Methodologies of Measuring Mechanical Power Delivered at the Shaft of an Induction Motor Driven by VFD

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Abstract: Measuring precise power used by a load of an induction motor driven by a VFD implies a few facts that need to be considered. First, the real electric power. When dealing with waveforms of electric current that contain harmonics, traditional methods of power measuring could lead to inaccurate results. Therefore, further investigation needs to be performed in order to provide meaningful values. Then there is the efficiency. Motor losses are to be taken into account for finding out exactly how much power is being used for a specific application. This paper shows a method of measuring and calculating the electric real power of fundamental harmonic and of extracting an actual output value of mechanical power at the motor shaft. For this purpose we used a data acquisition system made of a basic power quality analyzer and data acquisition software. Harmonic analysis of the waveforms is considered, combined with the use of the true power factor.

Key Words: Power measurements, harmonic distortion, induction motor, power factor, efficiency losses.

1. INTRODUCTION

Measuring the precise power used by induction motor driven by VFD is often a less simple task that requires advanced equipment for direct and accurate results. Simple measuring devices deliver inaccurate values that sometimes do not fulfill the accuracy requirements. For the correct calculation of power delivered at the motor shaft with a simple electric analysis instrument, both the irregularities of the current waveform and mechanical losses need to be taken into account.

The existence of voltage and current harmonics in rotational electric machines has, as an important effect, heat losses that lead to increased work temperature. This has a negative impact, among others, on the insulation, which in time leads to shorter lifetime.

Increased losses in the stator of three-phase motors, and even a small amount of voltage harmonic distortion, produce additional magnetic flux, which further leads to additional currents in the rotor windings and core. These additional currents, which in the case of a strong voltage distortion can be of the same order of magnitude as the magnetizing current, are the cause of additional active power loss, temperature rise and increase in machine failure rate [1]. In high-voltage induction motors the rotor and stator losses are
approximately equal. The wound-rotor induction motors allow for a larger rotor loss than squirrel-cage motors [1].

Additionally, in three-phase systems with neutral, all triplen harmonics (zero-sequence harmonics) accumulate in the neutral conductor of the star-connected load. In power systems containing substantial nonlinear loading, the triplen harmonic currents may be of great enough magnitude to cause neutral conductors to overheat. This is very problematic, as other safety concerns prohibit neutral conductors from having overcurrent protection. [2]

Additional harmonic torques are the effect of interaction between the air gap flux (mainly the fundamental component) and fluxes produced by rotor harmonic currents. Their effect on the resultant, average motor torque is practically small. Moreover, they have a tendency to mutual cancellation. [1] Positive sequence harmonics (7, 13, 19, ...), which "rotate" with the same sequence as the fundamental [2], produce a forward rotating field that adds to the torque and supports the machine rotation, whereas the negative sequence harmonics (5, 11, 17, 23, ...) [1], which "rotate" in the opposite sequence [2], have the converse effect. Harmonic torques influence the instantaneous value of the resultant torque and result in its fluctuation [1]. The resulting forces acting upon each other create heat, which leads to eventual premature failures.

However, zero sequence harmonics (3, 9, 15, 21 ...) which don't "rotate" at all because they are in phase with each other [2], do not develop usable torque, but produce additional losses in the machine [3].

The interaction between the positive and negative sequence magnetic fields and currents produces torsional oscillations of the motor shaft, resulting in shaft vibrations [3]. Mechanical oscillations of electric machines, supplied with distorted voltage, attain their maximum values when the frequency of the motor torque variations is equal or close to the mechanical resonance frequency of the motor and driven machine set [1]. In these cases, the vibrations are amplified and severe damage to the motor shaft may occur [3].

The presence of harmonic currents in motor windings increases the acoustic noise emission compared to that for sinusoidal waveforms. Also by affecting the air gap flux distribution, harmonics can hamper the soft start of a motor and increase its slip [1].

2. REAL POWER AND MOTOR LOSSES

When dealing with imperfect electric waveforms, that contain harmonics, traditional methods of real power measurement may lead to inaccurate results. Real power of one phase can be defined as follows:

\[ P = V_{rms} \cdot I_{rms} \cdot PF \]  

and in the three-phase case:

\[ P = P_a + P_b + P_c \]  

where \( V_{rms} [V] \) is the phase-to-neutral voltage, \( I_{rms} [A] \) is the phase-to-neutral current, \( PF \) is the power factor, \( a, b \) and \( c \) are the phases of the three-phase system.

One problem in power measuring lies in the fact that most simple power quality measurement devices calculate power factor as being the lag between the waveform of the fundamental current and the waveform of the fundamental voltage. However, the power factor is more than that. In fact, the power factor being the ability of the circuit to perform real work, the harmonic components of the electric waveform also contribute to its decrease.
Thus, the power factor can also be written as the product between the displacement component $PF_{disp}$, measured by most devices, and the distortion component $PF_{dist}$:

$$PF = PF_{disp} \cdot PF_{dist}$$

Therefore, determining the distortion power factor is important in accurate real power assessment. Additional losses caused by harmonic currents running through the system decrease its ability to deliver the necessary power to the load. This may require oversizing the system, unless countermeasures are taken.

Another important consideration in determining useful power regards the actual losses of the motor. An electric machine converts energy according to the energy conservation law. The power balance is:

$$Electric\ Power = Mechanical\ Power + Losses$$

If we neglect losses, the mechanical power would equal the electric power. Power losses are a significant issue, being the direct cause of decreased efficiency of electric machines and their heating. Controlling losses and heating, we can increase efficiency and also the function safety of the machine. From the power balance equation the following losses are considered: rotor losses, stator losses, iron losses, mechanical losses, friction and ventilation losses, and additional losses (Fig. 1).

Fig. 1 Power balance [4]

Stator losses are made of stator teeth losses and air gap losses. Rotor losses are due to heating of copper windings, which change their properties when the machine temperature increased after a certain level. Iron losses are represented by energy losses necessary for the magnetization of the stator core. Substantial iron losses can also be produced in induction motors with skewed rotors due to high-frequency-induced currents and rapid flux changes (i.e., due to hysteresis) in the stator and rotor. The magnitude of the iron losses is dependent on the iron loss characteristic of the laminations and the angle of skew. [5]

Mechanical losses are due to friction in bearings and air resistance caused by the fan. Additional losses include unequal distribution of current through the copper windings, magnetic flux distortion and losses due to power stoppage.

Motors with deep bar or double cage rotors are susceptible to additional losses, particularly on highly polluted supplies containing high order harmonics. In extreme cases
this can, lead to "hoto rotors" which, due to conduction along the shaft, can degrade the bearing lubrication and result in bearing collapse. [5]

After subtracting these losses, the mechanical power will be delivered to the shaft on the electric motor.

Slip for different harmonics can be expressed in relation to fundamental harmonic [6]:

\[
s_h = \frac{h + 1 - s}{h}
\]

where \( h \) is the harmonic order and \( s \) is the slip of fundamental harmonic.

Further we will discuss the method that can provide us with the value of the true power factor, calculation of electric power based on its value, as well as calculation of the power delivered at the shaft based on electric information and motor losses.

3. METHOD

In nonsinusoidal states, most harmonics are produced by power electronic loads such as speed drives and power converters.

Most significant harmonics are typically first odd multiples of the fundamental frequency.

The harmonic level is usually determined by the total harmonic distortion (THD), for the voltage, as well as for the current:

\[
THD_V = \frac{\sqrt{\sum_{k=2}^{\infty} V_{krms}^2}}{V_{rms}} \cdot 100\%
\]

(6)

\[
THD_I = \frac{\sqrt{\sum_{k=2}^{\infty} I_{krms}^2}}{I_{rms}} \cdot 100\%
\]

(7)

where \( V_1 \) [A] and \( I_1 \) [A] are the fundamental harmonics of voltage and current, respectively, and \( k \) is the higher harmonics order.

The distortion power factor can be expressed with respect to the THD as follows:

\[
PF_{dist} = \frac{1}{\sqrt{1 + THD_I^2}}
\]

(8)

neglecting however the distortion of the voltage waveform. If this is taken into account, equation (8) would become:

\[
PF_{dist} = \frac{1}{\sqrt{1 + THD_V^2} \cdot \sqrt{1 + THD_I^2}}
\]

(9)

Figure 2 illustrates the difference THD makes in the result of the true power factor. The higher amount of harmonics, the lower the overall efficiency of the system.
Introducing equation (9) in (2) or (3), the true real power which takes harmonic distortion into account can be extracted using the parameters offered by a simple power quality analyzer:

\[
P = V_{\text{rms}} \cdot I_{\text{rms}} \cdot PF_{\text{disp}} \cdot \frac{1}{\sqrt{1 + \text{THD}_V^2} \sqrt{1 + \text{THD}_I^2}}
\]  
(10)

or otherwise:

\[
P = V_{\text{rms}} \cdot I_{\text{rms}} \cdot PF_{\text{disp}}
\]  
(11)

where \(V_{\text{rms}}\) and \(I_{\text{rms}}\) are the values of the fundamental harmonic of voltage and current respectively.

Regarding losses that appear in power equation (4), we use the power efficiency in the following equation:

\[
P_{\text{out}} = P_{\text{in}} \cdot \eta / 100
\]  
(12)

where \(P_{\text{out}}\) [W] is the output power of the motor, \(P_{\text{in}}\) [W] is the input power of the motor (electric power), and \(\eta\) [%] is the motor efficiency.

4. EXPERIMENTAL SETUP

In order to calculate the real power according to the described method, we intend to use a specific electric setup. With this setup, all necessary input data is acquired. The system is made of a Carlo Gavazzi WM3-96 power quality analyzer that has current and voltage modules, and also a data transmission module with RS485, as well as a computer that runs LabView 2011 software from National Instruments.
These are connected to a three-phase induction motor, driven by a variable speed drive, as in the schematic in Figure 3.

![Connection schematic of the experimental assembly](image1)

The analyzer (Fig. 4) makes possible the data acquiring by current and voltage modules. It is capable of a harmonic analysis up to the 50th order harmonic. With the analyzer, the parameters of interest are read: $THD_i$, $THD_v$, $PF_{disp}$, $V$ and $I$.

They have corresponding addresses, whose values can be extracted in the LabView program. The power factor provided by the instrument is a displacement power factor, equivalent to the cosine of the angle between the current fundamental and the voltage fundamental.

Thus it is a power factor that doesn't take harmonic distortion into account, and so the power calculated by the device includes all voltage and current harmonic components.

However, only the fundamental actually contributes to the usable power. This can be verified with equations (1) and (10), noting which type of power factor the value from the device fits most with.

![The Carlo Gavazzi analyzer](image2)
In this case, calculating the value of the total power factor is needed for extracting the true power.

As the test setup is supposed to include the three-phase unbalanced case, variables on each phase are used and calculated single phase powers added together, as shown in equation (2). For current measuring, current transformers were used, with a ratio of 300A:5A. Figure 5 shows the connection diagram of the analyzer.

Data transmission is performed by RS485 interface, through the communication module on the analyzer.

The link with the analyzer unit is done by a RS485 – RS232 converter.

The data acquisition is made with the LabView software. Calling the memory addresses from the program, the variable values necessary for the test are extracted on the software panel.

Addressing is made by the MODBUS-RTU algorithm, i.e. the address of the value of interest is N-1, where N is the location listed in the specifications of the device.

The acquired values are introduced in the LabView equations and diagram made for determining the true power (Fig. 6).
Fig. 6 LabView diagram of data processing
5. FURTHER WORK

Further analysis, intending to include a real motor setup using the proposed equipment is in progress. This setup is shown in the pictures below (Fig. 7, 8):

![Fig. 7 The setup of the motor](image1)

![Fig. 8 The automation cabinet and additional equipment](image2)

Regarding the measurements during the run time of the motor, recorded values of current and voltage harmonic content should give us the necessary details for the calculation method.
previously described. Also the performance of the device's calculating method in this case will be compared with our more accurate algorithm.

The high THD values that are expected and their lack of effect on the resulting power factor and hence the real power on the screen of the analyzer would lead to the necessity of implementing this additional algorithm of true power calculation. The power factor resulting from this method is to be shown and compared with the supposed power factor collected directly from its address on the device.

Finally, the comparison between the calculated power and the directly acquired power should give us an idea about how important it is for us to take these details into account.

6. CONCLUSIONS

Usual methods for electric power calculation are useful in most cases, but not accurate enough when a high accuracy of the measurements is required. Power electronic devices, convertors, variable speed drives, imperfect AC sources, and other elements can lead to significant distortions of the electric waveforms, which have a negative effect on the true power factor, by its further decrease. This effect is often omitted except the case of advanced and costly measuring devices.

This paper underlines the fact that improving both components of the power factor (the displacement power factor and the distortion power factor) is important, with effect on power losses, energy costs, functioning and lifetime of the equipment.

Besides offering a complete harmonic analysis of the system's power quality, the method is also a good alternative to power measuring by mechanical means with more costly equipment that would involve speed and torque sensors and transducers.

7. REFERENCES