Effect of Loading of VSI-Fed Three-Phase Induction Motor on the Line Current THD

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Abstract— Three-phase inverters using PWM are widely used in industry for speed control of three-phase motors. However, these inverters may significantly reduce the quality of the ac supply to which these inverters are connected; such inverters draw non-sinusoidal current from the mains. This leads to the generation of high-order harmonic current content. Usually, these harmonics are reduced by using passive filters like dc chokes or line chokes or/and active filters, which should be carefully chosen. In this work, the effect of loading of VSI-fed three-phase induction motor on the line current total harmonic distortion (THD) is experimentally tested and analyzed; line current THD vs. line current fundamental harmonic curves for different inverters are developed. Recommendations about the use of filters with adjustable parameters for effective harmonics mitigation with mechanical load variations are given. The use of the recommended filters can significantly decrease the line current THD independent of the actual load on the driven motor, enhance the quality of the power system and increase the energy efficiency.

Keywords— Energy efficiency, harmonics mitigation, line current THD, PWM VSI.

I. INTRODUCTION

Modern variable speed drives are based on the use of pulse-width modulation voltage source inverters (PWM VSI) in conjunction with three-phase induction motors. These drives have several advantages: matching motor and load characteristics, energy saving, speed and position control, reduction of transients and stresses due to abrupt motion and ON/OFF operations, etc. VSI are also used in uninterruptable power supplies (UPS) and renewable power generation systems.

On the other hand, PWM VSIs are characterized by the absorption of non-sinusoidal current from the ac supply; they generate high-order current harmonics in the supply. This leads to the reduction of the quality of the electrical power system. Different methods to reduce the negative effect of VSI on the electrical power system quality were proposed in the recent decade; some of them are given in [1]-[5].

II. STATEMENT OF THE PROBLEM

Distortion of sinusoidal line current is the reason for sinusoidal voltage violation. The level of distortion is limited to the standard of quality of electric energy. In some countries, this standard places no restrictions on the level of current harmonics and restricts the distortion of sinusoidal voltage. In the countries of the European Union, a standard introduced by IEC (International Electro-technical Commission) limits the level of the distortion of the sinusoidal current which can be estimated by using an index called THD (Total Harmonic Distortion).

The level of the distortion of the line current from the standard sinusoidal form is determined by the following formula:

$$THDi_{\%} = \frac{\sqrt{\sum_{\nu=2}^{49} I_{\nu}^{2}}}{I_1} \cdot 100\,\% \tag{1}$$

where,

I_1- the RMS value of the line current of the first harmonic;

I_ν- the RMS value of the line current of the ν^{th} harmonic.

According to the IEEE 519 standard [6], the line current absorbed by variable speed drives should not have a THDi above 48%. Variable speed drives working in a continuous mode of operation are usually under-loaded. On the other hand, the load on VSDs operating in intermittent periodic modes with frequent starting, stopping and reverse is totally different from the load in the steady-state operation. According to the mode of operation of the drive, the actual load on the inverter may be far from the rated (nominal). The mitigation of current harmonics generated by the inverters used in variable speed drives was always of a big interest. More suggestions to eliminate the negative impact of the VSDs can be found in [7]-[9].

In the current article, the relationship between the line current THDi and the load on the inverter is experimentally tested and mathematically analyzed. The load on the inverter will be directly proportional to the RMS value of the first harmonic of the line current I_1. In the experiment, the load value will be replaced by the fundamental harmonic of the current in per unit as follows:

$$I_1(\text{pu})=I_1/I_1(\text{nom}) \tag{2}$$

where,

I_1(pu)- RMS value of the first harmonic of the current in per unit,

I_1(nom)- RMS value of the nominal current of the first harmonic.

In the catalogs of most inverters, manufacturers provide information about the level of current distortion, which is created by the inverter, and is usually given in THD for 5th, 7th,…, 49th harmonics.

III. EXPERIMENTAL SETUP AND RESULTS DISCUSSION

In order to identify the relationship between the load on the inverter and the level of current distortion, two inverters type Altivar 71, produced by Schneider Electric Co. were tested. The first inverter ratings are: 2.2kW, 380V, 4.4A. The second: 5.5kW, 380V, 9.83A. The first inverter drove a 3-phase squirrel cage induction motor of the following ratings: 2.8kW, 380V, 1370rpm, 50Hz, P.F.= 0.82, 82% efficient. The second inverter was respectively connected to a 3-phase squirrel cage induction motor of the following ratings: 5.5kW, 380V, 955rpm, 50Hz, P.F.=0.78, 83% efficient.

The line current of each inverter was saved through an interface card with an A/D converter that was connected to a PC. The load was changed from 25% to 100% of the full load. The schematic diagram of the experimental setup is shown in Fig. 1.

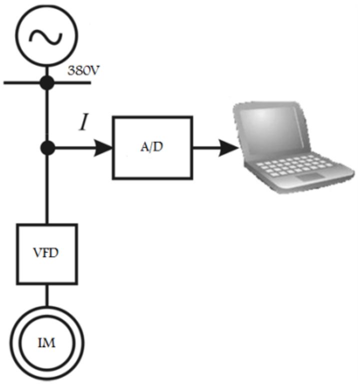


Fig. 1. Schematic diagram of the experimental setup

Fig. 2 shows the line current of the first VSD (2.2kW) when the inverter was 25% loaded (a), 50% loaded (b) and 100% loaded (c).

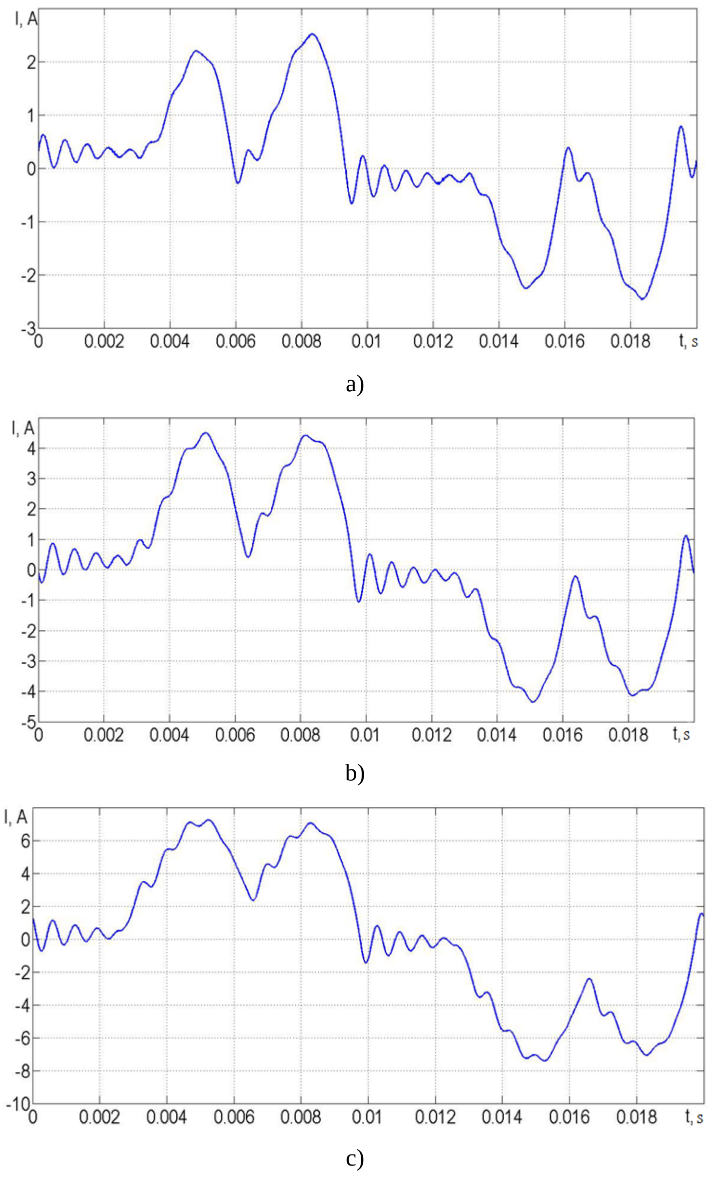


Fig. 2. The line current waveforms of inverter type Altivar 71 (2.2kW) when the inverter was a) 25% loaded, b) 50% loaded and c) 100% loaded

The line current waveforms shown in Fig. 2 were analyzed spectrally. The results of spectral analysis show that the major harmonics of the content are the 5th and 7th harmonics and the 11th harmonic is relatively less effective. Higher order harmonics (13, 17, etc.) are of relatively very low amplitude; thus, the analysis of the total harmonic distortion is limited to the 11th harmonic.
The results of spectral analysis are shown for the 5th, 7th, and 11th harmonics as a function of the load on the inverter in Fig. 3a, b, and c, respectively.

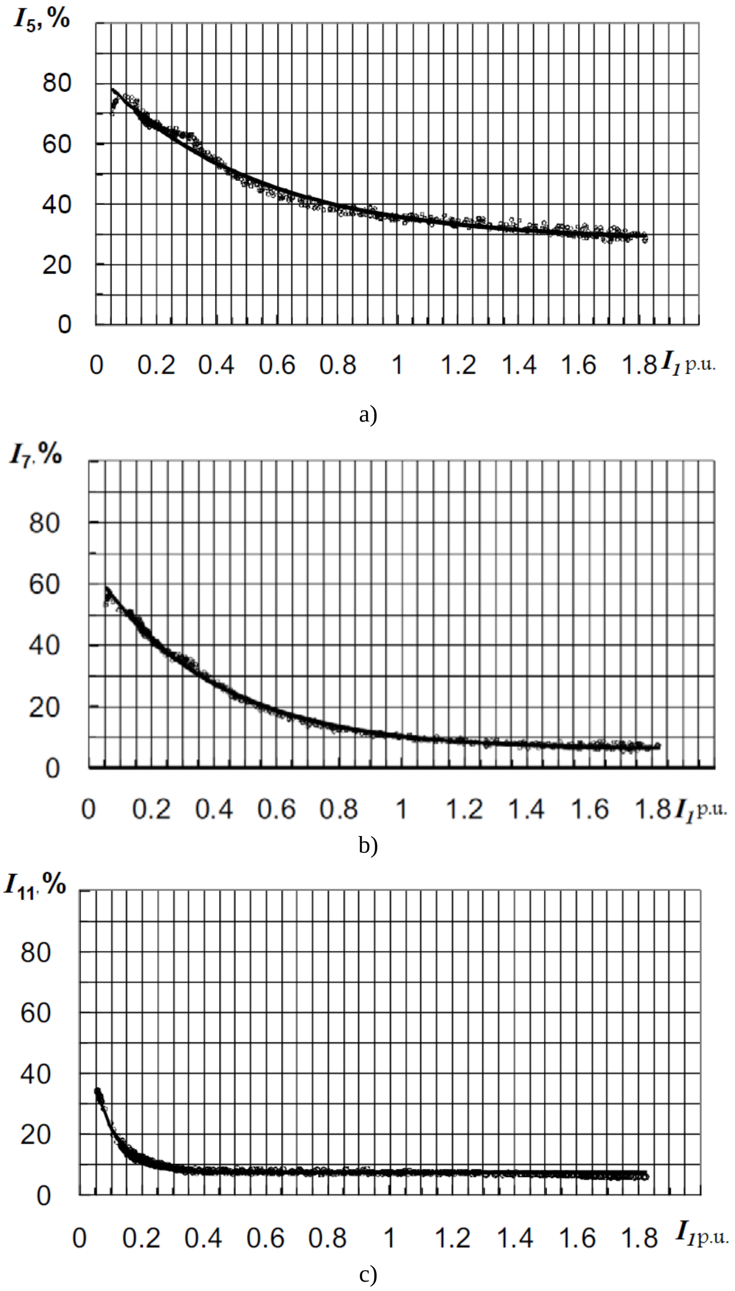
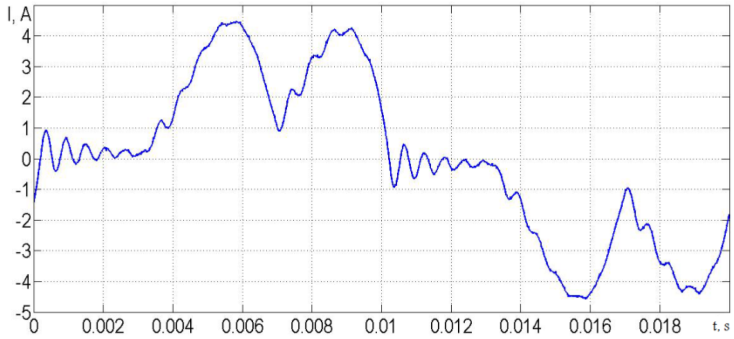
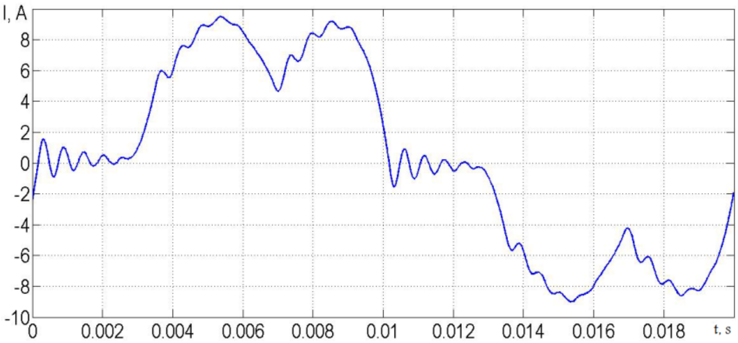


Fig. 3. Spectral analysis of line current waveforms in Fig. 2 are shown for the 5th, 7th and 11th harmonics as a function of the load on the inverter

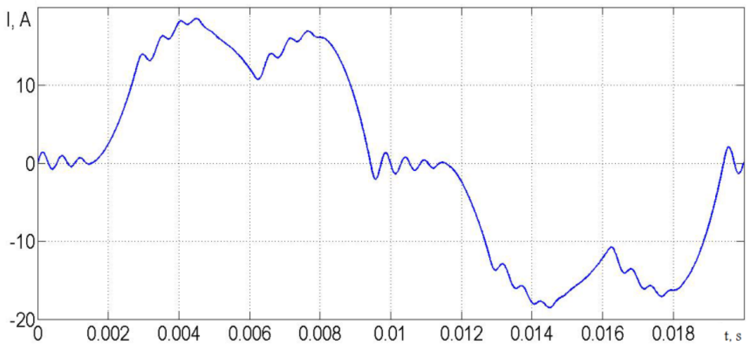
Fig. 4 shows the line current of the second VSD (5.5kW) when the inverter is 25% loaded (a), 50% loaded (b) and 100% loaded (c).



a)



b)

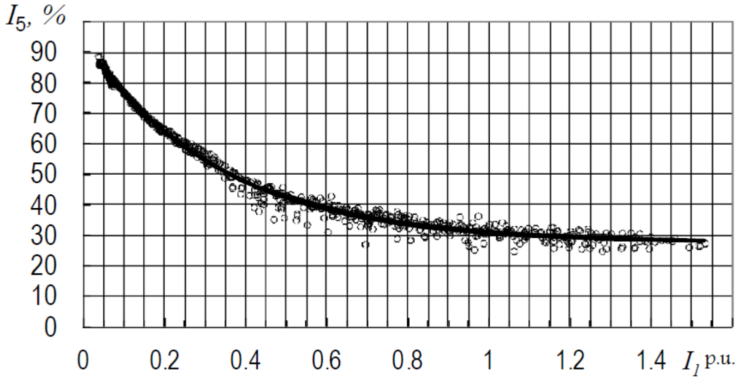


c)

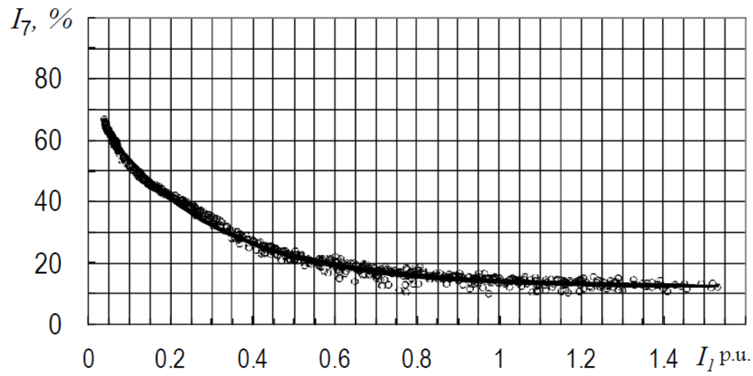
Fig. 4. The line current waveforms of inverter type Altivar 71 (5.5kW) when the inverter was a) 25% loaded, b) 50% loaded and c) 100% loaded

Spectral analysis of line current waveforms in Fig. 4 are shown for the 5^{th}, 7^{th} and 11^{th} harmonics as a function of the load on the inverter that is depicted in Fig. 5.

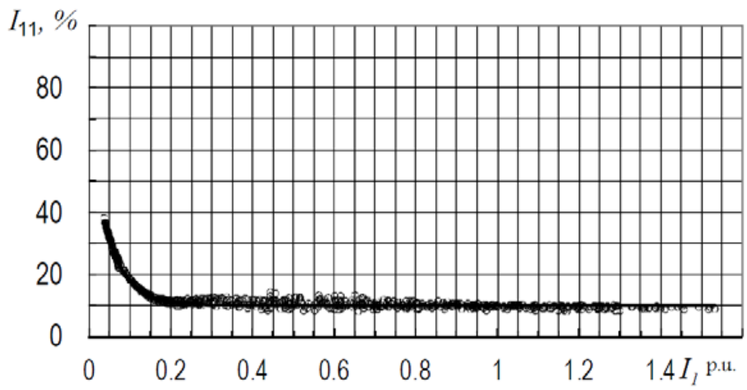
The line current total harmonic distortion THDi values for the first and second inverters type Altivar 71 have been calculated as a function of the load on the inverter. The results of calculations are shown in THDi versus I_1 pu curves (numbered 1) in Fig. 6 and 7. The effect of adding a filter that can suppress the 5^{th}, 7^{th} and 11^{th} harmonics is shown on the THDi versus I_1 pu curves (numbered 2) in Fig. 5 and 6.



a)



b)



c)

Fig. 5. Spectral analysis of line current waveforms in Fig. 4 are shown for the 5th, 7th and 11th harmonics as a function of the load on the inverter

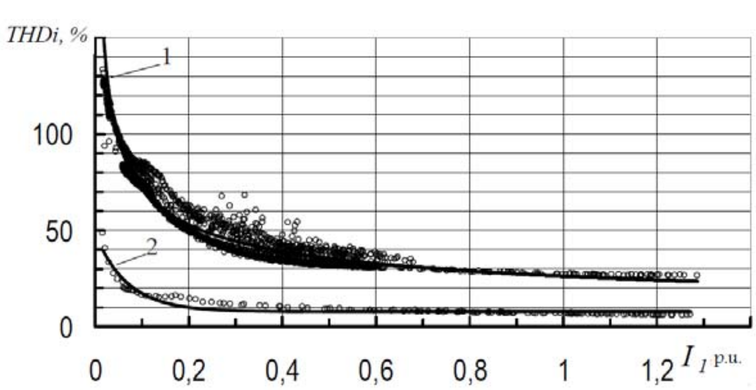


Fig. 6. THDi = $f(I_1)$ curves for inverter type Altivar 71, 2.2kW. 1- with the current filter recommended by the manufacturer (Schneider Electric Co.), 2- with the current filter suppressing the 5th, 7th and 11th harmonics

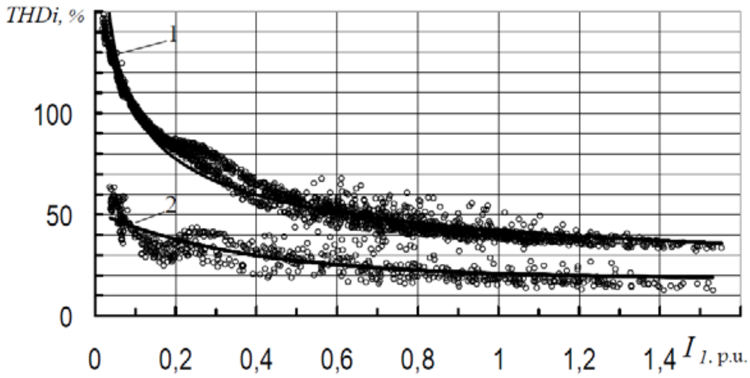


Fig. 7. THDi = $f(I_1)$ curves for inverter type Altivar 71, 5.5kW. 1- with the current filter recommended by the manufacturer (Schneider Electric Co.), 2- with the current filter suppressing the 5th, 7th and 11th harmonics

IV. CONCLUSIONS

The analysis of the experimental results reveals that the under-loaded variable speed drives (VSDs) create high-order harmonics in the line current which in turn increases the current total harmonic distortion THDi to 100% or even more at no-load mode and significantly decreases the quality of the power system. Such a THDi value is not acceptable anywhere in the world. The data that is usually given in the catalogs of the inverters about the THDi using the filters the manufacturers recommend is valid only when the inverters are fully loaded. Such value is around 45%.

Since most of the VSDs may operate for relatively long periods with underload, it is of a great importance to reconsider the design of the optimum filters that could improve the THDi of the under-loaded inverters as well. Such filters should eliminate the effect of 5th, 7th and 11th current harmonics that significantly increase the current THD especially when the inverters are under-loaded.

Simulation results show that including such filters in the power circuit of the VSDs can greatly improve the power system quality and energy efficiency by reducing the level of TDHi to 10%.

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