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SINEWAVE FILTERS AS AN EFFECTIVE PROTECTION OF HIGH-SPEED MOTOR IN HIGH FREQUENCY DRIVES

Abstract: Drive systems with increased frequency are a group of devices that has made a significant presence in the Oil & Gas industry in recent years. Increased frequency of the converter output voltage allows speed changes in a wider range. This increases the efficiency and versatility of the entire drive, but at the same time causes additional stresses for the insulation of the power cables, the step-up transformer and the motor itself. Therefore, an indispensable element of such a system is a sinusoidal filter, which ensures protection and reliability of the entire drive. The article presents an analysis of the selection of components of a sinusoidal LC filter and its parameters in a relation to the increased operating frequency and switching frequency. The results of the research on the influence of these parameters on the filter operation, output voltage and the THDu coefficient have been presented.

Keywords: *sinewave filters, high frequency drives, high-speed motor*

1. Introduction

Modern oil production systems (ESP - Electrical Submersible Pumping System) are required to use high-efficiency machinery and equipment and to control the speed over a wide range. They are usually equipped with PMMs (Permanent Magnet Motors). Unlike standard induction motors, PMM motors use rare earth magnets to create a permanent rotor magnetic field, which directly translates into higher performance and energy efficiency, as well as higher power density and smaller dimensions [1]. These motors are extremely efficient when operating at typical and higher speeds of 500 - 10000 rpm which is applicable in low viscosity and high fluid flow beds, as well as at lower speeds of 100 - 500 rpm in beds with high viscosity and low flow fluids.

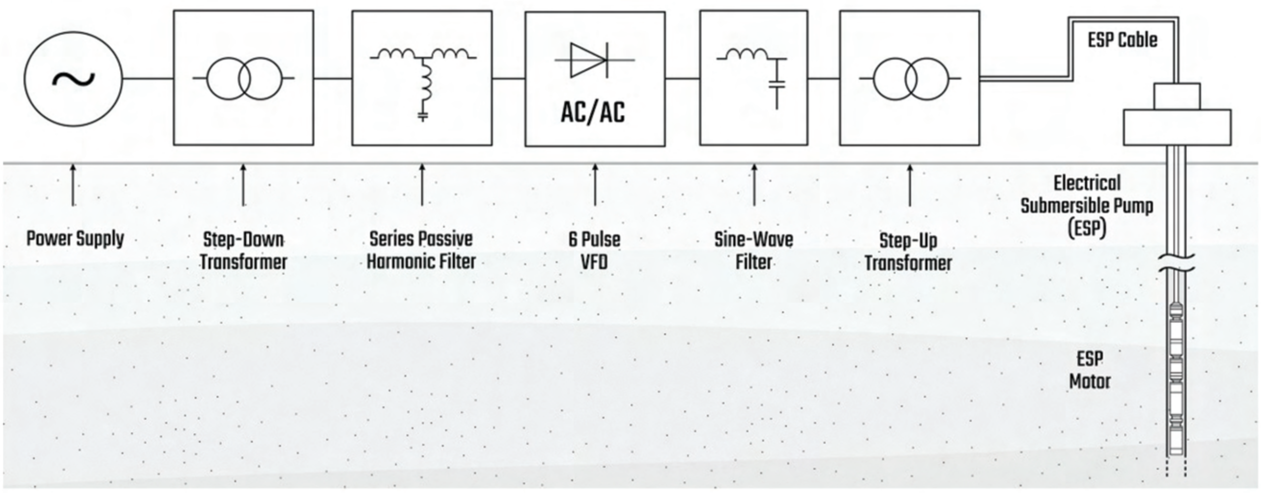

Fig. 1. Block diagram of the oil production systems (ESP) power supply system[2].

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The need for such extensive speed control of deep-sea motors and pumps is met by Variable Frequency Drive (VFD) converters. By regulating and controlling torque, VFD converters protect pumps and motors by reducing mechanical and current stresses during start-up and adapt the operation of the entire drive to dynamically changing load conditions. However, such an arrangement also has its drawbacks. The distorted output voltage of the converter (PWM - Pulse Width Modulation) poses an additional risk to the insulation of the supply cables, the step-up transformer and the motor itself (Fig.1). PMM motors are susceptible to switching frequency harmonics, which cause additional unwanted magnetic flux hysteresis and eddy currents, increasing losses and motor temperature. In addition, PMM motor rotors are sensitive to high temperatures. Elevated thermal conditions pose the risk of a decrease in torque and motor power and, in extreme cases, even permanent demagnetisation of the rotor. Therefore, sine-wave filters adapted for increased frequency are used to eliminate switching harmonics (PWM).

2. Power supply, starting and control of high-speed PMM motors

A motor's power is directly proportional to its speed, so it is not surprising that industries for which machine performance and dimensions are critical are keen to use high-speed PMM motors. These motors are usually started and controlled by VFDs (PMM motors do not have the option of direct mains starting), and high-speed operation requires a regulated output voltage with an increased base frequency (200 - 400 Hz). The increased base frequency forces the use of increased inverter switching frequencies to maintain frequency modulation *mf* at an acceptable level:

$$mf = f_{switching} / f_{base} \qquad (1)$$

The higher the switching frequency relative to the base frequency, the higher the modulation factor and the lower the THDu of the output voltage, making it easier to filter out the higher harmonics resulting from the switching frequency from the waveform.

For example, a 50 Hz waveform generated with a switching frequency of 2 kHz has a modulation factor of 40. However, when the base frequency is increased to 200 Hz, the modulation factor drops to 10 and the THDu factor increases significantly. Increasing the switching frequency to 5 kHz (at 200 Hz) increases the modulation factor to 25 and improves THDu (Fig. 2a,b,c). In actual power systems with increased base frequency, the mf factor of at least 20 is sought. Such a value is the minimum necessary to ensure adequate accuracy and ease of motor control. At lower *mf* values (Fig. 2b), the THDu of the output voltage is high and low-order harmonics are difficult to filter out. An additional difficulty in powering and controlling this type of system is the often long distances between the converter and the motor, reaching up to 2-3 km in some applications. Long power cables cause voltage drops, which are partially compensated by changing the voltage ratio of the step-up transformer equipped with regulating taps [3] or, to some extent, by over-modulating the output voltage of the VFD. Overmodulation allows the rms value of the voltage to rise above the rated voltage [4]. On the one hand, this function is very useful as it allows compensating for voltage (power) drop and, in some cases, can accelerate the dynamics of the power system's response to the set operating conditions. However, on the other hand, overmodulation has a detrimental effect on the harmonic content of the VFD voltage output waveform and thus the current harmonics, leading to increased motor torque ripple. This is due to an increase in the duration (width) of the middle pulse, resulting in the appearance of low-order harmonics in the output waveform, i.e. 5h, 7h, etc., which increases the THDu voltage distortion factor (Fig. 2d).

3. Selection of filter parameters for increased frequency operation

Sinusoidal filters designed for higher frequencies (200 - 400 Hz) serve essentially the same purpose as their mains frequency counterparts. They remove the higher harmonics associated with the switching frequency, producing a near-sinusoidal voltage and current waveform. The difference arises in the choice of LC parameters, resonant frequency and switching frequency, and choke design. The choice of inductance L is crucial, as any additional impedance causes an additional voltage drop and reduces the current flowing

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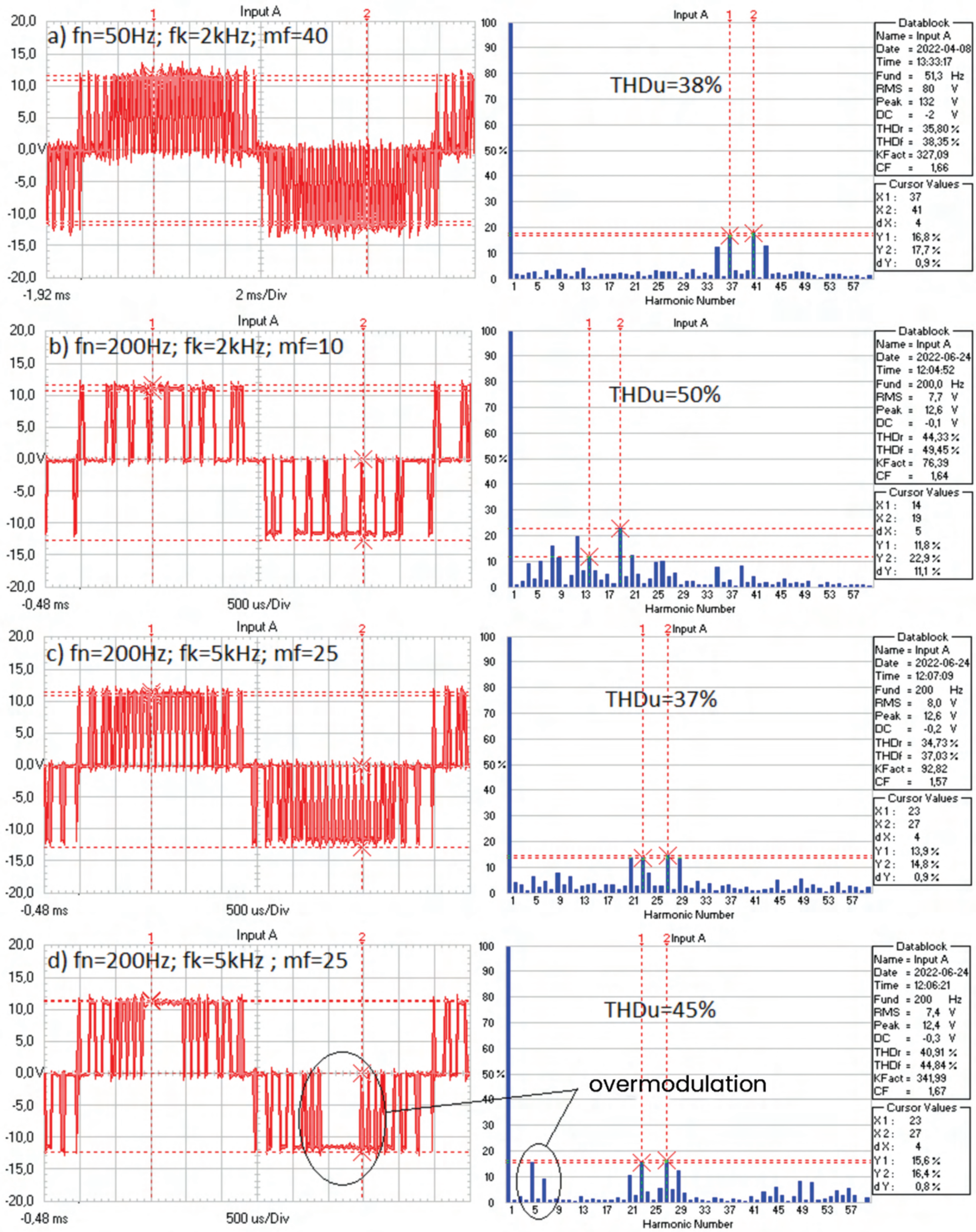

Fig. 2. Output voltage oscillograms and harmonic distribution with different operating and switching frequencies [2].

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flowing in the circuit, thus reducing the power supplied by the motor. Note that the voltage drop is proportional to the reactance of the choke and therefore to the frequency:

$$u_X[\%] = \frac{I_N X_L \sqrt{3}}{U_N} 100\% \qquad (2)$$

where:

$$X_L = \omega L = 2\pi f L \qquad (3)$$

Standard sinusoidal filters used at mains frequency have a reactance in the range of 6% to 12%, depending on the switching frequency used. If a standard filter were used in an increased frequency system, for example: 300 Hz, the reactance would increase by a factor of six. Would imply a reactance of between 36% and 72%, in which case the filter loses its functionality completely due to the enormous voltage drop. The same is true for the capacitive part of the filter. The capacitive current drawn by the capacitor in a 300 Hz system will be six times greater than in a 50 Hz system, as it is also proportional to frequency:

$$I_C = \frac{U_C}{X_C} = U_C \omega C = U_C 2\pi f C \qquad (4)$$

Limiting capacitive current is very important, as it causes additional load on the converter. As can be seen, standard mains frequency sinusoidal filters are not suitable for direct use in increased frequency systems. Suitable inductance and capacitance form a low-pass sinusoidal filter with a resonant frequency:

$$f_R = \frac{1}{2\pi\sqrt{LC}} \qquad (5)$$

The value of the resonant frequency should be appropriately chosen in relation to the operating frequency f_N and switching frequency f_K, separating the passband from the damping band and shaping the filter damping coefficient accordingly (Fig. 3). The higher the LC product, the lower the resonance frequency of the filter, which in turn translates into a higher damping factor for a given switching frequency.

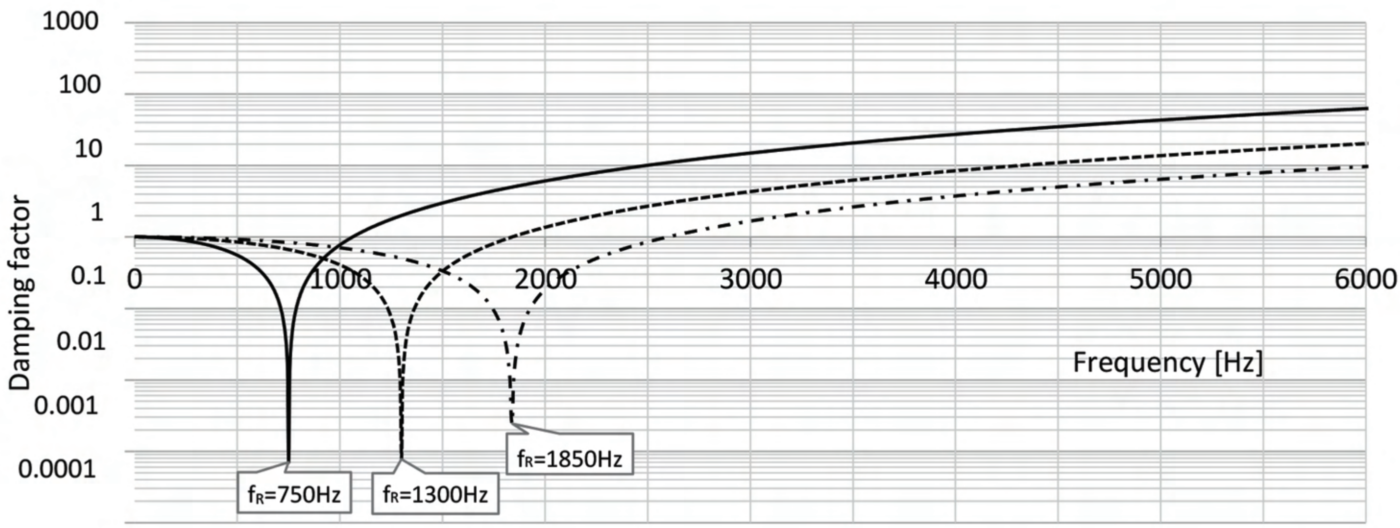

Fig. 3. Examples of LC filter frequency characteristics for different resonant frequencies [2].

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4. Switching frequency selection – why increase it?

The selection of switching frequencies in increased frequency systems is quite a complex issue. As shown earlier, increasing the switching frequency improves the coefficients *mf* and THDu of the output voltage. However, this also has its negative consequences in terms of additional thermal losses in the converter, which is why converter manufacturers are reluctant to increase it. Nevertheless, if sinusoidal filters are required at the converter output, we gain further arguments for increasing this switching frequency.

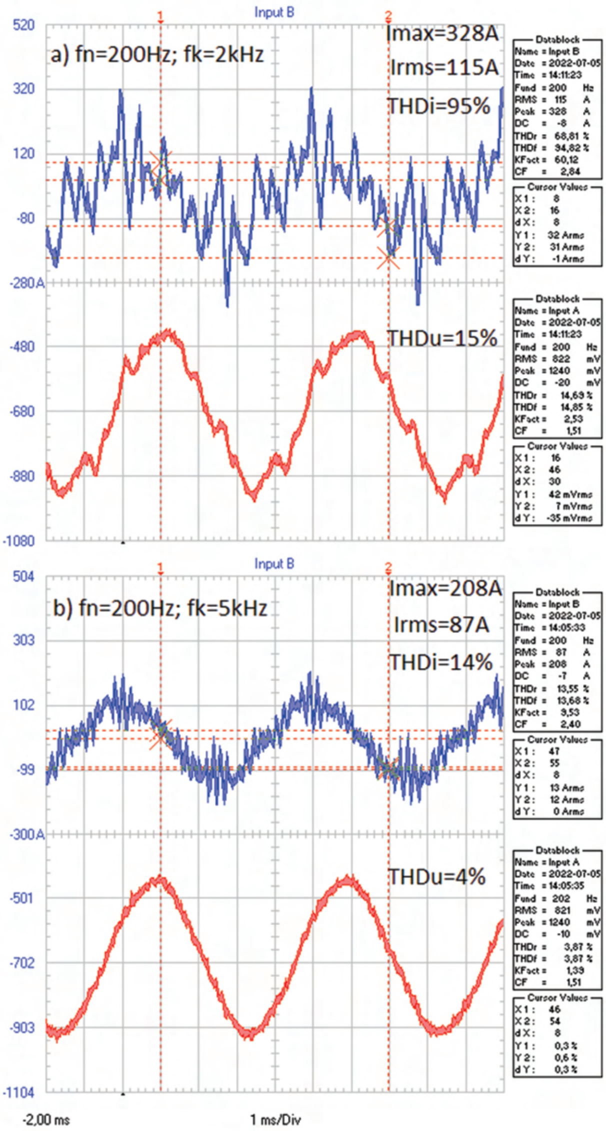

Fig. 4. Oscillograms of capacitive current and output voltage of EF3LC-415A 400V 200Hz filter for different frequencies [2].

One reason is the rms value of the capacitive current (4). The value of this current depends not only on the base frequency, but also on the switching frequency (Fig. 4). The higher the switching frequency, the lower the harmonic amplitudes and the lower the rms and maximum value of the capacitive current. Smaller harmonic current amplitudes have a significant impact on reducing the size of the filter choke and improving its operating conditions (lower losses and noise). A lower filter capacitive current value also means a lower load on the converter, so this is balanced to some extent by the increased additional losses of the converter from the switching frequency. Another reason for increasing the switching frequency is the THDu output voltage distortion factor. Here the issue is obvious, it is easier and cheaper to filter out a waveform that is initially less distorted. We can compare the output voltage waveform of the converter without filter and after applying the filter for switching frequencies of 2 kHz and 5 kHz (Fig. 2b and 2c and Fig. 4a and 4b). At a switching frequency of 2 kHz, the filter improves the THDu factor by approximately three times from a value of 50% to 15%. By contrast, the same filter at a switching frequency of 5 kHz reduces THDu from 37% to less than 4% (i.e. more than 9 times). The effect of switching frequency on the capacitive current and on the distortion of the filter output voltage is also shown in Table 1. These results clearly indicate that the higher switching frequency also leaves a lot of room to optimise the filter in terms of using less inductance and/or less capacitance, thus reducing the voltage drop and capacitive current. As can be seen from the above analysis and measurements, the use of a sinusoidal filter in an increased frequency system can reduce the THDu output voltage distortion of the converter to even less than 5%. These conditions are close to mains power, which is a great relief for both the step-up transformer and the power cable, and especially for the PMM motor. A sinusoidal filter smooths the output voltage sine wave at the expense of the distorted capacitive current. The capacitive current adds up to the actual load current of the filter, so the filter takes on the additional switching frequency losses that would occur in the transformer, cable and motor.

Table 1. Measurements of capacitive current and output voltage distortion of EF3LC-415A 400V 200Hz filter as a function of switching frequency [2].

f_N	f_K	Capacitive current			THDu
		I_{CRMS}	I_{CMAX}	THD_{IC}	
Hz	kHz	A	A	%	%
200	2	115	328	95	14.9
200	3	101	272	59	8.7
200	4	93	232	38	7.6
200	5	87	208	24	3.9
200	6	83	198	14	3.2

The effect of current distortion on the operation and design of the filter's magnetic elements is enormous. The additional losses due to parasitic phenomena in them necessitate the use of multi-gap core designs and limit the level of induction in the core. This reduces the eddy current losses in the core and windings created by the flux associated with the gaps, known as Fringing Flux [5]. By using a higher switching frequency, we reduce the current distortion and therefore have the effect of reducing losses and filter size. Therefore, the choice of switching frequency in this type of system is a compromise between the cost and ability to limit the additional losses in the converter resulting from the increased switching frequency, and the cost and effects of the passive filtering that is necessary when powering PMM motors.

5. Summary

The effects of installing sinusoidal filters in increased-frequency systems with high-speed, high-power PMM motors are more pronounced than for traditional mains-frequency induction motors. It should be remembered that in such systems, a sinusoidal filter is an improvement in operating conditions and increases the reliability not only of the motor itself, but also of the other components of the drive system, i.e. the step-up transformer or power cable. The filter eliminates the two biggest risks that affect the reliability and life of the entire drive system, i.e. voltage distortion, completely eliminating the steep voltage rise that is a direct threat to insulation, and reducing additional thermal losses resulting from both the flow of distorted magnetic flux in the core and distorted current in the operating windings. In turn, the switching frequency is important for the selection of passive filtering and other components in increased-frequency systems. The choice of switching frequency should take particular account of the effect on the performance of the passive components, the capacitive filter current and the efficiency and performance of the overall system.

6. References

[1]. J. F. Gieras „Permanent magnet motor technology: design and application" 3rd ed., Boca Raton, Floriza: CRC Press, 2010.

[2]. ELHAND Transformatory Sp. z o.o. - In-house materials and studies, Lubliniec, 2022.

[3]. T. Orlowski & L. Jasinski „Application of New Generation Transformer Harmonic Filter Hybrid Solution To Reduce Footprint and Operating Cost at the well site" ADIPEC - Abu Dhabi International Petroleum Exhibition & Conference, November 2019.

[4]. X. Guo, M. He, and Y. Yang, "Over modulation strategy of power converters: A review," IEEE Access, 2018.

[5]. J. Czornik, M. Haltof „Influence of harmonic filters on the improvement of electricity performance at the point of connection" Electrotechnical Review, No. 3, 2020.

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