Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2023, 74 (146), 28–34
ISSN 2392-0378 (Online)
DOI: 10.17402/561

Received: *02.06.2022*
Accepted: *12.04.2023*
Published: *30.06.2023*

Line start permanent magnet synchronous motor supplied with voltage containing subharmonics

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Keywords: interharmonics, line start permanent magnet synchronous motor, power quality, subharmonics, voltage fluctuations, vibration

JEL Classification: C93, L64, L94, Q40

Abstract

The presented study examines the effect of voltage subharmonics, which relates to components of the frequency less than the fundamental voltage harmonic, and the currents and vibration of the line start permanent magnet synchronous motor. The obtained experimental results corresponded to a production motor with a rated power of 3 kW and a rated speed of 1500 rpm. The main purpose of our study was to highlight that the subharmonic value had a non-linear effect on the vibration level of the considered motor. It was found that for subharmonic values up to approx. 0.5% of the vibration level could be considered acceptable for long-term operation, whereas vibration caused by voltage subharmonics of values greater than approx. 0.8% might promote machine damage.

Introduction

Line start permanent magnet synchronous motor (LSPMSM) is increasing in popularity. Its characteristics include self-starting capability, high efficiency, high power density, fast dynamic response, and ease of operation (Ganesan & Chokkalingam, 2019; Pechlivanidou & Kladas, 2019; Fonseca, Santos & Cardoso, 2020; Maraaba et al., 2020). The construction of LSPMSM exhibits features of both synchronous and asynchronous machines, where its rotor, aside from permanent magnets, also contains a cage winding (Ganesan & Chokkalingam, 2019; Pechlivanidou & Kladas, 2019). The motor under consideration is similar to other energy receivers, and is exposed to the impact of various power quality disturbances.

Especially harmful power quality disturbances include voltage subharmonics, which are voltage components with a frequency less than the fundamental harmonic. A reason for their occurrence is the work of non-linear loads, for example, inverters, cycloconverters, arc furnaces (Bollen & Gu, 2006; Testa et al., 2007; Soltani et al., 2018; Nasiff, 2019), and receivers consuming time-varying power, such as motors driven piston compressors (Zhiyuan et al., 2017; Arkkio et al., 2018). The presence of subharmonics in voltage waveforms is caused by renewable sources of energy, such as wind and photovoltaic power stations (Bollen & Gu, 2007; Testa et al., 2007; Xie et al., 2017). It should be noted that cyclic voltage fluctuations are a superposition of subharmonics and interharmonics (Bollen & Gu, 2006, Ghaseminezhad et al., 2021b).

In certain power systems, voltage subharmonics comparatively high levels are observed (Barros et al., 2007; Xie et al., 2017; Nasiff, 2019). For instance, as reported by (Barros, De Apraiz & Diego, 2007), the maximal value of square roots of the sums of the squares of subharmonic subgroups (of frequencies 5, 10,...,40 Hz) was 0.99%. Furthermore, Nasiff (2019) reported voltage subharmonic of value 0.9% and frequency of 45 Hz (in a system of the rated frequency 60 Hz), accompanied by interharmonics of approx. 1%. Xie et al. (2017) observed voltage subharmonics of frequency c. 8 Hz and value of 1–2% (on the grounds of additional information obtained from authors of the above study) during subharmonic resonance of a wind farm.

Voltage subharmonics have a noxious impact on various energy consumers, such as, among others, light sources, power and measurement transformers, control systems, and electrical machines (Tripp, Kim & Whitney, 1993; Bollen & Gu, 2006; Testa et al., 2007; Schramm et al., 2010; Ghaseminezhad et al., 2017a; 2017b; Gnaciński et al., 2019b; Gnaciński & Klimczak, 2020; Crotti et al., 2021; Ghaseminezhad et al., 2021a; 2021b; Gnaciński, Muc & Pepliński, 2021). In synchronous and asynchronous machines they can promote excessive vibration and torsional vibration (Tripp, Kim & Whitney, 1993; Schramm et al., 2010; Gnaciński et al., 2019b; Gnaciński & Klimczak, 2020; Gnaciński, Muc & Pepliński, 2021).

Despite voltage subharmonics being considered extraordinarily harmful, their permissible levels have not been specified in power quality standards. This is due to the lack of experience (EN Standard 50160:2010). In order to introduce their permissible levels into the standards, in-depth investigations must be carried out. The impact of voltage subharmonics on various components of power systems should be investigated in detail, including the impact on LSPMSM.

There are numerous studies on the effect of voltage harmonics, voltage unbalance, and voltage deviation on the motor under consideration (Debruyne et al., 2013; Donolo et al., 2019; Qiu et al., 2019; Sethupathi & Senthilnathan, 2020; Tabora et al., 2020; Tabora et al., 2021; Tshoombe et al., 2021). Furthermore, the impact of voltage subharmonics on LSPMSM is not presented in previous works, except for that reported by (Gnaciński, Muc & Pepliński, 2021). The main purposes of their study (Gnaciński, Muc & Pepliński, 2021) were as follows: 1) to initiate novel investigations concerning LSPMSM supplied with voltage concerning subharmonics; 2) to highlight that voltage subharmonics could exert an extraordinarily harmful effect on LSPMSM. Notably, all results of the investigations included in (Gnaciński, Muc & Pepliński, 2021) were limited to voltage subharmonics equal to 1% of the fundamental voltage component. Our work was an extension and continuation of (Gnaciński, Muc & Pepliński, 2021) study, where the experimental results on currents and vibration were presented for voltage subharmonics of various values.

Measurement stand

The measurement stand contained a multi-machine system for subharmonic generation, a system for vibration measurement, power quality analyzers, and the investigated, newly commissioned LSPMSM Quattro L100L-04, coupled with a DC generator. The basic parameters of the motor are given in Table 1.

Table 1. Nameplate data of the investigated motor WQATTRO L100L-04

Description	Value
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
Weight (kg)	39
Winding connection	Wye
Manufacturer	WEG Industries

The vibration was measured using a Bruel & Kjear (B&K) system, which included a standalone four-channel data acquisition module (B&K 3676-B-040), a three-axis accelerometer (B&K 4529-B), a computer with installed BK Connect software, and an accelerometer calibrator (B&K 4294). The multi-machine system for subharmonic generation (based on (Ho & Fu, 2001)) was composed of two synchronous alternators, connected via a transformer. One generated the fundamental voltage harmonic, and the other injected the subharmonic component. For measurements of the subharmonics and interharmonics, a PC-based power quality analyzer was applied, and an estimator-analyzer of power quality (Tarasiuk, 2011) was conducted at Gdynia Maritime University for commercial purposes and certified by the Polish Register of Shipping.

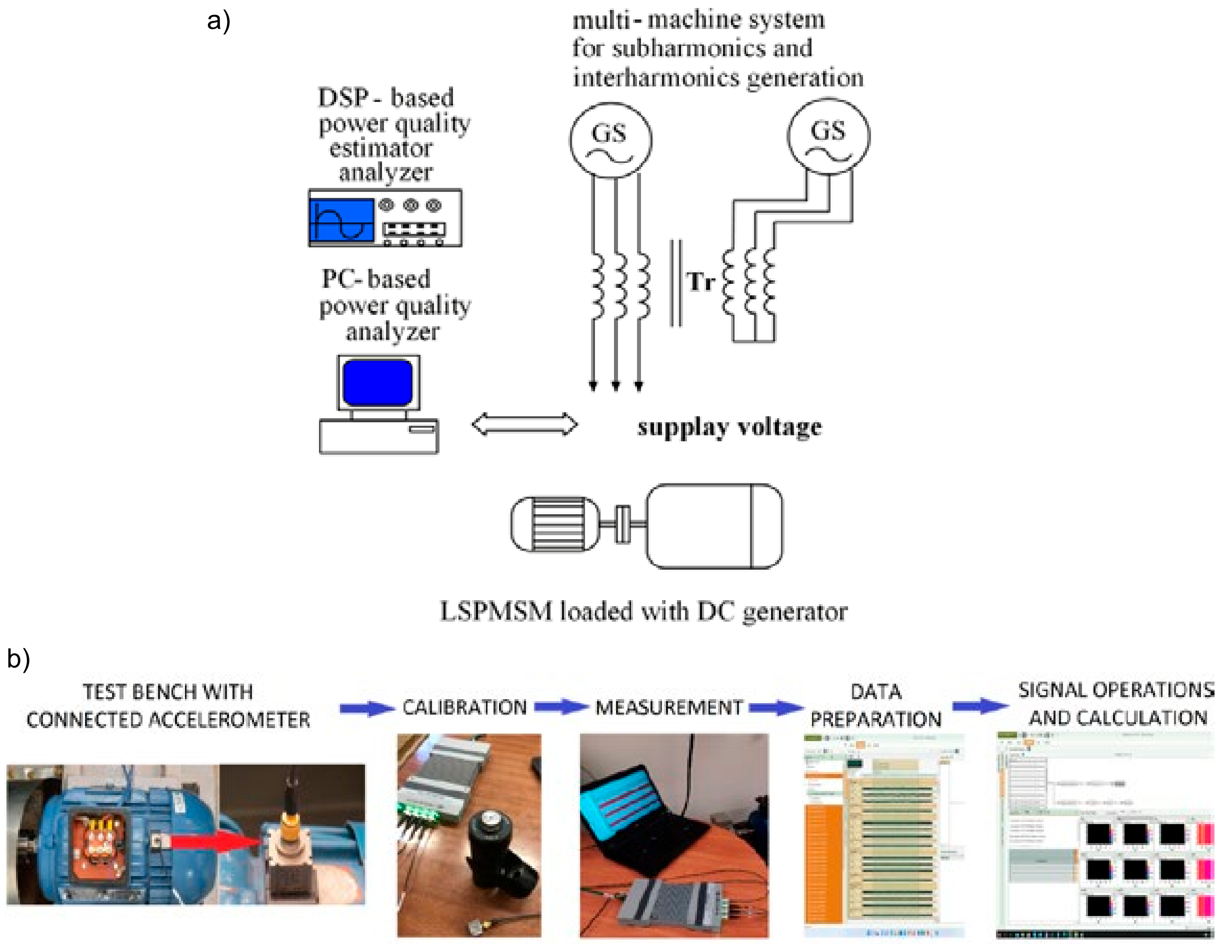

Figure 1. Simplified diagram of the measurement stand (a) and flowchart of the vibration measurement (b)

A simplified diagram of the measurement stand and the flowchart of the vibration measurement are provided in Figure 1 (based on (Gnaciński, Muc & Pepliński, 2021)), and the detailed description together with photographs is shown in (Gnaciński, Muc & Pepliński, 2021).

Result of investigations

The results of our empirical investigations are presented for three cases, labeled as *Case A*, *Case B*, and *Case C*:

Case A – uncoupled LSPMSM,
Case B – LSPMSM coupled with unloaded DC generator,
Case C – LSPMSM loaded with its rated torque by DC generator.

Justification for the aforementioned considered cases is provided in the following publications (Gnaciński et al., 2019a; Gnaciński, Muc & Pepliński, 2021). All presented tests were carried out for the fundamental voltage component equal to its rated value.

Measured broad-band vibration velocity (ISO Standard 20816-1:2016) versus the frequency of voltage subharmonic f_{sh} is provided in Figures 2, 3, and 4 for *Case A*, *Case B*, and *Case C*, respectively, for voltage subharmonics value of 0.5%. Due to undesirable motor current components causing torque pulsations (Gnaciński, Muc & Pepliński, 2021), which induce vibration (Tsypkin, 2017), current subharmonics and interharmonics were additionally presented in Figures 5, 6, and 7. Importantly, the reasons for the occurrence of interharmonics in the supply motor current were previously discussed (Gnaciński et al., 2021). For *Case A* (Figure 2), the measured broad-band vibration velocity was up to 1.4 mm/s. The highest vibration velocity was observed for f_{sh} = 5 Hz, despite the current subharmonics and interharmonics reaching a maximum (approx. 26% of the rated current) for f_{sh} = 19 Hz (Figure 5). Furthermore, the peak of current subharmonics and interharmonicsin shown in Figure 5, was explained by the resonance phenomena (Gnaciński, Muc & Pepliński, 2021). For *Case C* (Figure 4), the vibration velocity did not exceed 1.34 mm/s, and

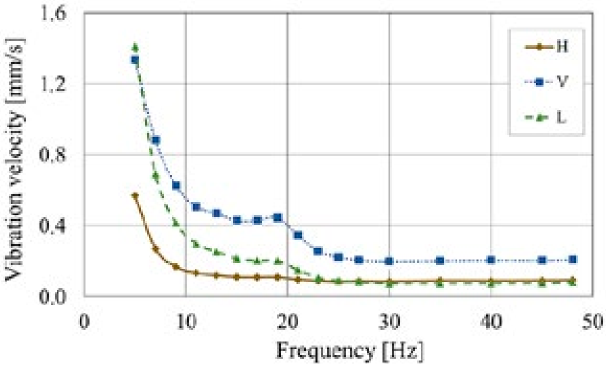

Figure 2. Measured broad-band vibration velocity for *Case A* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the frequency of voltage subharmonics

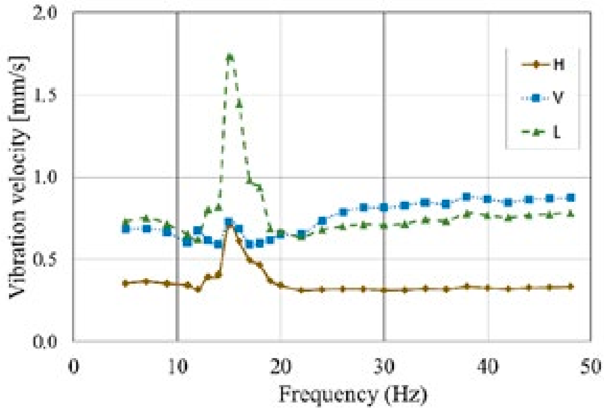

Figure 3. Measured broad-band vibration velocity for *Case B* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the frequency of voltage subharmonics

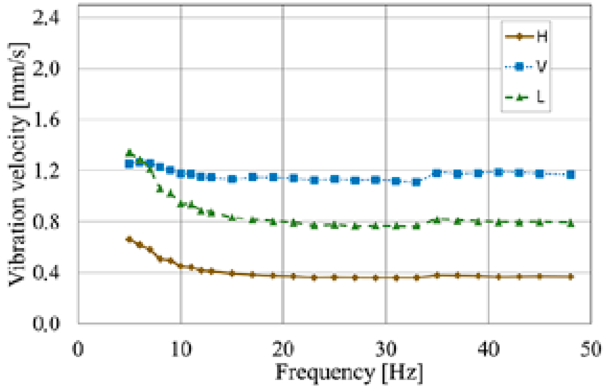

Figure 4. Measured broad-band vibration velocity for *Case C* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the frequency of voltage subharmonics

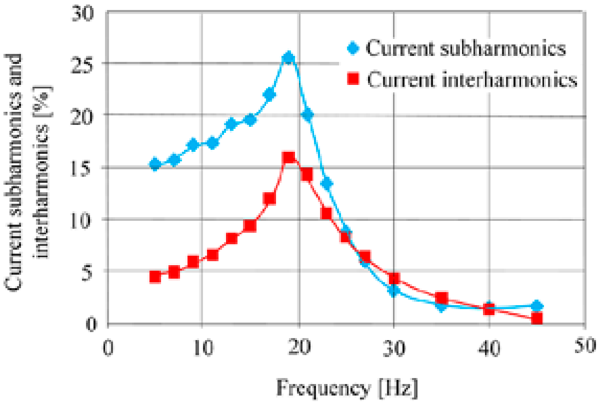

Figure 5. Current subharmonics and interharmonics versus the frequency of voltage subharmonics for *Case A*. The frequency components are related to the rated current

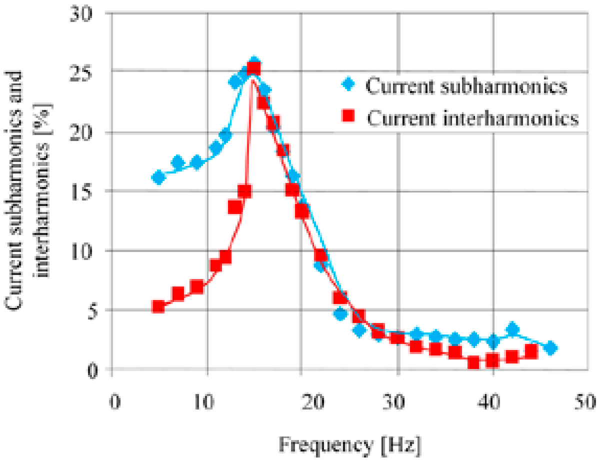

Figure 6. Current subharmonics and interharmonics versus the frequency of voltage subharmonics for *Case B*. The frequency components are related to the rated current

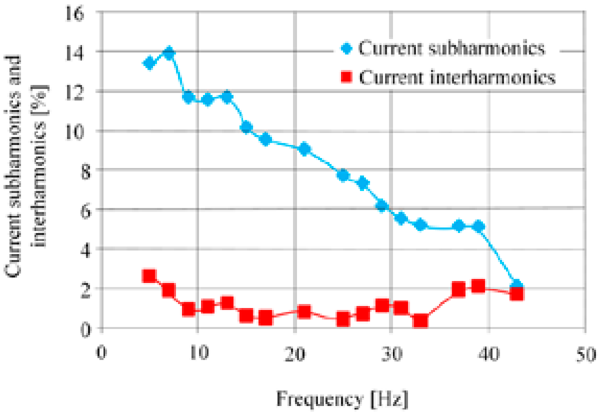

Figure 7. Current subharmonics and interharmonics versus the frequency of voltage subharmonics for Case C. The frequency components are related to the rated current

the corresponding current subharmonics and interharmonics were as high as 14% of the rated current (Figure 7). For *Case B* (Figure 3), the maximal vibration velocity was 1.74 mm/s for f_{sh} = 15 Hz. In practice, this vibration velocity approx. corresponded to the maximal acceptable vibration level (1.8 mm/s) for long-term operation of low power electric motors (ISO Standard 10816-1:1995; ISO Standard 20816-1:2016). Consequently, in the case of vibration, the sensitivity threshold of the investigated motor to voltage subharmonics was approx. 0.5%. For *Case B*, the same frequency f_{sh} = 15 Hz corresponded to the maximum vibration velocity (Figure 3) as well as to the maximum of current subharmonics and interharmonics (up to c. 25% of the rated current, Figure 6).

For *Case B*, the vibration shows a non-linear behavior. As mentioned above, (Gnaciński, Muc & Pepliński, 2021) provide results for the same motor and subharmonics equal to 1% of the fundamental voltage component. For subharmonics of this value, the vibration velocity peaks for the frequency f_{sh} = 11 Hz reached a velocity of 5.07 mm/s (Gnaciński, Muc & Pepliński, 2021). In order to illustrate the non-linear behavior, the measured vibration velocity versus subharmonic values is presented in Figures 8 and 9 for f_{sh} = 15 Hz and f_{sh} = 11 Hz. For f_{sh} = 15 Hz (Figure 8) and voltage subharmonics of values less than 0.6%, the vibration velocity was approx. 1.76 mm/s. For subharmonics of value c. 0.6–0.7%, the vibration velocity increased rapidly to approx. 3.0–3.5 mm/s. Furthermore, for f_{sh} = 11 Hz (Figure 9) and voltage subharmonics less than c. 0.8%, the vibration velocity was below 0.68 mm/s and then increased to above 5 mm/s. According to the standards (ISO Standard 10816-1:1995; ISO Standard 20816-1:2016), when the vibration of velocity exceeds 4.5 mm/s, it is “normally considered to be of sufficient severity to cause damage to the machine” in the case of low power electric motors.

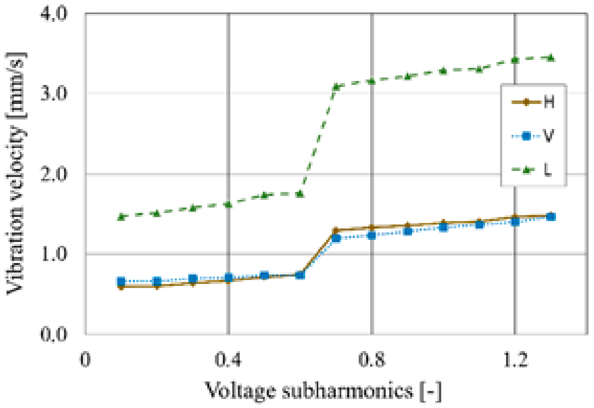

Figure 8. Measured broad-band vibration velocity for *Case B* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the value of voltage subharmonics for f_{sh} = 15 Hz

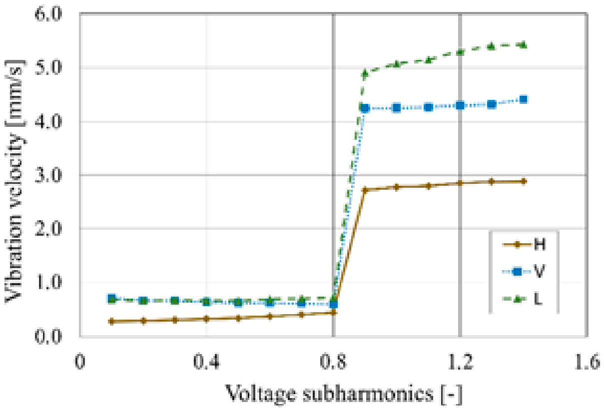

Figure 9. Measured broad-band vibration velocity for *Case B* in the horizontal (H), vertical (V) and longitudinal (L) directions versus the value of voltage subharmonics for f_{sh} = 11 Hz

Aside from permanent magnets, LSPMSM contained a rotor cage, which allowed the current subharmonics and interharmonics to flow. Their interaction with the synchronously rotating magnetic field caused torque pulsations and consequently – vibration, similarly to the induction motor. Notably, the vibration caused directly by the torque pulsations, was only one (but dominant) component of the measured vibration velocity. Furthermore, the shape of the characteristics presented in Figures 8 and 9 could result from non-linear properties of the coupling. An in-depth explanation of the observed phenomena will be the subject of future investigations.

In summary, for the investigated motor voltage subharmonics of values up to approx. 0.5% was considered acceptable for long-term operation. In contrast, vibration due to subharmonics of values exceeding approx. 0.8% could lead to machine damage.

Conclusions

Voltage subharmonics in the investigated motor caused significant vibration of non-linear character. For subharmonic value of up to approx. 0.5%, its level was considered acceptable for long-term operation, while for subharmonics greater than approx. 0.8%, the vibration severity was sufficient to cause machine damage.

In order to set permissible levels of voltage subharmonics for inclusion in power quality standards, sensitivity thresholds of various electrical equipment should be determined. In terms of vibration, the sensitivity threshold was approx. 0.5% for the motor under research. For comparison, in an exemplary 3 kW cage induction motor, the sensitivity threshold was c. 0.4% in respect to overheating (Gnaciński et al., 2019a). For another exemplary 3 kW cage induction motor, the sensitivity threshold was approx. 0.2% regarding vibration (Gnaciński et al., 2019b). It should be stressed that the above results should not be generalized. Determination of the permissible levels of voltage subharmonics requires further investigations, including their effect on LSPMSMs and induction motors of various rated powers and rotational speeds, made by various manufacturers.

Our presented results could be useful in the context of examining the potential limits for subgroups of subharmonics and interharmonics, which includes the recent standard (IEEE Standard 519-2022 Standard for harmonic control in electric power systems). Some recommendations concerning this standard will be presented in future works.

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Cite as: Gnaciński P., Muc A., Pepliński. M (2023) Line start permanent magnet synchronous motor supplied with voltage containing subharmonics. *Scientific Journals of the Maritime University of Szczecin, Zeszyty Naukowe Akademii Morskiej w Szczecinie* 74 (146), 28–34.