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Reduction of THD by switching frequency optimization in three-level NPC inverter

Abstract. *This paper aims to describe the effect of switching frequency selection for three-level NPC inverter and its impact on the quality of output waveforms for different cable lengths connecting the inverter with motor. Authors propose an optimal switching frequency selection as an option to overall limitation of THD. Traditional and the most popular techniques to limit the THD have been reviewed in order to compare with the proposed method. Simulation verification shows that harmonic spectrum generated by the inverter with the switching frequency selected at the minimum equivalent impedance of the network cable resulting in decrease of total level of harmonics contents.*

Streszczenie. *W artykule została przedstawiona analiza wyboru częstotliwości przełączania trójpoziomowego falownika napięcia, oraz jej wpływu na jakość przebiegów wyjściowych dla różnych długości kabli. Autorzy proponują wybór częstotliwości przełączania, jako jedną z opcji ograniczenia współczynnika THD. W artykule przedstawiono tradycyjne i najbardziej popularne techniki ograniczenia współczynnika THD w celu ich porównania z proponowaną metodą. Wyniki symulacyjne wykazały, że ilość harmonicznych generowanych przez falownik jest mniejsza, jeśli falownik pracuje przy częstotliwości, dla której impedancja zastępcza kabla jest najmniejsza. (**Redukcja współczynnika THD przez optymalizację częstotliwości przełączania trójpoziomowego falownika NPC**)*

Keywords: NPC inverter, cable connection, voltage reflections, LC filter.
Słowa kluczowe: trójpoziomowy falownik napięcia, połączenie kablowe, odbicia fali elektromagnetycznej, filtr LC.

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Introduction

Application of multilevel inverters leads to many advantages like e.g. limited steepness of the voltage applied (*dv/dt*), which substantially reduces the total harmonic distortions of the output waveforms. Advanced control schemes such as direct torque control (DTC) allows process optimization and increase of an efficiency of an electrical energy conversion. Also, classical *V/f* based control for such converters is useful and suitable for many applications [1, 2].

Nevertheless such multilevel inverters generate also some crucial problems, which essentially reduce motor lifetime. They might cause a premature failure of winding insulation, a bearing failure, higher electromagnetic interference levels (EMI) and wave reflections in the case of long cable connection between a drive and motor.

It is thus worth to investigate the long cable connections cases as they starts to play significant role, especially in the oil and gas industry. In such cases the high reliability is expected from the drive system as it operates in harsh environment, and the replacement of a faulty component might be extremely costly or impossible.

The traveling wave phenomena occurs in the case of a surge impedances mismatch [3, 4]. Additionally the PWM based control results in generation of higher harmonic content. These phenomenon are responsible for insulation degradation, partial discharges and additional heat losses in a power cable [5, 6].

In this paper the interaction between the drive switching frequency and a power cable length is investigated. The goal is to find the influence of those factors on the total harmonic distortion THD level at the output of the inverter filter. A three-level neutral point clamped inverter (3L-NPC) topology case study is presented with different cable lengths.

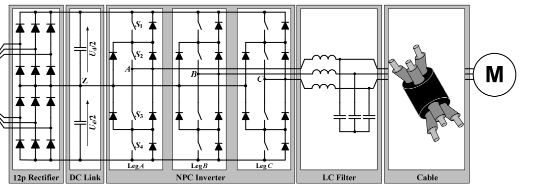

Fig.1. Three-level NPC inverter feeding the induction motor drive via the cable connection

The considered system consists of the drive unit, an optimal LC filter selected according to [9], a long cable connection and the induction motor as presented in Fig. 1.

3L-NPC inverters are widely used in many high power MV applications. A comprehensive circuit analysis of such converters can be found in [7, 8]. To limit overall harmonic content and *dv/dt* the output of the inverter is connected to the LC filter. This allows to mitigate overall effects caused by the converter *dv/dt*.

The filter design is a complex task as the several technical requirements must be met. The filter resonance frequency must be higher than the fundamental frequency and lower than the lowest bandwidth of the switching frequency. One need to select the filter topology, inductances and capacitances of the filter to limit filter while the overall goal is to minimize the filter weight taking into account the physical limitation of each component [9].

In the case where a long cable between drive and motor is present, also the design of the cable has a significant influence on the harmonic levels in voltage and current waveforms as demonstrated in [12]. Special performance is required for cables working under extreme environmental conditions. These conditions determine the complicated, multilayered structure, consisting of many different parts: conductor, insulation, shield and heavy armor which results in a number of nonlinear effects.

Another possibility to reduce weight and size of a filter components is to increase the switching frequency of the drive. Although this increases the value of the switching losses in semiconductors, it is still cost effective and commonly practiced [10, 11].

Since the lower switching frequency became a requirement for high power application, in order to reduce the losses an alternative methods should be investigated.

The power losses should be kept at the possible low level in order to improve efficiency. The use of semiconductors operated on lower voltage reduce the switching losses and therefore the switching frequencies can be increased. Lower voltage of switches is a natural consequence of the inverter topology used, specifically on the number of voltage levels generated by the inverter. The main remark is that the size of the filter can be effectively reduced by increasing the switching frequency due to the fact that the harmonics shift to higher frequencies, as well as torque and flux ripple are minimized.

The magnitude of the losses is closely associated with the presence of the harmonics. This is important for the determination of the size and type of power cables. The focus is on the quality of delivery of electrical energy [16] especially when power electronic systems are used. The amount of the losses is related to RMS value of current [17] by means of the following equation (DC component included):

$$I_{RMS} = \sqrt{I_{DC}^2 + \sum_{h=1}^{39} I_h^2} \tag{1}$$

Current distortion can be represented as a high content of higher harmonics. Due to skin effect in the conducting material [18] the resistance for a particular harmonic increases together with harmonic order. This resistance should be taken into account during losses estimation using Joule law [5].

Essentially information addressing the most popular techniques of the *dv/dt* mitigation of the inverter are discussed in the next paragraph. Their potential advantages applied to the selected application are described.

Studies of switching frequency impact on the quality of the output inverter waveforms was performed. The goal was to examine different cable lengths in order to obtain the optimal value of the switching frequency. The effectiveness of the proposed method has been verified by the numerical calculation in MATLAB & Simulink.

Overview of *dv/dt* compensation methods

High steepness of the applied voltage (*dv/dt*) produced in modern inverters is the source of numerous negative effects in the drive units. It is related to the high switching frequencies of power electronics devices. Mitigation techniques of some adverse aspects have been extensively discussed in literature [10, 11, 13, 14]. The most solutions which are most often used are as follow:

1. LC filters (*dv/dt* or sinusoidal) – conventionally installed to attenuate the high transient overvoltage. These transients are associated with the reflection phenomena on the motor terminals and absorption of low order harmonics [10, 11]. This is often the case when the inverter is used during retrofit of existing fixes speed motor. Alternative solution is to install the electric motors, with insulation designed to withstand such stresses. It is often the case the nominal voltage of the insulation is doubled. One need to keep in mind that AC motors efficiency is greater if the shape of the stator voltage is as close as possible to the pure sinusoidal [6].
2. Common mode (CM) chokes – are made of three symmetrical coils, with a common toroid core. When the directions of generated fluxes are the same, then the fluxes sum up, thereby choke has significant inductance for the path of the common mode currents [13]. In some cases a high *dv/dt* is responsible for generation of a current which flow via parasitic capacitances to the ground. On the other hand, differential mode currents flows through the coil and generate the opposite flux. In such cases the cumulative inductance is negligible.
3. Common mode transformer – such solution differs slightly from the previous one by means of an additional winding [13]. A dumping resistor is connected to this extra winding. Compared to CM chokes this allows to reduce the overall dimension of such solution.
4. PWM modifications – CM current is decreased or eliminated by change of the PWM control algorithm. Reconstruction of the inverter or addition of extra devices are not required. CM voltage generated by the inverter is reduced by elimination of zero voltage vectors, or the use of active voltage vectors with same value of zero sequence voltage [13]. Such solution will decrease the maximum allowable phase voltages and increase their harmonic content [14].
5. Active Compensation System of CM Voltage – this is the most advanced and sophisticated method, realized by the addition of the common mode voltage of the opposite polarity to each phase by the common mode transformer. The opposite polarity of voltages is obtained by the use of series active power filter [13, 14].

The main emphasis of this section is to overview the most common techniques for mitigation of negative effects of *dv/dt*. The discussed methods present various hardware or software means to solve presented *dv/dt* problem.

In this paper authors utilize aspect associated with nonlinearly effects which occur when a long cable connection is used between the inverter and the motor. The proposed method is to select an optimal switching frequency of the drive converter taking into account the traveling wave phenomena caused by the long cable connection.

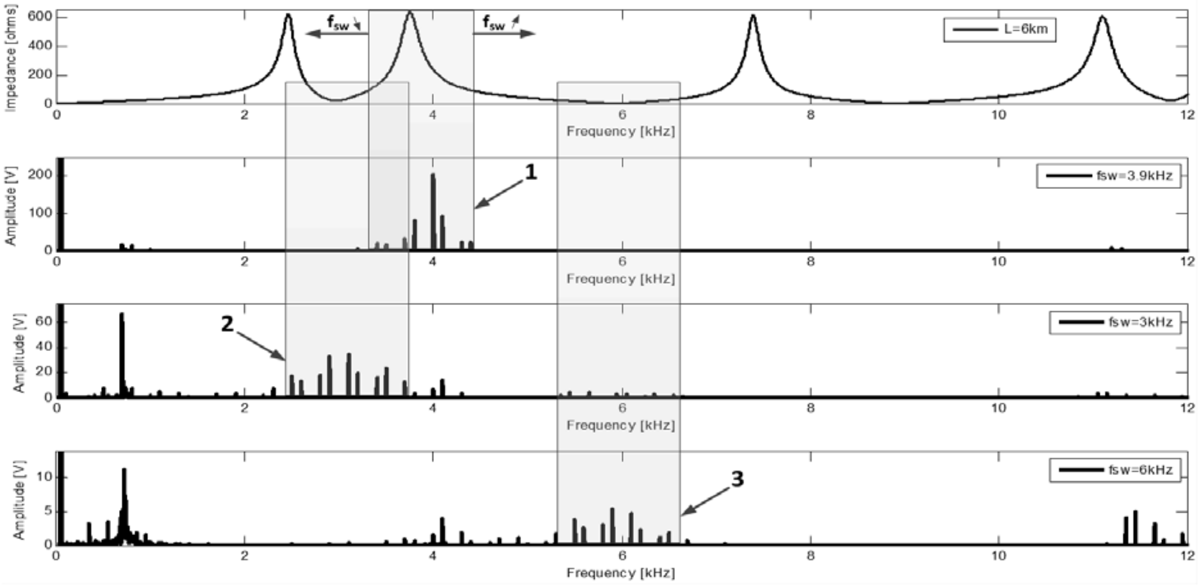

Fig.2. Network impedance for 6 km cable length and harmonics spectrums for three cases: (1) - rated f_{sw}, (2) - lower f_{sw}, (3) - higher f_{sw}

Proposed method and analyses results

A. Impact of switching frequency on voltage THD for different cable lengths

When long power cable is installed between drive and motor it is most likely that the cable resonance frequency might be in the same interval as harmonics caused by the inverter. It is required to make sure that both of these harmonic spectrums have no mutual interactions [15]. A natural cable resonance frequency depends on electrical parameters of the cable and its length. Because of traveling wave phenomenon, several impedance peaks can be observed. The expected results are that for longer cables the first resonance frequency would be lower.

Studies were carried out utilizing Matlab & Simulink model as described and analyzed in [9]. This model was used to evaluate the effects of switching frequency changes on harmonics content in the cable.

The cable connection between inverter and motor was modeled using a distributed parameters line with non-linear impedance characteristics. Additional detailed system parameters are provided in Appendix. Utilized model of distributed parameter line does not take into account phenomena associated with frequency dependent effects of conducting materials. The presented model appropriately represents traveling wave phenomena in the case of high sampling ratio of the simulation. This allows for appropriate analyses of the reflections caused by the traveling wave phenomena in the modeled cable.

A voltage THD coefficient was used as a benchmark to evaluate harmonic contents of waveforms on motor terminals. It is an important factor which influences power losses in devices such as transformers, cables, induction motors etc.

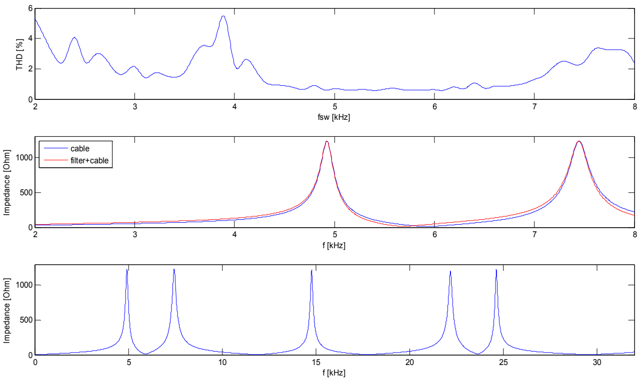

Fig.3. THD dependence on switching frequency and impedance curves for various cable lengths l = 3 km,

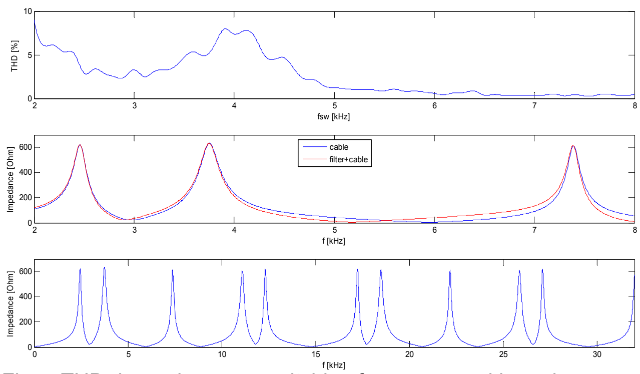

Fig.4. THD dependence on switching frequency and impedance curves for various cable lengths l = 6 km,

In order to investigate the harmonics behavior an example of the network impedance versus frequency is presented in Fig. 2 for 6 km cable length. Furthermore, three harmonic spectrums are also depicted in Fig. 3 to Fig. 5 to illustrate the effect of switching frequency changes for different cable lengths. Switching frequency in the range from 2 kHz to 8 kHz was investigated. The network impedance was plotted in considerable larger range due to the fact, that the integer multiples of f_{sw} may occur in other maximum of network impedance.

One can notice that filter arrangement influences the network impedance resonance frequency, as it is shown especially in Fig. 5. Therefore, if an optimum switching frequency needs to be found, a cumulative equivalent impedance of filters and cables should be investigated.

As expected, the harmonics are clustered close to the switching frequency f_{sw} and are the switching frequency integer multiples, such as $2{\cdot}f_{sw}$, $3{\cdot}f_{sw}$, etc. (see Fig. 2). The high-order harmonic components are easily suppressed by the filter or the load inductance. The frequencies which should be considered are presented in Fig. 2. Case 1 shows the basic harmonic spectrum of phase-to-phase voltage (f_{sw} = 3.9 kHz) which is observed in the maximum of the network impedance. Case 2 (f_{sw} = 3 kHz) and Case 3 (f_{sw} = 6 kHz) illustrate conditions where f_{sw} was decreased and increased respectively. Thereby, the harmonics appear as sidebands around f_{sw} and its integer multiples can be shifted to the minimum of the network impedance. This leads to a significant reduction of THD, as presented in simulation results.

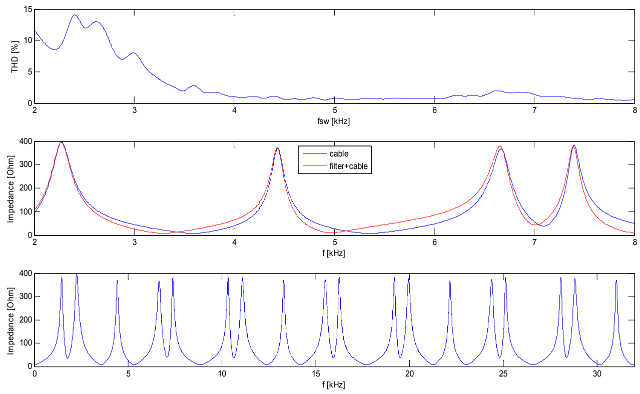

Fig.5. THD dependence on switching frequency and impedance curves for various cable lengths l = 10 km

B. Impact of switching frequency on voltage THD for different cable structure

In Fig. 3 to Fig. 5 one can examine the THD dependency on f_{sw}, for different network impedance. The network impedance was collected in the examined circuit for the three different cases, as specified above. The purpose of this evaluation was to understand how cables structure and its length influences the harmonic content.

Increase of voltage harmonic distortion occurred when f_{sw} was close to the one of the maximums of the network equivalent impedance. If the converter power losses are of concern, a selection of the switching frequency is to select the smallest, available value of f_{sw}, at one of the equivalent impedances minimum. By such selection an output inverter waveforms quality might be enhanced.

Conclusions

In this paper the method was presented on investigate the switching frequency impact on THD level in 3L-NPC inverters. The analyses results present typical phenomena which occur in the examined circuit as presented in Fig. 1.

The proposed method allows to minimize THD by appropriate selection of the switching frequency as presented in Fig. 3 to Fig. 5. The method was analyzed for application of different cable length and cable structure, as connecting inverter with the motor. It has been shown that even small change of f_{sw} leads to significant reduction of the THD coefficient.

The results suggest that appropriate selection of switching frequency of the inverter associated with the appropriately selected cable length may decrease the harmonic content of the voltage and current waveforms in the cable. Thereby, the phenomena associated with the long cable connection can be naturally utilized for effective reduction of undesirable harmonic level.

In practice, user may not have any information addressing the wave characteristic of the power cable. Experimental verification might be thus required to assess the best correlation between switching frequency and the cable impedance characteristics.

All switching frequencies f_{sw} considered in the paper were higher than the first maximum of the network impedance – thus the resonance frequency of the filter can be placed respectively higher.

One can notice that for certain values of f_{sw} and cable lengths, the fluctuations of THD are negligible – the value of this coefficient is significantly below the level determined in [19]. For such case, the parameters of the filter can be substantially reduced. Therefore, the proposed method allows for either filter dimension reduction or reduction of THD.

Appendix

Table 1. Ratings and parameters of the induction machine [20]

P_N	kW	100
U_N	kV	3
f_N	Hz	50
ω_N	rpm	3000 (2963)
Poles	-	2
J	kg·m^2	2.7
T_N	Nm	322

Table 2. Ratings and parameters of the cable [21]

Cross section	mm^2	70
U_N	kV	10
C_L	μF/km	0.31
L_L	mH/km	0.41

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