6-2011

Fault-Tolerant Technique for Δ-Connected AC-Motor Drives

Ahmed Mohamed Sayed Ahmed
Marquette University

Behrooz Mirafzal
Marquette University

Nabeel Demerdash
Marquette University, nabeel.demerdash@marquette.edu

Recommended Citation

Ahmed, Ahmed Mohamed Sayed; Mirafzal, Behrooz; and Demerdash, Nabeel, "Fault-Tolerant Technique for Δ-Connected AC-Motor Drives" (2011). *Electrical and Computer Engineering Faculty Research and Publications*. 202.
https://epublications.marquette.edu/electric_fac/202

Electrical and Computer Engineering Faculty Research and Publications/College of Engineering

IEEE Transactions on Energy Conversion, Vol. 26, No. 2 (June 2011): 646-653. DOI. This article is © The Institute of Electrical and Electronics Engineers and permission has been granted for this version to appear in e-Publications@Marquette. The Institute of Electrical and Electronics Engineers does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from The Institute of Electrical and Electronics Engineers.

Fault-Tolerant Technique for Δ-Connected AC-Motor Drives

Ahmed Sayed-Ahmed
Rockwell Automation, Mequon, WI
Behrooz Mirafzal
Florida International University, Miami, FL
Nabeel A. O. Demerdash
Department of Electrical and Computer Engineering, Marquette University, Milwaukee, WI

Abstract:

A fault-tolerant technique for motor-drive systems is introduced in this paper. The technique is merely presented for ac motors with Δ-connected circuits in their stator windings. In this technique, the faulty phase is isolated by solid-state switches after the occurrence of a failure in one of the stator phases. Then, the fault-tolerant technique manages current-flow in the remaining healthy phases. This technique is to significantly mitigate torque pulsations, which are caused by an open-Δ configuration in

the stator windings. The performance of the fault-tolerant technique was experimentally verified using a 5-hp 460-V induction motor-drive system and the results are presented in this paper.

SECTION I. Introduction

The results of many investigations have been reported in the literature in the area of fault-tolerant motor-drive systems, e.g., in [1]–[2][3][4][5][6][7][8][9][10][11][12][13][14]. It is well-known that a three-phase ac motor can operate in a two-phase mode of operation. However, this mode of operation may produce a large torque pulsation with a frequency equal to double the line frequency. The major challenge in the case of a Y-connected circuit topology for the stator windings is that the two remaining active phases are dependent on each other. Therefore, they cannot be independently controlled. In order to overcome this hurdle, the neutral point of the Y-connection has to be accessible and connected to the mid-point of the drive's dc-bus [2], [3]. This configuration will result in a relatively high neutral current (i.e., three times the motor line currents), which requires an over-size design for the dc-bus capacitors. In another approach, the neutral point can be connected to an additional leg, i.e., fourth-leg, into the inverter topology as described in [4], [5]. This will require a special design for the power circuit structure, which will increase the system cost and reduce the reliability of the overall system. Another approach is to inject current harmonics to the remaining two active (healthy) phases to compensate for the aforementioned torque pulsations [6], [7]. Meanwhile, other investigations were centered on developing fault-tolerant motor-drive systems due to current sensor failure [8], switching device/gate drive failure [9], [10].

The concept of multiphase systems in which five and six phases are utilized instead of standard three-phase motor-drive systems have been discussed in a number of publications such as in [11]–[12][13]. The main objective of this concept is to generate a rotating magnetomotive force (MMF) similar to the healthy case, with a minimum fluctuation in the case of phase loss. For instance, a five-phase motor drive can continue to operate using only four phases, while generating the same rotating MMF magnitude as that of a five-phase machine with a proper derating of the motor-drive system. However, this approach is limited to certain custom applications and may result in a significant increase in the system cost.

To the best of these authors' knowledge most of the fault-tolerant techniques for three-phase motors are mainly directed towards Y-connected machines which are the most common connection type for low horsepower machines. It should be noted that Δ-connected machines are frequently used in high-horsepower applications, usually higher than 100 kW [15]. Fault-mitigation strategies for Δ-connected machines are almost absent from the literature. Therefore, the main focus of the work presented in this paper is to introduce a robust fault-tolerant control technique that enables a Δ-connected three-phase machine to run as a two-phase machine, i.e., an “open-Δ” mode, supplied by a three-phase inverter. This topology utilizes the additional degree of freedom inherently provided in an open-Δ-connected stator. In this case, the currents in the remaining two active phases can be independently controlled.

It should be highlighted that the technique presented here enhances the survivability of the Δ-connected three-phase motor-drive systems in case of winding failures. It is presumed that the stator winding has an open-coil “open-turn” due to winding rupture [16]. The origin of this type of faults is mainly caused by excessive mechanical vibrations which may produce disconnection in the U-shaped end-turn region (champ) of a coil. Another possibility is that the stator winding has an interturn short-circuit fault that has been detected and the faulty phase has been isolated in an early stage (only one or two turns are shorted) using one of the techniques already documented in the literature (see [17]). In this case, the circulating faulty loop current has an insignificant “ampere-turn” effect on the stator MMF, [18]. The other possibility is that the fault might start as an interturn short-circuit fault, which consequently causes the circulation of a high current in the faulted-coil that might end up rupturing this coil. In such applications, it is imperative to adequately design the motor windings to be able to keep the faulted-motor in service under such mode of operation without jeopardizing the safety of the electrical installation and prohibit fault propagation to other coils in the windings.

In this paper, the results obtained from the experimental testing will be demonstrated to confirm the efficacy of the introduced control topology in diminishing the torque pulsations for two-phase “open-Δ” mode of operation of Δ-connected ac-motor drives, and its efficacy in diminishing the unbalances in their line currents. In the next section, the two-phase open-Δ mode of operation will be examined. This is followed by a detailed explanation of this present control topology and its theory of operation.

SECTION II. Two-Phase Operation of Δ-Connected Machines

The two-phase operation of an inverter-fed induction motor with Δ-connected stator phase windings has two possible network configuration scenarios. The first scenario is that one of the power lines connecting the supply voltage to the motor is disconnected. This might be due to a blown fuse, an accidental rupture in the cable connecting the drive to the motor, a faulty switch or failure of the gate drive circuit of a switch. In this case, a motor's phase currents will not be independent of each other, hence loosing two degrees of freedom, and the machine will operate as a single-phase machine. The second scenario is that one of the phases in the stator winding is disconnected, as shown in Fig. 1. This might be due to one of the reasons mentioned earlier in the previous section. It should be noted that the analysis and the topology presented in this paper are centered on providing an acceptable motor performance while the machine is running under a faulty condition that resembles the second scenario which will be referred to throughout the remainder of this paper as a “two-phase open-Δ mode of operation.”

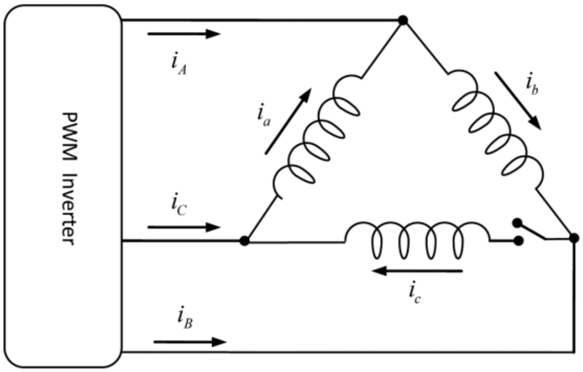

Fig. 1. Open-Δ connection in stator windings with three isolating switches.

As mentioned earlier, it is presumed that the motor windings are connected to the supply voltage. However, one of the motor phases was disconnected due to an internal fault in the windings, as depicted in Fig. 1. Therefore, the relationship between the motor terminal currents, $i_A(t)$, $i_B(t)$, $i_C(t)$, and phase currents $i_a(t)$, $i_b(t)$, $i_c(t)$ can be expressed as follows:

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) = 0 \end{bmatrix}.$$

(1)

Examining (1) illustrates that the phase currents, $i_a(t) = i_C(t)$ and $i_b(t) = -i_B(t)$, can be independently controlled. In general, the resultant MMF produced by the stator phase windings, assuming that phase-c is isolated (failed), will consist of a negative-sequence and a positive-sequence component.

In order to clarify this discussion, let us assume that the line currents are set by the inverter to be equal to $i_C(t) = i_a(t) = I_m \cos(\omega t)$ and $i_B(t) = -i_b(t) = I_m \cos(\omega t - \psi)$, while phase-*c* is isolated. Here, ψ is an angular phase shift between the two currents. This means that the resultant MMF of the stator phase currents can be expressed as follows:

$$F_s(t) = N_s \left\{ \cos(\theta)\, i_a + \cos\left(\theta - \frac{2\pi}{3}\right) i_b \right\}$$

(2)

and hence

$$\begin{aligned} F_s(t) \quad &= \frac{N_s I_m}{2} \{ \cos\,(\theta - \omega t) + \cos\,(\theta + \omega t) - \cos\,(\theta - \omega t \\ &\quad -2\pi/3 + \psi) - \cos\,(\theta + \omega t - 2\pi/3 - \psi) \} \end{aligned}$$

(3)

Where I_m is the peak value of the phase current and N_s is the effective number of turns of the stator winding per phase. The negative-sequence MMF component of the stator can be set to zero by controlling the stator line currents such that $\psi = \frac{4\pi}{3}$. In this case, the resultant stator MMF is expressed as follows:

$$F_s(t) = \frac{N_s I_m}{2} \left\{ \cos(\theta - \omega t) - \cos\left(\theta - \omega t + \frac{2\pi}{3}\right) \right\}$$

(4)

or

$$F_s(t) = \sqrt{3} \frac{N_s I_m}{2} \left\{ \cos\left(\theta - \omega t - \frac{\pi}{3}\right) \right\}.$$

(5)

Inspection of (5) shows that the magnitude of the remaining two active phase currents should be increased by a factor of $\sqrt{3}$ in order to maintain the same amplitude of the stator MMF, $\{(3/2)(N_s I_m)\}$, under healthy conditions. This means that the line currents are set to be $i_C(t) = \sqrt{3} I_m \cos(\omega t)$ and $i_B(t) = \sqrt{3} I_m \cos(\omega t - 4\pi/3)$. However, if the motor phase currents in the remaining two active phases are limited to the rated phase current value (I_m), the output power will be limited to $1/\sqrt{3}$ of the rated power. The phasor diagram of the current waveforms for this case is shown in Fig. 2.

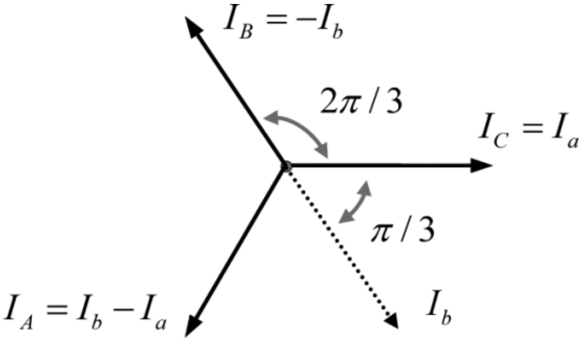

Fig. 2. Motor line currents in an open-Δ configuration for a balanced operation.

SECTION III. Description of the Control Topology

The aforementioned line-current regulation concept in an open-Δ motor can be implemented by a current regulated vector control method or by a hysteresis current regulated modulation technique [19]. Because the control of most of these drives is based on the conventional scalar constant volts-per-hertz control, this concept has been developed herein for a conventional constant (*V/f*) scalar control method. The conventional reference signals fed to the pulsewidth-modulated (PWM) modulator in the drives that are operating based on the constant (*V/f*) scalar control method are generated as follows.

The reference frequency in radians per second is multiplied by the *V/f* block, “which is usually a constant value depending on the line voltage and frequency rating of the machine.” The outputs of this block are three reference sinusoidal signals, v_a^{ref}, v_b^{ref}, and v_c^{ref}, that have a proper amplitude and operating frequency with an interphase shift of 120 electrical degrees (˚e) (see Fig. 3). These signals, which depend on the operating speed of the machine, are fed to the modulator in which they are compared with a saw-tooth signal with a frequency that is equal to the desired switching frequency. It should be noted that these signals do not change either for the case of a healthy three-phase operating condition or a faulty two-phase mode of operation. However, they only depend on the reference operating speed.

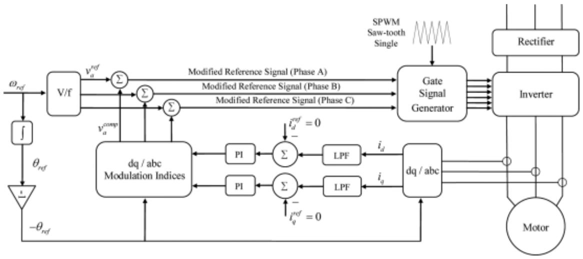

Fig. 3. Functional block diagram of the proposed algorithm.

In addition to these conventional reference signals, the three-phase line currents are measured and transferred to a negative sequence reference frame, rotating at a speed equal to the synchronous speed (see Fig. 3). The reference angle, –&#xθ_{ref}, used in the transformation is obtained from the reference speed in electrical radians per second, and it is generated in the controller. In this frame of reference, the negative-sequence component of the stator current space-vector appears as a dc value in both the *d*-axis and the *q*-axis, while the positive-sequence component of the stator current space-vector appears as an ac component with a frequency equal to double the line frequency. This ac component is filtered through a low-pass filter, while the dc components in the *d*-axis and in the *q*-axis are processed through two PI controllers to drive these components to zero. It should be noted that the negative-sequence component of the stator current space-vector is very small or negligible under normal operation for a balanced machine. In this case, the dc component of the stator current space vector in the synchronous frame of reference is almost zero.

The isolation of a faulty phase in the motor winding causes the negative-sequence component of the stator current space vector to increase to a nonzero value. Accordingly, the aforementioned negative-sequence component will appear as a dc component in the negative sequence reference frame. Therefore, the introduced controller will act to force this dc component to zero. The controller output signals, i.e., v_a^{comp}, v_b^{comp}, and v_c^{comp}, are then added to the main reference signal normally generated in a conventional constant (*V/f*) scalar control system. The resultant summations are then fed to the modulator to generate the appropriate switching pattern (see Fig. 3).

Forcing the negative-sequence component of the active stator phase current space-vector to zero results in a balanced three-phase set of line currents equal in magnitude with a phase shift angles of 120 °e. Meanwhile, the remaining two active phase currents are rendered equal in magnitudes and a phase shift angle of 60°e, which leads to only positive-sequence (i.e., counterclockwise) rotating MMF component, recall (5). This can be explained as a result of the nature of a Δ-connected winding, in which the end (finish) of each phase is connected to the beginning (start) of the other, with phase-c deactivated (see Fig. 1). This is the corresponding active two-phase currents of phase-a and phase-b, in a stator winding with open-Δ, are equal to each other in magnitude with a phase shift equal to 60°e between them (see Fig. 2).

SECTION IV. Experimental Results

In order to examine the performance of the introduced fault-tolerant control method, a Δ-connected 5-hp induction motor controlled by a modified 10-hp adjustable-speed drive was tested in the laboratory (see Fig. 4). The power structure of the drive was interfaced to a DSP board "EZDSP F2812" in which the DSP chip “TMS320F2812” was the main processor to host the fault-tolerant control method. The control code was executed through an interrupt-service-routine, which was periodically called every 100 µs. Note that the PWM switching frequency was set to 10 kHz.

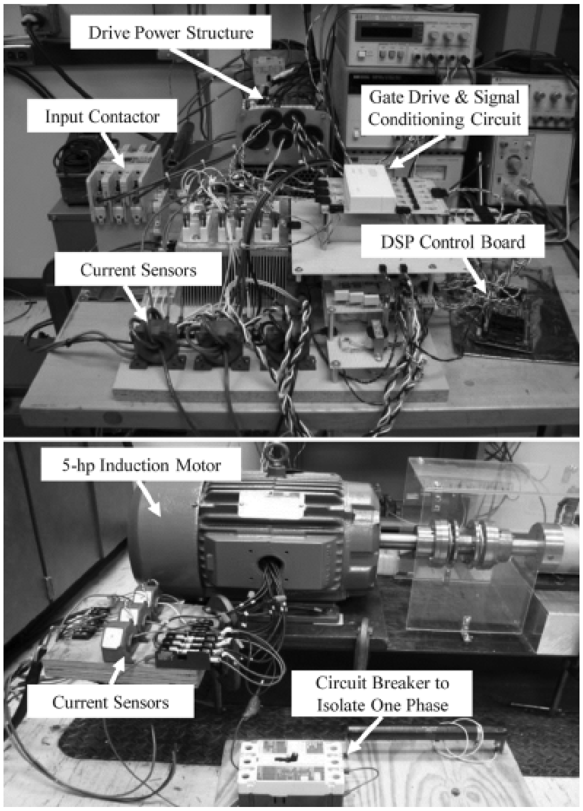

Fig. 4. Power converter and motor setup utilized in the experimental testing.

The case-study motor is a 5-hp six-pole induction motor, which was designed such that it can be configured either as a six-phase or as three-phase induction motor, with the stator connected either as Y or Δ [20]. The motor consists of 36 stator slots and 45 rotor bars with closed slots. These design particulars implied the existence of the third, fifth and seventh harmonics in the phase currents, and consequently, fifth and seventh harmonics in the line currents. In this study, the total measured harmonic distortion “THD” for the line currents was 1.6% and the THD of the phase currents was 3%. The data was collected using a data acquisition system with sampling rate of 50 kHz. More details about the experimental setup are provided in the Appendix.

The experimental results of this work are presented in Figs. 5–12, while the motor was running at half-load condition, i.e., 15.0 N·m and 60 Hz. This is to ensure that the motor will not be overloaded during the faulty two-phase mode of operation. In these figures, the performance of the motor-drive system is demonstrated when the introduced controller was deactivated and when this controller was activated. The line current waveforms obtained from the experimental test setup for the open-Δ case study are depicted in Figs. 5 and 6, without and with the controller, respectively. The transient performance of the controller was also experimentally examined through monitoring the magnitude of the negative sequence component of the line currents, which is depicted in Fig. 7. It can be noted in this figure that there is a sudden increase in the magnitude of the negative sequence component magnitude of the line currents at the instant that one of the phases was disconnected. Nevertheless, this controller was able to reduce the magnitude of the negative sequence component of the line currents to a value close to zero within a period of approximately two seconds after the occurrence of the fault (see Fig. 7).

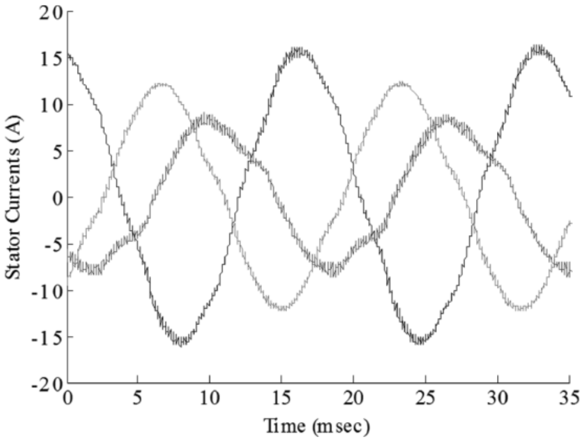

Fig. 5. Experimentally obtained line currents, the introduced controller deactivated, two-phase open-Δ operation, 60 Hz.

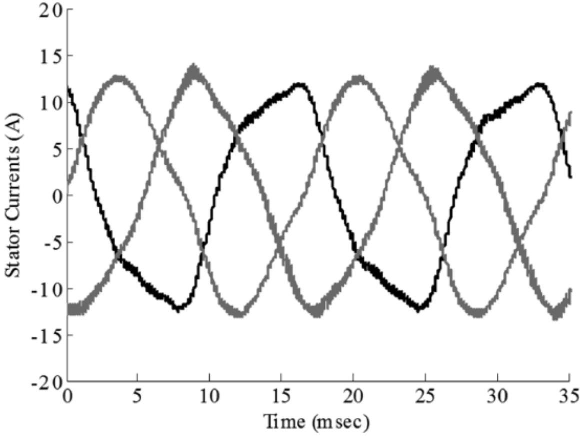

Fig. 6. Experimentally obtained line currents, when the introduced controller was activated, two-phase open-Δ operation, 60 Hz.

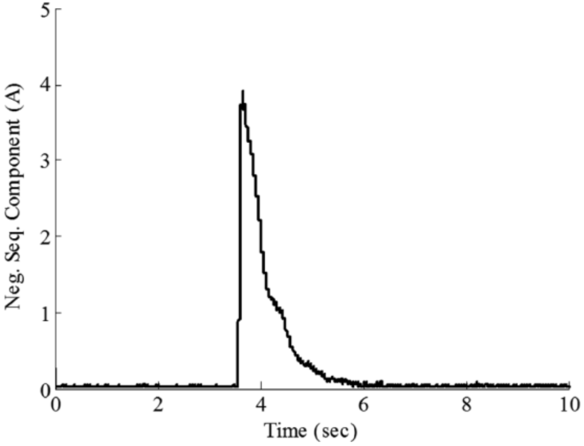

Fig. 7. Experimentally obtained negative sequence component of the line currents, during the transition from a normal three-phase mode to a two-phase open-Δ mode when the introduced controller was activated.

The effectiveness of this controller can be verified through comparing the unbalanced line-current waveforms for the case of the two-phase open-Δ operation. The experimentally obtained line current waveforms for the case of the two-phase open-Δ mode of operation, when this controller was deactivated are depicted in Fig. 5. Meanwhile, the waveforms for the case when this controller was activated are depicted in Fig. 6. These figures show that this controller has reduced the magnitude of the negative sequence component in the line currents, which significantly improved the quality of the output torque of the machine as will be given next.

It should be pointed out that this controller compensates only for the unbalance in the fundamental components of the motor currents but not for their harmonic components. The effectiveness of this controller in balancing the line currents is self-evident upon comparison of the waveforms in Figs. 5 and 6. The distortion in the line current waveforms, as depicted in Fig. 6, in comparison with a normal healthy three-phase condition, as depicted in Fig. 8, is mainly due to the space harmonics associated with the machine's winding design, and the corresponding magnetic circuit; see [21] for more details.

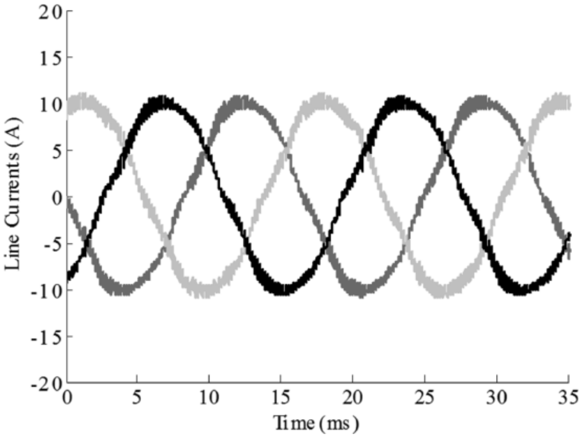

Fig. 8. Experimentally obtained line currents, when the introduced controller was activated, three-phase normal operation, 60 Hz.

The experimentally obtained torque profile during the transition of a three-phase normal mode to the two-phase open-Δ mode of operation is depicted in Fig. 9. This figure demonstrates the efficacy of this fault mitigation method and associated quality of the new controller in preserving the motor's torque quality under faulty operating conditions, almost to the same degree of “goodness” as that of the healthy mode of operation. The effect of the compensation controller on the motor output torque can also be verified by examining the output torque profiles when this controller was deactivated, case (a), versus case (b) when the controller was activated. The torque profiles measured by the torque transducer in the experimental tests are depicted in Fig. 10 over 300 ms. These measured torque signals were filtered through a low pass filter that has a cutoff frequency equals to 350 Hz. A peak-to-peak torque ripples of approximately 16 N·m, where the average developed torque is 15.0 N·m, can be observed when this controller was deactivated at steady-state condition, as shown in Fig. 10 case (a) and its associated spectrum shown in Fig. 11. However, the torque ripple reduces to less than 4.0 N·m, when the controller was activated, as shown in case (b) of Fig. 10 and its associated spectrum shown in Fig. 12. It can be observed that activating the controller significantly reduces the torque pulsation amplitude.

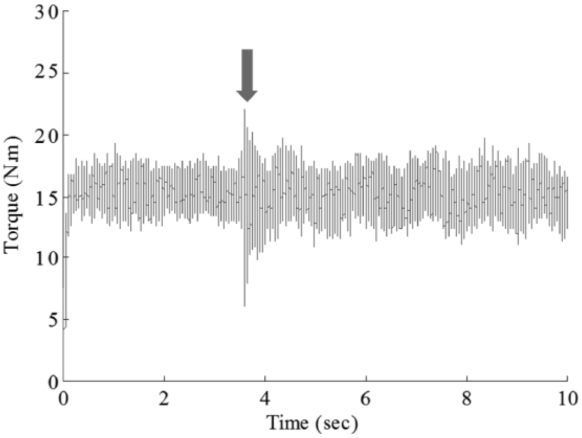

Fig. 9. Experimentally measured output torque, during the transition from a normal three-phase mode to a two-phase open-Δ mode when the introduced controller was activated.

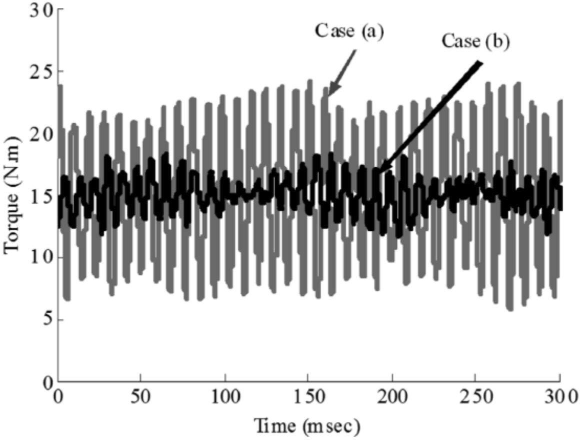

Fig. 10. Experimentally measured output torque, two-phase open-δ operation. Case (a) the introduced controller deactivated and case (b) the introduced control activated.

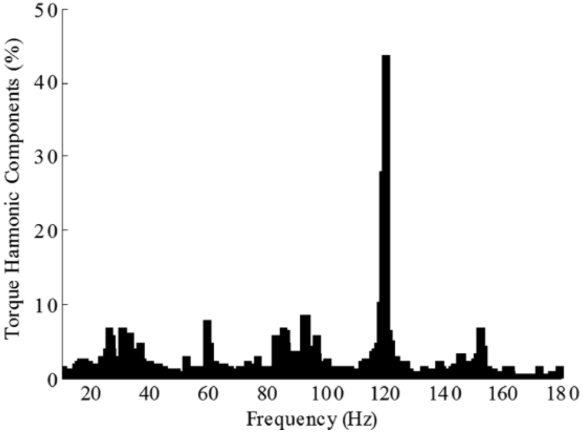

Fig. 11. Frequency spectrum of the measured output torque in percentage (%) with respect to the average developed torque, in the case of two-phase open-Δ operation when the introduced control was not activated.

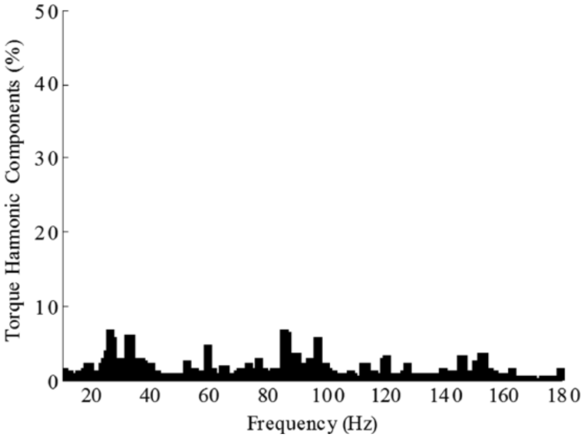

Fig. 12. Frequency spectrum of the measured output torque in percentage (%) with respect to the average developed torque, in the case of two-phase open-Δ operation when the introduced control was activated.

SECTION V. Discussion

Although the current waveforms in the healthy condition and the compensated condition are not exactly the same, as can be seen in Figs. 6 and 8, respectively; the presented fault-tolerant technique can significantly improve the performance of the ac motor (see Figs. 5 and 6) under an open-Δ condition. It should be noted that this was achieved with adding a simple control loop to the widely used constant (*V/f*) scalar control method, as is described in Section III. A comparison between the torque profiles, which were experimentally obtained from the compensated and the noncompensated cases under an open-Δ condition, i.e., case (b) and case (a) of Fig. 10, and their associated spectra shown in Figs. 12 and 11 for the same cases, respectively, demonstrates the relative effectiveness of the fault-tolerant technique. Moreover, the transient response of this technique can be seen in Fig. 9, while the ac motor was switched from a normal three-phase mode to a two-phase open-Δ mode, where the instant of switching is indicated by the thick vertical arrow.

This fault-tolerant technique can be a part of an intermediate remedial process for the so-called self-healing mode of operation of modern/smart motor-drive systems. The self-healing mode is immediately activated after detecting an incipient abnormal condition. In this mode, while the user can be advised of a need for repair and an estimated life-time, an intermediate remedial process is activated to let the system safely operate, or limp, long enough before turning into a safe shut-down mode for repair.

SECTION VI. Conclusion

The conceptual and theoretical background as well as the validating experimental results of a new control technique that enables the two-phase mode of operation of an open-Δ induction motor configuration has been presented in this paper. This technique takes advantage of the additional degree of freedom of the stator phase currents in the two remaining active phases in this configuration. This is inherently provided in a Δ-connected three-phase stator winding in which the current in the two remaining active phases can be independently controlled. In this paper, it has been shown that one of the advantages of the open-Δ configuration is that the phase currents in the remaining active phases can be independently controlled such that an only positive-sequence rotating component of MMF can be produced while keeping a nearly balanced set of line currents with only a positive sequence component.

The introduced control topology does not require over-sizing of the drive. However, the machine has to be oversized if it is required to deliver the rated output power under a faulty two phase open-Δ mode of operation. Moreover, no hardware modifications in the drive are required. In other words, a power structure of a standard drive can be utilized. It has been also shown in this paper that the proposed controller can be activated under a normal “three-phase” mode of operation without adversely affecting the drive's performance. Meanwhile, the introduced controller has been able to significantly moderate unbalances in line currents, as well as reduce the torque pulsations resulting from the faulty “two-phase open-Δ” mode of operation from a ripple level of 95% peak-to-peak of the average developed torque to a ripple the level of 14% peak-to-peak of the average developed torque. This technique was successfully implemented and tested using a 5-hp motor-drive setup.

The ratings and design particulars of the experimental setup utilized to test and verify the previous introduced topology is discussed in more details in this appendix. As mentioned earlier, the implemented topology doesn't require any special hardware design requirement of the power structure of the drive as compared to standard three-phase drive available in the market. Therefore, the power structure of a commercial drive was utilized. The ratings and type of various components associated with the drive circuit are given in Table I. Also, the motor design parameters are given in Table II.

Table I Design Parameters of the Power Converter (Drive)

Rectifier	Semikron, SKD 82/16
DC link capacitor	2@2000μF/430 Vdc each
Inverter	Simikron, 75 GB123D
Gate drive	6 PWM output, SKHI 61
Current sensor	LEM, Current transducer, LF-305 S. BW 100 KHz
Control board	EZDSP F2812
Switching frequency	10KHz

Table II Design Parameters of the 5-hp **Machine**

Rated power	5-hp
Stator Connection	Y/Δ
Rated Voltage (line-to-line)	460/265 volt
Rated Current (line)	6.5/11.5 amps
Rated Frequency	60 Hz
Rated Speed	1185 rpm
Rated Torque	30 Nm
Phases	3/6
Number of Poles	6
Stator Resistance	1.2417 Ω
Rotor Resistance	1.0217 Ω

Stator Leakage inductance	0.00563277 H
Rotor Leakage inductance	0.0056 H
Magnetizing Inductance	0.21345 H

The control algorithms outlined in this paper were coded into a standard C language and hosted on the DSP chip. The memory utilization and the program execution speed are given in Table III. In this table, the standard constant volt-per-hertz scalar control has been compared to the speed and the memory requirement with the addition of the compensation control loops (see Fig. 3).

Table III Memory Requirement and Execution Times

Control Type	**Execution time**	**Memory Utilization**
Standard (V/F)	13.6 µsec	2.95 kB
Standard (V/F) + Proposed Fault Tolerant Topology	21.6 µsec	3.233 kB

The torque measurement was a key element in the experimental stage of this work. This measurement was mainly achieved using a torque transducer that is mechanically coupled to the motor shaft from the drive end (DE) side. Flexible coupling were utilized in the setup to couple the motor's DE to the torque transducer and the torque transducer to the dc dynamometer DE side. The torque transducer data are given in Table IV.

Table IV Torque Transducer Main Data

Torque Transducer Model	MCRT-2904T
Signal Conditioner and Amplifier	66042
Signal Conditioner Bandwidth	500 Hz
Torque Meter Installation	Foot mounted

References

1. T. Jahns, "Improved reliability in solid-state drives for large asynchronous ac machines by means of multiple-independent phase-drive units", *IEEE Trans. Ind. Appl.*, vol. 1 A-16, no. 3, pp. 321-331, May/Jun. 1980.

2. L. Tian-Hua, F. Jen-Ren and T. A. Lipo, "A strategy for improving reliability of field-oriented controlled induction motor drives", *IEEE Trans. Ind. Appl.*, vol. 29, no. 5, pp. 910-918, Sep./Oct. 1993.

3. F. Jen-Ren and T. A. Lipo, "Disturbance-free operation of a multiphase current-regulated motor drive with an opened phase", *IEEE Trans. Ind. Appl.*, vol. 30, no. 5, pp. 1267-1274, Sep./Oct. 1994.

4. R. Ribeiro, C. Jacobina, E. Silva and A. Lima, "Fault-tolerant voltage-fed PWM inverter ac motor-drive systems", *IEEE Trans. Ind. Electron.*, vol. 51, no. 2, pp. 439-446, Apr. 2004.

5. O. Jasim, C. Gerada, M. Sumner and J. Arellano-Padilla, "Investigation of induction machine phase open circuit faults using a simplified equivalent circuit model", *Proc. 18th Int. Conf. Electr. Mach. 2008. (ICEM) pp. 1--6*, 2008-Sep. 69.

6. D. Kastha and B. K. Bose, "Fault mode single-phase operation of a variable frequency induction motor drive and improvement of pulsating torque characteristics", *IEEE Trans. Ind. Electron.*, vol. 41, no. 4, pp. 426-433, Aug. 1994.

7. D. Kastha and B. K. Bose, "On-line Search based pulsating torque compensation of a fault mode single-phase variable frequency induction motor drive", *IEEE Trans. Ind. Appl.*, vol. 30, no. 4, pp. 802-811, Jul./Aug. 1995.

8. W. Jiang and B. Fahimi, "Current reconstruction techniques for survivable three-phase PWM converters", *IEEE Trans. Power Electron.*, vol. 25, no. 1, pp. 188-192, Jun. 2010.

9. M. Corra, C. Jacobina, E. Silva and A. Lima, "An induction motor drive system with improved fault tolerance", *IEEE Trans. Ind. Appl.*, vol. 3, no. 3, pp. 873-879, May/Jun. 2001.

10. A. Mendes and A. J. M. Cardoso, "Fault-tolerant operating strategies applied to three-phase induction-motor drive", *IEEE Trans. Ind. Electron.*, vol. 53, no. 6, pp. 1807-1817, Dec. 2006.

11. S. Dwari and L. Parsa, "Fault-tolerant control of five-phase permanent magnet motors with trapezoidal back-EMF", *IEEE Trans. Ind. Electron.*.

12. R. S. Miranda, H. A. Toliyat, C. B. Jacobina and A. M. N. Lima, "Short-circuit fault mitigation in six-phase induction machine drives", *Proc. IEEE Vehicle Power Propulsion Conf. (VPPC) pp. 370--376*, 2007-Sep. 912.

13. N. Bianchi, S. Bolognani and M. D. Pre, "Strategies for the fault-tolerant current control of a five-phase permanent-magnet motor", *IEEE Trans. Ind. Appl.*, vol. 43, no. 4, pp. 960-970, Jul./Aug. 2007.

14. A. M. S. Mendes and A. J. M. Cardoso, "Fault-tolerant operating strategies applied to three-phase induction-motor drives", *Ind. Electron. IEEE Trans.*, vol. 53, no. 6, pp. 1807-1817, Dec. 2006.

15. I. Boldea and S. A. Nasar, The Induction Machine Handbook, FL, Boca Raton:CRC Press, 2002.

16. B. A. Welchko, T. M. Jahns and S. Hiti, "IPM synchronous machine drive response to a single-phase open circuit fault", *IEEE Trans. Power Electron.*, vol. 17, no. 5, pp. 764-771, Sep. 2002.

17. S. Grubic, J. M. Aller, B. Lu and T. G. Habetler, "A survey on testing and monitoring methods for stator insulation systems of low-voltage induction machines focusing on turn insulation problems", *IEEE Trans. Ind. Electron.*, vol. 55, no. 12, pp. 4127-4136, Dec. 2008.

18. C. Gerada, K. J. Bradley, M. Sumner and P. Wheeler, "Operating induction motor drives with turn-to-turn faults", *Proc. IEEE IEMDC*, pp. 770-776, 2005-May.

19. P. Vas, Sensorless Vector and Direct Torque Control, U.K., Oxford: Oxford Science, 1998.

20. A. Kadaba, “Design and modeling of a reversible 3-phase to 6-phase inductionmotor for improved survivability under faulty Conditions,” M.S. thesis, Dept. Electr. Comput. Eng.,Marquette Univ., Milwaukee, WI, May 2008.

21. A. Sayed-Ahmed, “Control of PWMAC motor drive systems under faulty conditions,” Ph.D. dissertation, Dept. Electr. Comput. Eng., Marquette Univ., Milwaukee, WI, Dec. 2009.