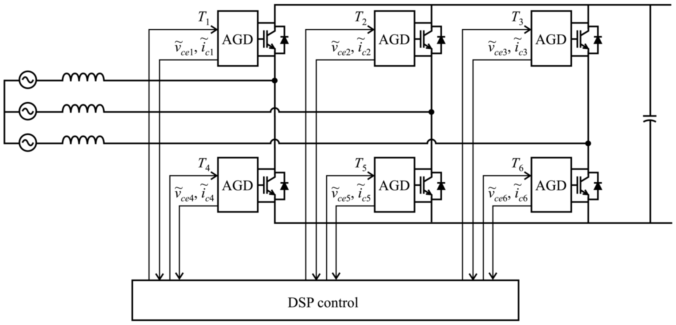

Figure 2. Active rectifier circuit using advanced gate drives.

An additional advantage of the AGD is complete elimination of the ac current and dc voltage sensors. The DSP control can determine this information from the voltage and current samples which is obtained from the AGDs using some local intelligent control. It should also be pointed out that since this information comes from every single IGBT, there is an over-determination of the voltage and current signals. This makes the control with the AGD more reliable and fault-tolerant.

III. THE DOUBLE-LAYER GATE DRIVE

The AGD is a future concept and on the path to its development, a version of the double-layer gate drive (DLGD) has been created. Fig. 3 shows the double-layer gate drive concept. A commercial-off-the-shelf gate drive is used and a custom-built board is mounted directly underneath. This second-layer board takes voltage signals from the COTS gate drive and reconstructs the IGBT collector-to-emitter voltage and collector current signals on the power side of the transistor. The reconstructed signals can then be sent to a high-level control for condition monitoring and fault detection.

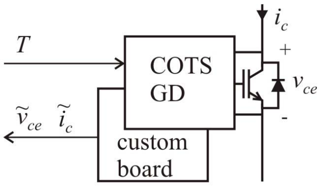

Figure 3. The double-layer gate drive.

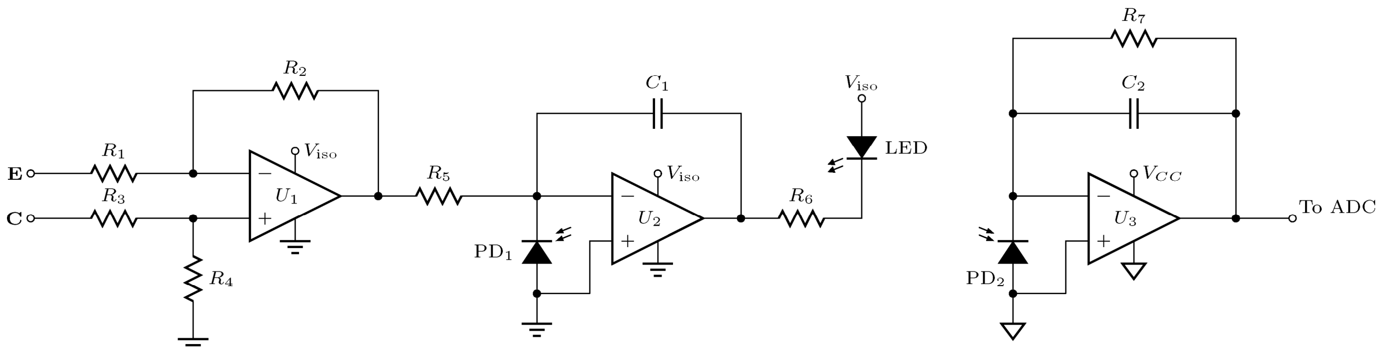

Figure 4. Off-state IGBT voltage sensing schematic

A. Voltage Signal Sensing Circuits

At this time, the double-layer gate drive sends analog voltage signals to the DSP. For each power transistor, two signals are sensed: the on-state collector-to-emitter voltage and the off-state collector-to-emitter voltage. The transistor current information can be derived based on the on-state voltage and the characteristics of the switching device.

When the high power transistor is in the off state, a large portion of the dc link voltage is applied across its collector and emitter terminals. In most cases the off-state voltage can have a magnitude of several hundred volts or even higher. Since neither the collector nor the emitter is permanently connected to the ground, a differential amplifier circuit is used, which also scales down the voltage magnitude from hundreds of volts to several volts. The op-amps have a relatively high slew rate so that the signal integrity of the high frequency PWM voltages is not compromised.

Although the circuit for off-state voltage sensing can also sense the on-state voltage, in practice it cannot be used for both purposes because the off-state voltage has a much larger range than the on-state voltage. If an analog to digital converter is used to convert the sensed voltage to digital signals, the on-state voltage would have a very poor resolution and may be easily corrupted by noises. Thus a dedicated circuit is needed to sense the on-state voltage. Fortunately, the COTS gate drive board provides a convenient way to measure the on-state voltage. Most gate drive boards contain desaturation protection circuits that compare the on-state voltage with some thresholds to determine if an over-current or a short-circuit condition is present. Thus the second-layer board can obtain this information directly from the COTS gate drive board.

Depending on the direction of the collector current, the sensed on-state voltage can have different meanings. If the current is flowing from the collector to the emitter, the sensed voltage is

$$V_{O(on)} = V_{CE}(I_C) + V_D \tag{1}$$

where V_{CE} is the actual on-state collector-to-emitter voltage, which is a function of the collector current I_C; and V_D is the forward voltage drop across a blocking diode in the desaturation circuit. If the current is flowing from the emitter to the collector, the sensed voltage is

$$V_{O(on)} = -V_{EC}(I_D) + V_D \tag{2}$$

where V_{EC} is the forward voltage drop of the antiparallel diode, which is a function of the diode current I_D.

B. Electrical Isolation and Power Supply

Two types of isolation are provided so the high-power side circuitry is completely isolated from the low-power control/monitoring circuitry. On the COTS gate drive board, transformers and isolated DC-DC converters are used to separate the PWM generation circuit from the power transistors. On the second layer board, linear analog opto-couplers are used to transmit the analog signals to DSP controllers.

The commercial gate drive product used in the design is SCALE 6SD106E from CONCEPT. It is a six-pack driver for IGBTs and power MOSFETs. A unique feature of this product is that it provides full electrical isolation between the low-power control side and high-power transistor side by using miniaturized transformers and isolated DC-DC converters. The design of the second-layer board circuit allows it to obtain power directly from the isolated power supplies on the COTS gate drive board, thus eliminating the need for additional cumbersome isolated DC-DC converters for each channel.

Fig. 4 shows how the collector-to-emitter voltage is sent back to the DSP. This circuitry is contained on the second layer of the double-layer gate drive and the first two op-amps are powered from the COTS layer. The input stage is a differential amplifier followed by an analog opto-coupler driver. The opto-coupler feeds back to the driver for improved accuracy. The final op-amp is powered by the controller (DSP power supply). Its output is electrically isolated from the gate drive and is read into the DSPs analog-to-digital input.

C. Laboratory Test Results

A prototype double-layer gate drive was developed to test the concept. The second-layer board was mounted beneath a SCALE 6SD106E commercial gate drive board, which was used to drive six IGBTs in an active rectifier system. The rated dc bus voltage was 350 V, and the IGBTs were switched at a frequency of 20 kHz.

The test results for the off-state voltage sensing circuit are shown in Fig. 5. The top trace is the voltage measured directly with a differential probe, and the bottom trace is the voltage measured with the DLGD circuit. It can be seen that the two signals match very well, except the high frequency noises in the double-layer circuit output caused by switching. The noises can be reduced by proper shielding of the circuit from the high-voltage IGBTs. The impact of switching noises can be further reduced by scheduling the sampling time of the off-state voltage when no transistor is being turned on or off.

Fig. 6 shows the test results for the on-state voltage sensing circuit. The top trace is still the collector-emitter voltage measured with a differential probe, and the bottom trace is the on-state voltage measured by the DLGD circuit. When the IGBT is in the off state, it collector-to-emitter voltage is about 350 V. In this case, the DLGD output is zero. When the IGBT is turned on, its collector-to-emitter voltage is only several volts. The DLGD amplifies it and send the signal to the DSP control.

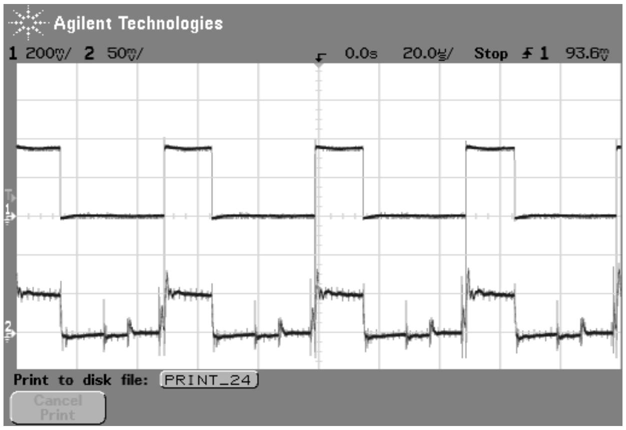

Figure 5. Off-state collector-to-emitter voltages. Top trace: voltage measured directly with a differential probe; Bottom trace: voltage measured with double-layer gate drive circuit

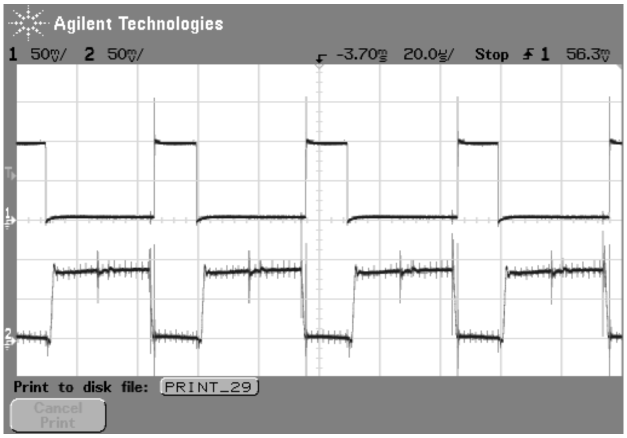

Figure 6. On-state collector-to-emitter voltages. Top trace: voltage measured directly with a differential probe; Bottom trace: voltage measured with double-layer gate drive circuit

IV. INTELLIGENT FAULT DETECTION NETWORK

Current and voltage information, gathered by the double-layer gate drive concept, is fed to intelligent networks to identify the type of fault and its location. The networks are trained to identify abnormal signatures and localize the cause. This allows reconfiguration of the electric machinery system for continued operation of the machine. The intelligent network consists of three sub-networks: fault detection, fault localization and reconfiguration. Sensor faults, drive circuit faults, and motor faults can all be accounted for. The drop of a sensor signal that seems to have no effect on the other sensor signals can be diagnosed as a sensor failure. Likewise, by knowing what faults occur and what effect they have on the outputs, faults can be isolated. The use of other external sensors, such as torque sensors and temperature sensors, are also examined as additional inputs to isolate more complex faults. The intelligent computation allows incorporation of many types of sensor inputs.

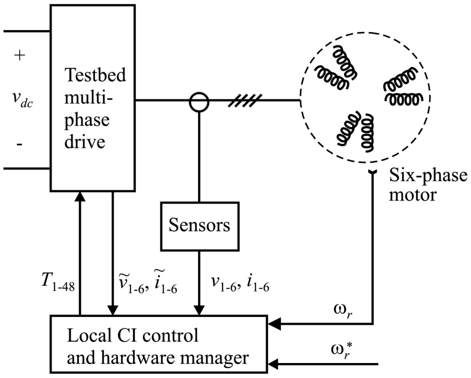

Figure 7. Diagram of the six-phase PMSM drive system

A six-phase permanent magnet synchronous motor (PMSM) drive testbed system shown in Fig. 7 is studied in this paper, with an intelligent monitoring network to detect and identify inter-turn short-circuit faults in the motor stator windings. These faults are usually caused by the failure of insulation materials between stator coils. At the initial phase of the fault, the resistance of the shorted path is relatively high, and the impact of the fault on the operation of the motor is small. However, if the fault is not rectified, the short-circuit circulating current caused by the back MMF can create a local hot spot, which may cause further insulation deterioration or mechanical damage. To prevent such severe faults from happening, it is thus necessary to detect and locate these inter-turn faults at their early stages.

Extensive simulation shows that the fault signature is more obvious when the motor phase currents are transformed into the synchronous *qd* reference frame. Specifically, the second-harmonic components in the *qd* quantities are suitable for the detection and identification of inter-turn faults. Several factors affect the magnitude and phase angle of the second-order harmonic currents, including the number of winding turns that are short-circuited, the fault resistance, stator phase voltage unbalance, and machine saturation. An intelligent algorithm, learning vector quantization, is thus used to establish the complex relationship between the phase current information and the faulted phase.

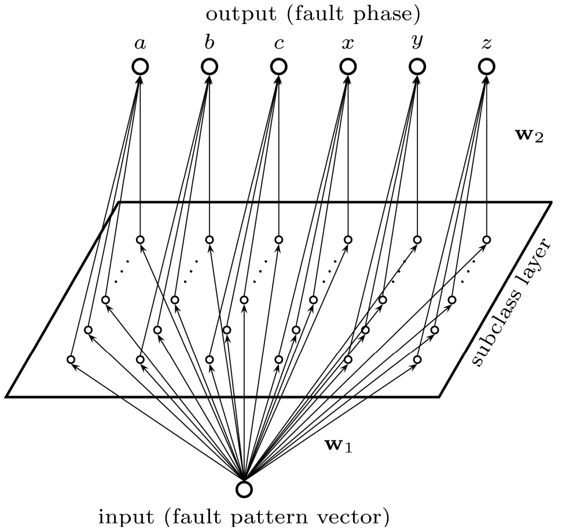

Figure 8. Diagram of the LVQ network used for fault identification.

Learning vector quantization is a supervised clustering algorithm. The aim of a clustering algorithm is to construct clusters of similar input vectors, where similarity is usually measured in terms of Euclidean distance. The training process of LVQ is based on competition, which is among the cluster output units. During training, the cluster unit whose weight vector is the "closest" to the current input pattern is declared as the winner. The corresponding weight vector and that of neighbor units are then adjusted to better resemble the input pattern.

To identify inter-turn faults with a LVQ network, the magnitude and phase information of the *qd* harmonic currents together with other relevant values are used as the input patterns. The output of the network has six nodes, each corresponds to one phase of the six-phase machine. The number of subclasses depends on the complexity of fault patterns for a single phase. The network is then trained with various fault signature patterns until it is able to correctly identify the phase in which the each fault occurs.

As shown in Fig. 8, a LVQ network with 6 output nodes and 60 subclasses was used. Each fault type corresponds to 10 subclasses in the middle layer. These 10 subclasses cover various operating and fault conditions for faults that occur in a single phase.

To train the LVQ network, a representative dataset was created which included 270 test cases. Each test case has a different combination of fault resistance, number of turns that are short-circuited, and faulted phase. In the training process, of the 270 input patterns, 190 (70%) was used to train the network, and the rest 30% was used for validation. The test results are shown in Fig. 9. It can be seen that after 200 iterations (in each iteration, all 190 input patterns are used to adjust the weights), about 99% of the faults in the training cases can be correctly identified by the LVQ network. The network can also correctly identify about 94% of the faults in the validation cases.

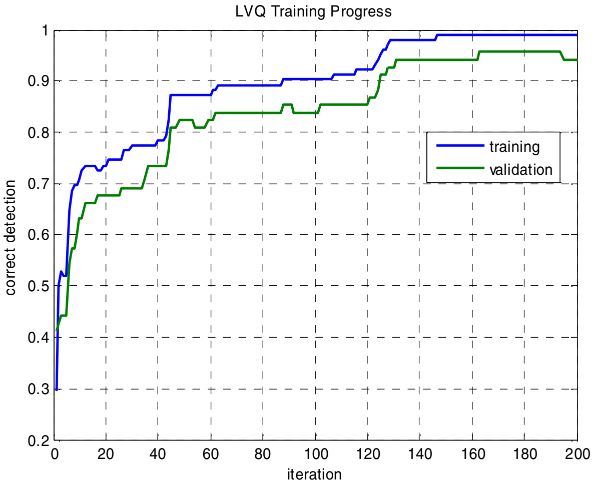

Figure 9. Training results of the LVQ network

V. SELF-HEALING CONTROL STRATEGY

The self-healing capability of a power conversion system enables it to continue operation even when certain types of severe faults have occurred. For example, if a multi-phase motor has a fault that renders one or more phases incapable of carrying current to the motor stator, self-healing control recognizes the loss of one or more phases, responds to the fault by mathematically calculating what the current and appropriate phase angle needs to be in each of the remaining phases, then the machine can continue to be operated, albeit with reduced performance. When the self-healing control strategy is used in conjunction with the prognostic fault identification technique described above, it is also possible to isolate those components with non-severe faults (such as a high-impedance inter-turn fault) and continue operation through reconfiguration, which prevents the faults from developing into more threatening ones. The system can also notify engineers of the unusual or abnormal conditions so that planned downtime and maintenance can be scheduled.

A. *Open-phase Faults in Six-phase PMSM*

In this study, the operation of a six-phase PMSM with one phase open is considered. A general model of six-phase induction machines under open phase fault was proposed in [11], which allows the study of cases with up to four phases open. The authors also pointed out that torque oscillations with a high magnitude can appear under open phase fault conditions. Another modeling approach was presented in [12] for dual three-phase induction machines with one phase open. There is also studies reported in the fault-tolerant operation of five-phase induction or permanent magnet machines [13]. However, most of these studies focused on star-connected winding topologies and tried to treat the healthy phases as a single group when modeling the machine, which often resulted in very complicated control algorithms.

In the testbed system shown in Fig. 7, each phase of the PMSM stator winding is connected to an H-bridge converter. This provides the advantage that if a fault occurs in one phase, the winding can be completely isolated by turning off the switches in its H-bridge structure. In addition, the current through each phase can be independently controlled. Thus, there is more flexibility in the design of the self-healing control strategy.

B. *Self-healing Control Strategy*

In this paper, a decoupled control algorithm is proposed, which divides the remaining healthy phases into a three-phase set and a two-phase set. The three-phase set are balanced, and can be treated as a regular three-phase PMSM. Since each phase of the stator winding is connected to an H-bridge structure, the two-phase set is also capable of generating a rotating magnetic field. The combined efforts of the two sets of windings produce the desired electromagnetic torque.

For a healthy round-rotor six-phase PMSM with dual three-phase windings *abc* and *xyz*, the output torque can be expressed in the rotor reference frame as

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_m'\left(i_{qs1} + i_{qs2}\right) \tag{3}$$

where P is the number of poles, λ_m' is the amplitude of the flux linkages established by the permanent magnet, i_{qs1} is the q-axis current of phase set *abc*, and i_{qs2} is the q-axis current of phase set *xyz*. The transformation from *abc* to the rotor reference frame is

$$\begin{bmatrix} i_{q1} \\ i_{d1} \\ i_{01} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 2\pi/3) & \cos(\theta_r + 2\pi/3) \\ \sin\theta_r & \sin(\theta_r - 2\pi/3) & \sin(\theta_r + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4}$$

where θ_r is the rotor electrical angle. The inverse transformation is

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 2\pi/3) & \sin(\theta_r - 2\pi/3) & 1 \\ \cos(\theta_r + 2\pi/3) & \sin(\theta_r + 2\pi/3) & 1 \end{bmatrix}\begin{bmatrix} i_{q1} \\ i_{d1} \\ i_{01} \end{bmatrix} \tag{5}$$

The transformation for *xyz* phases is similar, except that θ_r is replaced with $\theta_r - \pi/6$.

Assume that phase c is open, then i_c is zero. The above transformation becomes

$$\begin{bmatrix} i_{q1} \\ i_{d1} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 2\pi/3) \\ \sin\theta_r & \cos(\theta_r - 2\pi/3) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} \tag{6}$$

with inverse transformation

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \sqrt{3}\begin{bmatrix} -\sin(\theta_r - 2\pi/3) & \cos(\theta_r - 2\pi/3) \\ \sin\theta_r & -\cos\theta_r \end{bmatrix}\begin{bmatrix} i_{q1} \\ i_{d1} \end{bmatrix} \tag{7}$$

According to (3), torque T_e is directly proportional to the q-axis currents. It can be seen that to produce the same amount of torque, a two-phase winding set must have a current magnitude that is $\sqrt{3}$ times that of a three-phase winding set.

Since both the three-phase set and the two-phase set can contribute to torque production, an optimal solution is needed. In this paper, the optimization goal is to minimize the copper losses in the stator windings. Let the stator winding resistance be r_s, then the copper losses are

$$P_{loss} = \left[2\left(\frac{\sqrt{3}i_{q1}}{\sqrt{2}}\right)^2 + 3\left(\frac{i_{q2}}{\sqrt{2}}\right)^2\right]r_s \tag{8}$$

Solving this optimization problem with constraint described in (3), the optimal current distribution for the two sets of windings can be found to be

$$\begin{aligned} i_{q1} &= \frac{1}{3}\frac{4T_e}{3\lambda_m' P} \\ i_{q2} &= \frac{2}{3}\frac{4T_e}{3\lambda_m' P} \end{aligned} \tag{9}$$

Since the d-axis currents do not contribute to torque generation, they should be kept at zero for maximum efficiency.

In order to verify the effectiveness of the presented self-healing control algorithm due to an open stator phase fault, a simulation program was developed in MATLAB/SIMULINK. The control is designed so that the machine outputs torque to follow a predefined torque command, which has a step change at time $t = 0.05$s. Fig. 10 shows the currents in the five healthy phases. It can be seen that currents in the three-phase set are balanced, and have a higher magnitude than that of the two-phase set. The electromagnetic torque of the machine is shown in Fig. 11, which follows the command very well. Also, the steady-state torque is free of second-order harmonic oscillations.

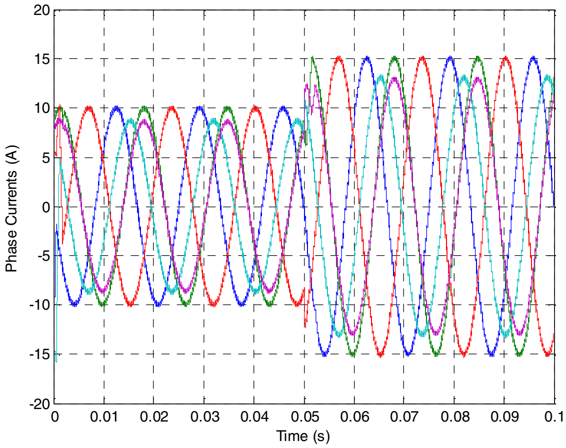

Figure 10. Phase currents of the six-phase PMSM with one phase open

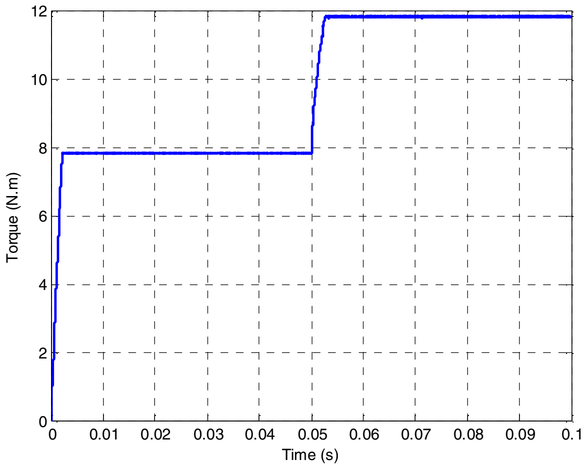

Figure 11. Electromagnetic torque of the PMSM with self-healing control

VI. CONCLUSIONS

This paper has presented a fault-prognosis system for naval and commercial power electronic systems by developing and demonstrating several key components, including a double-layer gate drive, LVQ based fault detection and identification, and self-healing control of six-phase PMSM drive system under open phase conditions. The double-layer gate drive is an attempt towards the development of advanced gate drive circuit, which gathers and processes voltage and current information of the switching devices. Through commutation, the gate drive circuit sends the information to the intelligent monitoring networks for fault detection. The redundancy of the sensor scheme further improves the reliability of the system. To prevent incipient inter-turn short-circuit from developing into severe fault, a LVQ network is used to establish the relationship between motor phase currents and faulty phases. Once a fault or a pre-fault condition is identified, self-healing control strategy can be used to isolate the faulty components while reconfiguring the rest of the system so that uninterrupted operation is maintained. This paper has proposed a control algorithm for the continued operation of a six-phase PMSM when one phase is open. The algorithm achieves minimized stator copper losses by distributing torque load between a balanced three-phase set and a two-phase set. The effectiveness of these proposed concepts are validated through simulation and laboratory tests.

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