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An Accurate Measurement Procedure of Power Losses Variations in Electrical Drives

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***Abstract* –This paper presents a general procedure for the accurate measurement of power losses variations in electrical drives. More specifically, the paper addresses the issue related to the efficiency comparison of electrical drive controlled with different control algorithms. This procedure is applied to a permanent magnet synchronous motor drive, assessing its power losses by means of two different measurement systems, each one characterized by different accuracy and cost. The comparison between these two systems is carried out for different working conditions in terms of load, speed and magnetization in order to demonstrate that the power losses variations can be accurately measured even with not expensive instrumentation.**

I. INTRODUCTION

Over the last decades, the field of electrical drives has achieved a significant extensive use in industrial applications. In particular, the energy required by the electrical drives corresponds to 46% of the world electrical energy demand and the 2/3 of the global electrical energy consumption by industrial applications [1]. These facts have been mainly determined by the recent advances on high-performance power converters and electric motors, allowing a relevant improvement of the electrical drives in terms of both efficiency and adaptability for challenging operating conditions.

In this scenario, the scientific research has directed his effort towards the optimization of every element composing the electric drive, with the aim of minimizing the power losses, maximizing, thus, the related overall efficiency and increasing the energy savings. In the recent past, the IEC 60034-2 [5]-[7] introduced standardized methods in order to determine the efficiency of electrical machines fed by the electrical grid and converter-fed AC induction motors with adequate accuracy, repeatability and reproducibility. One of the latest standard referred to the electrical drives is the IEC 61800-9, issued in 2017 [8]-[9], which is a valid reference that provides the methodologies needed for the determination of the efficiency of electric motors, Complete Drive Modules (CDMs) and Power Drive Systems (PDS).

In this context, this work presents a general procedure for the measurement of power losses variations involved in electrical drives. More in detail, the issue related to the efficiency comparison of electrical drive controlled with different control algorithms is addressed. Generally, this task would require the electric drive efficiency measurement for each control algorithm by the use of accurate and expensive measurement equipment. Instead, the proposed methodology allows the accurate estimation of the power losses variation, even by the use of low-accuracy and cheap measurement equipment.

In order to validate the proposed approach, this procedure is applied to a permanent magnet synchronous motor drive, assessing its power losses (ΔP), as prescribed by the IEC 61800-9 standard, for different working conditions in terms of load, speed and magnetization and by means of two different measurement systems, each one characterized by different accuracy and cost.

The paper is organized as follows: Section II deals with the power losses measurements and the evaluation of its uncertainty in electrical drives, Section III describes the test bench set up for the experimental investigations and, in particular, deals with the uncertainty specifications of the two used measurement systems and Section IV presents the experimental results and their analysis.

II. POWER LOSSES MEASUREMENTS IN ELECTRICAL DRIVES AND UNCERTAINTY EVALUATION

By considering Fig. 1, which schematically represents the three main sections of a Power Drive System (single-phase section, nr. 1, three-phase section, nr. 2 and motor section, nr. 3), the power losses of the PDS can be measured with the direct method by means of the following equation:

$$\Delta P = P_E - P_M \tag{1}$$

where P_E is the active power measured in section 1 and P_M is the mechanical power measured in section 3.

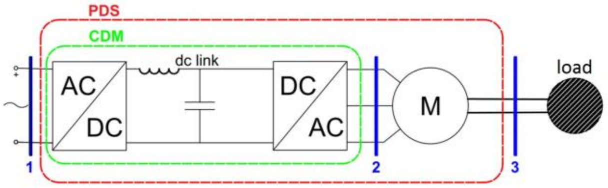

Fig. 1 Schematic representation of a PDS.

Otherwise, by referring to the Standard IEC 60034-2-1, the power losses can also be indirectly determined from the computation of the power losses involved in the system, namely ΔP, by adopting the following equation:

$$\Delta P = \sum \Delta P_i \tag{2}$$

where ΔP_i are all power losses typologies involved in the section of both converter and motor, namely, switch losses, conduction losses, iron losses, copper losses, friction and windage losses and additional losses (including the additional losses due to inverter voltage harmonics).

The indirect method is very time-consuming since it requires many tests for the computation and separation of all power losses classes. Moreover, the indirect method, because of its complexity, entails a huge amount of calculations for the uncertainty evaluation.

Generally, the standards suggest applying the indirect method only for high-power motors, leaving the direct method only for low-power machines with power less than 1 kW [5]. However, an interesting study demonstrates that the direct method is suitable, with the adoption of technologically advanced instrumentation, for the measurement of torque and speed, independently from the size of the machine, providing simpler and straight efficiency determination with uncertainties even lower than those obtained by means of the indirect method [10]. For the aforementioned reasons, the paper deals only with the direct method of power losses.

In this case, by applying the uncertainty propagation law to eq. (1) and by considering that there is no correlation between the electric power measurement and the mechanical power measurement, the uncertainty associated to the power losses measurement can be expressed as:

$$u(\Delta P) = \sqrt{u^2(P_E) + u^2(P_M)} \tag{3}$$

and, therefore, the relative uncertainty is:

$$\dot{u}(\Delta P) = \frac{u(\Delta P)}{\Delta P} = \frac{\sqrt{P_E{}^2 \dot{u}^2(P_E) + P_M{}^2 \dot{u}^2(P_M)}}{P_E - P_M} \tag{4}$$

The eq. (4) shows that, mainly for high-efficiency systems, the input and output powers must be assessed with a small percentage error, in order to measure the power losses with the accuracy requested by the standards. This aspect entails the usage of expensive and properly calibrated instrumentations and requires skilled operators able to master the whole measurement process.

Not always, nevertheless, there is the need to measure the absolute value of the power losses. For instance, in order to verify the effectiveness of a software or hardware solutions adopted to increase the PDS efficiency, the characterization of the power losses variations can be already adequate. In scientific literature, several control algorithms for the power losses minimization are proposed for all types of drive modules and motors. For instance, the use of the so-called Loss Model Algorithms (LMAs) involves the search for the optimal value of the direct-axis current component i_d for the power losses minimization of the motor [11]-[14] in any working operation in terms of speed and applied load. In these cases, to compare the control algorithms, the measurement of the PDS power losses variation, namely $\Delta\Delta P$, is suitable.

The power losses variation, switching between two different control algorithms, can be evaluated as:

$$\Delta\Delta P = \Delta P_1 - \Delta P_2 = P_{E1} - P_{M1} - P_{E2} + P_{M2} \tag{5}$$

where: ΔP_1, P_{E1} and P_{M1} are the power losses, the electrical power and the mechanical power measured by driving the motor with the algorithm *1*; ΔP_2, P_{E2} and P_{M2} are the power losses, the electrical power and the mechanical power measured driving the motor with the algorithm *2*.

The uncertainty associated with the power losses variation measurement can be expressed as:

$$\begin{aligned} u(\Delta\Delta P) = \big[& u^2(P_{E1}) + u^2(P_{M1}) + u^2(P_{E2}) + u^2(P_{M2}) + \\ & - 2r(P_{E1}, P_{M1}) u(P_{E1}) u(P_{M1}) - 2r(P_{E1}, P_{E2}) u(P_{E1}) u(P_{E2}) + \\ & + 2r(P_{E1}, P_{M2}) u(P_{E1}) u(P_{M2}) + 2r(P_{M1}, P_{E2}) u(P_{M1}) u(P_{E2}) + \\ & - 2r(P_{M1}, P_{M21}) u(P_{M1}) u(P_{M2}) - 2r(P_{E2}, P_{M2}) u(P_{E2}) u(P_{M2}) \big]^{\frac{1}{2}} \end{aligned} \tag{6}$$

Since both the input electric power and mechanical power are measured with the same equipment and the measured values are similar when employing the two algorithms, it is possible to assert that:

$$u(P_{E1}) = u(P_{E2}) = u(P_E) \tag{7}$$

$$u(P_{M1}) = u(P_{M2}) = u(P_M) \tag{8}$$

If the components of the uncertainty due to random errors are neglected, then, by considering only the systematic errors, in the eq. (6), the correlation coefficient *r*, if the uncertainty quantities involved in the double product are both electrical or both mechanical, is equal to 1, otherwise is equal to 0. Consequently, uncertainty expression can be written as follows:

$$u(\Delta\Delta P)=\sqrt{2u^2(P_E)+2u^2(P_M)-2u^2(P_E)-2u^2(P_M)}= \\ =0 \qquad (9)$$

The obtained result emphasizes that the power losses variation measurement is not affected by systematic errors. Therefore, its measurement uncertainty can be assessed just evaluating its short-term repeatability.

III. TEST BENCH

With the aim of validating the proposed approach, IPMSM low-power electrical drive has been set up and it is mainly composed by:

- A Complete Drive Module (CDM), composed by a DPS 30-A power converter (Automotion Inc.), which is directly connected to a single-phase electrical grid. The IGBT bridge of the inverter is made by POWEREX, Model PM30CSJ060;
- A commercial 6 poles, three-phase Interior Permanent Magnet Synchronous Motor (IPMSM) (Magnetic S.r.l., type BLQ-40, Italy) with interior SmCo magnets, whose main rated values are summarized in Table 1;
- A Magtrol hysteresis brake (Model HD-715-8NA), connected to the shaft of the motor and used as a mechanical load for the IPMSM. The brake is controlled in real-time through a digital dynamometer controller (Magtrol DSP6001), which comes with two outputs for torque and speed signals;
- a PC with the dSPACE-based electrical drive user interface, which allows performing the real-time control of the proposed system.

Table 1. Rated values of IPMSM under test.

Parameter	Value
Voltage [V]	132
Current [A]	3.6
Rated mechanical speed [rpm]	4000
Nominal Torque [Nm]	1.8

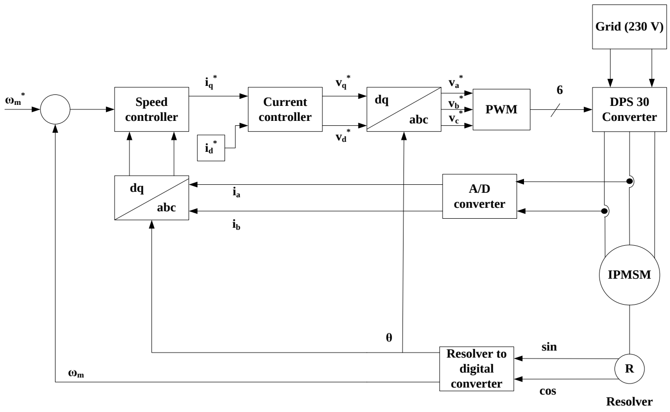

Fig. 2 Block diagram of the control system.

A traditional Field Oriented Control (FOC) strategy, shown schematically in Fig. 2, has been experimentally implemented. This IPMSM drive system implements a closed-loop control of the motor speed: the reference speed ω_m^* is compared with the motor speed ω_m, which is measured by means of a resolver. The corresponding speed error is processed with a PI regulator in order to obtain the reference value of the current quadrature axis component i_q^*. In addition, the system controls the magnetization level of the motor by regulating the reference value of the current direct axis component i_d^*. Both i_d^* and i_q^* are, then, compared with the actual values of i_q and i_d to obtain the reference values of the supply voltage Park components v_d^* and v_q^*, which are, finally, transformed in a three-phase coordinate system and applied to the motor through a Pulse Width Modulation (PWM) technique.

Generally, the losses minimization control strategies regulate the i_d^* value in order to minimize the overall power losses for whatever working point. Therefore, two control algorithm are simulated by imposing two different values of the direct axis current i_d, namely 0 A (algorithm 0), and -1 A (algorithm -1).

According to the IEC 61800-9-2 standard, the power losses must be evaluated for various working points of the motors, in particular the ones reported in Table 2.

With regard to the ω_m=0, the standard refers to a sufficiently low speed, corresponding to a supply frequency of the motor lower than 12 Hz. The low speed chosen for the motor under test was equal to 200 rpm.

Table 2: IPMSM working points

Working points	$\omega_m=\omega_n$	$\omega_m=0.5\omega_n$	$\omega_m=0$
$T_{em}=T_n$	1) ω_n; T_n	2) $0.5\omega_n$; T_n	3) 0; T_n
$T_{em}=0.5T_n$	4) ω_n; $0.5T_n$	5) $0.5\omega_n$;$0.5\ T_n$	6) 0;$0.5\ T_n$
$T_{em}=0.25T_n$	7) ω_n; $0.25T_n$	8) $0.5\ \omega_n$;$0.25\ T_n$	9) 0;$0.25\ T_n$

The power losses, related to the entire PDS (CDM and motor), were assessed by using two measurement systems (system *A* and system *B*), rather different for their accuracy and price. In order to reduce the effect of the efficiency variations due to the time constants of the control systems, the standard [8]-[9] prescribes to evaluate the power losses for a time not less than 1 min.

With the first measurement system, the voltage is acquired through a direct connection to a NI 9225 data acquisition module (DAQ), avoiding the usage of voltage transducers. The current is acquired by means of a non-inductive Fluke A40B Precision AC Current Shunt, whose output signal is sent to a NI 9239 DAQ, which was used also to acquire the speed and torque signals provided by the Magtrol DSP6001 dynamometer controller. The input electrical power and mechanical power are measured by multiplying the respectively acquired signals and by calculating the mean value, in 1 minute of the instantaneous powers.

The DAQs (placed in a NI cDAQ 9172 chassis) have the following features: four analog input channels, simultaneous sampling mode, sampling frequency $f_s = 1.613-50$ kS/s, ADC delta-sigma with analog pre-filtering (alias-free bandwidth of 0.453 fs), 24-bit resolution, and input ranges of 300 Vrms for NI 9225 and ±10 V for NI 9239. The shunt has the following features: I_N =20 A, $R_N = 0.04\ \Omega$, accuracies of ±43 μA/A up to 1 kHz and ±52 μA/A up to 10 kHz (95% confidence level), and typical phase displacements < 0.008◦ up to 1 kHz and < 0.075◦ up to 10 kHz. The dynamometer controller sends out the speed signal with an accuracy of 0.01% of reading and the torque signal with an accuracy of 0.6 x 10^{-3} N·m.

The four signals were acquired at a rate of 50 kS/s that is perfectly adequate to the frequency bandwidth of the signals. The measurements were performed after the calibration of the dynamometer and by controlling the temperature and humidity of the test laboratory. In these conditions, the measurement system A guarantees an expanded uncertainty not exceeding 0.13% with a 99% of a confidence level for the electric active power [15] and an expanded uncertainty not exceeding 0.20% with a 99% of a confidence level for the mechanical power. Therefore, the measurement system A complies with the IEC-61800 standard recommendations and can be used for the PDS classification.

With the second measurement system, the voltage is sensed by a Yokogawa 700924 differential probe and the current is sensed by a Fluke i400 current probe. The output of both probes are sent to a low-cost NI 9215 DAQ and acquired at a 50 kS/s sampling frequency. Both probes have a gain accuracy equal to 2% but, since their phase errors are not even stated in the manufacturer's specifications, it is not possible to correctly assess the active power measurement uncertainty. In any case, the expanded uncertainty, with 99% of confidence level, cannot be lower than 4%. The mechanical power is directly read from the dynamometer interface. Without the dynamometer calibration, the mechanical power measurement expanded uncertainty is equal to 3%.

Because of the high values of obtainable uncertainties, the measurement system B does not comply with the IEC-61800 standard recommendations and cannot be used for the PDS classification.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

For each working point, for each value of the magnetization current and for each measurement systems, the power losses were measured 40 times, where each measurement sample presents a durations of 60 s. From the acquired values of active power, it is possible to determine both the power losses and the efficiency of the entire PDS under test. For instance, Fig. 3 reports the efficiency for i_d = -1 A as function of the mechanical speed n_m measured with the system A and the system B.

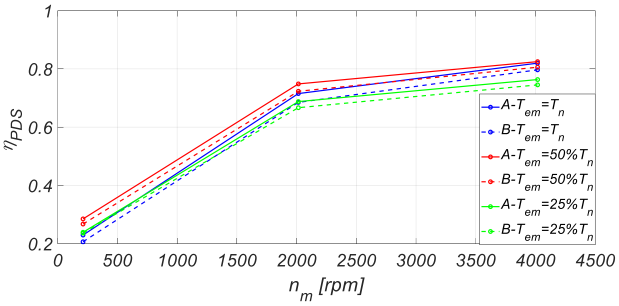

Fig. 3 PDS efficiency measured at i_d=-1 A.

It can be noticed that the highest efficiency values are detected for the load torque condition T_{em}=50% T_n. Moreover, for the speed condition ω_m=0, the PDS efficiency obtained at T_{em}=25% T_n is higher than the one obtained at T_{em}=50% T_n. However, for speed conditions $\omega_m \geq 50\%\ \omega_n$, the PDS efficiency obtained at T_{em}=25% T_n is lower than the one obtained at T_{em}=50% T_n. In any case, for all the proposed working points, the PDS efficiency values measured with the shunt resistor (continuous lines) are higher than those measured with the Fluke current probe (dot lines). The PDS efficiency uncertainty is affected by errors on power measurement both in the input single-phase section and in the output mechanical section. As mentioned before, the system A complies IEC61800-9 uncertainty prescriptions and, therefore, can be used for the PDS energy classification. On the contrary, the second measurement system is not suitable for the PDS energy classification.

For validation purpose of the methodology of measurement described in Section II, a variation of the i_d current is applied to the FOC system, determining a variation of the power losses $\Delta\Delta P$ involved in the PDS. This variation is measured by means of the two measurement systems described and the related values are compared. Tables 3 reports for the nine working points, the mean values of the difference of power losses measured with the measurement system A ($\Delta\Delta P_{A0-1}$) and the measurement system B ($\Delta\Delta P_{B0-1}$), when the current i_d is switched from a value of 0 A to a value of -1 A. The same table reports the expanded uncertainty values assessed by multiplying the standard deviation of the 40 measurements by a coverage factor k = 2.58.

Table 3 IPMSM Power Losses Differences between i_d=0 A and i_d=-1 A

Working points	$\Delta\Delta P_{A0-1}$ [W]	$\Delta\Delta P_{B0-1}$ [W]	$u(\Delta\Delta P_{A0-1})$ [W]	$u(\Delta\Delta P_{B0-1})$ [W]
1	4.98	4.87	0.42	0.33
2	5.52	5.62	0.27	0.19
3	3.62	3.68	0.45	0.42
4	-0.8	-0.84	0.23	0.19
5	-1.04	-1.18	0.18	0.13
6	2.85	-3.22	0.20	0.27
7	-2.42	-2.54	0.18	0.17
8	-3.05	-3.2	0.15	0.12
9	5.08	-5.16	0.29	0.2

It is possible to notice that, the measurement evaluated with the two measurement systems are compatible, validating the proposed uncertainty assessment. In particular, the difference between the measurements performed by using the two systems are negligible, since this difference is not greater than 0,7 % (0.37 W in the worst case). Moreover, since the short term repeatability is practically the same for systems A and system B, the estimated expanded uncertainties generated by the two measurement systems are very similar.

The obtained results show that as theoretically expected, even cheap and not very accurate instrumentation can be correctly used to detect even very small changes that a possible modification of whatever component of the electrical drive can cause.

V. CONCLUSIONS

This paper has presented a novel and general procedure for the measurement of efficiency variation in electrical drives. The proposed methodology allows estimating the power losses variations suitable for the comparison between different PDS control algorithms. The proposed methodology has been applied for two different measurement systems of power losses, each one characterized by different accuracy and cost. The comparison between the two systems has demonstrated that the introduced parameter $\Delta\Delta P$ results as a valuable index for the characterization of the control system and it can be evaluated even with low-accuracy instrumentation.

VI. ACKNOWLEDGEMENTS

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