A Novel Phase Loss Detection Method for Low-Cost Motor Drives

Anton Dianov, *Senior Member, IEEE*

***Abstract*—This article proposes a novel method for detection of open-phase faults, which was specifically designed for usage in low-cost motor drives. The proposed algorithm uses analysis of current signals to detect the failure and it was developed for usage with conventional configuration of motor drives, where phase currents are measured with the shunt sensors placed in motor phases, or dc-link and which signals are corrupted with a noise. The author discusses the specifics of inverter hardware design for low-cost applications and explains why the conventional techniques are not applicable. After that a new method capable of operating at high noise to signal ratio is proposed and implemented. The experimental results verified feasibility of the developed technique and demonstrated its reliable operation under different load conditions. In order to perform comparative analysis, several conventional algorithms were implemented and their performance was compared to the performance of the proposed method. After experimental verification, this algorithm was included into the existing control scheme of commercial permanent magnet synchronous motors, as a part of the safety module. The modified motor drive successfully passed standardization according to UL 60730 safety standards and was put into mass production.**

***Index Terms*—Fault diagnosis, fault protection, fault tolerant control, motor drives.**

I. INTRODUCTION

THE open-phase failure, which is also called single phasing and loss of phase is the most frequent fault of electrical motor drives, therefore control programs must detect it on time and properly handle it in order to prevent hazardous after-effects. This type of failure can be caused by a variety of factors, such as blown fuses, broken wires, oxidized contacts, open switches, improper maintenance, etc. All major reasons of this failure and their classification are discussed in [1].

Generally speaking, there are two types of phase loss failures, which are distinguished by the place of occurrence. They are "converter phase loss" and "motor phase loss," which interrupt desired power flow in the grid-inverter and inverter-motor connections, respectively. These faults have different impacts on equipment, which depends on the hardware configuration, direction of power flow, etc. However, this article considers only open-phase failure, which happens between inverter and motor, because low-cost drives are typically supplied with a two phased grid and converter phase loss in this system, is similar to disconnection from the grid.

Another specific of low-cost drives is usage of shunt-based current sensors, which outputs are corrupted with noise, therefore, phase loss detection algorithms have to operate properly with high noise to signal ration. Moreover, low-cost drives typically involve one-shunt current sensing techniques, when the shunt is placed in the dc-link and motor phase currents are reconstructed using measurements of dc-link current in proper moments of time. The phase currents calculated using this approach are sensitive to signal noise and offset errors, measurement errors are amplified.

When open-phase failure occurs, it does not immediately cause any failure or damage, but it forces equipment to operate under higher stress, therefore without proper handling it may cause overheating of equipment and may be a reason of an error after a period of time. A good example is presented in [2], where the authors claimed that voltage imbalances of 3% may increase motor temperature up to 25%, but loss of phase causes more serious distortion and temperature can be significantly higher. It happens because after phase loss, the motor is supplied with negative sequence currents, which produce parasitic magnetic fields and lowers torque of the motor. As a result, control system commands higher currents, which rapidly overheat motors and may start a fire. Another negative after-effect of single phasing happens, when motor operates in the field weakening mode, where the rotor field is weakened by the stator current direct component. In this case, the control system may not properly control the direct component of the stator current after failure, so high back electromotive force (EMF) applies to the dc-link causing its over-voltage, which may damage the electrolytic capacitor [3], [4].

As a result of analysis of possible hazardous situations due to the loss of phase, the open-phase detection algorithms became a vital part of the protection code according to IEC/UL 60730 safety standards. This standardization is typically used for low and middle cost drives, e.g., [5], which can exclude some protective devices and decreases total cost of the drive, if the higher safety grade is obtained. According to the standardization rules, analysis of risk and possible hazardous situations must be performed and protection measures for avoiding negative consequences must be proposed. Taking into account the discussed after-effects of single phasing, it is considered

Manuscript received August 23, 2021; revised November 21, 2021; accepted January 7, 2022. Date of publication January 18, 2022; date of current version February 18, 2022. Recommended for publication by Associate Editor H. Hofmann.

The author is with Daeyoung R&D Center, Yongin 16954, South Korea (e-mail: anton.dianov@gmail.com).

This article has supplementary material provided by the authors and color versions of one or more figures available at https://doi.org/10.1109/TPEL.2022.3143822.

Digital Object Identifier 10.1109/TPEL.2022.3143822

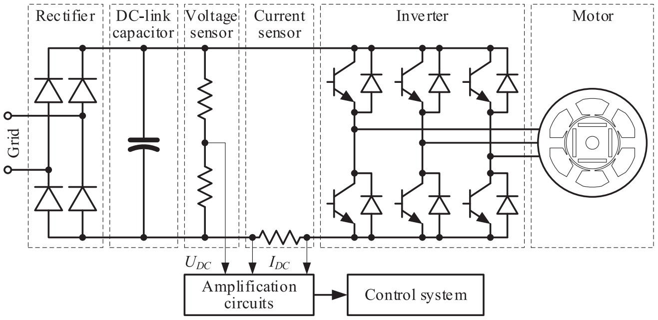

Fig. 1. Typical structure of low-cost motor drives.

a possible hazardous situation, which must be detected in time, therefore open-phase detection techniques must be involved.

It should also be noted that phase failure detection techniques are important for the fault tolerant electrical drives, where these methods are an inevitable part of control software [6]–[8]. They are extremely important for the fast detection of faulty conditions and switching to the proper fault control mode.

In order to prevent single phasing, different protective devices like phase failure relay may be utilized. If a fault happens, they turn the equipment under protection OFF, notifying the high-level control system. Despite the simplicity of this approach, the additional hardware complicates the motor drive, increases total cost and demands more space. Aree [9] proposed the use of an additional neutral wire because it increases motor torque and decreases undesired heating of the motor under fault conditions. However, this approach also needs additional modifications of motor drives and increases the cost, especially in systems with long wires. As a result, many researchers propose software algorithms for fault detection, which can keep the drive safe without worsening other characteristics of the motor drives.

The simplest solution for phase loss detection is revelation of zero current in motor phases [10]–[12]. This approach is simple in implementation and tuning, but its complexity increases with a number of motor phases [13], [14]. Furthermore, it may fail at low load conditions, when the sensed current signals are significantly corrupted by noise. The author implemented this technique in motor drive discussed in [15], where it worked as desired, however, it failed at drives mentioned [16], which frequently operates at zero load.

In order to exclude the influence of number of motor phases on the computational complexity, The detection of single phasing by analysis of oscillations in direct and quadrature components of the stator current are proposed in [17]–[23]. They showed that under phase loss conditions, these components oscillate with a frequency twice higher than the fundamental one, while during normal operation, direct and quadrature components are almost constant. The authors of those papers proposed to detect oscillations, but they used different techniques for such detection. Another technique, which uses the phenomenon of current oscillation in *dq* reference frame was proposed in [22] and [23], where the authors detect fault of phase by comparing actual currents with the commanded values. This approach was also implemented by the author and showed good results in motor drives for reciprocating compressors [24], however, this algorithm failed with the same motor operating in the test jig and rotating at low loads.

The work in [25]–[27] analyzed stator current trajectory in the $\alpha\beta$ (stationary) reference frame. They demonstrated that in normal operation, the trajectory has a circular shape, while under fault conditions it changes to an ellipse. Furthermore, the orientation of the ellipse contains information on the failed motor phase. This method is relatively simple and does not depend on the number of motor phases, however it needs low noise signals, which restricts the usage area. Furthermore, this method fails if motor load varies over mechanical revolution, like in reciprocating compressors.

One of the most popular algorithms for single phase detection is analysis of current spectrum using Fourier transformation, which was considered in detail in [28]–[32]. However, requirements to powerful microcontroller and quality of sensed signals make this method inapplicable in practical solutions, therefore it is mainly used in laboratories.

In order to decrease the impact of noisy signals, the proposed techniques which are based on the calculation of the average value of stator current at one fundamental period are given in [33]–[37]. They claimed that during normal operation, the average value of phase current should be zero, therefore the fault condition can be easily detected. Furthermore, this algorithm is easy in implementation and can distinguish phase fault and open-switch failure. The author implemented this idea and checked its operation. It was found that the method is less sensitive to noise but sensitive to sensor offset errors. Furthermore, it cannot operate with varying load, such as loads in reciprocating compressors [38], where the average value of a phase current over fundamental period is not zero, and detection time of this technique is high, which may be not convenient in many applications.

The complete analysis of the phase loss detection techniques was reported in [39] and [40], which considered their pros and cons in detail. After detailed study of the existing techniques some of them were selected for the implementation, however all of them failed UL60730 safety certification. After that, it was decided to develop a new method for the open-phase detection, which can operate with noisy signals, typical for low-cost drives and which are also insensitive to load variation.

II. STRUCTURE OF LOW-COST MOTOR DRIVE

The proposed algorithm was developed for low-cost motor drives, where the typical structure is shown in Fig. 1. This drive is supplied by a two-phased grid, where the exact voltage depends on the country of usage. The input voltage is rectified by the typical bridge converter and fed to the dc-link, which contains electrolytic capacitors for filtering of voltage ripples. The target motor is connected to the dc-link via an inverter, which modulates dc-link voltage and supplies the motor with an ac voltage of the desired waveform and frequency. In order to provide feedback and perform control of the electrical drive, the system is equipped with a voltage and current sensors in the dc-link. The phase voltages applied to the motor are calculated using signals from the voltage sensor and duty-factors, commanded to inverter switches as well as phase currents, which are reconstructed by using the one-shunt current reconstruction technique.

The voltage sensor in this system is implemented as a voltage divider with a gain of about 0.01, which means that sensor outputs about 3 V, when dc-link voltage is about 315 V, corresponding to 220 V of the grid. In general, the dc-link voltage is quite stable and contains ripples with a frequency twice higher than the input frequency, which makes possible usage of filters with higher time constants. As a result, the voltage signal has a high signal-to-noise ratio and it is easy for measuring.

At the same time, the measurement of dc-link current is not so simple. In order to lower the total cost, the current sensor is implemented using shunt resistors, which need additional circuits and increases communication lines, which in turn, increases noise to signal ratio. Furthermore, the operational range of current sensing circuit is frequently narrowed, which decreases power dissipation at the resistor and allows for the use of shunt of lower power range and saves more money and space in the board. A good example of this approach is the project described in [41], where rated current of the motor corresponds to the voltage drop of 0.7 V at the shunt resistor. As a result, the signal from the current shunt sensor is significantly corrupted with noise, especially with noise caused by modulation. Simultaneously, the requirement for rapid detection of overcurrent errors makes the usage of filters with higher time constants impossible, which makes motor control in low load range a challenging task.

Another problem of current measurement in this system is an offset error. Even if ADC is calibrated at zero current point every time before the system starts, the offset error may appear during operation of a motor drive. Taking into account that in systems as shown in Fig. 1, two phase currents are reconstructed using measured signals and the current in third phase, say i_c, is calculated using two measured or restored phase currents

$$i_c = -i_a - i_b, \tag{1}$$

where i_a and i_b are the measured (restored) currents in two motor phases, the maximum offset error in third is twice higher. Since offset error is not significant, this problem can be insignificant at higher loads, but it significantly worsens control at no load and low load conditions.

Under these difficult conditions, the conventional techniques did not work well and could miss phase loss failure or detect false events, therefore a new technique has to be developed.

III. Proposed Algorithm

In order to overcome the problem of measurement noise and offset errors, it was proposed not to use absolute values, e.g., predefined constants to compare with measured currents. It has been found that the comparison of current signals to each other shows more stable results, since they contain the same errors, which may compensate each other. Therefore, current ranging and detection of the middle current may help to recognize the open-phase failure.

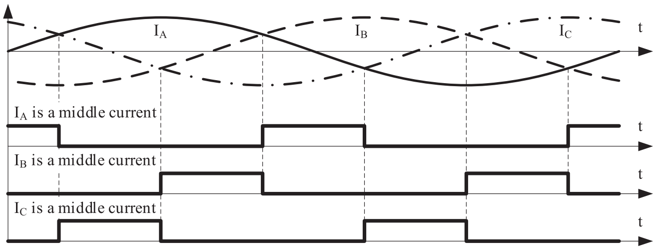

Fig. 2. Middle currents of normally operating motor.

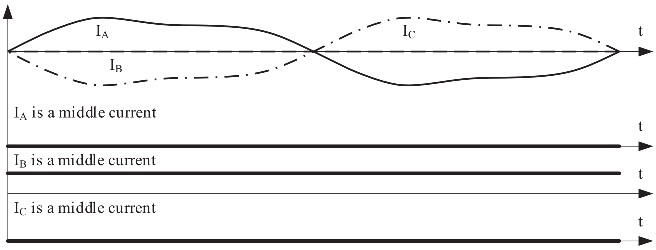

Fig. 3. Middle currents at open phase B failure.

The currents in motor phases at normal operation under field-oriented control (FOC) have sinusoidal waveforms, which are shown in Fig. 2. These currents may be slightly distorted, depending of the motor design, however for the purpose of simplicity it is not considered and motor currents are assumed to be pure sine. Let us define middle current in the system of three phase currents as a signal, which is greater or equal than one of two other currents, but less than another one. For example, the phase "A" current is a middle current, when

$$(i_b \le i_a < i_c) \; || \; (i_c \le i_a < i_b). \tag{2}$$

Therefore, each phase current is a middle current during 60°, with the following 120° delay, as demonstrated in Fig. 2. These values relate to pure sine waveforms and can differ a little for the distorted currents (typically $\pm 15°$). When phase failure happens, the current in the failed phase is a middle one during longer periods of time, 360° in the ideal case, Fig. 3. Practically, the middle current can be unstably detected at the point of crossing currents, but the period of stable detection is about 180°, which is easy to distinguish with 60° intervals of normal operation.

The simplest scheme for the fault phase recognition using middle current detection is depicted in Fig. 4. It receives motor currents at the input and sorts them, outputting index of the middle current. After that, it feeds XOR block with the index of the middle current at current and previous steps. If the indexes are the same, the XOR block outputs zero, however, when the middle current changes the XOR block produces logical "high" signal, which lasts one sampling period. This signal resets the integrator, which calculates the angle, when the middle current is unchanged. This angle θ_f is considered as a fault index and is compared to threshold value θ_{th}. If the fault index exceeds

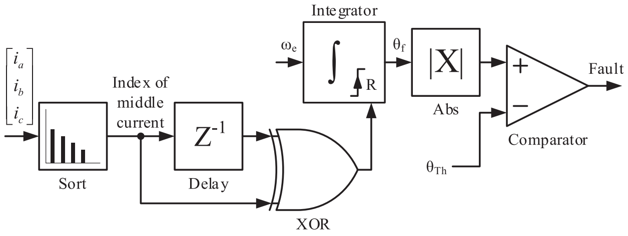

Fig. 4. Proposed open phase detection algorithm.

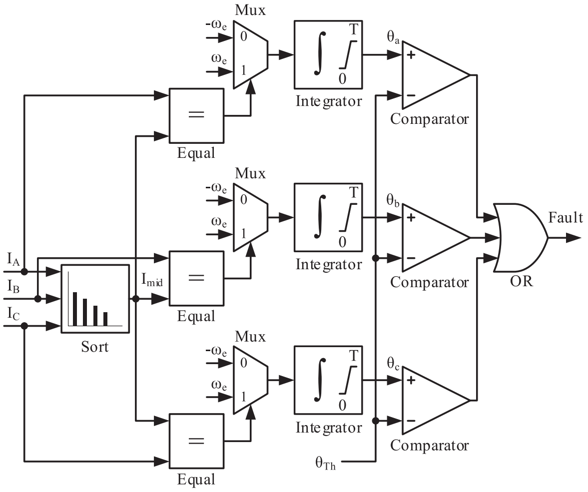

Fig. 5. Improvement of the proposed algorithm.

θ_{th}, the fault signal is generated. This threshold value has to be selected higher than 60°, due to the nature of motor operation and has to be less than 180° in order to provide stability.

If current signals are significantly distorted for any reason and their zero crossing happens more than two times per period, the proposed method can be improved a little, as shown in Fig. 5, which increases its filtering capability. In this algorithm, three channels operate independently and calculated middle current intervals θ_a, θ_b, and θ_c are not reset, when the middle current changes. The output of the integrator is limited with 0 and period of the phase current *T*, in order to exclude overflow/underflow. These current intervals are considered as a fault indexes and compared with a threshold value θ_{th} separately, which makes distinguishing of faulty phase possible. Since the improved algorithm calculate calculates middle current intervals for each phase independently and does not reset them, when the middle current changes, it operates more stably in case of highly distorted currents, when zero crossing may occur more than two times per period.

At the same time, this algorithm has higher computational complexity, increasing with the number of motor phases, therefore selection of the exact method can be done only after experimental verification with a target motor drive.

The most significant superiority of the proposed technique is proper operation with noisy current signals, which are typical for low-cost systems. Another advantage of the developed algorithm is stable work at load variation and transients and absence of false detections. The computational complexity of this method is not significant and does not load the microcontroller too much, therefore chip devices can be used for design of the control system. The tuning of the proposed method is quite simple and even nonexperienced engineers can easily do it. One more benefit of usage of the proposed method is its versatility and proper operation with motors of other types, which have star connected windings and are supplied with a system of sinusoidal signals. It should be also noted, that the proposed method can operate under rectangular control as well because this type of control uses three-phase bipolar currents, shifted at 120°. However, the threshold level θ_{th} must be increased at 5°–15°.

The main drawbacks of this algorithm are the increase in computational complexity, with the number of motor phases and minimum detection time, which is limited to one-sixth of the current period.

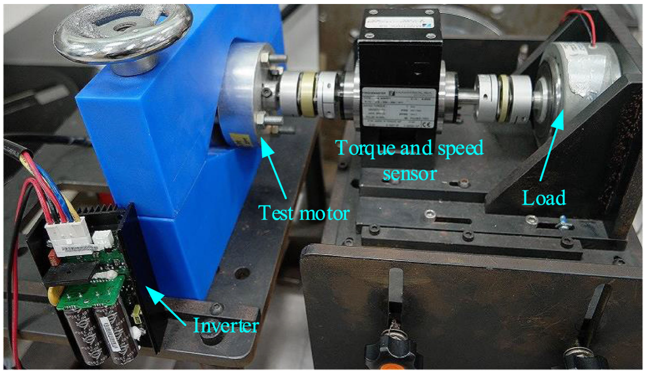

Fig. 6. Schematic diagram of the experimental test rig.

TABLE I
MOTOR RATED PARAMETERS

Parameter	Value
Number of poles	2P = 6
Rated power, W	150
Rated torque, N·m	0.35
Rated speed, r/min	4000
Phase resistance, Ω	1.5
d-axis inductance, mH	47
q-axis inductance, mH	63
Back-EMF constant, V·s/rad	0.15

IV. EXPERIMENTAL SYSTEM

The test jig used in the experimental verification of the proposed method is shown in Fig. 6. The motor used in these tests was a commercial type machine, which is typically built into reciprocating compressors of small air-conditioners and refrigerators. The parameters of the motor are given in Table I. The motor is loaded with a Magtrol hysteresis brake HB-140M-2, which provides a stable load with low level of ripples. The speed and torque of the motor were measured by the Magtrol TM 304/011 transducer and displayed by the Magtrol 3410 display unit. This display was also connected to the PC by serial communication for the data monitoring and acquisition. The electrical signals

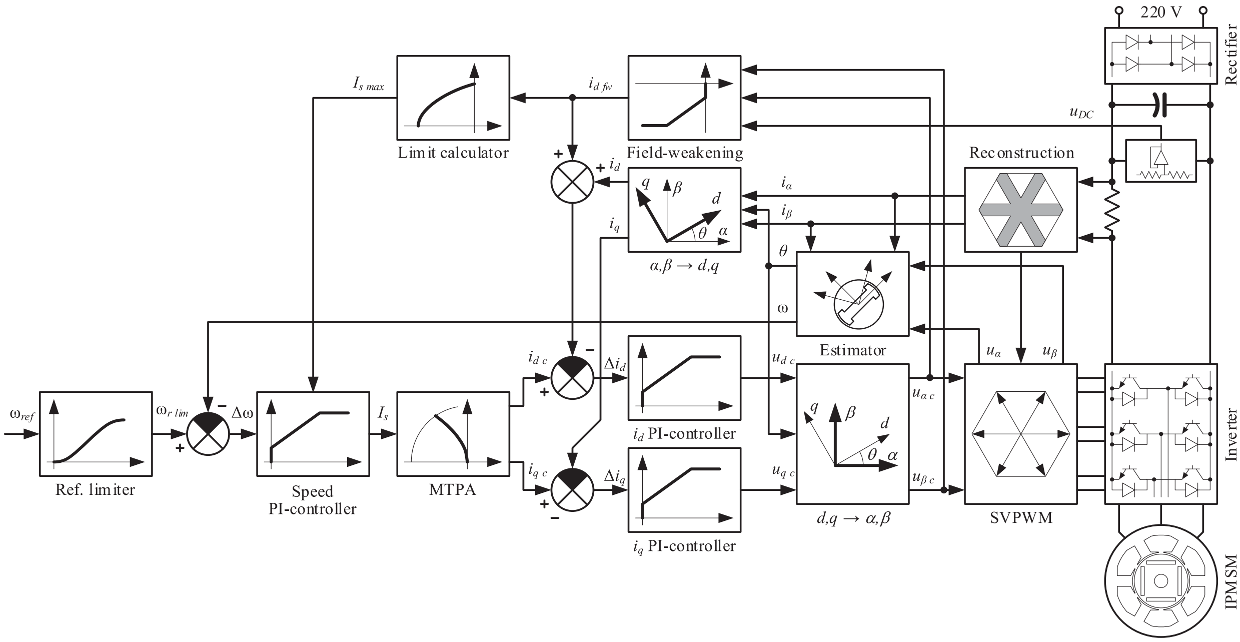

Fig. 7. Control scheme of the experimental motor drive.

were measured by means of an oscilloscope Yokogawa DL 850, capable of saving both oscillograms and raw data.

The voltage source inverter (VSI) involved in tests was a commercial device based on the IGCM04B60GA (600 V/4 A) power module from Infineon Technologies and designed to be used in standard 220 V (50–60) Hz grids. The structure of this VSI was the same as the typical structure of low-cost inverters shown in Fig. 1 and contained one voltage and one current sensors in the dc-link. This current sensor operated together with the current reconstruction algorithm based on the principles considered in [43], in order to obtain motor currents. The case of the inverter was made of aluminum and equipped with fins, therefore it operated as a heatsink.

The core of the motor drive control system was an 80 MHz iHart i910 microcontroller with a Cortex M3 core. It controlled inverter switches at 8 kHz and sampled electrical signals with a sampling time of 125 μs. The signals from sensors were processed by the built-in adjustable operational amplifiers and digitalized with a 12-bit Adc. The laboratory sample of the inverter was equipped with an additional serial communication interface, used to connect it to the PC and perform monitoring of the internal variables.

The control system of motor drive used for the experimental verification of the proposed phase loss detection method, was standard commercial software for driving reciprocating compressors, which was enhanced with a safety module used for the standardization according to UL 60730 safety standard, including the proposed fault phase detection algorithm, Fig. 7. This system was intended for sensorless control of interior permanent magnet synchronous motors (IPMSM), which de facto became a standard in refrigerating and air-conditioning applications, and enhanced with the algorithm for estimation of initial rotor position [44], necessary for the prevention of reverse rotation at start. The control system of the test inverter included an outer speed loop and two inner current loops in *dq* frame. Speed and position for feedback and transformations are provided by the estimator, which uses electrical signals of the motor. The minimum speed for stable operation of the sensorless algorithm was defined as 10 Hz and the maximum error was lower than five electrical degrees [15]. Current and speed controllers were implemented as explained in [12], which included antiwind-up techniques and provided better dynamics. Square root calculation was implemented using techniques discussed in [45] decreasing microcontroller unit (MCU) load, which is desirable for low-cost systems. The open-loop starting and operation until closing of the control system are discussed in [42].

The control system was equipped with maximum torque per ampere (MTPA) block to increase motor drive efficiency and field-weakening controller (FWC) used to increase speed operation range at 30%. The FWC receives commanded and measured dc-link voltages. Then the demanded voltage vector and the maximum possible voltage level (with 5% gap) are calculated. The difference between them is sent to the PI-controller, which calculates field weakening component of the stator current. In order to provide the compatibility with MTPA algorithm, the limit calculator outputs the maximum acceptable command of the stator current.

V. EXPERIMENTAL RESULTS

The proposed algorithm for phase loss detection was implemented and checked using the motor test jig discussed above. The motor phase current at load is shown in Fig. 8, which clearly demonstrates that the waveforms are close to sine, which are easier to process. At the same time, motor currents at no load

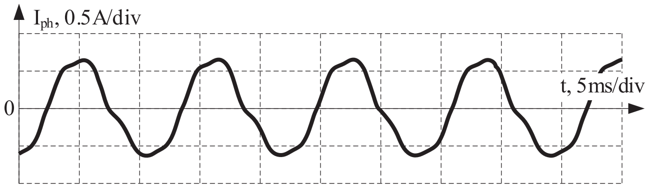

Fig. 8. Motor phase current at load, 1800 r/min.

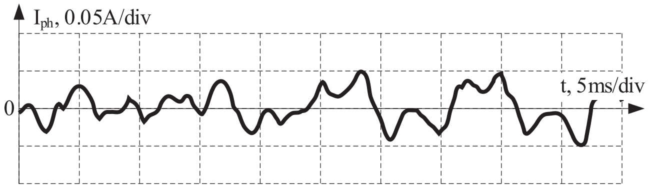

Fig. 9. Motor phase current at no load conditions 1800 r/min.

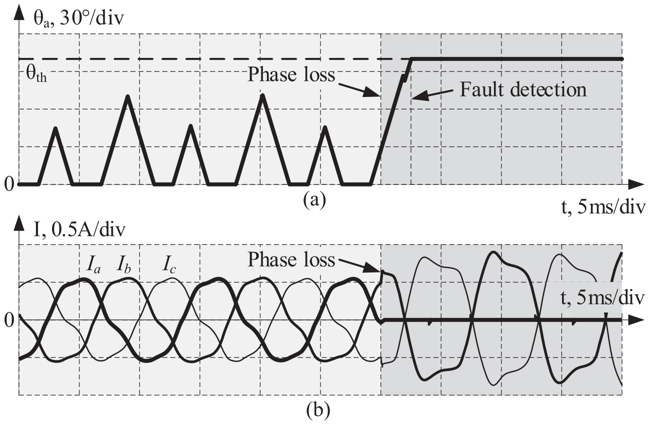

Fig. 10. Open phase fault detection at load 1800 r/min. (a) Fault index of phase "A." (b) Phase currents.

conditions are significantly distorted, and contain several zero crossing points per period Fig. 9, which complicates operation of the phase loss detection algorithms. Taking into account these distortions, we selected the improved version of algorithm Fig. 5, which provides better stability. In all our experiments, the threshold value of phase current middle position θ_{th} was selected as 100°, which was found to be a compromise between detection time and stability.

A. Fault Detection at Rated Load

In this experiment, the value of motor commanded speed was set to 1800 r/min and rated load was applied. The motor rotated for 1 min, until stabilization of system. After that, the phase "A" was manually disconnected from the motor using a circuit breaker. The results of this test are shown in Fig. 10, which illustrates that the fault detection algorithm worked as desired. Since the current waveforms are quite clear, the proposed method easily detects regions, where phase "A" current is in the middle position and calculates their length. In normal operation, they are in the range of 40°–70°, but in the case of failure θ_a raises until the threshold value θ_{th}, where the fault is detected, Fig. 10(a). The detection angle was less than 100°, which proves proper operation of the developed algorithm.

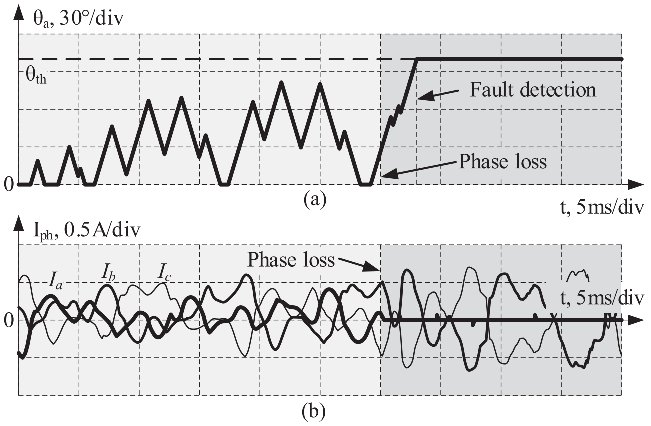

Fig. 11. Open phase fault detection at no load, 1800 r/min. (a) Fault index of phase "A." (b) Phase currents.

B. Fault Detection at Low Load

In this test, the conditions were similar to the previous experiment, but the load was removed, which resulted in highly distorted phase currents. The operation of the proposed method is shown in Fig. 11, which illustrates that the phase loss was detected properly, despite highly distorted current waveforms with numerous zero crossings per period. It can be clearly seen that fault index θ_a accumulates at several intervals Fig. 11(a), however its value does not exceed 80°, leaving a stability gap of 20°. The proposed algorithm properly detected loss of phase in several consecutive experiments with the detection angle not exceeding 100°, therefore this test was successfully passed.

C. Fault Detection at Low Speed

In this experiment, operation of the algorithm was verified at low speed. For this purpose, motor speed was set at 300 r/min and the load was applied. The motor rotated for one minute, until stabilization of system. After that, the phase "A" was manually disconnected from the motor using a circuit breaker. The results of this test are shown in Fig. 12, which demonstrates that the fault detection algorithm operated as desired even in the low-speed region.

D. Performance at Load Disturbance

The purpose of this test was verification of the phase loss detection algorithm performance under the load disturbance conditions, checking of presence of false positive detections and the analysis of its stability. In order to do this, the load of 20% of the rated load was applied and the motor was rotated at 1800 r/min. After about one minute, the load was increased to 100% with one step, and operation of the phase loss detection algorithm was checked. As it can be clearly seen from Fig. 13,

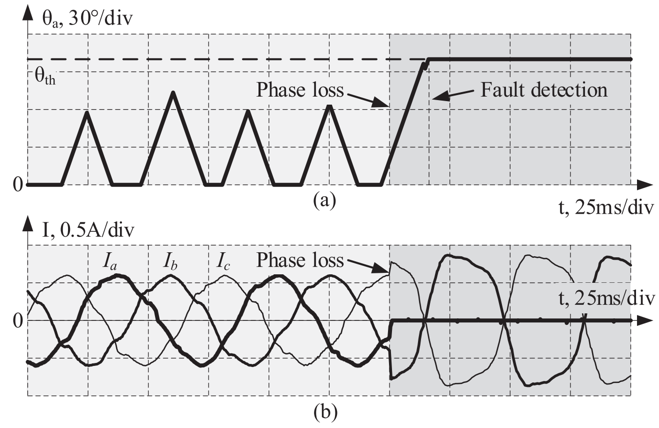

Fig. 12. Open phase fault detection at no load, 300 r/min. (a) Fault index of phase “A.” (b) Phase currents.

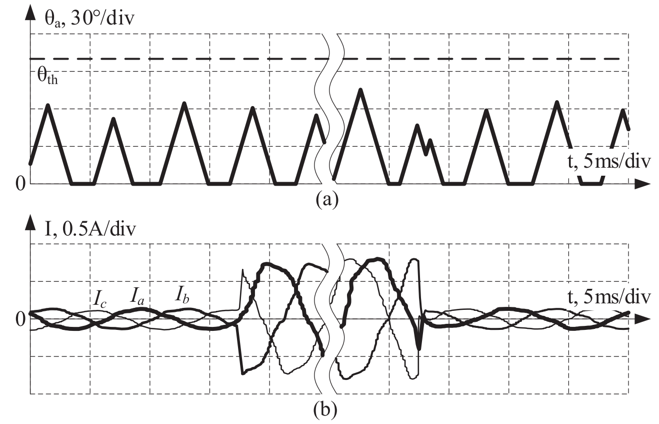

Fig. 13. Operation of the proposed algorithm at load disturbance, 1800 r/min. (a) Fault index of phase “A,” (b) Phase currents.

the algorithm works stably and this disturbance had almost no impact.

In the next step, the load was decreased from 100% to 20% in one step and performance of the proposed method was checked. As it can be clearly seen from Fig. 13, this disturbance also has minor impact on the operation of the proposed algorithm and it does not output false fault signals.

E. Performance at Load Varying Over Revolution

This experiment was conducted to verify the proper operation of the proposed technique under load torque, varying over mechanical revolution, which frequently happens in the mechanical systems, e.g., reciprocating compressors. The specifics of this load is nonsymmetrical phase currents, with average values which differ from zeroes. Furthermore, the difference between phase current amplitudes can be as high as 3–4 times, which creates problem for the operation of some phase loss detection techniques.

For the purpose of verification, the motor was operated at low-speed of 900 r/min, because at lower speeds, the kinetic energy of the system is lower and the difference in current amplitudes is more pronounced. The phase current at rated load, when the motor drives reciprocating compressor, is shown in Fig. 14, which illustrates the waveform of phase current, as discussed above. The operation of the proposed algorithm at compressor load is depicted in Fig. 15, which clearly shows that the loss of phase fault was properly detected and there were no false detections. The minimum margin between fault index and threshold value was about 20°, which guarantees stability of operation.

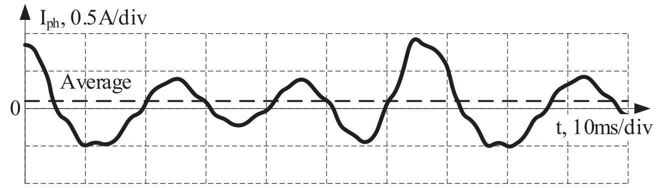

Fig. 14. Motor phase current at compressor load 900 r/min.

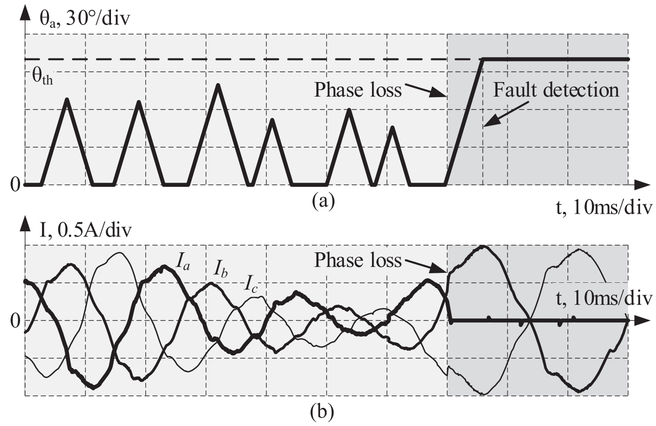

Fig. 15. Open phase fault detection at compressor load 900 r/min. (a) Fault index of phase “A.” (b) Phase currents.

F. Performance at Speed Transients

In order to analyze behavior of the proposed algorithm in speed transients and check presence or absence of false fault detection, the motor was accelerated from 2500 to 2700 r/min and then, after some period of time, decelerated back to 2500 r/min. In the normal operation of motor drives, the acceleration and deceleration are limited by the rate limiter at 1 Hz/s^2, which is caused by the mechanical design of reciprocating compressors. It results in slow speed transients, which almost do not impact the waveforms of electrical signals. Therefore, for the purpose of verification of algorithm behavior in the fast transients the acceleration and deceleration limits were set to 300 Hz/s^2.

The experiment was conducted at the rated load and load equal to 20% of the rated. The operation of the proposed method at higher load was quite stable and similar to Fig. 13, since motor currents were high enough in all transients, therefore these figures are not provided. Simultaneously, operation at the lower load is more interesting and is demonstrated in Fig. 16.

TABLE II
COMPARISON OF PHASE LOSS DETECTION ALGORITHMS

Criteria Algorithm	Computational complexity	Tuning	Detection Time	Sensitivity to$^{(1)}$	Reliability	Recognition of fault type and location
Proposed	Simple	Easy	> T/6	-	High	Faulty phase
Zero current detection	Simple	Easy	0.1·T	Noisy signals, low load	Medium	Faulty phase
dq currents oscillations	Medium	Medium	>T/2	Noisy signals, current harmonics	Medium	No
Average current	Medium	Easy	T	Noisy signals, sensor offset error, varying load	High	Faulty phase, faulty switch
Current trajectory in $\alpha\beta$	Complex	Difficult	(2~3)·T	Noisy signals, low load	Medium	Faulty phase, faulty switch

(1). The method failed at least in one of ten tests

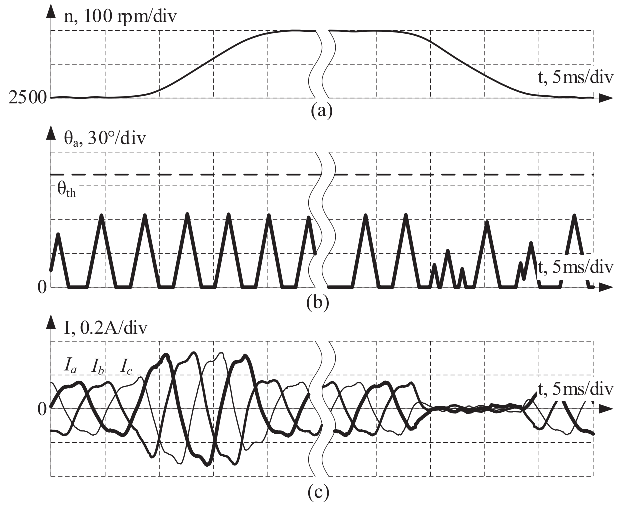

Fig. 16. Operation of the proposed algorithm at speed transients, 1800 r/min. (a) Motor speed. (b) Fault index of phase "A." (c) Phase currents.

It is clearly seen, that during acceleration motor currents increase, and do not significantly disturb the phase loss detection algorithm. However, at deceleration the motor currents decrease to a lower value, which disturbs the proposed algorithm. Furthermore, this fast speed transient forces motor to operate in a braking mode during deceleration. Nevertheless, its operation is stable and false fault detections were not observed. Furthermore, as can be seen from Fig. 16(b), the minimum margin between the fault index and threshold value was about 50°, which guarantees stable operation.

VI. DISCUSSION

In order to compare the proposed method with the most popular existing techniques, all of them were implemented in the experimental system discussed above and tested under different conditions. The most important criteria were selected and put into the Table II, which can be used for comparison and selection of different methods. It should be noted that, these methods can also detect single switch fault, which produces currents similar to the open-phase fault at half period of the current signals. At the same time, some of them may not distinguish these faults.

Comparing techniques in that table using provided criteria, it was found that the proposed method combines simplicity, reliability, relatively fast fault detection and is not sensitive to noise inherent to measurement circuits in low-cost applications.

It should be noted, that in all experiments the margins between the fault index and threshold value were higher than 20°, which provides acceptable stability. At the same time, the stability of the proposed method may be increased more by enlarging the negative gains of integrators in Fig. 5, which will reset integrator outputs faster and prevent accumulation of the fault indices.

The proposed algorithm successfully passed company tests and the following UL safety certification according to UL60730. After that it was approved for mass production and became a part of commercial motor drives. More than two years of operation in millions of commercial devices proves its reliability.

VII. CONCLUSION

A novel method for detection of open-phase fault has been presented in this article. This method analyzes phase currents of motor drives under protection and detects the failure within half the period of fundamental period. The proposed technique is specifically designed to operate at high noise to signal ratio conditions inherent to low-cost motor drives with shunt current sensors, where conventional algorithms may fail. The experimental results proved the feasibility of the developed method and its superiority over conventional techniques, when working with sensed signals corrupted by noise. The proposed algorithm was included in the safety part of the existing commercial motor drive control software and passed certification according to UL 60 730 safety standards. After that, the developed phase loss detection method became an indispensable part of commercial drives, which are produced nowadays.

Despite this method was initially developed for IPMSM, it can operate with motors of other types, which have star connected windings and are supplied with a system of sinusoidal signals.

REFERENCES

[1] F. J. T. E. Ferreira, A. M. Silva, and A. T. de Almeida, "Single-phasing protection of line-operated motors of different efficiency classes," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2071–2084, May/Jun. 2018.

[2] T. Smith and B. Graves, "Detection of loss of voltage phase," in *Proc. Ann. Pulp Paper Ind. Tech. Conf.*, 2013, pp. 1–5.

[3] H. D. Do *et al.*, "Overvoltage protection for interior permanent magnet synchronous motor test bench," in *Proc. Int. Workshop Elect. Drives, Optim. Control Elect. Drives*, 2017, pp. 1–5.

[4] A. Dianov, K. N. Su, and K. Y. Kwan, "Future drives of home appliances: Elimination of the electrolytic DC-link capacitor in electrical drives for home appliances," *IEEE Ind. Electron. Mag.*, vol. 9, no. 3, pp. 10–18, Sep. 2015.

[5] A. Dianov, N. S. Kim, and S. M. Lim, “Sensorless starting of horizontal axis washing machines with direct drive,” in *Proc. Int. Conf. Elect. Mach. Syst.*, 2013, pp. 1–6.

[6] G. I. Odnokopylov and A. D. Bragin, “Algorithms of fault tolerant control of induction motor electric drive in phase loss operate mode,” in *Proc. Int. Siberian Conf. Control Commun.*, 2015, pp. 1–5.

[7] J. Afsharian, D. Xu, B. Wu, B. Gong, and Z. Yang, “A new PWM and commutation scheme for one phase loss operation of three-phase isolated buck matrix-type rectifier,” *IEEE Trans. Power Electron.*, vol. 33, no. 11, pp. 9854–9865, Nov. 2018.

[8] C. Liu, K. T. Chau, and W. Li, “Comparison of fault-tolerant operations for permanent-magnet hybrid brushless motor drive,” *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 1378–1381, Jun. 2010.

[9] P. Aree, “Effects of neutral conductor on induction motor steady-state performance under loss of one phase of supply voltages,” in *Proc. 2nd IEEE Int. Conf. Power Electron., Intell. Control Energy Syst.*, 2018, pp. 837–840.

[10] Y. Fan, W. Zhu, X. Zhang, M. Cheng, and K. T. Chau, “Research on a single phase-loss fault-tolerant control strategy for a new flux-modulated permanent-magnet compact in-wheel motor,” *IEEE Trans. Energy Convers.*, vol. 31, no. 2, pp. 658–666, Jun. 2016.

[11] O. Béthoux, E. Labouré, G. Remy, and E. Berthelot, “Real-time optimal control of a 3-phase PMSM in 2-phase degraded mode,” *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2044–2052, Mar. 2017.

[12] A. Anuchin *et al.*, “Adaptive efficient control for switch-reluctance drives with DCDC-regulator for inverter supply,” in *Proc. Power Electron. Motion Control Conf.*, 2004, pp. 1–5.

[13] H. A. Toliyat, “Analysis and simulation of five-phase variable-speed induction motor drives under asymmetrical connections,” *IEEE Trans. Power Electron.*, vol. 13, no. 4, pp. 748–756, Jul. 1998.

[14] S. Dwari and L. Parsa, “An optimal control technique for multiphase PM machines under open-circuit faults,” *IEEE Trans. Ind. Electron.*, vol. 55, no. 5, pp. 1988–1995, May 2008.

[15] A. Dianov, “Stoppage noise reduction of reciprocating compressors,” *IEEE Trans. Ind. Appl.*, vol. 57, no. 5, pp. 4376–4384, Sep./Oct. 2021.

[16] A. Anuchin, A. Dianov, and F. Briz, “Synchronous constant elapsed time speed estimation using incremental encoders,” *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 4, pp. 1893–1901, Aug. 2019.

[17] S. C. Yang *et al.*, “Comparison of open-phase fault detection for permanent magnet machine drives using different fault signals,” in *Proc. Energy Convers. Congr. Expo.*, 2017, pp. 385–390.

[18] S. Sandun *et al.*, “D-Q current signature based single winding open fault detection for SM-PMAC machine drives,” in *Proc. Int. Elect. Mach. Drives Conf.*, 2013, pp. 1343–1347.

[19] K. Rothenhagen and F. W. Fuchs, “Performance of diagnosis methods for IGBT open circuit faults in voltage source active rectifiers,” in *Proc. 35th Ann. Power Electron. Specialists Conf.*, 2004, pp. 4348–4354.

[20] A. Anuchin *et al.*, “Speed estimation algorithm with specified bandwidth for incremental position encoder,” in *Proc. Int. Conf. Mechatronics - Mechatronika*, 2016, pp. 1–6.

[21] A. Hajary, R. Kianinezhad, S. G. Seifossadat, S. S. Mortazavi, and A. Saffarian, “Detection and localization of open-phase fault in three-phase induction motor drives using second order rotational park transformation,” *IEEE Trans. Power Electron.*, vol. 34, no. 11, pp. 1893–1901, Nov. 2019.

[22] J. O. Estima and A. J. Marques Cardoso, “A new algorithm for real-time multiple open-circuit fault diagnosis in voltage-fed PWM motor drives by the reference current errors,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 8, pp. 3496–3505, Aug. 2013.

[23] J. O. Estima and A. J. Marques Cardoso, “A new approach for real-time multiple open-circuit fault diagnosis in voltage-source inverters,” *IEEE Trans. Ind. Appl.*, vol. 47, no. 6, pp. 2487–2494, Nov./Dec. 2011.

[24] A. Dianov, “Estimation of the mechanical position of reciprocating compressor for silent stoppage,” *IEEE Open J. Power Electron.*, vol. 1, no. 1, pp. 64–73, Mar. 2020.

[25] H.-U. Shin *et al.*, “Fault detection and fault-tolerant operation of a five-phase induction motor driving system,” in *Proc. 8th Int. Power Electron. Motion Control Conf.*, 2016, pp. 1–6.

[26] K. Rothenhagen and F. W. Fuchs, “Performance of diagnosis methods for IGBT open circuit faults in three phase voltage source inverters for AC variable speed drives,” in *Proc. Eur. Conf. Power Electron. Appl.*, 2004, pp. 1–5.

[27] A. Khlaief *et al.*, “A real-time open phase faults detection for IPMSM drives based on discrete Fourier transform phase analysis,” in *Proc. Int. Conf. Elect. Eng. Softw. Appl.*, 2013, pp. 1–6.

[28] M. Yakovenko *et al.*, “Implementation of a protected low-cost voltage-source inverter,” in *Proc. Int. Conf. Elect. Power Drive Syst.*, 2018, pp. 1–4.

[29] A. Khlaief, M. Boussak, and M. Gossa, “Open phase faults detection in PMSM drives based on current signature analysis,” in *Proc. 19th Int. Conf. Elect. Mach.*, 2010, pp. 1–6.

[30] X. Gong and W. Qiao, “Imbalance fault detection of direct-drive wind turbines using generator current signals,” *IEEE Trans. Energy Convers.*, vol. 27, no. 2, pp. 468–476, Jun. 2012.

[31] C. Bilal *et al.*, “Review on external and internal faults of an association inverter-motor and their impact on the motor operation,” in *Proc. Int. Conf. Green Energy Convers. Syst.*, 2017, pp. 1–7.

[32] S. S. Refaat, H. Abu-Rub, M. S. Saad, E. M. Aboul-Zahab, and A. Iqbal, “Detection and discrimination between unbalanced supply and phase loss in PMSM using ANN-based protection scheme,” in *Proc. 7th IEEE GCC Conf. Exhib.*, 2013, pp. 430–435.

[33] Y. Yu, J. Hu, Z. Wang, and D. Xu, “IGBT open circuit fault diagnosis in VSI fed induction motor drives based on modified average current method,” in *Proc. IEEE Conf. Ind. Electron. Appl.*, 2014, pp. 1334–1338.

[34] M. Salehifar, R. S. Arashloo, J. M. Moreno-Equilaz, V. Sala, and L. Romeral, “Fault detection and fault tolerant operation of a five phase PM motor drive using adaptive model identification approach,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 2, no. 2, pp. 212–223, Jun. 2014.

[35] M. A. Zdiri, B. Bouzidi, and H. H. Abdallah, “Improved diagnosis method for VSI fed IM drives under open IGBT faults,” in *Proc. 15th Int. Multi-Conf. Syst., Signals Devices*, 2018, pp. 905–910.

[36] F. Meinguet, P. Sandulescu, X. Kestelyn, and E. Semail, “A method for fault detection and isolation based on the processing of multiple diagnostic indices: Application to inverter faults in AC drives,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 3, pp. 995–1009, Mar. 2013.

[37] M. Trabelsi *et al.*, “Open-switch and open-phase real time FDI process for multiphase PM synchronous motors,” in *Proc. Int. Symp. Ind. Electron.*, 2016, pp. 179–185.

[38] A. Dianov *et al.*, “Sensorless vector controlled drive for reciprocating compressor,” in *Proc. Power Electron. Specialists Conf.*, 2007, pp. 580–586.

[39] A. Dianov and A. Anuchin, “Phase loss detection using current signals: A review,” *IEEE Access*, vol. 9, pp. 114727–114740, 2021.

[40] A. Dianov and A. Anuchin, “Phase loss detection using voltage signals and motor models: A review,” *IEEE Sensors J.*, vol. 21, no. 23, pp. 26488–26502, Dec. 2021.

[41] K. W. Lee, D. Kim, B. Kim, and B. Kwon, “A novel starting method of the surface permanent-magnet BLDC motors without position sensor for reciprocating compressor,” *IEEE Trans. Ind. Appl.*, vol. 44, no. 1, pp. 85–92, Jan./Feb. 2008.

[42] A. Dianov, N. S. Kim, and S. M. Kim, “Sensorless starting of direct drive horizontal axis washing machines,” *J. Int. Conf. Elect. Mach. Syst.*, vol. 3, no. 2, pp. 148–154, Apr. 2014.

[43] G. Wang *et al.*, “Current reconstruction considering time-sharing sampling errors for single DC-link shunt motor drives,” *IEEE Trans. Power Electron.*, vol. 36, no. 5, pp. 5760–5770, May 2021.

[44] A. Dianov *et al.*, “Initial rotor position detection of PM motors,” in *Proc. Power Electron. Motion Control Conf.*, 2004, pp. 1–6.

[45] A. Dianov and A. Anuchin, “Review of fast square root calculation methods for fixed point microcontroller-based control systems of power electronics,” *Int. J. Power Electron. Drive Syst.*, vol. 3, no. 11, pp. 1153–1164, 2020.

Anton Dianov (Senior Member, IEEE) received the B.Sc.(Hons.), M.Sc.(Hons.), and Ph.D.(Hons.) degrees in electrical engineering from the National Research University “Moscow Power Engineering Institute,” Moscow, Russia, in 2000, 2002, and 2005, respectively.

From 2005 to 2021, he was a Senior Engineer with Samsung Electronics, where he developed motor drives for home appliances. Since 2022, he has been a Senior Research Engineer with Daeyoung R&D Center, Yongin, South Korea. He is the author of more than 40 publications in the referring journals and conferences on electrical drives and motor control. He is the author of several patents on control algorithms for electrical drives and power electronics. He is a member of editorial board of several journals on power electronics and electrical drives including IEEE OPEN JOURNAL OF THE INDUSTRIAL ELECTRONICS SOCIETY, *International Journal of Power Electronics,* and *Journal of Power Electronics*. His research interests include electrical drives, sensorless, and advanced control algorithms.

Dr. Dianov was the recipient of several personal scholarships including the scholarship from the President of Russian Federation.