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Phase Loss Detection Using Current Signals: A Review

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ABSTRACT This paper discusses open phase faults, which can happen in a system grid-converter-motor drive, and measures to properly handle this type of fault. The authors of this paper provide classification of algorithms used for the detection of the loss of phase and explain the distinctive features of each group of methods. They review existing algorithms, which are based on the analysis of the current signals, discuss their pros and cons and suggest possible areas of usage for each group of methods. The authors also propose one novel method for detection of open phase, which was developed for low-cost systems with low resolution analog-to digital converters (ADC). This paper mainly considers methods for three-phase motors as the most popular machines, however some algorithms can be used in multiphase drives. The authors of the paper also share their more than 20 years' experience combined, in this area, which was obtained by developing industrial and commercial drives, and focus on the requirements of the IEC/UL 60730 safety standard, where the phase-loss detection algorithm is one of the essential parts of control system.

INDEX TERMS Motor drives, Fault diagnosis, Fault protection, Fault tolerant control

I. INTRODUCTION

The loss of phase, which is also called open phase, phase failure or single phasing, is one of the most frequent faults of industrial and commercial electrical drives, so control software of modern power converters must properly handle this situation in order to prevent negative after-effects [1]. There are a lot of possible causes of this fault, among which are blown fuses, open switches, broken or damaged wires, worn or oxidized contacts, melted conductors, mechanical damage, etc. Full list of possible reasons and their classifications are given in [2].

If this kind of failure interrupts normal power flow between the grid and the power converter, it is called "converter phase loss", or if phase loss distorts power exchange between the converter and the motor, it is called "motor phase loss". Despite their similarities, they have divergent impacts on the drives, which depends on the direction of power flow, hardware configuration, etc.

Once loss of phase happens, it does not immediately cause any damage or failure, however without recognition, it may force equipment to operate under stress, cause overheating and produce errors after a period of time [3]. The authors of [4, 6] studied impact on the voltage unbalance on the motor drives and claimed that voltage imbalances as small as 3%, had the ability to increase the motor temperature by up to 25%, but single phasing causes a more significant distortion of voltage.

Converter loss of phase results in higher ripples of DC-link voltage and currents, which causes faster degradation of electrolytic capacitors and shortens their lifetime. Taking into account that electrolytic capacitors are the weakest part of electrical drives [7, 8], it significantly shortens the lifetime of the entire drive. Furthermore, failure of this capacitor may start a fire and might be the reason for serious damage. In the regenerative drives, converter phase loss may cause distortion of the grid voltage and negatively impact other devices in the grid as can be seen in [4, 9 – 11].

Motor phase loss results in suppling motors with currents of negative sequence, which create parasitic magnetic fields and decrease motor torque [4]. It leads to rapid overheating of the motor and can result in hazardous after-effects [5].

One of the worst cases of the loss of phase failure is operation in the field weakening modes, when the field of the rotor is weakened by the direct component of the stator current. When open phase happens, the control system cannot properly control the direct component of stator current, therefore high back-EMF may be applied to the

DC-link, which causes its overvoltage and may damage the electrolytic capacitor and/or inverter switches. This hazardous situation and simple protective measures are discussed in [12].

For prevention of the open phase failure, different protective devices can be utilized and three-phase monitor relay, also called a phase failure relay, is the most popular hardware solution in order to protect against single phasing in the low and middle power ranges of electrical drives [4]. In case of an error, the relay turns the equipment under protection off and may notify the monitoring system. Other protective devices for this kind of faults are discussed in detail in [2], where the authors also pay specific attention to the standard related to motor protection. At the same time, the authors of [3] propose to use additional neutral wire as a simple solution for the open phase operation of induction motors. They found that the neutral conductors increase motor torque, and decrease heating of the motor in the operation, under loss of phase conditions. Simultaneously, if a motor drive uses topology with a neutral wire, it is better to involve fault tolerant control as described in [13], which provides more reliability and flexibility. Nevertheless, despite the simplicity of hardware protection, it complicates the system, enlarges used space and increases total cost of the drive. Therefore, many engineers develop software methods for the phase loss detection, which allows proper measures to be taken in time and avoid more serious failure.

At the same time, phase loss detection algorithms are important, not only for conventional drives, but for the fault tolerant three phase electrical drives [14 – 16], multiphase electrical drives [17 – 23], dual electrical machines [24, 25] and power converters [26 – 30]. These drives are becoming more and more popular in applications, especially where failure of the drive may cause serious damage or result in dramatic consequential effects [31 – 37]. Good examples of these applications are electric vehicles, electrical equipment of aircrafts and ships, especially propulsion systems, drives used in military applications and the chemical and nuclear industries.

All of these fault tolerant drives use different principles in order to increase reliability, but despite this fact, all of them have common fault processing algorithms, which consist of the following steps: fault detection, isolation of faulted part and application of the new control strategy [38 – 40]. As can be seen, the loss of phase detection algorithm is one of the key algorithms used for the detection of drive faults, therefore it is an essential part of all fault tolerant drives.

It should be mentioned that some other faults are similar to the open phase failure, e.g., inverter open switch failure, whereby the faulted motor phase conducts only one half of a fundamental period, therefore some phase loss detection techniques could be adjusted for detection of open switch failures as well [41 – 43].

Loss of phase detection algorithms are also very important parts of the protection code according to IEC/UL 60730 safety standards. Typically, the drives for this standardization are low and middle cost drives e.g. [44, 45], which undergo this process to obtain a higher safety grading, which, in turn, allows the exclusion of some protective hardware and decreases total cost of the drive. According to the standard, risk and hazard analysis should be performed for the drive under certification. Typically, this analysis considers loss of phase as a possible hazardous situation, because if the phase is disconnected, when the motor rotates, it can still continue to operate in two-phase mode, producing lower torque. If the control system does not recognize that failure, speed controller increases current commands to produce higher torque, which can result in motor overheating and a fire starting. At the same analysis, if motor phase was opened at standstill, the motor may not start rotation, which results in a locked rotor – another dangerous case with the possibility of overheating the motor. Therefore, loss of phase detection algorithm is a vital part of the safety code for the satisfaction of IEC/UL 60730 safety standard.

II. CLASSIFICATION

The proposed classification for phase loss detection algorithms and methods is shown in Fig. 1. It includes methods found in the latest publications and middle current detection algorithm, which was developed and implemented by the authors. The techniques for detection of open phase, which need additional sensors, equipment or special maintenance [46 – 48] may show more precise results, but are out of scope of this paper due to their expense and complexity. A substantial part of these algorithms was checked in the laboratory and some of them were put in mass production (MP).

Open phase detection algorithms utilized for the identification of converter phase and motor phase losses, use similar ideas, and their applicability depends on the system behaviour and topology. Therefore, methods proposed for the converter phase loss detection can be used for motor phase loss detection as well, provided the motor drive is equipped with the necessary sensors. For this reason, location of phase loss is not involved in the classification.

Basically, phase loss detection algorithms can be divided into three classes as depicted by the type of signal they use for analysis: current, voltage and combined. Current signals are more popular, because the presence of current in the phase definitely acknowledges connection and absence of the failure. At the same time, the detected voltage may not discover phase loss behind the sensor. Furthermore, many cheap systems are not equipped with the voltage sensors necessary for the detection of open phases. The third class of algorithms, which uses currents and voltages, typically involves motor models for the estimation techniques and detects loss of phase based on the data from these models. It is clearly seen from Fig 1, that the detection of single phasing is a wide topic, which is hard to discuss in one paper, therefore this paper highlights only methods, which

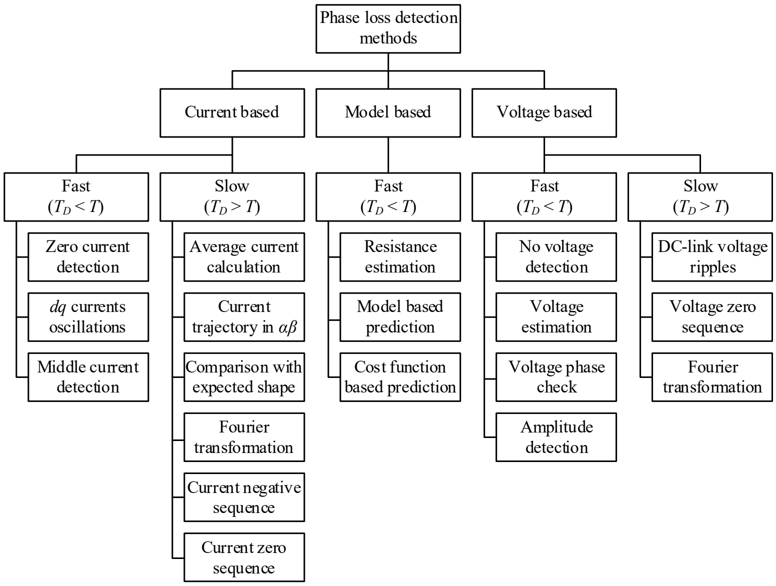

FIGURE 1. Classification of phase loss detection algorithms.

use current signals. The other techniques, which involve model-based and voltage-based algorithms will be discussed in another paper.

All the methods for phase loss detection can be divided by the detection time T_D into fast and slow, where slow methods detect the failure after one period T or more, of the fundamental component of the signal used for analysis. It is obvious that quick detection of single phasing is more preferable, but it is not easy in many systems, due to different factors such as high noise to signal ratio, distorted input voltages, etc. Therefore, such systems involve various filtering techniques, which increase detection time, and the most challenging task is to find a balance between detection time and reliable definition of the failure, despite possible distortion of the signals used for detection.

Sometimes, proposed methods use combined techniques, i.e., involve several different detection criteria for better operation. In this paper they are classified by the main idea or criteria used for the detection of the open phase fault.

The classification demonstrated in Fig 1 does not include any data-driven and quantitative approaches, which popularity increases last several years. A good example of the usage of such techniques for fault detection can be found in [49 – 51], where the authors adapted these approaches to the fault detection of high-speed trains. Unfortunately, at the current state there are no papers, which adapt data-driven and quantitative approaches exactly to detection of open phase and which provide experimental data possible to use for comparative analysis. Despite this fact, the authors think that abovementioned techniques will be used for the detection of phase faults and more detail papers will be published in next several years.

Before discussion of the different algorithms, the following facts have to be taken into consideration. The current signals can be measured by sensors utilizing different physical principles considered in detail in [52 – 54], however the most popular devices are hall-effect [55, 56] or shunt sensors. The hall-effect current sensors are designed as a separate chips or components, which interrupt current lines or use hole-through technologies. They have internal amplification and compensation circuits and output more stable and precise signal [57], which makes implementation of additional protection algorithms possible [58, 59], however these sensors need additional space and significantly increase cost of the power converter, which restricts their usage in low-cost drives. Simultaneously, shunt-based current sensors are small, cheap and suitable for low-cost solutions, but their amplification circuits are placed distantly, which increase noise to signal ratio. Furthermore, these shunt-based sensors are typically optimized to work at the rated load and therefore their performance at low load conditions may be poor. As a result, the measurements with shunt sensors can provide confusing results, indicating that current and voltage in the lost phase of multiphase drives do not fall down to zero.

Furthermore, shunt-based sensors are typically designed for low power loss, so they output voltage in the limited range, e.g., if the controller operates in 0 – 5 V range, the shunt-based measuring system may output in 2 – 3 V, where 2.5 V corresponds to zero current and 3 V corresponds to the rated current. This effect can be emphasized if measurements are organized with a reduced number of sensors and low-cost microcontroller is equipped with a low-resolution ADC. A good example of the first case is a system, where three phase currents are measured with two phase current sensors or one current sensor in the DC-link, while other currents are calculated or reconstructed. In this case, the error of the calculated current can be twice as high than in other channels. In the second case a quantization error becomes significant and increases errors at low-currents.

III. FAST METHODS

The methods pertaining to this class are able to detect the loss of phase error faster than the fundamental period of current signal used for the detection. Nevertheless, the exact detection time depends on the time constants of the filters used, and may exceed the fundamental period.

A. ZERO CURRENT DETECTION

This group of methods includes algorithms which process currents separately in each phase and detect failure, if one of the phase currents is close to zero longer then the allowed period of time.

These methods are simplest and easy for implementation, so they have been mentioned in many papers. However, some traps and pitfalls still exist. For example, implementation of this idea proposed in [60] for the fault tolerant control, is illustrated by Fig. 2. However, it is clear for practical engineers that proposed implementation will not work in the real system. The comparison of phase current with zero is incorrect, due to noise impacting the sensing channel. Furthermore, the proposed schematic could not be improved by using other threshold values because the combining of signals with logical OR may result in error, when time interval of being of one phase current near zero, is intersected with time interval when another current is near zero. Thus, these two events will be considered as one long event and false faults may be detected. Another mistake is using signals compared with zeroes as a trigger for the integrator, because it will result in jittering of the integrator output.

The correct implementation of the simple threshold technique is shown in the Fig. 3, where signals are separately filtered using low pass filters (LPF), processed using non-zero threshold I_{Th} and only after that, are logically combined. The algorithm may be improved, if cut-off frequency is not fixed and varies, together with the fundamental frequency of the stator current.

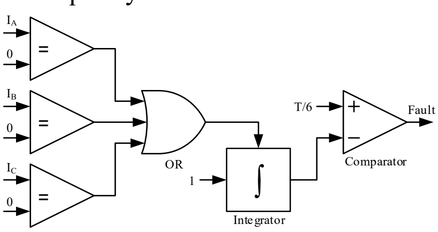

FIGURE 2. Incorrect implementation of fault detection.

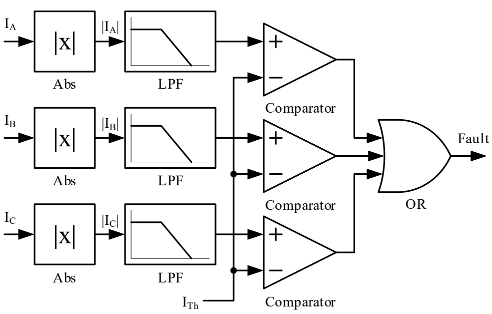

FIGURE 3. Fault detection by comparing with threshold.

The similar idea was adapted by the authors of [61], who injected high frequency (HF) current for sensorless control of the PM motor. In order to detect phase fault, they analysed HF component of motor phase currents and calculated time between zero crossings. If this time exceeded the period of HF signal, the fault was detected.

The advantages of these methods are simple structure and simple principle of operation, therefore it can easily be tuned even by inexperienced engineers. The detection time can be adjusted to be fast enough - about one sixth to one fourths of the current period.

However, despite strong suites, it has several disadvantages, which restrict its usage. The most significant is its sensitivity to noise in the current measurement channels. Therefore, this method is difficult to use together with shunt-based current sensors. This obstacle gets more serious if the motor drive operates in the full range of loads, including no load conditions. The computational complexity of this method is another problem, because it rises together with the increase of motor phase numbers, so it may not be applicable to control systems of multiphase motors.

Another implementation of this approach was proposed in [62], where the authors used a second order filter applied to each phase current in order to detect zero current. This filter tracks the current derivative, which was used for detection of the faults, where the current is supposed to change to zero quickly. However, this implementation is hard in tuning and calculation intensive, which eliminates main advantages. Moreover, the operation in transients was not reported, therefore this idea is suggested for further study.

After analysis of the pros and cons of the group of these methods, the authors suggest it be utilized in conventional three-phase drives with low noise current sensors, or alternatively, drives with cheaper current sensors, but not operating at low loads, such as drives of compressors, blowers, vacuum cleaners, etc. A good example of the drives which use this method are given in [63 – 66].

B. dq CURRENTS OSCILLATIONS

The problem with the computational complexity of detection algorithms, which rise together with the number of motor phases, forced researchers to pay attention to phase invariant motor models, i.e., models in stationary ($\alpha\beta$) or rotational (dq) reference frames. In these reference frames, multiphase motors can be expressed as a two-phase motor, which simplifies calculations.

These phase loss detection methods are discussed in [67 – 70], where the authors involved the following feature for detection of the fault. When a motor operates in normal conditions, direct and quadrature currents are almost constant, but if the one phase of a motor is lost, these currents begin oscillating, which can easily be detected. It is illustrated by Fig. 4 obtained for motor drive discussed in [71], when one of motor phases was open manually via circuit breaker. This phenomenon was studied in [69],

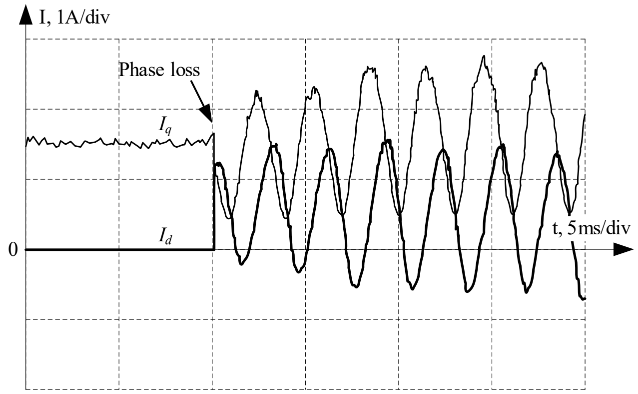

FIGURE 4. **Motor direct and quadrature currents at loss of phase.**

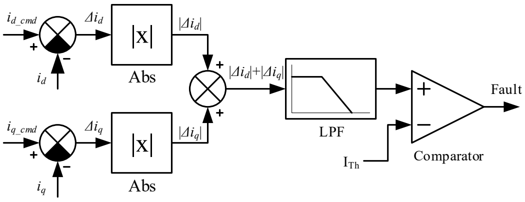

FIGURE 5. **Phase loss detection by dq currents oscillations.**

where the authors tested open phase detection in drives with surface mounted PM motor. They claimed that current relation in faulty condition is:

$$\frac{I_q}{I_d} = -\tan\left(\theta - \frac{\pi}{3}\right), \tag{1}$$

where θ is rotor position. Therefore, they proposed a signal for the fault detection:

$$S_{SS} = \frac{\mathrm{d}\left(\operatorname{atan}\left(\frac{I_q}{I_d}\right)\right)}{\mathrm{d}t} = \frac{I_d^2}{I_d^2 + I_q^2}. \tag{2}$$

The authors claimed that this detection signal is close to zero in normal operation and inhibits false positive fault indications during start-up transient, so additional measures must be taken.

Despite good results shown in [69], it can be seen that this implementation is suitable only for surface mounted machines and furthermore, does not cover field weakening mode. Therefore, we do not suggest the use of this implementation. Instead, we propose a more effective method, which was implemented and successfully used in MP drives of various types, which is shown in Fig. 5. This algorithm calculates absolute values of current errors and summarize them. The result is filtered using LPF and compared with threshold value I_{Th}.

The implementation of this method is also simple and does not require a lot of memory or computation time. LPF is a typical block of the control scheme, so it does not need additional implementation. Current errors calculated in the algorithm can be taken from current controllers. Therefore, this method is very simple and much faster.

Simultaneously, it may need time to adjust the threshold value and cut-off frequency of the LPF. The oscillations of direct and quadrature currents strongly depend on the system parameters and gains of the current controllers. Moreover, we found that this method may not be applicable to some drives, where current errors in transients are comparable with those under phase loss conditions, therefore its applicability has to be checked only experimentally.

The similar approach is used by the authors of [72, 73], but they converted reference values into natural motor coordinates *abc* and calculated errors there, which does not differ their method too much.

The similar approach was reported in [74 – 76], where the authors of [74, 75] worked with multiphase motors. The authors of [76] analysed the behaviour of direct and quadrature currents in the fault mode and showed that currents contain constant component and a second order harmonic related to fundamental component of stator current. Therefore, they proposed to perform one more Park transformation of currents with doubled angle 2θ, which transfers the rotor reference frame $(dq)_\theta$ into the second order rotor reference frame $(dq)_{2\theta}$. In the $(dq)_{2\theta}$ reference frame, healthy currents oscillate with double frequency and do not have constant components, so LPF applied to them outputs values close to zero. At the same time, faulty currents transformed into the second order rotor reference frame, contain constant component, so LPF applied to them, outputs constant values. Thus, analysing LPF outputs may help detect loss of phase and even localize it. This method improves performance of the phase loss detection, but it is more calculation-intensive and still unable to handle the problem of noisy signal.

After analysis of the pros and cons of this group of methods, we can suggest its use in three phase and multiphase drives without specific requirements to precision of current sensors. This method was successfully implemented and is currently being used in commercial drives of different type and power [77 – 78].

C. MIDDLE CURRENT DETECTION

This method was developed by the authors specifically for cheaper motor drives with noisy current sensing channels and low-resolution ADCs. As mentioned above, the main problem of phase loss detection in drives with noisy current sensing is that measured currents may not be zero, even if real currents do not flow. This problem can worsen if the system uses a reduced number of current sensors, i.e., one or two current sensors for three phase drives. For overcoming this obstacle, we developed a middle current detection method, which pays attention to the position of phase current, relative to other currents. It was designed for three phase drives, but this approach may be extended to multiphase drives.

During normal operation, phase currents are sine waves (may be distorted) shifted at one third of the period to each other, thus, one phase current is placed between two other phase currents twice per period, with intervals lengths of one sixth of fundamental period, Fig. 6. Even if current

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waveforms are distorted, the length of these intervals does not change significantly. However, when open phase happens, the current in the faulty phase is always between two others. This feature is used for the design of the algorithm for detection of single phasing, which is shown in Fig. 7. According to the proposed idea, the middle current is found and then compared with all phase currents. The resulting signal controls multiplexer, sending positive or negative electrical speed ω_e to the integrators. The output of the integrator is the angle interval, where phase current is in the middle position. If this value exceeds the threshold angle θ_{Th}, a fault is detected.

The main advantage of this method is the ability to work with noisy signals of the sensed currents. Another superiority of the proposed method is its ability to operate stably in transients and at load variation without false fault detections. It also operates perfectly with highly distorted currents, where other methods often fail. The computational complexity of this algorithm is a little bit higher than the complexity of the previously discussed methods, but it still remains quite simple. The tuning of algorithm is not difficult and may be done quickly, even by inexperienced engineers.

The drawbacks of this algorithm are increased complexity, which depends on the number of phases, and minimum detection time, which cannot be less than one sixth of the current fundamental period.

After analysis of the pros and cons of this group of methods, we can suggest it be used in low-cost three phase and multiphase drives with high noise to signal ratio of the current measurement system. This method was successfully implemented and being used in MP drives as described in [79, 80].

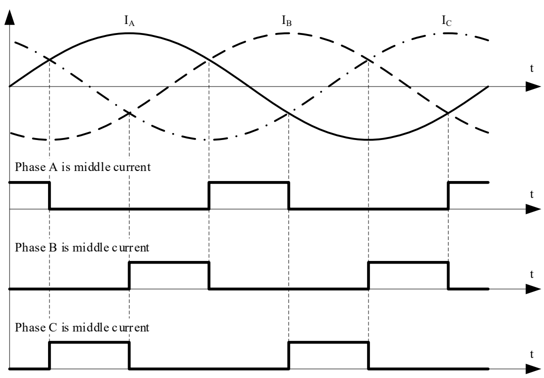

FIGURE 6. Middle current detection.

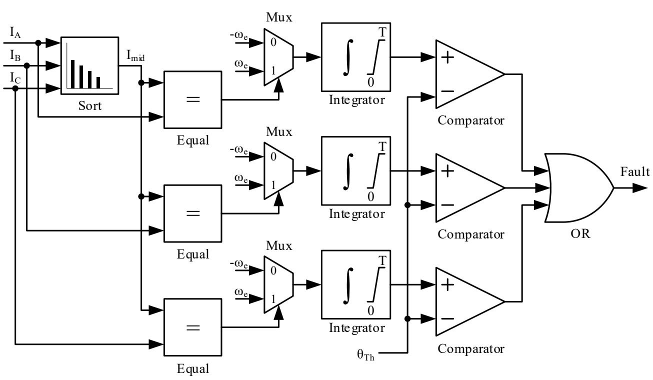

FIGURE 7. Phase loss detection using middle current.

IV. SLOW METHODS

The methods pertaining to this class are typically not able to detect the loss of phase error faster than the fundamental period of current signal used for the detection. Simultaneously, the exact detection time depends on the filter settings and exact implementation of the proposed ideas.

A. AVERAGE CURRENT CALCULATION

The methods which use average phase currents are similar to the zero current detection-based methods, however the difference is that these methods analyse average current over the fundamental period. Methods of this type are proposed in [41, 43, 81 – 85] and brief algorithm they use is shown in Fig. 8. The exact implementations discussed in each of these papers vary slightly, but the indicated core part is the same for all of them.

Initially each phase current is normalized before further processing, which is needed to make the algorithm insensitive to load variation. After that, absolute values of currents are obtained and averaged over one fundamental period T. Then, average currents are compared to expected value and, if difference of at least one phase is higher than the threshold value I_{Th}, the fault is generated. The expected value of currents is average value of the modulus of sine with amplitude of one, which is equal to $2/\pi$. However, it may differ in different systems, depending on the gains used in Clarke (*abc* to *αβ*) transformation. The same idea of currents averaging is discussed in papers [90, 91], where the authors expand it to multiphase drives and propose their own criteria of fault detection. A similar method, which uses root mean square (RMS) values instead of averaging, was proposed in [86, 87]. Calculation of square roots is a high load for the microcontroller even when using acceleration techniques [88, 89], so it is desired to avoid it if possible. Since there is no big difference between the averaging and RMS-based methods, the latter will not be discussed separately.

A minor improvement of this technique was proposed in [83], where the authors added fuzzy-logic controller for faster and more reliable recognition of the fault conditions. They claimed, that the fuzzy-logic improved reliability and stability of the fault detection, however the experimental result do not cover speed transients and load varying over mechanical revolution, where average phase current may not be zero.

Summarizing above mentioned, the advantages of current averaging methods are simplicity of their structure, ease of tuning and the ability to detect open switch failure of the inverter, which can be implemented only by minor modifications of the existing algorithm.

At the same time, these algorithms have several disadvantages. They are slow, because need one period for

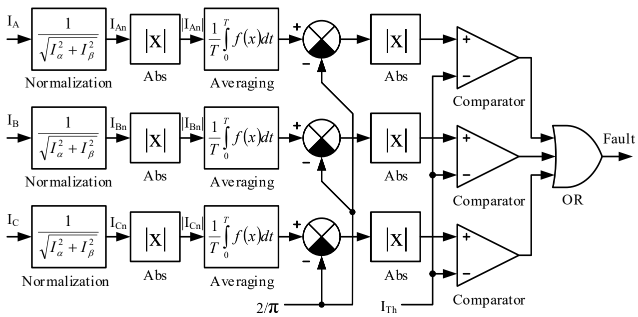

FIGURE 8. Fault detection by averaging currents.

averaging; they are sensitive to noise but less than zero current detection method, because of stronger filtering; implementation of these algorithms with calculation of the average current at every PWM period, needs too much memory and this value increases with the number of motor phases; and computational complexity also rises with the number of motor phases. Furthermore, these algorithms may fail, when motor operates under load varying at mechanical revolution, e.g., reciprocating compressors, where average values of phase currents are not equal to zero.

After analysis of the pros and cons of this method, we can suggest it be used in conventional three-phase drives with high-quality current sensors, or drives with cheaper current sensors, but not operating at low loads, such as drives, blowers, vacuum cleaners, etc. This method was implemented and perfectly operates in the commercial drives, which were discussed in [92 – 94].

B. CURRENT TRAJECTORY IN αβ REFERENCE FRAME

This method was proposed in [95] and uses analysis of the stator current trajectory in the stationary (*αβ)* reference frame of the machine. The authors used a five-phase induction motor as an example and demonstrated distortions of the stator current trajectory in case of each phase failure, Fig 9. In this picture *U, V, W, X, Y* denote motor phases, where loss of phase happened. This paper proposes to calculate average currents over one fundamental period:

$$I_{\alpha\_mean} = \frac{1}{T}\int_0^T I_\alpha dt, \qquad I_{\beta\_mean} = \frac{1}{T}\int_0^T I_\beta dt, \qquad . \tag{3}$$

and then to calculate the magnitude of the faulted current:

$$I_{Fault} = \sqrt{I^2_{\alpha\_mean} + I^2_{\beta\_mean}} \,. \tag{4}$$

In normal state average currents I_{α_mean} and I_{β_mean} are almost equal to zero, so the resulting faulted current I_{Fault} should also be zero. If it differs from zero more than at threshold value, the loss of phase happened.

For the definition of the faulted phase the authors proposed to calculate the fault angle:

$$\theta_F = \text{atan}\left(\frac{I_\beta}{I_\alpha}\right), \tag{5}$$

and then change of the fault angle:

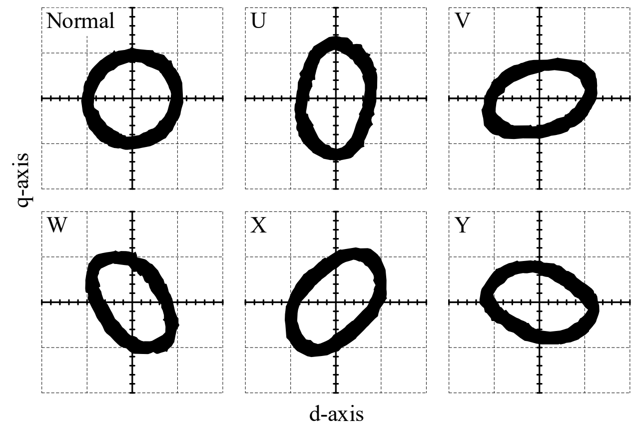

FIGURE 9. Current trajectories in αβ reference frame in normal and fault modes. This picture was taken from [95] with permission.

$$\theta_{F\_Err} = \theta_F^k - \theta_F^{k-1}, \tag{6}$$

where k denotes the calculation step. If motor operates normally, the fault angle θ_F should be constant, but if the fault occurred, it changes rapidly. Moreover, value of the fault angle can be used for definition of the faulted phase. This idea was also involved in the algorithm enhancements discussed in [81], which was designed to work together with fault detection, using average currents method. Combining together two different methods, the authors improved stability of operation and distinguishing of the fault. This method was evaluated and compared to other fault detection techniques in [96], where the authors found its marginal behaviour at low loads about 10% of the rated load. Talking about current trajectories in the *αβ* plane, we must mention [97], where authors proposed to use phase angles φ_α and φ_β for detection of the phase loss. They claimed that these angles significantly change at the fault and single phasing can be detected very quickly, in less than 10 ms. Despite results reported by the authors, there are doubts with regards to the feasibility of this method, because the indicated experimental results do not cover starting and transients, the research does not analyse change of angles and its dependence on the parameters of motor drives, therefore it is recommended for further study.

The advantage of this approach is its simplicity and independence of motor phase counts, however its usage is restricted with requirements to quality of the sensed currents and parameters of load. If sensed current signals are noisy, it is hard to track the trajectory, sometimes impossible. The load value and its variation also impact the performance of this method, therefore it is not applicable in motor drives with load varying over mechanical revolution, such as reciprocating compressors, washing machines, etc. Another problem is that current distortions depend on the system parameters and settings of current controllers, so tuning of this algorithm may be complicated and sometimes impossible to be achieved.

Taking into account the above mentioned, it is suggested to use this method in multiphase drives, with high signal to noise ratio and which do not operate under low or significantly varying load.

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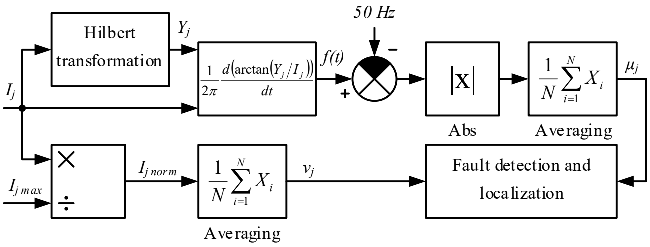

FIGURE 10. Fault detection using calculation of instantaneous frequency.

C. COMPARISON WITH EXPECTED SHAPE

The methods of this group compare the waveform of stator currents with the expected one and, if significant difference is detected, they consider it as a fault. The methods belonging to this group were proposed and studied in [99 – 98], which suggested different criteria for the current waveform analysis.

The authors of [99] proposed to detect the instantaneous frequency of the phase currents and analyse its deviation from the expected frequency. For this purpose, they suggested an algorithm shown in Fig. 10, which uses Hilbert transformation for calculation of the instantaneous frequency and which is able to detect and localize fault by analysis of fault indexes v_j and μ_j for all phases.

The main disadvantages of this method are its demands to power of microcontroller and its memory size, which are needed for the calculation of Hilbert transformation, difficulties in implementation and tuning, inability to work with distorted currents and low reliability. As a result, this method is out of interest of commercial systems.

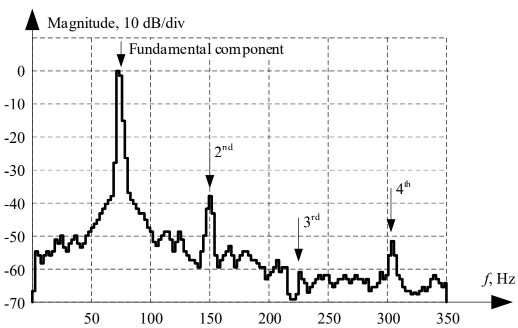

FIGURE 11. Frequency spectrum of the stator current for normal operation.

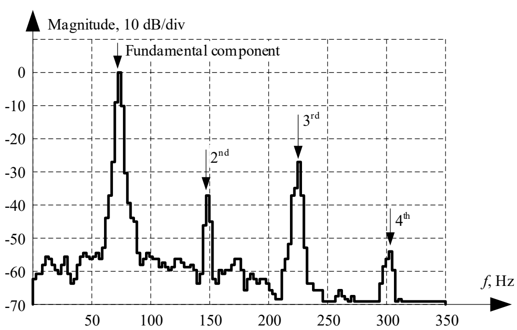

FIGURE 12. Frequency spectrum of the stator current for loss of phase operation. This picture was taken from [95] with permission.

The research published in [82] suggested the usage of several criterial, including frequency of motor phase currents. However, for the detection of the frequencies, the authors used phased lock loop (PLL) algorithm, which is easier in implementation and tuning, however still sensitive to noise and varying load. The authors did not analyse behaviour of their technique in transients, therefore, this method is recommended for further studying.

Another approach for current waveform identification was suggested in [98], where the authors worked with switched reluctance motor (SRM). They involved the entropy theory and proposed to use normalized indexes, which do not depend on the speed and load. The authors suggested to use sliding window for each phase current and calculate entropy of each phase current. After that, they suggested to compare entropies of each phase current using similarity indexes and detect the fault, if the index of one phase significantly differs from others.

This method is more resistant to measurement noise, but it is sensitive to offset errors. Since the methods checks similarity of phase currents, it may fail, if their waveform differs, which can take place in transients and load varying over revolution. Furthermore, it needs a lot of memory to keep current data for each phase, and demands extremely powerful microcontrollers.

Summarizing above-mentioned, the methods of this group are difficult in implementation and demand powerful microcontroller, however they do not provide reliable detection of the faults, therefore they are not suggested for commercial usage and further study is recommended.

D. FOURIER TRANSFORMATION

Discrete Fourier transformation (DFT) or fast Fourier transformation (FFT), whichever is more preferable, are some of the popular approaches for detection of the signal distortion. It helps to obtain a spectrum of the signal and analyse its fundamental component and harmonics. Since open phase causes strong distortions of currents and voltages, DFT-based analysis can be used for the identification of this failure, which is shown and discussed in various papers [100 – 106].

The authors of [101] provided the comparative stator current spectrum analysis of a loaded 6-pole PMSM, Fig. 11, 12, where Fig. 11 illustrates normal operation of the motor and Fig. 12 shows current spectrum for motor operation with single phasing. The motor operates at electrical frequency of 75 Hz, and the peak in the current spectrum corresponding to this frequency can be clearly seen. These pictures show that the current spectrum in a faulty operation differs from that in the normal mode, especially in the magnitude of the third harmonic. The change in the current spectrum depends on the system parameters, its nonlinearities and gains of current controllers, therefore it is hard to define it theoretically. The higher harmonics except the third one may have minor differences and be hard to distinguish, while the third harmonic significantly changes at open phase. It caused by the fact that the third harmonic is theoretically zero for perfectly symmetric star-connected three phase electric machines, because third harmonics of three motor phases compensate each other. Despite it never happens in real motors, this harmonic is still low under normal operating conditions. At the same time, when one phase is disconnected, the third harmonic appears and can be easily detected. Therefore, the authors of the mentioned paper propose to use this feature in the analysis of faulty conditions.

The same idea is proposed in [104 – 106], where the authors suggest to analyse the relation of the third harmonic to the fundamental component of stator current. However, for this simple purpose they use an artificial neural network and did not prove its superiority to the simple math functions.

Summarizing advantages of this approach, we can state that this idea is simple for understanding and may be easy to tune, in some drives. Furthermore, this method can be used for detection of other faults and their distinguishing [107].

On the other hand, the DFT-based method has many more disadvantages, which significantly restricts its usage. A lot of electrical drives operate with distorted currents, which can be caused by nonlinearities of the motor, load variations (such as compressors) etc., however none of the above-mentioned researches studied current spectrums of such drives in normal and faulty operations. This method also cannot solve the problem of noisy signals in the current measurement circuits. Moreover, the presence of the third harmonics indicates asymmetry of the motor and may not be used for distinguishing of the fault type. If the system needs recognition of exact faults it is recommended to record spectrum images for all possible types of faults and perform correlation analysis in case, when abnormal third harmonic was detected.

The method under discussion involves DFT, so it needs big data arrays, who's size depend on the motor frequency, and a lot of computational power. FFT is faster than DFT, but its implementation is complicated, because 2N sampling points, where N is positive integer, must be placed at the fundamental period of current. This task is not easy, since current period vary together with drive acceleration, deceleration, change of load, etc. Thus, it is an additional challenge in this approach, and many researches prefer to use DFT.

Nonetheless, this method is slow and can detect the phase loss at least after one period of fundamental current. However, in practice the custom DFT procedure should be used, which computes only third harmonic component online each step each PWM cycle. This can help to avoid extra computation load to CPU as the method analyses only one harmonic component. Furthermore, the usage of several fundamental periods is preferable to increase resolution. The usage of longer time intervals for analysis significantly increases data procession and fault detection time.

Taking into account the above-mentioned characteristics of this method, it is suggested to use it only for research purposes, when the involved control system is high quality; has enough computational power and memory; and when DFT is already implemented and can be easily utilised. In this case, usage of Fourier transformation-based approaches may save time used for the implementation and tuning of the phase loss algorithm.

E. CURRENT NEGATIVE SEQUENCE

The methods of this group are based on the analysis of negative sequence of the consumed current, which is discussed in [4, 111 – 110]. The authors of [4] showed that negative sequence of current can be equal to positive sequence and can be easily used for detection of phase loss. At the same time, they analysed negative sequence of voltage and concluded that it does not vary significantly - approximately 1.8% - so it is hard to use this signal for detection of the open phase. Unfortunately, this paper does not contain any experimental parts, so it is recommended for further study. The authors of [111, 112] extended this approach to five-phase motor and showed that this technique can also be used for the error localization.

Another approach, which uses similar techniques was proposed in [108]. The authors studied motor behaviour in the fault mode and concluded that the asymmetry in the stator winding resulting from an open-phase fault disturbs the air-gap magnetic field distribution and causes this field distribution to develop two motions: one motion is the original rotation of the axis at synchronous speed, whilst the other motion constitutes an oscillation around the field distribution's original axis. They called it the "magnetic field pendulous oscillation (MFPO) phenomenon" and proposed to use this for phase loss detection.

For this purpose, they suggested to design a PLL algorithm, which uses commanded rotor speed as input and outputs reference angle θ^*. This angle is supposed to be stable and should not contain any oscillations. Then the authors compared current oscillations with reference angle θ^* and made conclusions on the fault conditions.

From our experience, we are of the opinion that this algorithm is hard for implementation and tuning. PLL will output reference angle without any oscillation only in stable conditions, so this algorithm may falsely detect open phase conditions. The authors did not prove feasibility of their method in transients, therefore, it is recommended for further studying.

F. CURRENT ZERO SEQUENCE

The method was proposed in [113] for the detection of open phase in a delta connected PMSM motor as shown in Fig. 13. The authors analysed motor behavior under fault conditions and conclude that fundamental component of the zero sequence current component is:

TABLE I. COMPARISON OF PHASE LOSS DETECTION ALGORITHMS

Algorithm \ Criteria	Computational complexity	Complexity depends on phase №	Tuning	Detection speed	Sensitivity to	Reliability	Suggested drive structure	Recognition of fault type and fault location
Zero current detection	Simple	Yes	Easy	Fast	Measurement noise	Medium	VC, DTC	Faulty phase
dq currents oscillations	Simple	No	Medium	Fast	Measurement noise	Medium	VC, MPD	Faulty phase
Middle current detection	Simple	Yes	Easy	Fast	-	High	VC, DTC	Faulty phase
Average current calculation	Simple	Yes	Easy	Slow	Measurement noise, Load variation	Medium	VC, DTC	Open switch, Faulty phase
Current trajectory in αβ reference frame	Medium	No	Difficult	Slow	Measurement noise, Load variation	Low	VC, DTC, MPD	Open switch, Faulty phase
Comparison with expected shape	Complex	Yes	Difficult	Slow	Load variation	Low	VC, DTC	Faulty phase
Fourier Transformation	Complex	Yes	Medium	Slow	Measurement noise	High	VC, DTC	Type of fault, Faulty phase
Current negative sequence	Medium	Yes	Medium	Slow	Measurement noise	Medium	VC, DTC, MPD	-
Current zero sequence	Medium	Yes	Medium	Slow	-	Low	VC, DTC, MPD	-

VC – Vector control; DTC – Direct torque control; MPD – Multiphase drives

$$i_{zsc} = \frac{N}{\sqrt{\omega_e^2 (L+M)^2 + R_s^2}} \sin(\theta + \theta_f + \gamma), \qquad \gamma = \mathrm{atan}\left(\frac{-\omega_e (L+2M)}{R_s}\right) \tag{7}$$

where:

N – amplitude of the voltage fundamental component,
θ_f – phase of the voltage fundamental component,
R_s – stator resistance,
L – phase inductance,
M – mutual inductance between phases,
ω_e – electrical speed,
θ – rotor position.

Therefore, the authors suggest the use of fault index *FI*, calculated as follows:

$$FI = I_1 \frac{\sqrt{\omega_e^2 (L+M)^2 + R_s^2}}{U_{DC}} = \frac{N}{U_{DC}}, \tag{8}$$

This index is close to zero in the normal operation and increases in case of the fault, so comparison of this index with threshold value is used for open phase detection.

The similar idea was generalized and spread on the multiphase machines with neutral points in [114] and [115], where the authors proved the rapid and reliable operation of this technique adapted this approach to analysis of short-circuit faults as well.

The main disadvantage of this method is its restricted usage area. It can be used only for delta connected motors or multiphase motors, which are not popular. Furthermore, in case of delta connected motors, it detects only open phase of the motor and does not work for open phase taking place outside the motor. Therefore, this method may be suggested to be used only for drives, which involve delta connected or multiphase motors.

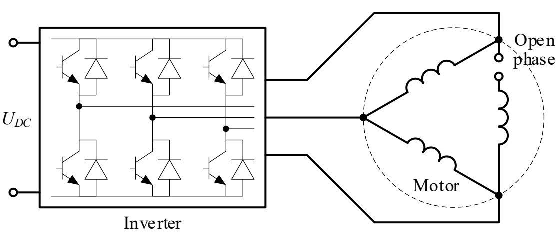

FIGURE 13. Delta connected PMSM with inverter.

V. DISCUSSION

After detailed analysis of the existing phase loss detection algorithms, which use current signals, the summary of their performance and implementation was put into Table I, which can be used for selection and comparative analysis of the techniques depending on needs of exact project.

VI. CONCLUSIONS

Detection of a phase loss faults is a very vast topic, which involves various hardware configuration, utilizes different principles of detection, having their own pros and cons. As a result, the selection of exact technique is a challenging and complicated task, where price of mistake is high since it may lead to redesign of hardware and control algorithms, which in turn, delays projects and increases expenses. Therefore, it was a motivation to share our more than 20 years' experience combined and prepare this review.

This paper explains open phase fault and considers its after-effects, which might be hazardous. The authors give classification of the existing phase loss detection techniques and review the methods, which are based on the analysis of current signals. Moreover, the novel algorithm proposed and implemented by the authors is also briefly discussed. This paper discusses the pros and cons of the methods under consideration; describes their limitations and area of usage, etc. The authors share their experience in the practical use and implementation of some of the discussed methods, especially those, which were put into mass production. The main characteristics of the considered techniques are summarized into the table in Discussion section, which makes selection of the appropriate algorithm easier.

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