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Influence of Voltage Subharmonics on Line Start Permanent Magnet Synchronous Motor

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ABSTRACT A particularly promising industrial prime mover is a line start permanent magnet synchronous motor (*LSPMSM*). *LSPMSMs*, just as other energy receivers, are exposed to the noxious impact of various power quality disturbances. Previous works on this issue have been limited to the effect of voltage harmonics, voltage unbalance and voltage deviation on the motor. This study initiates novel research on the *LSPMSM* supplied with the voltage containing subharmonics, which involve components with frequencies less than that of the fundamental component. The results of experimental investigations are presented for a factory-made 3-kW *LSPMSM*. Voltage subharmonics were found to exert an extraordinarily harmful influence on motor under consideration. Subharmonics of values similar to those reported in real power systems were determined to cause unacceptable vibration.

INDEX TERMS AC motors, harmonic distortion, permanent magnet motors, vibrations, voltage fluctuations.

I. INTRODUCTION

Industrial prime movers need to be both energy-efficient and reliable. From the point of view of energy efficiency, a line start permanent magnet synchronous motor (*LSPMSM*) [1]–[3], being a hybrid of an induction cage motor and a permanent magnet synchronous motor [4], is especially advantageous. The *LSPMSM* rotor contains a cage winding and permanents magnets [1], [3]. In addition to high efficiency, an *LSPMSM* has many other benefits, such as self-starting capability, high operational power factor, high power density, fast dynamic response and simple operation [1]–[5]. Therefore, *LSPMSM* is considered a promising type of machine [2] and is a good candidate for the substitution of older induction motors [4].

Furthermore, the reliability of an electric motor depends on various factors [2], [4], [6]–[9], including the quality of the supply voltage. In practice, energy receivers are exposed to various power quality disturbances, like voltage deviation, unbalance and waveform distortion. The voltage waveform distortion is interconnected with the occurrence of voltage harmonics and sometimes voltage interhamonics and subharmonics [10]–[12]. The former is defined as components with frequencies that are not integer multiples of the frequency of the fundamental component. Subharmonics are components with frequencies less than that of the fundamental component. Of note, these are often classified as a kind of interharmonics (subsynchronous interharmonics). However, in some works (for example, [13]–[17]), subharmonics are considered separately because of their specific impact on electrical equipment [13].

Subharmonics are injected into the power system by non-linear or pulsating loads, such as inverters, arc furnaces cycloconverters, automated spot-welders, power supplies of traction systems [11], [13], [14], [18], [19], AC motors driving a load of pulsating torque (for example, recip-rocating compressors) [20], [21] and renewable energy sources [12]–[14], [18]. Periodic voltage fluctuations are related to the presence of voltage subharmonics and interharmonics [22].

Examples of significant subharmonic contaminations are presented in [10]–[12]. In [10], the square roots of the sums of the squares of subharmonic subgroups having frequencies 5, 10, . . .40 Hz were reported as high as 0.99%

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(for the aggregation time of 10 min). The measurements were performed in a building near steelworks with numerous nonlinear loads. In [11], a voltage subharmonic of 0.9% and frequency of 45 Hz was observed in a system with a rated frequency of 60 Hz, powered from diesel-driven generators. The voltage subharmonic and interharmonics were caused by inverters supplying high-power induction motors. Ref[12] analysed the subharmonic resonance in a wind farm, lasting about 2 min. It resulted among the others in the voltage subharmonic of the frequency 8.1 Hz and value 1–2% (on the basis of additional information provided by authors of [12]).

Voltage subharmonics have a detrimental impact on various elements of a power system, including light sources, converters, power and measurement transformers, control systems and synchronous generators [14], [18]. A particularly noxious effect of voltage subharmonics was reported in the case of induction motors [15]–[17],[22]–[26]. The considered power quality disturbance may cause a local saturation of the magnetic circuit [24], [25], a significant increase in power losses [15], [16], [23], overheating [16], excessive vibration and torsional vibration [15], [17], [25], [26].

Despite the harmfulness of voltage subharmonics, power quality standards generally do not specify their permissible levels because of the lack of sufficient experience. For instance, the standard *EN 50160 Voltage characteristics of electricity supplied by public distribution systems* [27] contains the following comment (also concerning subharmonics, understood as the specific case of interharmonics): "The level of interharmonics is increasing due to development of the application of frequency converters and similar control equipment. Levels are under consideration, pending more experience". In another standard *IEEE-519: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*[28], the limits of voltage interharmonics (including subharmonics) are provided in an informative annex. For low voltage networks and interharmonics (subharmonics) with frequencies less or equal to 16 Hz, the suggested limit is 5% [28], which is considerably higher than that of the voltage subharmonics expected in real power systems (based on [10]–[12], [14], [18], [21]). The limits are provided with the following note: "It is important to recognize that the suggested voltage interharmonic limits are based on lamp flicker (...). The recommended limits (...) are not based on the effects of interharmonics on other equipment and systems such as generator mechanical systems, motors, transformers, signaling and communication systems, and filters. Due consideration should be given to these effects..." [28].

To protect energy receivers against the harmful impact of voltage subharmonics, their permissible levels need to be determined for the power quality standards and regulations. This task requires in-depth investigations on the effects of subharmonics on various equipment, including *LSPMSMs*. However, previous works on *LSPMSMs* supplied with the voltage of lowered quality have been limited to the effects of voltage unbalance [5], [29]–[33], voltage deviation (including over- and under-voltage unbalance) [5], [30]–[32] and voltage harmonics [30], [34], [35], while the impact of voltage subharmonics (or interharmonics) on these motors has not been studied yet, to the best of the authors' knowledge.

Based on this review, the following purposes of the paper were formulated: 1) to initiate pioneer investigations on *LSPMSMs* supplied with voltage containing subharmonics to establish any limitations on the considered power quality disturbance and 2) to demonstrate that voltage subharmonics are extraordinarily harmful to *LSPMSM*s.

The empirical investigations on current and vibration in this study are performed on the factory-made four-pole *LSPMSM* with a rated power of 3 kW.

II. ELECTROMAGNETIC FORCES IN LSPMSM

In electric machinery, the flow of current and the presence of magnetic flux result in electromagnetic forces. The forces produce electromagnetic torque but also lead to undesirable phenomena, such as noise, vibration and torsional vibration [8], [9], [15], [17], [26], [36]. Two primary types of electromagnetic force can be distinguished: radial and tangential.

The density distribution of the radial electromagnetic force (*EF*) occurring on the inner surface of the stator core is described as follows [36]:

$$p_r(\theta,t) = \frac{B_r^2(\theta,t) - B_t^2(\theta,t)}{2\mu_0} \approx \frac{B_r^2(\theta,t)}{2\mu_0} \tag{1}$$

where θ is the circumference angle along the inner surface of the stator core, μ_0 is the permeability of air, $B_r(\theta,t)$ is the distribution of the radial air-gap flux density and $B_t(\theta,t)$ is the distribution of the tangential air-gap flux density.

If for simplicity the permeability of the stator and rotor core is assumed infinite, the radial *EF* density distribution in *LSPMSM* can be expressed as follows (based on [36]):

$$\begin{aligned} &p_r(\theta,t) \\ &\quad = \frac{\mu_0}{2\delta_e^2}\left[F_w^2(\theta,t) + 2F_w(\theta,t)\,F_{PM}(\theta,t) + F_{PM}^2(\theta,t)\right] \\ &\qquad \times \mathrm{P}_s^2(\theta)\,P_r^2(\theta,t) \end{aligned} \tag{2}$$

where δ_e is the equivalent air-gap length with stator and rotor slotting taken into account, $F_w(\theta,t)$ is the distribution of the magnetomotive force of windings, $F_{PM}(\theta,t)$ is the distribution of the magnetomotive force of permanent magnets and $P_s(\theta)$ and $P_r(\theta,t)$ are the relative air-gap permeance function of stator and rotor slots, respectively.

The tangential *EFs* are intertwined with electromagnetic torque. The torque produced by *LSPMSM* can be calculated as a sum of reluctance torque, cage torque and magnet synchronous torque [37], [38]:

$$\begin{aligned} T_{em} = {} & \frac{3p}{2}\left(L_{sd} - L_{sq}\right) i_{sd} i_{sq} \\ & + \frac{3p}{2}\left(L_{md} i'_{rd} i_{sq} - L_{mq} i'_{rq} i_{sd}\right) + \frac{3p}{2}\lambda'_m i_{sq} \end{aligned} \tag{3}$$

where p is a number of pole pairs and i_{sd}, i_{sq}, i'_{rd}, i'_{rq} are currents described by voltage equations in a stationary reference frame:

$$V_{sq} = r_s i_{sq} + \omega_r \lambda_{sd} + \frac{d\lambda_{sq}}{dt} \tag{4}$$

$$V_{sd} = r_s i_{sd} - \omega_r \lambda_{sq} + \frac{d\lambda_{sd}}{dt} \tag{5}$$

$$V'_{rq} = r'_{rq} i'_{rq} + \frac{d\lambda'_{rq}}{dt} = 0 \tag{6}$$

$$V'_{rd} = r'_{rd} i'_{rd} + \frac{d\lambda'_{rd}}{dt} = 0 \tag{7}$$

where V_{sq}, V_{sd}, V'_{rq}, V'_{rd} are stator and rotor voltages; ω_r, r_s, r'_{rq}, r'_{rd} are speed, stator and rotor resistances; λ'_m is permanent magnet flux and λ_{sq}, λ_{sd}, λ'_{rq}, λ'_{rd} are stator and rotor linkage fluxes:

$$\lambda_{sq} = L_{sq} i_{sq} + L_{mq} i'_{rq} \tag{8}$$

$$\lambda_{sd} = L_{sd} i_{sd} + L_{md} i'_{rd} + \lambda'_m \tag{9}$$

$$\lambda'_{rq} = L'_{rq} i'_{rq} + L_{mq} i_{sq} \tag{10}$$

$$\lambda'_{rd} = L'_{rd} i'_{rd} + L_{md} i_{sd} + \lambda'_m \tag{11}$$

where L_{sq}, L_{sd}, L'_{rq}, L'_{rd} are stator and rotor leakage inductances and L_{mq} and L_{md} are mutual inductances.

The presence of subharmonics in the supply voltage causes distorted currents to flow through windings, which leads to the occurrence of additional *EF* components with a pulsating character. It should be noted that pulsating *EF* components due to power-quality disturbances are reported to cause extraordinarily high vibrations in electric machinery [9], [17], including an induction motor supplied with voltage containing subharmonics [17]. A similar effect can be expected in the case of *LSPMSM*.

III. MEASUREMENT STAND

The experimental setup comprised a system for vibration measurement, a multi-machine system for subharmonic generation, power quality analysers and the newly commissioned *LSPMSM* WQuattro L100L-04, coupled with a DC generator. The nameplate data of the motor under investigation are provided in Table 1.

TABLE 1. Name plate Data of the Investigated Motor WQuattro L100L-04.

Rated power (kW)	3
Rated frequency Hz)	50
Rated voltage (V)	400
Rated current (A)	5.84
Rated power factor (-)	0.82
Rated rotational speed (rpm)	1500
Manufacturer	WEG Industries

For the vibration measurement, a Bruel&Kjear (B&K) system was employed, consisting of a standalone four-channel data acquisition module (B&K 3676-B-040), a three-axis accelerometer (B&K 4529-B), an accelerometer calibrator (B&K 4294) and a computer with BK Connect software. The accelerometer was glued directly to the aluminium casing of the motor (after paint removal). A photograph of the investigated motor equipped with the accelerometer is given in Fig. 1. It is worth adding that the vibration measurement and analysis were performed in accordance with the chief provisions of ISO Standard 20816-1 *Mechanical vibration —— Measurement and evaluation of machine vibration– Part 1: General guidelines* [39].

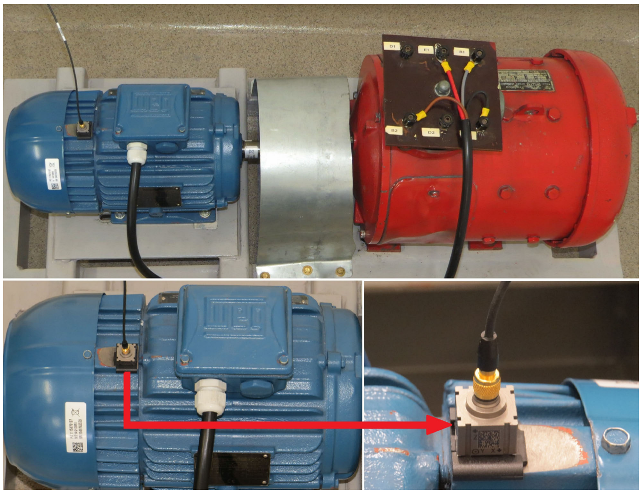

FIGURE 1. Investigated motor and the accelerometer (bottom right).

The multi-machine system for subharmonic generation (based on [40]) consisted of two synchronous generators coupled via a transformer. One generator produced the fundamental voltage component, and the other produced voltage subharmonic. More details concerning this system are presented in [17]. The subharmonic content was measured with a computer-based power quality analyser and an estimator-analyser of power quality [41], which was developed in Gdynia Maritime University for commercial purposes and certified by the Polish Register of Shipping.

The simplified diagram of the measurement stand is shown in Fig. 2.

IV. RESULTS OF INVESTIGATIONS

In this section, the results of experimental research on current and vibration are presented. The voltage subharmonic was assumed to be 1% of the fundamental component (as similar subharmonic contamination was reported in [10]–[12]).

Appropriate tests were carried out for positive-sequence subharmonics and the following three cases:

Case A – the investigated motor uncoupled from the DC generator (see Section III);

Case B – the motor coupled with the idling DC generator;

Case C – the motor coupled with the DC generator and loaded with the approximate rated power.

Case A and *Case B* correspond to a motor under no-load. A practical instance of such working conditions is an idle period under continuous-operation duty S6 [17], [42]. For *Case A*, the working conditions conform to a motor driving a

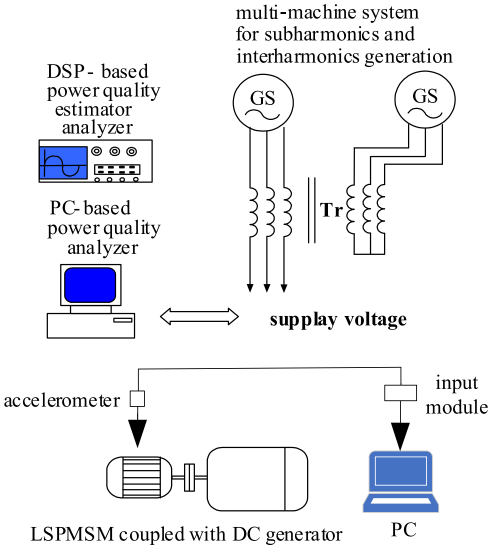

FIGURE 2. Simplified diagram of the measurement stand.

load with a moment of load inertia much less than the motor moment [17]).

A. EFFECT OF VOLTAGE SUBHARMONICS ON CURRENT

The results of investigations on current subharmonics and interharmonics (*SaI*) are presented in Figs. 3–6. Fig. 3 shows the current waveform and its spectrum for *Case A* and the frequency of the subharmonic f_{sh} equal to 18 Hz. The voltage subharmonics resulted in a current subharmonic equal to 62.6% of the rated current I_{rat}. For comparison, the fundamental current harmonic was 64.5% of I_{rat}. The current subharmonic was accompanied by the interharmonic component equal to 37.8% of I_{rat} and a frequency of 82 Hz. The additional current component was likely caused by speed fluctuations, similarly to the case of an induction motor [15]–[17], [22]. Of note, also the speed fluctuations of synchronous motors were reported to cause the flow of current *SaI* [20].

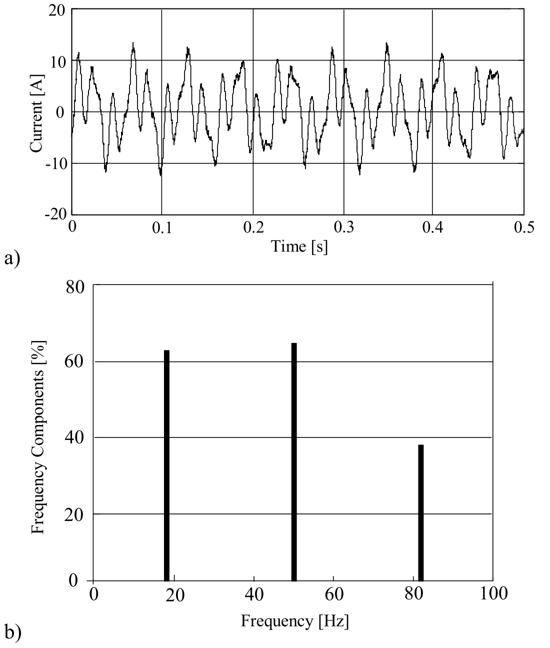

FIGURE 3. Current waveform (a) and its spectrum (b) for *Case A* and voltage containing subharmonics of frequency f_{sh} = 18 Hz. The frequency components are related to the rated current.

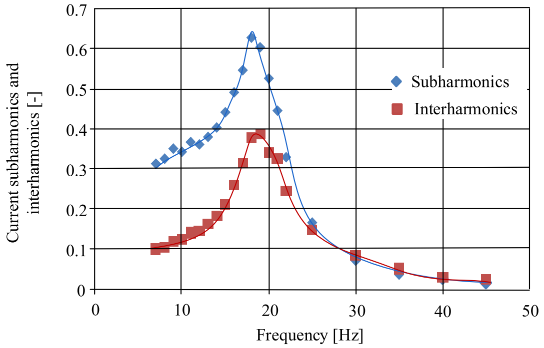

FIGURE 4. Current subharmonics and interharmonics versus the frequency of voltage subharmonics for *Case A*. The frequency components are related to the rated current.

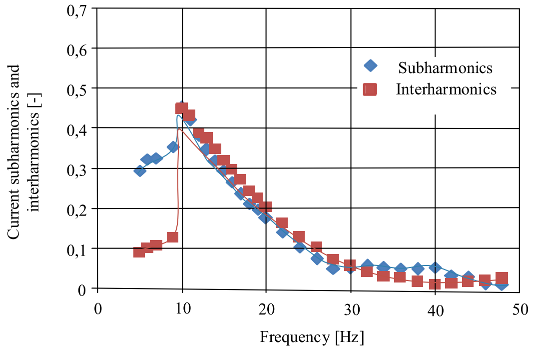

FIGURE 5. Current subharmonics and interharmonics versus the frequency of voltage subharmonics for *Case B*. The frequency components are related to the rated current.

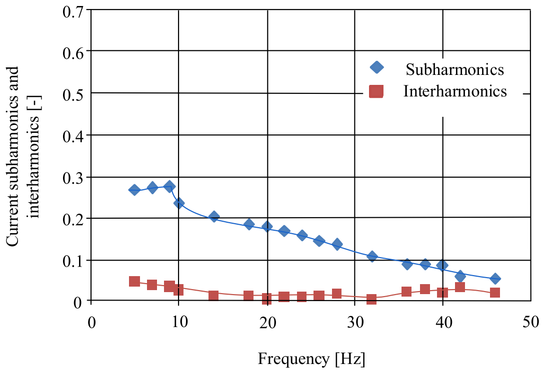

FIGURE 6. Current subharmonics and interharmonics versus the frequency of voltage subharmonics for *Case C*. The frequency components are related to the rated current.

Figs. 4–6 show the characteristics of the current *SaI* versus the frequency f_{sh} for the three cases under consideration. For *Case A* (Fig. 4) and *Case B* (Fig. 5), the frequencies peak at 18–19 Hz and 10 Hz, respectively. For *Case A*, the current *SaI* reach 62.6% and 38.6% of I_{rat}, respectively, and for *Case B*, they reach 45.2% and 44.8% of I_{rat}. These analogical peaks, caused by resonance phenomena, were reported for induction motors [15]-[17]. A studied 3-kW uncoupled induction motor had a maximal subharmonics value of 33.9% of I_{rat}, which is about half of that the investigated *LSPMSM*.

Furthermore, for *Case C* (Fig. 6), *SaI* components are lower. Current interharmonics do not exceed 5% of I_{rat}, while the maximal value of current subharmonics is 27.4% for the frequency $f_{sh} = 9$ Hz. The effect of load on *SaI* content will be presented in a separate paper. For all the considered cases having f_{sh} values greater than 30 Hz, the current *SaI* generally does not exceed 12% of I_{rat}.

In summary, voltage subharmonics of levels similar to those reported in real power systems [10]–[12] may cause high *SaI* values in *LSPMSMs*. For the investigated machine, the current subharmonics reached roughly 63% of I_{rat}. High *SaI* values can cause various harmful phenomena, such as an increase in power losses, overheating, torque pulsations and vibration.

B. EFFECT OF VOLTAGE SUBHARMONICS ON VIBRATION

1) ASSESSMENT OF VIBRATION SEVERITY

General recommendations concerning the assessment of the vibration severity are included in ISO Standard 20816-1 *Mechanical vibration —— Measurement and evaluation of machine vibration– Part 1: General guidelines* [39]. In the standard [39], four evaluation zones are defined – *A*, *B*, *C* and *D*. According to [39], the vibration within boundaries of *Zone A* is considered typical for newly commissioned machines; within *Zone B*, it is acceptable for unrestricted long-term operation, and within *Zone C*, the vibration is unsatisfactory for long-term continuous operation. Furthermore, the vibration within *Zone D* is ‘‘normally considered to be of sufficient severity to cause damage to the machine’’ [39]. The unequivocal boundaries between each zone are not provided in the standard [39]. The limits are more precisely listed in the former standard *ISO 10816-1 Mechanical vibration —— Evaluation of machine vibration by measurements on non-rotating parts —— Part 1: General guidelines* [43]. For machines of *Class I* (for example, production electric motors of power up to 15 kW), the broad-band vibration velocity less than 0.71 mm/s corresponds to *Zone A*, 0.71–1.8 mm/s is associated with *Zone B*, 1.8–4.5 mm/s is *Zone C*, and *Zone D* includes velocities greater than 4.5 mm/s. In this study, the above threshold values were assumed in order to assess the vibration severity.

2) RESULTS OF TESTS

Figs. 7, 8, 9 show the characteristics of the broad-band vibration velocity for *Cases A*, *B* and *C* in the horizontal (H), vertical (V) and longitudinal (L) directions. For *Case A* (Fig. 7), the vibration velocity generally corresponds to *Zones A* and *B*, despite the high values of current *SaI* (see Subsection IVA). Nevertheless, the vibration level directly depends on the behaviour of the mechanical structure [8], [9].

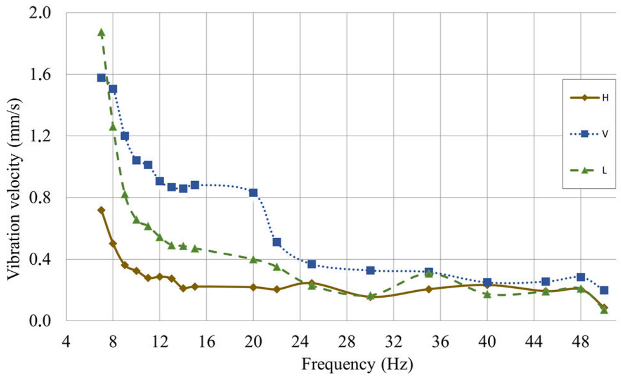

FIGURE 7. Measured broad-band vibration velocity for *Case A* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the frequency of voltage subharmonics.

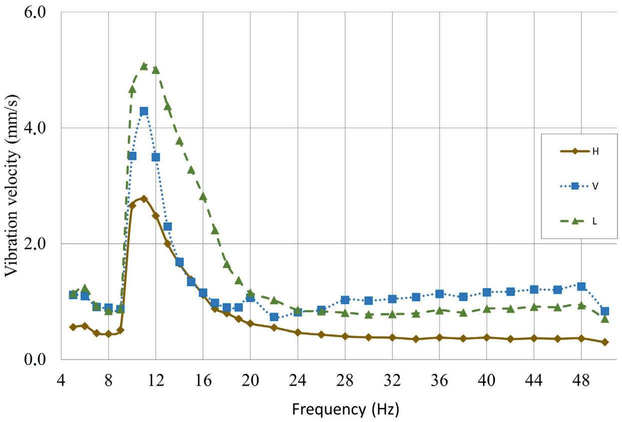

FIGURE 8. Measured broad-band vibration velocity for *Case B* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the frequency of voltage subharmonics.

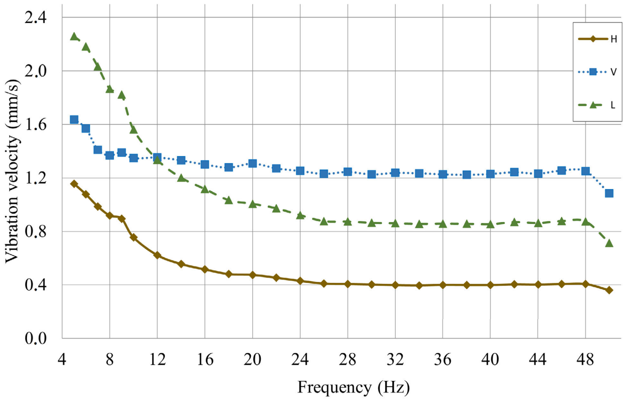

FIGURE 9. Measured broad-band vibration velocity for *Case C* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the frequency of voltage subharmonics.

Furthermore, for *Case B* (Fig. 8), the vibration velocity reaches extremely high values. For the frequency $f_{sh} = 11$ Hz and the direction L, the vibration velocity is 5.07 mm/s, exceeding the threshold level of *Zone D*. For the directions V and H, the vibration velocity is 4.29 mm/s and 2.77 mm/s, respectively. For electric machines supplied with the voltage of lowered quality, the highest vibration is usually reported in the transverse direction [8], [9], [17] but also observed in the longitudinal direction [8]. The maximum vibration velocity approximately corresponds to the peak of current *SaI* (see Subsection IVA). For f_{sh} greater than 18 Hz, the vibration velocity is comparatively low, falling into *Zones B* and *A*.

Fig. 9 shows the characteristic of the vibration velocity for *Case C*. The highest vibration occurs for the frequency f_{sh} less than 10 Hz; the vibration velocity peaks at 2.26 mm/s, corresponding to *Zone C*.

Similarly, for an induction motor, the most significant vibration was reported under no-load, [17]. According to [17], this phenomenon occurs for two reasons. Firstly, at idle the rotational torque alternates between positive and negative values. Consequently, the possible interaction with the coupled DC generator could lead to high vibration. Additionally, under load conditions, the rotor is more stable because it is weighed down to the bearings [17].

In summary, voltage subharmonics may result in extreme vibration of *LSPMSMs*. The maximal vibration velocity occurred under no-load, peaking at 5.07 mm/s. Of note, some motors idle for the majority of their operation, such as a motor under duty type S6 15% [17], [42]. At the same time, the provisions of power quality standards shall enable the reliable and durable operation of any electrical equipment, including *LSPMSMs*, under various operational conditions.

V. CONCLUSION

This paper initiates novel investigations on *LSPMSMs* supplied with voltage containing subharmonics. This power quality disturbance was found to exert an extreme noxious impact on the motor under consideration. Voltage subharmonics of values similar to those reported in real power systems [10]–[12] resulted in excessive vibration. The maximum measured vibration velocity was 5.07 mm/s, corresponding to *Zone D* (defined in [39], [43]), and "vibration values within this zone are normally considered to be of sufficient severity to cause damage to the machine" [39].

The experimental research also shows that voltage subharmonics could cause extremely high current subharmonics and interharmonics (*SaI*). For voltage subharmonic values of 1% of U_{rat}, the current subharmonics reached 63% of the rated current – about twice that of an induction motor of the same rated power [17]. High current *SaI* values might cause a significant increase in power losses, motor overheating and excessive torsional vibration. The detrimental phenomena will be a subject of future research.

The presented results also indicate the need for updated power quality standards that comprise permissible levels of voltage subharmonics. The appropriate limits should consider the harmful effects of voltage subharmonics on various equipment, including *LSPMSMs*.

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