

Article

Steady-State Vibration Level Measurement of the Five-Phase Induction Machine during Third Harmonic Injection or Open-Phase Faults

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Abstract: Multiphase electric machines are increasingly used in various industries and for electromobility. Complex systems have been developed for the control and powering of multiphase machines, which require verification. The quality of control and the power supply of electric machines is usually evaluated by analyzing various electrical parameters. On the other hand, taking into account the fact that a motor is an electrical-mechanical object, its full diagnostics should also include the analysis of vibration signals to verify the operation of the motor as a mechanical device. In this paper, a sensorless control algorithm was studied and applied to a 5-phase induction motor. Various scenarios were considered; in particular, the operation of the studied motor in the absence of one or two phases and in the case of the introduction of the third harmonic to increase the torque was analyzed. In the scenarios considered, the motor was connected to another machine and operated with no load as well as with a preset load. The results obtained were analyzed in the time and frequency domain and were related to the standards used.

Keywords: 5-phase motor; sensorless control; vibrodiagnostics; NTD measurements; third harmonic injection; open-phase faults; multiphase electric motor



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1. Introduction

The importance of power electronic converters in various areas of the industry is not in doubt [1–3]. In particular, they are commonly used to power and control electric drives on land and sea. The cooperation quality of converters with electric drives is usually evaluated based on the selected parameters of electrical signals and the level of their distortion (e.g., based on the level of higher harmonics) [4,5]. Rarely, mechanical quantities are used in this evaluation. In a full assessment of the power supply quality and control of a given drive by a power electronic converter, it is important to comprehensively consider diagnostic information of an electrical and mechanical nature [6–8]. Only then will it be possible to fully assess the impact of the converter on the electrical machine from both the electrical and mechanical sides (e.g., the state of wear of mechanical components or their damage). The answer to this need is the combination of electrical measurements with measurements and diagnostics in the area of the registration of vibrations and noise of the operating machine [9,10]. By analyzing vibration and electrical characteristics in parallel, important diagnostic information can be obtained about both the operation of the electric machine itself and the converter that supplies and controls it [10,11].

Multi-phase motors are finding increasingly widespread use in industry, and perhaps even greater use in automotive applications. One of the most commonly used multi-phase motors is the 5-phase or 6-phase motor [12,13]. In this paper, the authors focused their attention on studying the control and power quality of a 5-phase motor. These drive systems are characterized by higher torque density (by injection of the third harmonic)

and overall higher reliability compared to the three-phase counterparts. Higher reliability means that motor operation is maintained under single or even double open-phase faults. During such a failure, a five-phase induction motor has a starting torque of about 50% of the rated torque when two non-adjacent phases are supplied. It can be stated that increasing the number of phases leads to an increase of the drive system cost. However, by spreading power to a larger number of phases, it is possible to use transistors for lower rated currents. In addition, the amount of material (copper and iron) to produce a five-phase induction machine is comparable to that of its three-phase counterpart. Because of this, the cost of five-phase induction motors series production can be close to that of the three-phase equivalent. Nonetheless, the use of a more complex five-phase drive has benefits with additional degrees of freedom. The main advantage relates to reliability, which concerns possible continuous operation under open-phase faults [14,15].

Wilczyński et al. [15] presented the possibility of the load torque maintaining, when one or even two stator phases are opened, without significant changes in the control and estimation system. This advantage is particularly crucial in drives with high reliability requirements, such as for e-mobility, aircraft actuators and medical applications [16–18].

Another advantage of five-phase drives (applies to motors with concentrated windings) is that the torque can be increased by controlled injection of the third harmonic. To achieve this, the supply voltage contains a higher harmonic, which has an adverse impact in three-phase machines with further losses, but can be used in five-phase machines to increase the electromagnetic torque [15]. Controlled injection of the third harmonic should provide a quasi-trapezoidal rotor flux pattern, resulting in better utilization of the five-phase machine magnetic circuit [19].

This paper presents a multivariate analysis of the five-phase motor control quality at selected and characteristic operating points: (1) no-load tests, (2) tests with rated load, (3) tests under single open-phase fault (failure of phase A), (4) under double open-phase faults (failure of phases A and C). Measurements were made for steady states. The study also considered the mechanism of injecting a third harmonic. Dual-plane sensorless field-oriented control (FOC) was applied for the five-phase machine.

2. Selected Strategy for Sensorless Control of a 5-Phase Motor

Several control methods were implemented in connection with five-phase induction motors, i.e., Field-Oriented Control [15], Direct Torque Control [20], and multiscalar model-based control [21,22]. For controlled third harmonic injection, two independent control systems for every orthogonal plane have to be implemented. To achieve the desired quasi-trapezoidal flux distribution, the synchronization of two rotor flux vectors (1st and 3rd harmonics, respectively) was used in the control system. Figure 1 shows the used control structure, in which three main blocks can be distinguished: (1) 1st harmonic system, (2) 3rd harmonic system, and (3) synchronization unit. Control as well as estimation are synthesized on the basis of the machine model in two planes—Figure 1. Variables in two planes are obtained after performing a modified Clarke transformation for a five-phase system. These variables are independent of each other. Figure 1 presents vectors of voltage, current and rotor flux in two planes $\alpha^{(1,2)}-\beta^{(1,2)}$. The first block realizes the control of variables oriented in the first coordinate system $d^{(1)}-q^{(1)}$. The control system associated with the fundamental harmonic includes a cascade of speed and torque controllers, as well as rotor flux and magnetization current. The second control system contains a controller of torque, flux, and magnetization current in the plane $d^{(3)}-q^{(3)}$. The last main block provides synchronization of the two rotor flux vector positions. Based on the angle controller output, the reference torque in the second coordinate system is calculated. Finally, based on the outputs of the PI controllers and decoupling blocks, the reference voltage components for two coordinate systems $d^{(1,3)}-q^{(1,3)}$ are determined. These quantities are delivered to the observer blocks and the Space Vector Pulse Width Modulation (PWM) block. The modulation algorithm allows for the independent generation of first and third harmonic waveforms [18].

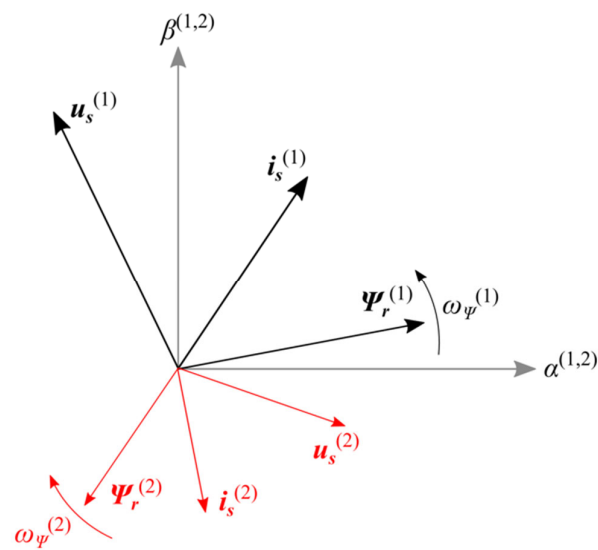


Figure 1. Vectors of voltage, stator current and rotor flux in the double coordinate system $\alpha^{(1,2)}$ - $\beta^{(1,2)}$.

This paper does not directly describe the control system, therefore a more detailed description is included in [15]. Figure 2 describes the configuration of the control system with rotor flux synchronization.

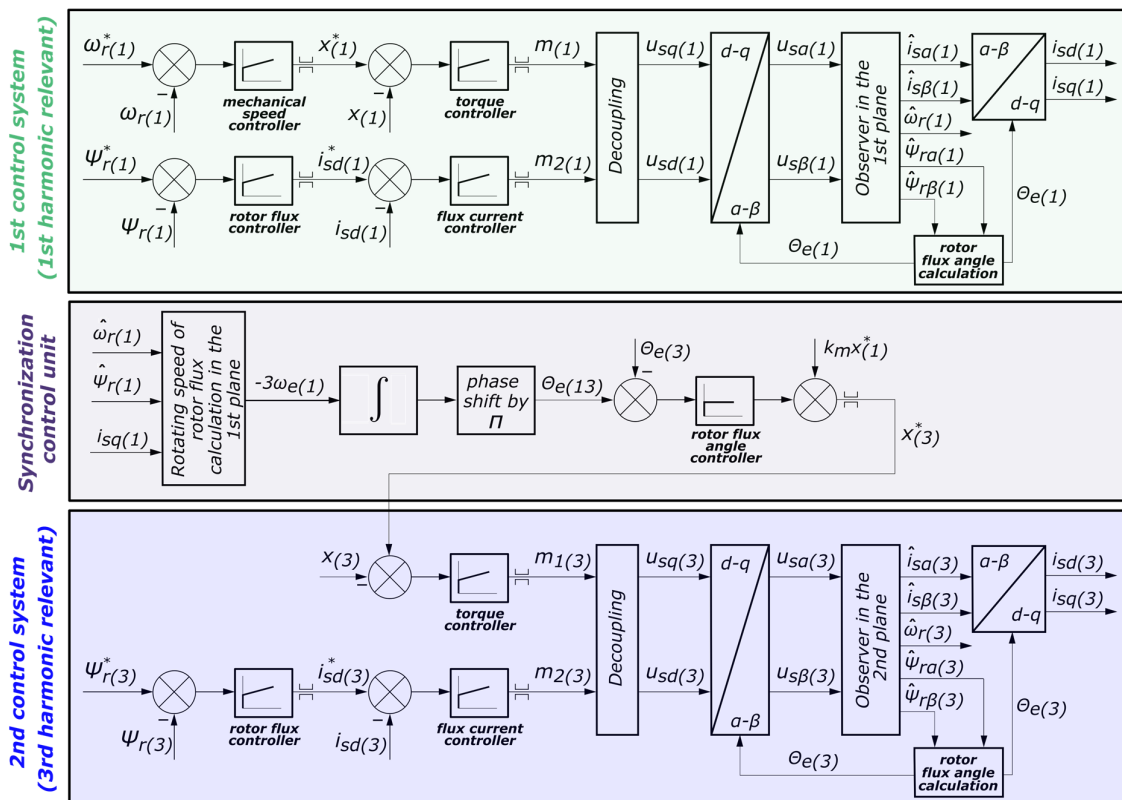


Figure 2. The control system configuration with rotor flux synchronization.

3. Laboratory Stand and Measurement Methods

Experimental tests were conducted using a drive unit consisting of a 5-phase induction motor, which acted as the driving motor (DM) in the tests, and a second motor, which acted as the load motor (LM). Figure 3 shows the 5-phase motor under study with the accelerometer location marked [15,21].

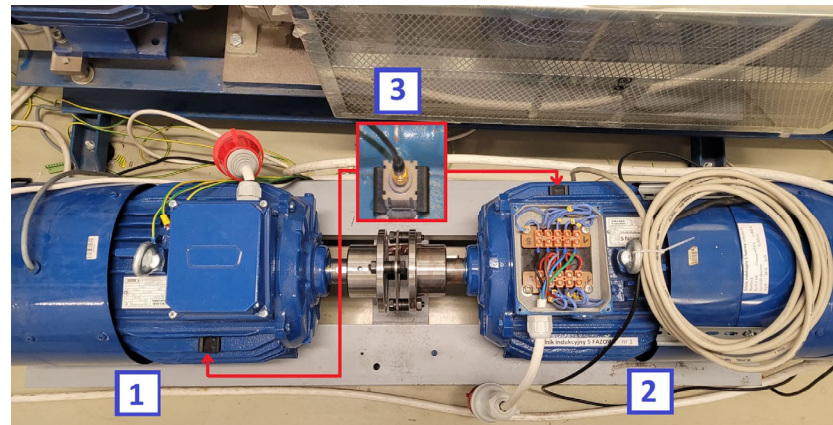


Figure 3. The tested drive unit with a 5-phase motor (1) as a driving motor and a second motor (2) as a loading motor. The number (3) indicates the locations of the accelerometers.

Table 1 shows the relevant parameters of the tested 5-phase induction motor drive.

Table 1. Parameters of the five-phase drive system with load motor [15].

Parameters	Fife-Phase Drive Motor	Three-Phase Load Motor
Rated output power	5.5 kW	5.5 kW
Rated current	8.8 A	11 A
Rated phase voltage	173 V	230 V
Number of poles	4	2
Rated torque	36.5 Nm	36.5 Nm
Rated speed	1440 rpm	1440 rpm
Transistor switching frequency	3.3 kHz	3.3 kHz

A system from Brüel & Kjær (B&K) was used for vibration measurements. The measurement system included a four-channel data acquisition module (B&K type: 3676-B-040), a 3-axis accelerometer (B&K type: 4529-B, its parameters are: frequency band: 0.3–12,800 Hz, weight: 14.5 g, sensitivity: 10 mV/ms^{−2}), a calibrator (B&K type: 4294), and a laptop computer that was equipped with B&K's firm vibration measurement and analysis software called BK Connect. A vibrodiagnostic measurement system was used in the work of Refs. [8,23], which used a similar measurement methodology. The accelerometer was mounted to the motor housing using connectors that are included with the system by its supplier. A flow diagram of the measurement procedure is shown in Figure 4.

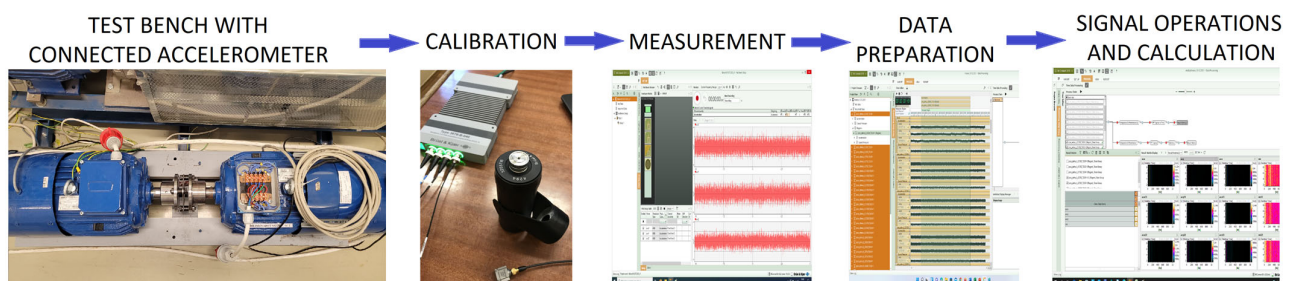


Figure 4. Flowchart of the vibration measurement.

According to the vibration-diagnostic measurement procedure, the accelerometer was calibrated before each measurement and the experimental tests were carried out according to the rules defined in the standard [24,25]. It should be added that vibration measurements were performed simultaneously in three axes. For each measurement point, accelerometer readings were recorded three times. Statistical metrics such as variance or mean value were used to evaluate the recorded acceleration waveforms and select the most appropriate. The

selected waveforms were then converted to vibration velocity. It is worth noting that the broadband velocity [25] is required by the standards [25,26] to assess vibration severity.

A prototype five-phase voltage-source inverter was used to supply the tested five-phase machine. The inverter contained IGBT transistors and its switching frequency was 3.3 kHz. The controller used in the prototype included a signal processor DSP ADSP21363 and FPGA CYCLONE II EP2C8F256. The measured quantities were two stator phase currents and the DC-link circuit voltage [15]. In order to carry out tests under load, the analyzed five-phase machine was coupled with a three-phase induction motor (5.5 kW), which was supplied by a bidirectional converter. During the tests, the five-phase machine was loaded to about 80% of its rated torque.

4. Analysis of Results from Electrical Measurements

Since the algorithm used to control the motor, as well as the motor itself, has already been presented in other scientific works [27–29], the authors decided to limit the presentation of the motor's electrical signals and parameters to the necessary minimum. The paper [29] investigated the operating capabilities of a drive with a five-phase induction motor when operating correctly and when the phases were open. The study used mechanical torque and current characteristics analysis. In contrast, the paper [28] describes a sensorless fault detection procedure that was performed on a five-phase induction motor with a third harmonic injection. Estimated load moment analysis has been shown to provide sufficient results to identify disturbances.

Therefore, Figure 5 shows spectra for a properly running motor, as well as a motor running without one or two phases. Figure 6 also shows an example spectrum for a motor operating after the addition of the third harmonic as a result of control. The current spectra shown in Figures 5 and 6 were recorded for a motor that was connected to a second, unloaded motor. Figures 5 and 6 show the spectra and waveforms for the B-phase currents. Based on extensive testing, they were found to be representative of the considered operating scenarios for the drive train under study. They were recorded at two speeds, one at 150 rpm (2.5 Hz) and the other at 750 rpm (12.5 Hz).

The spectra labeled (a) and (d) in Figure 5 show the current spectra when all phases are properly connected. These spectra represent the first and, very limited in value, third harmonics. The remaining current spectra represent the case when phase A was switched off—these spectra are labeled (b) and (e)—and when two phases, i.e., A and C, were switched off simultaneously—these spectra are labeled (c) and (f). In the case when the motor was operated without one or two phases, the influence of the fifth harmonic can be seen. In addition to the apparent appearance of an additional harmonic in the current spectrum, a clear increase in the value of the fundamental harmonic can also be observed. The largest increase in the value of the first harmonic was noticed when both phases (A and C) were disconnected.

In turn, Figure 6 shows oscillograms, which present current waveforms with the third harmonic added as a result of control. These are the results recorded for a motor running with no load at 150 rpm. In addition to the current waveform, its spectrum is also shown. In the spectrum shown, the influence of the third harmonic, whose value exceeds that of the fundamental harmonic, can be clearly seen.

Comparing the spectrum in Figure 5 label (a) with the spectrum in Figure 5 label (b), it can be seen that the value of the third harmonic in Figure 5 labels (b) and (d) has changed. The change is noticeable for both speeds. The value of the third harmonic of the current has increased, while the other harmonics are imperceptible. Analysis of the current spectrum shows that none of the currents contain an increased THD (Total Harmonic Distortion) value.

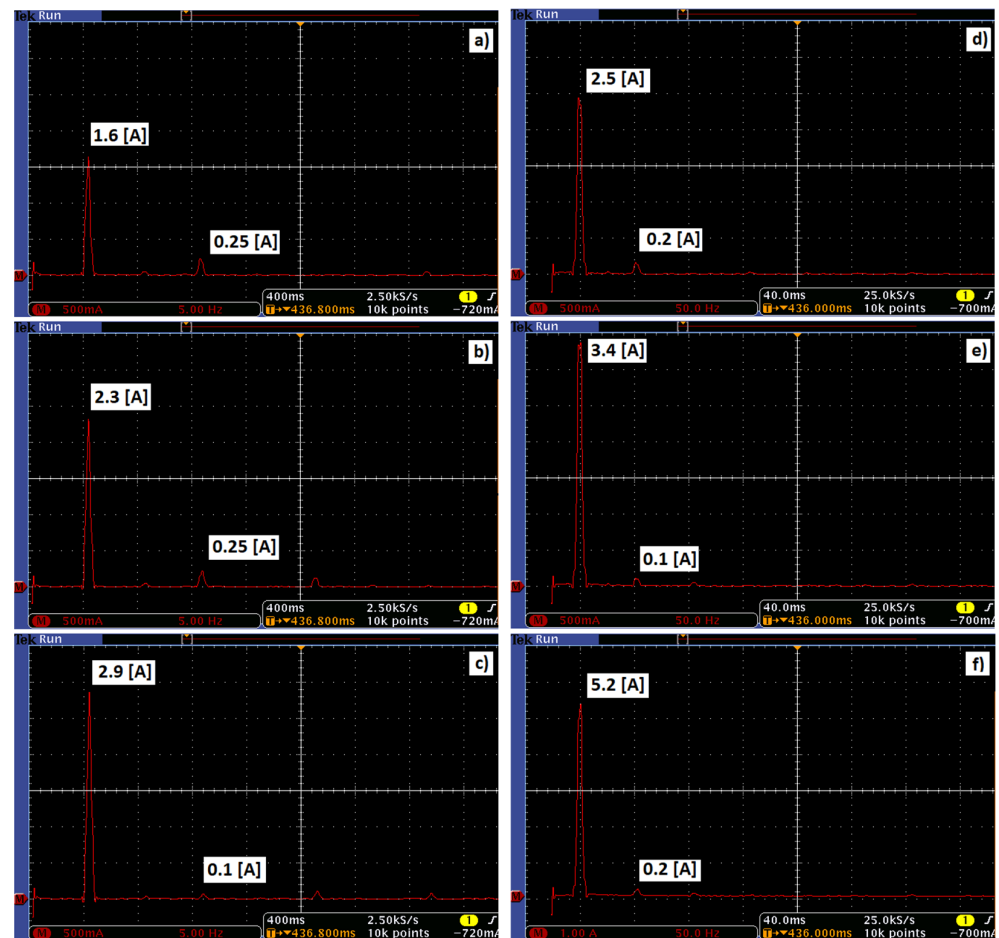


Figure 5. Current spectra recorded with an oscilloscope for phase B at no-load motor operation in the following cases: (a) motor operating with all phases at 150 rpm, (b) motor operating without phase A and at 150 rpm, (c) motor operating without phases A and C at 150 rpm, (d) motor operating with all phases at 750 rpm, (e) motor operating without phase A at 750 rpm, (f) motor operating without phase A and C at 750 rpm.

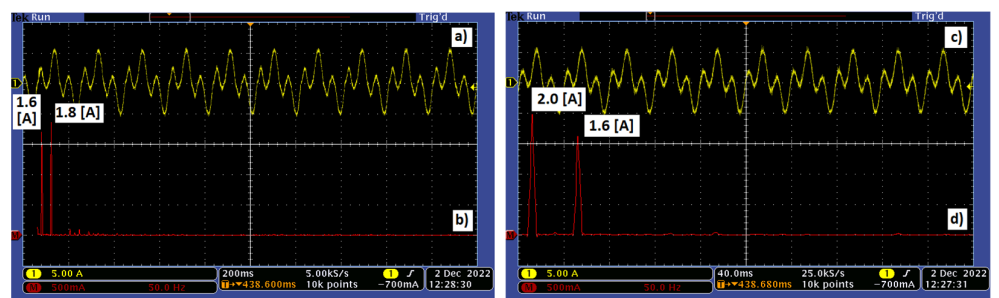


Figure 6. Current waveform for phase B ((a) rotational speed 150 rpm, (c) rotational speed 750 rpm) for a motor supplied with a voltage containing the third harmonic and its spectrum ((b) rotational speed 150 rpm, (d) rotational speed 750 rpm).

5. Analysis of Results from Vibrodiagnostic Measurements

The work of [7,11,30] presented an analysis of the effect of vibration on the operation of an electric motor and focused on using this analysis to study the operation of multiphase motors [31–33].

Vibrations of electrical machines can be divided into three categories: mechanical vibrations, electromagnetic vibrations, and aerodynamic vibrations. Benefiting from con-

tinuous improvements in the level of design and production, the efficiency of electrical machines has been greatly improved and their volume has become very small. In common small and medium-sized electrical machines, the main type is electromagnetic vibration. Electromagnetic vibrations are usually generated by the distorted air gap field of an eccentric rotor in electrical machines [11,30]. Under ideal conditions, the air gap between the stator and rotor is homogeneous and the magnetic circuit is symmetrical. The rotor rotates in a homogeneous magnetic field and the total radial electromagnetic force is zero. If mechanical or electromagnetic factors cause the radial force around the rotor circumference to be unequal, an electromagnetic force, also known as an unbalanced magnetic force (UMF), will be generated. Uneven air gaps cause UMF [34] to act on the rotor, leading to mechanical stresses in some parts of the shaft and bearing. These factors, after prolonged operation, cause broken mechanical parts or even the stator to rub against the rotor, causing serious machine failures [35].

For the vibrodiagnostic studies presented in this article, vibration accelerations in the band up to 12.8 kHz were recorded. Such a bandwidth was deliberately chosen, as the intention of the authors was to capture the widest possible range of signals that could affect the control system and the resulting vibrations in the motor. Measurements were taken in three directions of vibration propagation, i.e., in the vertical (V), horizontal (H) and longitudinal (L) directions. The recorded vibration signals were then converted to velocities using dedicated functions available in the BK Connect software, which were then analyzed in depth in the time and frequency domains.

In the first stage of the analysis, RMS values for vibration velocities in the band up to 1 kHz were determined in accordance with the recommendations of the standard [25,26] and are presented as characteristics in Figures 7–10.

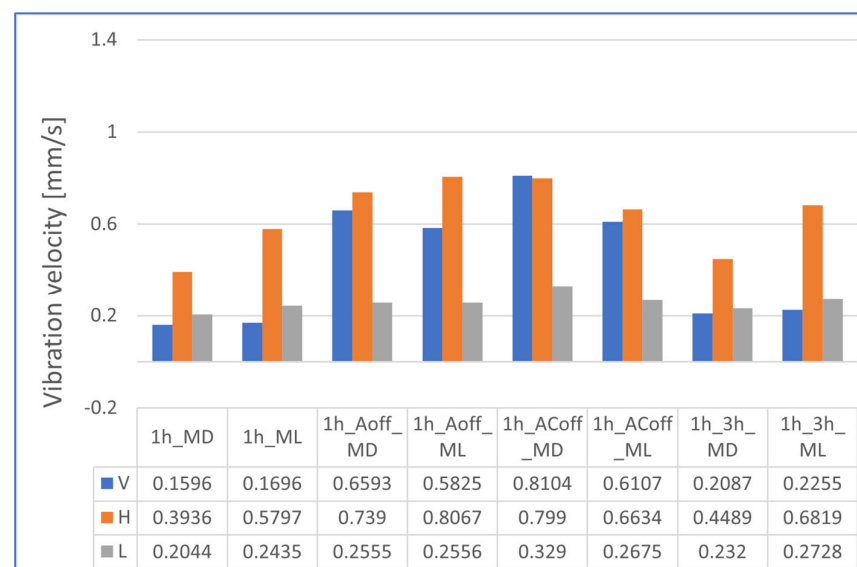


Figure 7. Vibration rms distribution characteristics for an unloaded motor and a rotational speed of 150 rpm.

For a better representation of the analyzed data, designations have been introduced:

- MD—measurement of vibrations on the drive motor;
- ML—measurement of vibrations on the load motor;
- 1 h—supply of the first harmonic;
- 1 h_3 h—1st and 3rd harmonic power supply;
- Aoff—power supply without phase A;
- ACoff—power supply without phases A and C.

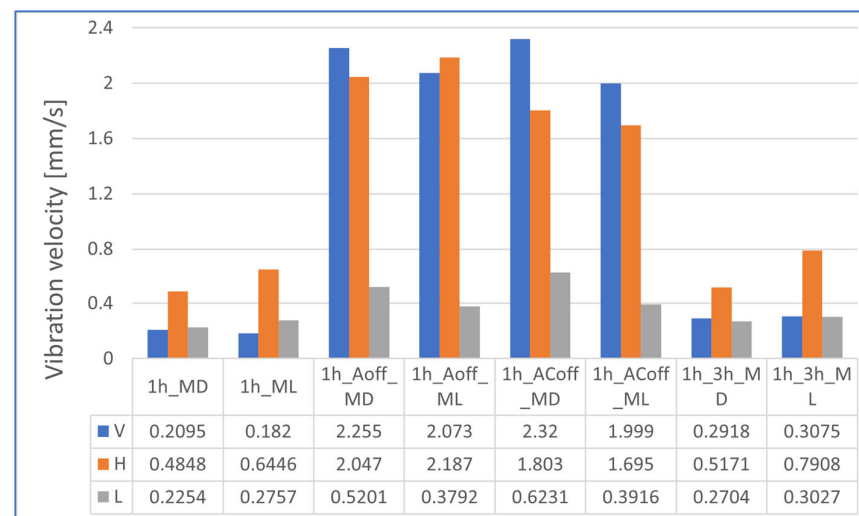


Figure 8. Vibration RMS distribution characteristics for a loaded motor and a rotational speed of 150 rpm.

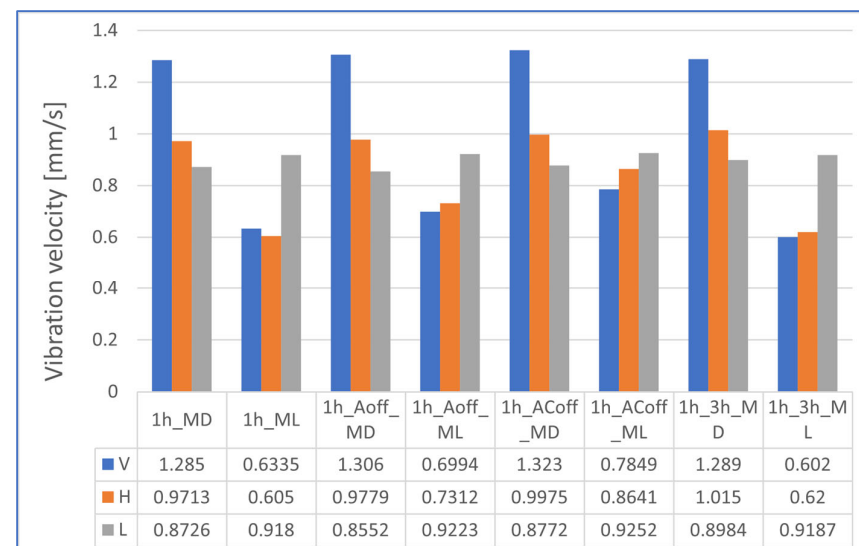


Figure 9. Vibration RMS distribution characteristics for an unloaded motor and a rotational speed of 750 rpm.

The characteristics shown in Figures 7–10 use the designations described above in various configurations. For example, the notation “1 h_Aoff_MD” means the vibrations RMS value calculated for the vibration velocity that was recorded for the drive motor when voltage supplied without the third harmonic and the A phase turned off, or the notation “1 h_3 h_ML” means the vibrations RMS value calculated for the vibration recorded for the load motor when voltage supplied with the third harmonic was added.

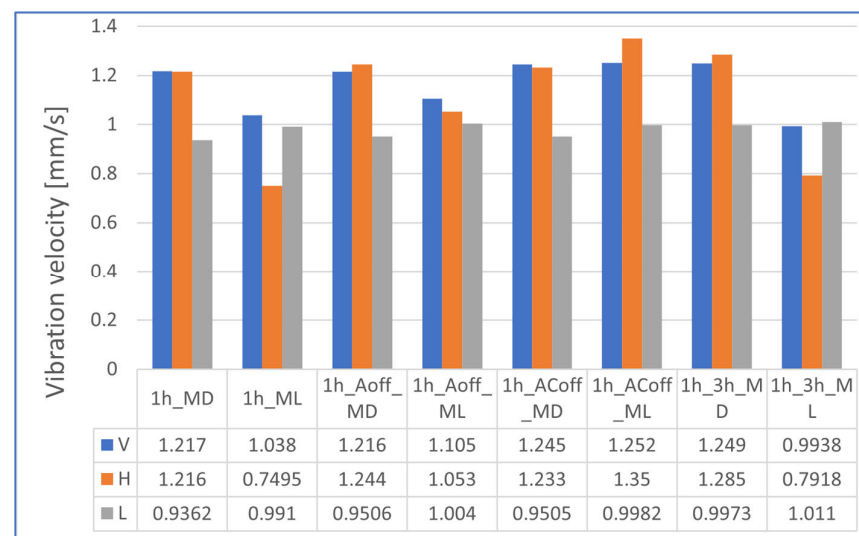


Figure 10. Vibration RMS distribution characteristics for a loaded motor and a rotational speed of 750 rpm.

The experimental results presented in this paper are limited to the following machine working points:

- 10% of nominal rotor speed—150 rpm;
- 50% of nominal rotor speed—750 rpm;
- 50% of nominal load torque;
- All machine phases are turned on (health condition);
- Phases A and/or C are turned off (fault condition).

Figure 7 shows the distribution of vibration RMS values for a 5-phase motor connected to a load motor. Vibrations were recorded for 150 rpm speed.

In the case of an unloaded motor operating at low speed (150 rpm), a pronounced increase in vibration can be observed for the case when phase A or both phases A and C are disconnected at the same time. On the other hand, feeding the motor with a fundamental harmonic or adding a third harmonic does not contribute to large vibrations (they fall within zones A or B, i.e., no more than 1.8 mm/s).

Figure 8 shows the distribution of vibration RMS values for the case of combining the tested 5-phase motor with a load motor. Vibrations were recorded for a rotational speed of 150 rpm.

For a motor operating under load (Figure 8) and at low speed (150 rpm), a significant increase in vibration was observed when one or two phases were switched off (vibration reaches a level contained in zone C, i.e., greater than 1.8 mm/s). The introduction of the third harmonic to the supply voltage does not cause major changes in the vibration level.

Figures 9 and 10 show further distributions of vibration RMS values but this time for a rotational speed of 750 rpm.

For the motor operating without load (Figure 9) and at increased speed (750 rpm), a general increase in vibration can be observed, which remains at a similar level for all cases considered. These vibrations fall within zone B, that is, they do not exceed 1.8 mm/s. Significantly smaller vibrations were registered on the load motor than on the drive motor. In this case, it can also be seen that vibrations in the axis of the motor shaft (L direction) are at a similar level, while vibrations in the V and H directions change.

For the loaded motor (Figure 10) and at increased speed (750 rpm), similar vibration levels were observed as for the unloaded motor at the same speed. The vibrations fall within zone B, i.e., do not exceed 1.8 mm/s. A difference worth noting is that vibration levels in the V and H directions are at a similar level.

An important observation that emerges from the analysis of the RMS vibration distributions of the cases considered is that the vibrations are transmitted through the shaft to

the load motor. The level of vibration recorded on both motors is similar. Therefore, this observation is all the more worrisome and should be taken into account when maintaining drive trains.

In the next step of vibrodiagnostic analysis, the spectral characteristics in different configurations are presented. Based on an analysis of the works [11,35], it appears that the base frequency of vibration is related to the speed of the motor. The other vibration frequencies, assuming that the motor is mechanically efficient, depend on the frequency of the phase voltage with which the motor is supplied and on the slip [35–37].

From the analysis of the literature and the research carried out, it appears that vibrations of electromagnetic origin are characterized by the greatest impact in the vertical (V) and horizontal (H) directions. Therefore, in the following analysis, vibration velocity spectra in the vertical (V) direction are presented as representative. All spectral characteristics shown in the following figures have been normalized to the vibration values resulting from the frequency corresponding to the motor speed when voltage was supplied containing only the fundamental harmonic (Table 2).

Table 2. Theoretical vibration frequencies were calculated for considered rotational frequency (f_r) and power phase frequencies (f_1).

Motor Speed	150 rpm	750 rpm
f_r	2.5 Hz	12.5 Hz
$f_1 = 2f_r$	5.0 Hz	25.0 Hz
$2f_1 = 4f_r$	10.0 Hz	50.0 Hz
$3f_1 = 6f_r$	15.0 Hz	75.0 Hz
$4f_1 = 6f_r$	20.0 Hz	100.0 Hz
...	...	...

Figures 10–13 show the spectral characteristics of vibrations for the cases when the motor operates with all phases, and then when phase A and then phase A and C were turned off.

For the characteristics recorded at low speed (Figures 11 and 12), i.e., 150 rpm, it is possible to observe a general regularity in that switching off one or two phases causes a pronounced increase in vibration consistent with a multiple of the power phase frequency (f_1) at a given motor speed. It is worth noting that the dominant $2f_1$ vibration frequency, which is revealed when the drive motor is loaded, shifts on the frequency axis by approximately 10%. Note that when the drive motor is loaded, the $2f_1$ vibration frequency begins to dominate, and the influence of the $3f_1$ vibration frequency decreases. Under the influence of the drive motor load, the rotational frequency increased by about 3%. When the A and C phases are turned off, the spectra show a clear increase in vibration values for frequencies that are four times the frequency f_1 .

For the characteristics recorded for a much higher speed (Figures 13 and 14), i.e., 750 rpm, it was noted that switching off one or two phases results in only a slight increase in vibration for the frequency resulting from the motor's operating speed, and a slight increase in vibration values for a frequency ($2f_1$) that is twice the frequency f_1 . For a motor operating under load, an increase in frequency $2f_1$ of about 4% can be observed. Similarly, as for the lower motor speed (150 rpm), there was a change in the frequency of vibration f_r of about 1%.

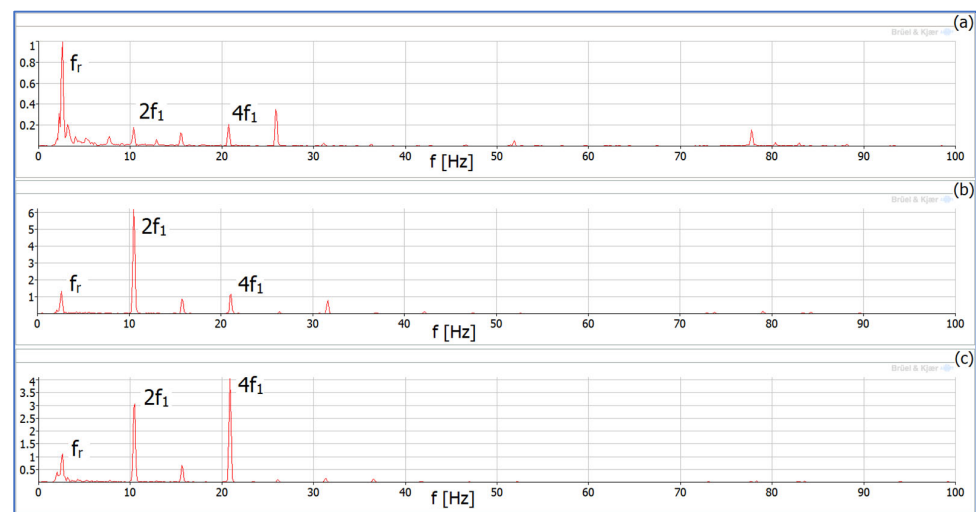


Figure 11. Vibration spectral characteristics for a rotational speed of 150 rpm and no load, where (a)—supply 1 h, (b)—supply 1 h and Aoff, (c)—supply 1 h and ACoff.

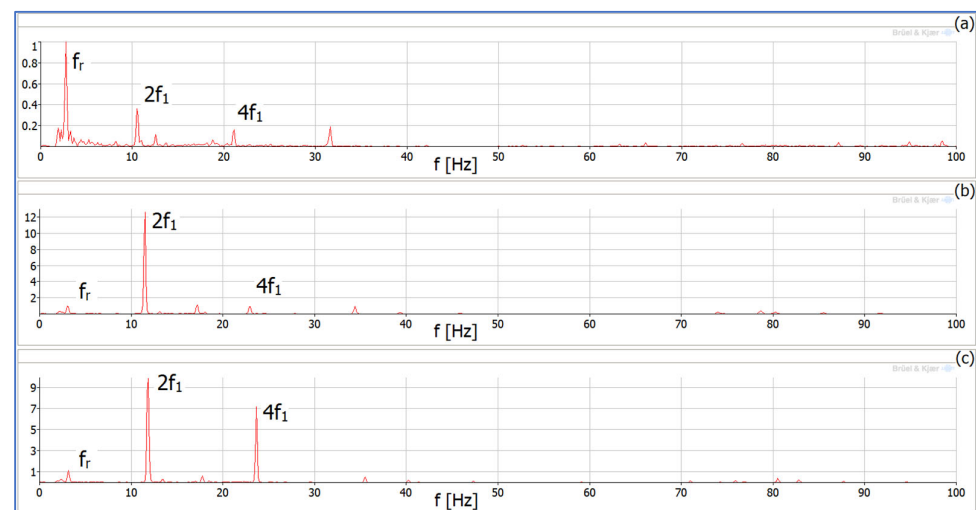


Figure 12. Vibration spectral characteristics for a rotational speed of 150 rpm and under load, where (a)—supply 1 h, (b)—supply 1 h and Aoff, (c)—supply 1 h and ACoff.

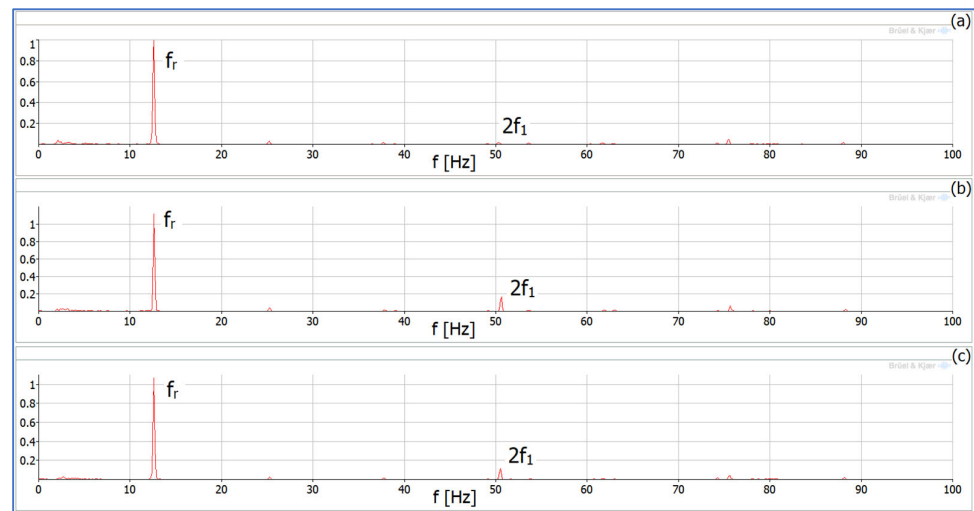


Figure 13. Vibration spectral characteristics for a rotational speed of 750 rpm and no load, where (a)—supply 1 h, (b)—supply 1 h and Aoff, (c)—supply 1 h and ACoff.

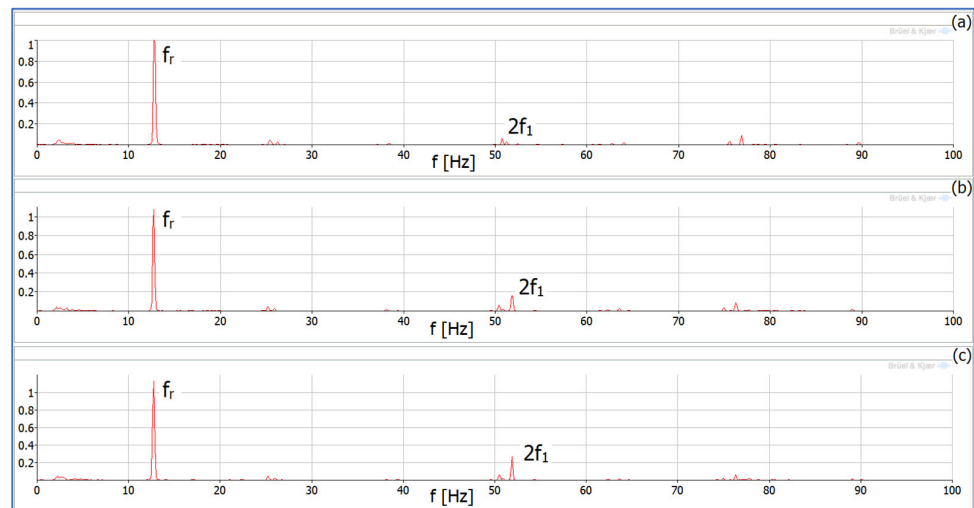


Figure 14. Vibration spectral characteristics for a rotational speed of 750 rpm and under load, where (a)—supply 1 h, (b)—supply 1 h and Aoff, (c)—supply 1 h and ACoff.

At a low motor speed (150 rpm) (Figures 15 and 16) operating without load as well as with load, a clear change in vibration frequency was observed. The addition of the third harmonic also results in the appearance of new vibration frequencies with frequencies other than those derived from the assumed power frequency and the frequency corresponding to the rotational speed. The load on the drive motor contributes to the frequency shift on the time axis.

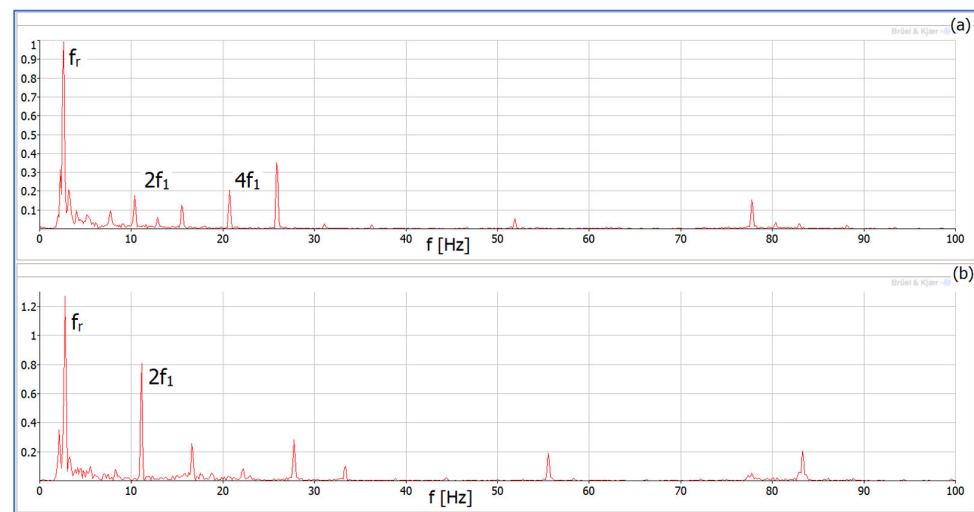


Figure 15. Vibration spectral characteristics for a rotational speed of 150 rpm and no load, where: (a) characteristics—1 h supply, (b) characteristics—1 h and 3 h supply.

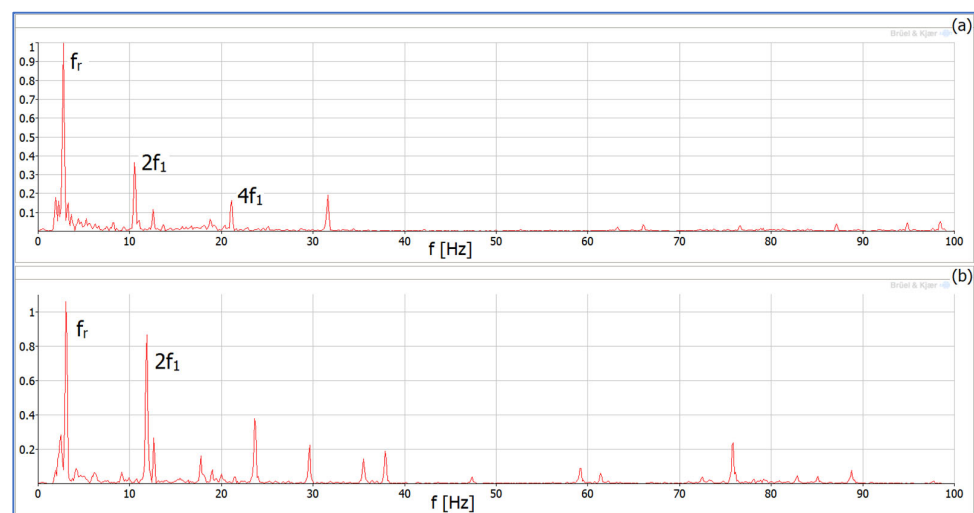


Figure 16. Vibration spectral characteristics for a rotational speed of 150 rpm and under load, where (a) characteristic—1 h supply, (b) characteristic—1 h and 3 h supply.

At an increased motor speed (750 rpm) (Figures 16 and 18), one can see the dominance of vibrations with frequencies corresponding to motor speed, and frequencies that are multiples of the power phase frequency f_1 are noticeable. The vibration level when the third harmonic is added to the voltage is at practically the same level.

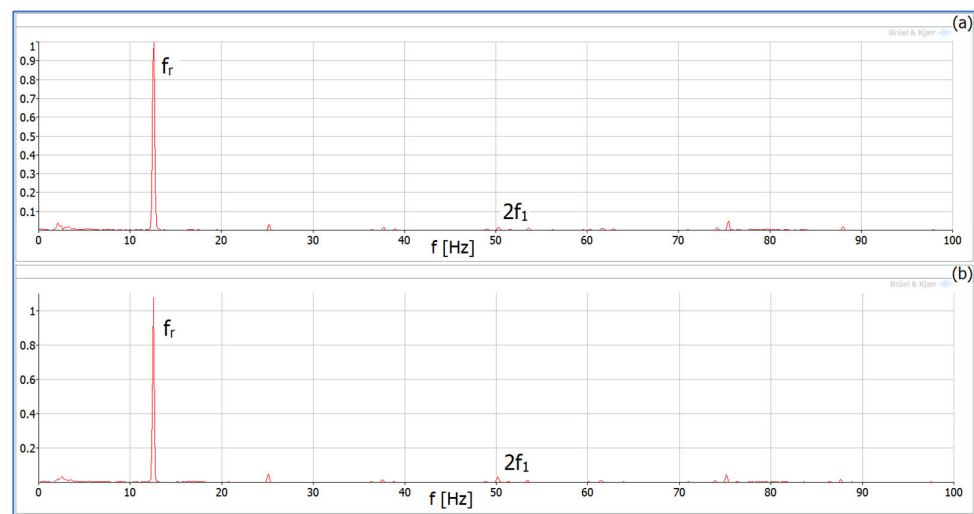


Figure 17. Vibration spectral characteristics for a rotational speed of 750 rpm and no load, where (a) characteristics—1 h supply, (b) characteristics—1 h and 3 h supply.

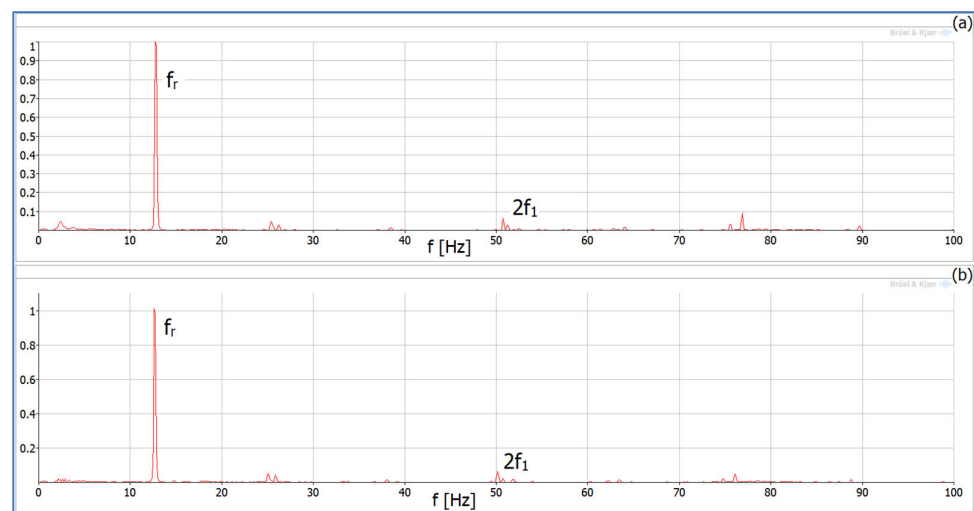


Figure 18. Vibration spectral characteristics for a rotational speed of 750 rpm and under load, where (a) characteristic—1 h supply, (b) characteristic—1 h and 3 h supply.

6. Conclusions

This paper presents vibration analysis using vibration spectral characteristics in a drive system with a five-phase machine powered from a voltage inverter. This approach is little known in the literature relating to polyphase machines. Typically, such analysis is based on electrical quantities such as voltages and currents in the drive system (THD coefficient measurements). As was visible in the presented waveforms, for chosen machine working points, there exists a direct correlation between THDs and vibration level. During simulated faults (one and two stator phases were off) in the presented vibration spectral characteristics, higher sub-harmonics occurred which are not visible in the electrical THDs analysis.

By analyzing the operation of the motor at low speed, it was noted that there was clearly a greater susceptibility to vibration when one or two phases were switched off. In contrast, the motor's low-speed vibration operation was not much affected by supplying it with a phase-frequency voltage or a voltage with an additional third harmonic. In contrast, a different response can be observed when the motor is running at a higher speed. Then it is not very important to introduce the third harmonic to increase the motor torque or even to switch off one or two phases.

This study also showed that the vibrations induced in the drive motor are transmitted through the shaft to the motor acting as the load. It should also be noted that the recorded vibration levels for the drive motor and the motor acting as the load have very similar values, which, according to the authors, is very dangerous for the operation of the drive unit.

Vibration-diagnostic studies of drive units, especially those containing multiphase motors, are not well recognized, so further work in this area is advisable.

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References

1. Lee, S.S.; Bak, Y.; Kim, S.-M.; Joseph, A.; Lee, K.-B. New Family of Boost Switched-Capacitor Seven-Level Inverters (BSC7LI). *IEEE Trans. Power Electron.* **2019**, *34*, 10471–10479. [\[CrossRef\]](#)
2. Ramirez, H.; Restrepo, C.; Konjedic, T.; Calvente, J.; Romero, A.; Baier, C.; Giral, R. An efficiency comparison of fuel-cell hybrid systems based on the versatile buck–boost converter. *IEEE Trans. Power Electron.* **2017**, *33*, 1237–1246. [\[CrossRef\]](#)
3. Gorecki, K.; Detka, K. Analysis of influence of losses in the core of the inductor on parameters of the buck converter. In Proceedings of the 2018 Baltic URSI Symposium (URSI), Poznan, Poland, 14–17 May 2018; pp. 129–132. [\[CrossRef\]](#)
4. Siddique, M.D.; Mekhilef, S.; Shah, N.M.; Sarwar, A.; Iqbal, A.; Tayyab, M.; Ansari, M.K. Low Switching Frequency Based on Asymmetrical Multilevel Inverter Topology with Reduced Switch Count. *IEEE Access* **2019**, *7*, 86374–86383. [\[CrossRef\]](#)
5. Muc, A.; Iwaszkiewicz, J. Active Filtering of Inverter Output Waveforms Based on Orthogonal Space Vector Theory. *Energies* **2022**, *15*, 7861. [\[CrossRef\]](#)
6. Tsyppkin, M. Induction motor condition monitoring: Vibration analysis technique—diagnosis of electromagnetic anomalies. In Proceedings of the 2017 IEEE AUTOTESTCON, Schaumburg, IL, USA, 9–15 September 2017; pp. 1–7. [\[CrossRef\]](#)
7. Tsyppkin, M. The origin of the electromagnetic vibration of induction motors operating in modern industry: Practical experience—Analysis and diagnostics. *IEEE Trans. Ind. Appl.* **2016**, *53*, 1669–1676. [\[CrossRef\]](#)
8. Gnaciński, P.; Hallmann, D.; Muc, A.; Klimczak, P.; Pepliński, M. Induction Motor Supplied with Voltage Containing Symmetrical Subharmonics and Interharmonics. *Energies* **2022**, *15*, 7712. [\[CrossRef\]](#)
9. Kabul, A.; Unsal, A. A Diagnosis Method of Multiple Faults of Induction Motors Based on Vibration Signal Analysis. In Proceedings of the 2021 IEEE 13th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED), Dallas, TX, USA, 22–25 August 2021; Volume 1, pp. 415–421. [\[CrossRef\]](#)
10. Ayala, J.; Meira, M.; Verucchi, C.; Bossio, G.; Acosta, G. Combined Vibration and Stator Current Techniques for Induction Motors Fault Detection—A Review. In Proceedings of the 2021 XIX Workshop on Information Processing and Control (RPIC), San Juan, Argentina, 3–5 November 2021; pp. 1–6. [\[CrossRef\]](#)
11. Saravanan, M.; Rajini, G.K. Vibration Analysis of Electrical Machine. In Proceedings of the 2021 Innovations in Power and Advanced Computing Technologies (i-PACT), Kuala Lumpur, Malaysia, 27–29 November 2021; pp. 1–6. [\[CrossRef\]](#)
12. Iwaszkiewicz, J.; Muc, A. State and Space Vectors of the 5-Phase 2-Level VSI. *Energies* **2020**, *13*, 4385. [\[CrossRef\]](#)
13. Iwaszkiewicz, J.; Muc, A.; Bielecka, A. Polar Voltage Space Vectors of the Six-Phase Two-Level VSI. *Energies* **2022**, *15*, 2763. [\[CrossRef\]](#)
14. Wu, J.; Xu, Q.; Xu, L. A Study on Winding MMF Harmonic and Vibration of Polyphase Motor. In Proceedings of the 2021 Power System and Green Energy Conference (PSGEC), Shanghai, China, 13–16 May 2021; pp. 732–737. [\[CrossRef\]](#)
15. Wilczyński, F.; Strankowski, P.; Guziński, J.; Morawiec, M.; Lewicki, A. Sensorless field oriented control for five-phase induction motors with third harmonic injection and fault insensitive feature. *Bull. Pol. Acad. Sci. Tech. Sci.* **2019**, *67*, 253–262. [\[CrossRef\]](#)
16. Luu, P.T.; Lee, J.; Jeong, Y.; Kim, J.; Lee, J.; Lee, K. Investigation of Multi-Physical Characteristics in Coupling-Five-Phase Motor under Driver-Open-Phase Fault Condition for Small Propulsion System. In Proceedings of the 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), Harbin, China, 11–14 August 2019; pp. 1–4. [\[CrossRef\]](#)
17. Lanciotti, N.; Ojeda, J.; Gabsi, M.; Boukhobza, T. Open-phase fault detection using vibrations in five-phase flux switching machine. In Proceedings of the 2017 18th International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering (ISEF) Book of Abstracts, Lodz, Poland, 14–16 September 2017; pp. 1–2. [\[CrossRef\]](#)

18. Lewicki, A.; Odeh, C.I.; Kondratenko, D.; Morawiec, M. Hybridized Space-Vector Pulsewidth Modulation for Multiphase Two-Level Voltage Source Inverter. *IEEE Trans. Power Electron.* **2022**, *37*, 7663–7674. [\[CrossRef\]](#)
19. Sculler, F. Third harmonic current injection to reduce the pulsating torque of a five-phase SPM machine. In Proceedings of the IECON 2015–41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 9–12 November 2015; pp. 000811–000816. [\[CrossRef\]](#)
20. Buja, G.; Casadei, D.; Serra, G. Direct torque control of induction motor drives. In *ISIE '97 Proceedings of the IEEE International Symposium on Industrial Electronics, Guimaraes, Portugal, 7–11 July 1997*; IEEE: New York, NY, USA; Volume 1, pp. TU2–TU8. [\[CrossRef\]](#)
21. Adamowicz, M.; Guzinski, J.; Krzeminski, Z. Nonlinear control of five phase induction motor with synchronized third harmonic flux injection. In Proceedings of the 2015 First Workshop on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, 22–23 March 2015; pp. 1–6.
22. Adamowicz, M.; Krzeminski, Z.; Morawiec, M.; Strankowski, P.; Guziński, J. Multiscalar control of five phase induction motor. *Electr. Rev.* **2016**, *1*, 108–115.
23. Gnacinski, P.; Muc, A.; Peplinski, M. Influence of Voltage Subharmonics on Line Start Permanent Magnet Synchronous Motor. *IEEE Access* **2021**, *9*, 164275–164281. [\[CrossRef\]](#)
24. *IEC Standard IEC61000-4-7*; Electromagnetic Compatibility (EMC)—Part 4-7: Testing and Measurement Techniques—General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto. International Electrotechnical Commission: Geneva, Switzerland, 2002.
25. *ISO Standard 20816-1*; Mechanical Vibration—Measurement and Evaluation of Machine Vibration—Part 1: General Guide-lines. ISO: Geneva, Switzerland, 2016.
26. *ISO Standard 10816-1*; Mechanical Vibration—Evaluation of Machine Vibration by Measurements on Non-Rotating Parts—Part 1: General Guidelines. ISO: Geneva, Switzerland, 1995.
27. Tani, A.; Mengoni, M.; Zarri, L.; Serra, G.; Casadei, D. Control of Multiphase Induction Motors with an Odd Number of Phases Under Open-Circuit Phase Faults. *IEEE Trans. Power Electron.* **2011**, *27*, 565–577. [\[CrossRef\]](#)
28. Strankowski, P.; Guzinski, J.; Morawiec, M.; Lewicki, A.; Wilczynski, F. Sensorless disturbance detection for five phase induction motor with third harmonic injection. In Proceedings of the 2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Cadiz, Spain, 4–6 April 2017; pp. 387–391. [\[CrossRef\]](#)
29. Strankowski, P.; Jaderko, A.; Blecharz, K.; Morawiec, M. Fault Detection Algorithm for Five-Phase Induction Motor Drive. In Proceedings of the 2019 Applications of Electromagnetics in Modern Engineering and Medicine (PTZE), Podlaski, Poland, 9–12 June 2019; pp. 215–218. [\[CrossRef\]](#)
30. Xu, X.; Han, Q.; Chu, F. Review of Electromagnetic Vibration in Electrical Machines. *Energies* **2018**, *11*, 1779. [\[CrossRef\]](#)
31. Hennen, M.D.; Niessen, M.; Heyers, C.; Brauer, H.J.; De Doncker, R.W. Development and Control of an Integrated and Distributed Inverter for a Fault Tolerant Five-Phase Switched Reluctance Traction Drive. *IEEE Trans. Power Electron.* **2011**, *27*, 547–554. [\[CrossRef\]](#)
32. Glose, D.; Qian, P.; Kennel, R. Efficiency and Vibration Observations of a Symmetrical Six-Phase Drive applying Interleaved Space Vector Modulation. In Proceedings of the PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 10–12 May 2016; pp. 1–8.
33. Ding, A.; Huang, C.; Sun, Z.; Zeng, R.; Mao, Y.; Jia, G.; Luo, H.; Xu, J. Six-phase cylindrical linear induction motor with high-frequency vibration suppression and experimental study. In Proceedings of the 2022 IEEE 5th International Electrical and Energy Conference (CIEEC), Nanjing, China, 27–29 May 2022; pp. 1976–1981. [\[CrossRef\]](#)
34. Smith, A.C.; Dorrell, D.G. Calculation and measurement of magnetic pull in cage induction with eccentric rotors. Part 1: Analytical model. *IEEE Proc. Electr. Power Appl.* **1996**, *143*, 193–201. [\[CrossRef\]](#)
35. Nandi, S.; Bharadwaj, R.M.; Toliyat, H.A. Mixed eccentricity in three phase induction machines: Analysis, simulation and experiments. In Proceedings of the 2002 IEEE Industry Applications Conference—37th IAS Annual Meeting (Cat. No. 02CH37344), Pittsburgh, PA, USA, 13–18 October 2002; pp. 1525–1532.
36. Xing, Z.; Wang, X.; Zhao, W.; Wang, F. Calculation of Stator Natural Frequencies of Electrical Machines Considering Complex Boundary Conditions. *IEEE Trans. Ind. Appl.* **2022**, *58*, 7079–7087. [\[CrossRef\]](#)
37. Ojeda, J.; Boisson, J.; Gabsi, M. 5-phase flux switching machine insulation failure detection using vibration monitoring. In Proceedings of the 2014 17th International Conference on Electrical Machines and Systems (ICEMS), Hangzhou, China, 22–25 October 2014; pp. 1039–1043. [\[CrossRef\]](#)

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