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Fast Method for the Iron Losses Prediction in Inverter Fed Induction Motors

A. Boglietti, *Senior member, IEEE*, A. Cavagnino, *Member, IEEE*, M. Lazzari
Politecnico di Torino – Dipartimento di Ingegneria Elettrica – ITALY
aldo.boglietti@polito.it, andrea.cavagnino@polito.it, mario.lazzari@polito.it

Abstract – In this paper an easy method for the iron loss prediction in PWM inverter fed induction motors is presented. The method was initially proposed and validated for the prediction of the iron losses in non-oriented soft magnetic material with PWM supply. Starting from the iron losses measured with sinusoidal supply and the PWM waveform characteristics, a fast and reliable prediction of the iron losses in the motor can be obtained too. The method requires the separation of the iron losses in the hysteresis and eddy current components with sinusoidal supply, plus the average rectified and RMS values of the applied PWM voltage. The proposed method has been proved on an induction motor prototype able to provide a good accuracy in the iron losses measurement. The comparison between the measured and predicted iron losses with PWM supply have shown an excellent agreement with an error lower than the 5%, confirming the method validity.

Index terms – Induction motors, iron losses, PWM voltage

I. INTRODUCTION

Nowadays, the simplicity and the flexibility in the use of induction motor inverter supply is out of discussion, but some of the effects of the static converters on the machine are still under analysis by the electrical machines and drives scientific community. In particular, one unsolved problem is the prediction of the iron losses in inverter fed induction motors. On the contrary, the techniques for the prediction of the iron losses under PWM supply in magnetic samples (Epstein Frame or toroidal samples) can be considered well settled. In fact, in the nineties the first approaches to the problems can be found in literature [1]. Anyway, it is in the last ten-fifteen years that the most interesting formulations for the prediction of the iron losses in magnetic material have been proposed [2]-[10]. In the same period, the authors gave their contribution with an intensive experimental campaign and proposed a formulation for the iron loss prediction passing from a sinusoidal to an arbitrary supply [11]-[16].

In the last years, the researchers' interest is moving on the prediction of the iron losses in electrical machines, in particular under inverter supply condition. The most used approach is based on Finite Element Method "FEM". In [17] and [18] excellent results have been presented by the authors. Unfortunately, FEM approach requires a lot of time for the model preparation (geometry mesh, material definition, etc.) and a lot of computational time. In this paper, the authors propose a fast and reliable method based on the theoretical

approach presented in [15]. The method has been validated, from the experimental point of view, using an "ad hoc" prototype.

This prototype has a rubber rotor cage, which allows to eliminate the rotor bar currents and to minimize the errors in the motor iron loss measurement.

II. THEORETICAL APPROACH

As previously mentioned, the proposed method was proposed and adopted for the iron loss prediction in soft magnetic material and it was presented and deeply discussed in [15]. Hereafter a short summary of the theoretical basic is reported. The method is based on the separation of the iron loss in hysteresis and eddy current contributions, while in order to simplify the approach, the excess losses have not been separated from the classical eddy current contribution [19]. As well known, the hysteresis losses can be written as:

$$P_h = a f B_p^x \quad (1)$$

where B_p is the peak value of the flux density, f is the frequency, x is the Steinmetz coefficient. The eddy current losses can be written as reported in (2). In (1) and (2) "a" and "b" are material parameters depending on the flux density and frequency, as shown in [24], [25]. In order to simplify the computational approach in the proposed method "a" and "b" are kept constant.

$$P_{ec} = b f^2 B_p^2 \quad (2)$$

When the iron losses and the two contributions are known in sinusoidal supply, a variation of these values has to be expected depending on the voltage waveform source. Making reference to an ideal inductor without winding losses, the supply voltage can be written as:

$$v(t) = NS \frac{dB}{dt} \quad (3)$$

where N is the turn number and S is the cross section of the magnetic core. If the supply voltage $v(t)$ is alternate and the instantaneous value has the same sign of its first harmonic, the relation between the peak to peak value of the flux density B_{pp} and the supply voltage can be written as:

$$\int_0^T |v(t)| dt = 2 NS B_{pp} \quad (4)$$

The previous condition on the voltage waveform assures that no minor loops are present in the main hysteresis loop. Introducing the average rectified value of an alternate voltage V_{av} , the peak value of the flux density can be written as:

$$B_p = \frac{V_{av}}{4 NS} T = k \frac{V_{av}}{f} \quad (5)$$

After the previous theoretical considerations, in the following the hysteresis and eddy current contribution variation under distorted voltage supply condition is discussed. Decomposing the supply voltage in harmonic series, the flux density can be written as:

$$B(t) = \frac{1}{2 \pi NS} \sum_n \frac{V_{n,max}}{n f} \sin(2 \pi n f t + \varphi_n) \quad (6)$$

and the peak value of the generic harmonic $B_{n,max}$ is equal to:

$$B_{n,max} = \frac{V_{n,max}}{n} \frac{1}{2 \pi f NS} \quad (7)$$

where $V_{n,max}$ is the peak value of the n^{th} harmonic. Starting from (2) and (7), the eddy currents contribution due to all flux density harmonics can be written as:

$$P_{ec} = \sigma \sum V_{n,max}^2 = 2 \sigma V_{rms}^2 \quad (8)$$

with V_{rms} the voltage RMS value and σ a constant material coefficient. In other words, (8) shows that the eddy current losses depend on the rms value of the supply voltage. Taking into account (1) and (5), the hysteresis contribution can be written as

$$P_h = \zeta V_{av}^x f^{1-x} \quad (9)$$

with ζ a constant material coefficient. As a consequence, (9) shows that the hysteresis losses are depending on the rectified average value of the supply voltage. It is important to underline that (9) can be used only if the supply voltage does not produce minor loops in the hysteresis cycle. Taking into account the previous results, it is possible to correlate the iron losses measured in sinusoidal supply and the iron losses with an arbitrary supply voltage, when the characteristics of the voltage distortion are known. In particular, if the supply voltage is alternate and it can be represented by two half waves having constant sign in the half period, (10) can be adopted for the iron losses prediction, where α, β are constant coefficients, depending on the lamination material.

$$P_{ir} = \alpha V_{av}^x + \beta V_{rms}^2 \quad (10)$$

It is important to underline, that the condition imposed on the voltage waveform is always true for three phase PWM voltage usually adopted in low voltage industrial inverters. As a direct consequence of the imposed conditions on the supply voltage, an arbitrary alternate supply voltage can be characterized by means of the following two parameters:

$$\eta = \frac{V_{av}}{V_{av,fund}} \quad (11)$$

$$\chi = \frac{V_{rms}}{V_{rms,fund}} \quad (12)$$

It is important to underline that η and χ can be easily determinable using the modern digital powermeters. Using these two coefficients, the iron losses with an arbitrary waveform can be rewritten as reported in (13).

$$P_{ir} = \eta^x P_{h,sin} + \chi^2 P_{ec,sin} \quad (13)$$

In (11)-(13) the meaning of the used symbols is

- $P_{h,sin}$ is the hysteresis losses with sinusoidal supply;
- $P_{ec,sin}$ is the eddy current losses with sinusoidal supply;
- V_{av} is the voltage mean rectified value;
- V_{rms} is the voltage rms value;
- $V_{av,fund}$ is the mean rectified value of the fundamental voltage;
- $V_{rms,fund}$ is the rms value of the fundamental voltage.

Consequently, when the separation between hysteresis and eddy current losses with sinusoidal supply and the supply voltage characteristics are known, the iron losses with arbitrary voltage waveform can be predicted.

III. TEST BENCH FOR INDUCTION MOTOR IRON LOSS MEASUREMENTS

Before to introduce the adopted test bench, it is important to highlight the following considerations on the electrical machine loss segregation. Every time a comparison between predicted and measured iron losses has to be made, it is important to put the following question to himself: "Which is the meaning of the measured iron losses?". In fact, the iron losses in induction motors are measured by no-load test and the iron loss calculation is defined by the International Standards. These iron losses must be considered as convectional iron losses and it is wrong to considered them as the actual ones. In particular, the additional iron losses in no-load condition due to the stator space harmonics give a contribution up to 10% of the convectional measured iron

losses. In [20], this was proven by experimental tests using the same induction motor prototype used in this research. In addition, the determination of the mechanical losses is questionable as well, and the mechanical loss value determines the value of the measured iron losses [26]. Several examples of methodological inaccuracy on the measurement of the iron losses can be analyzed. As a consequence, in discussions concerning the goodness of a method for predicting the iron losses, the accuracy of the measured data is of fundamental importance. Consequently, the iron losses defined by the International Standards are not of course the best ones and the used prototype must be considered as a test bench, which allows the measurement of a quantity as close as possible to the actual iron losses.

Hereafter, these concepts will be discussed in detail. In this work the validity of the proposed procedure for the induction motor iron losses prediction with inverter supply is the main target. As a consequence, the comparison between predicted and measured iron losses must be done using iron losses values measured with the best possible accuracy. As an example, the standard IEEE 112B requires the classical no-load test for the induction motor iron losses loss determination [26]. In the no-load test the following power balance is imposed.

$$P_{no-load} = P_{ir} + 3R_s I_0^2 + P_{mech0} \quad (14)$$

where $P_{no-load}$ are the absorbed electrical power, P_{ir} are the iron losses, R_s is the stator resistance, I_0 is the no-load current and P_{mech0} are the mechanical losses in no-load condition.

The iron losses computed by (14) must be considered as conventional one. In fact, taking into account all the physic phenomena inside the machine a more accurate no-load power balance can be defined [27], as reported in the following relation:

$$P_{no-load} = P_{ir} + 3R_s I_0^2 + P_{mech0} + P_{add-0} \quad (15)$$

where P_{add-0} are the additional losses in no-load condition. The loss contribution due to the mechanical losses in no-load condition can be nullified adopting a no-load test at synchronous speed connecting the motor under test to a synchronous motor with the same pole pair. Among the several contributions to the additional losses, the rotor cage joule losses due to the harmonic current induced by the winding spatial harmonics are not a negligible contribution in no-load conditions too. Unfortunately, these losses cannot be segregated from the conventional iron losses and when (14) is used, these additional rotor losses are erroneously attributed to the iron losses. As a consequence, the conventional iron losses are not the most accurate quantity to be considered for a good comparison with computed ones. In order to overcome this limitation an “ad hoc” rotor with a rubber cage has been cast as shown in Fig.1. The rotor prototype is derived by an 11 kW, 4 poles, 230 V, 50 Hz, delta connection induction motor.



Fig.1: Rotor prototype with rubber cage

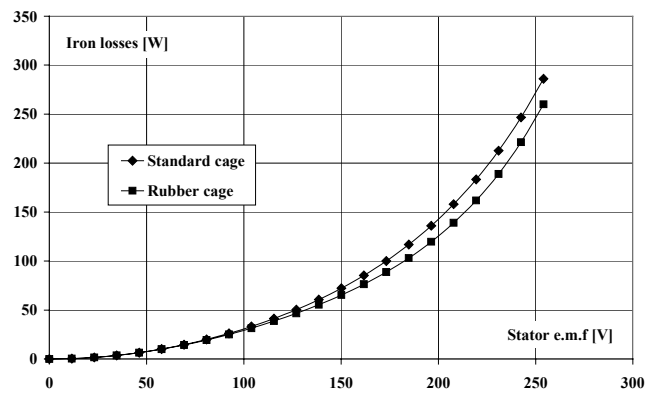


Fig.2: Comparison between the convectional iron losses measured at synchronous speed using a standard rotor cage and the rubber rotor cage (tests performed with the same stator).

In order to quantify the additional joule losses in the rotor cage due to the harmonic current induced by the winding spatial harmonics, synchronous no load tests have been performed [20]. All the tests have been made using the stator of the original industrial motor. In Fig.2 the comparison between the convectional iron losses measured using the standard cage rotor and the rubber cage rotor is reported. At rated voltage an iron loss difference of about 12% with respect to the convectional iron losses of the standard rotor has been highlighted.

In order to get the most accurate values of the iron losses, all the experimental tests used for the proposed method validation have been performed using the rubber cage rotor prototype.

The prototype has been assembled using a lamination material previously tested on an Epstein frame for getting the loss contribution separation, following the procedure

described in [15]. As a consequence, all the elements requested for the iron losses prediction with arbitrary voltage supply are available. Obviously, due to the plastic rotor cage the rotor is not able to run by itself. For this reason, the rotor prototype was initially driven using a synchronous machine with same pole pair. In order to avoid the presence of slip (and related rotor iron losses) during the no load at synchronous speed, the supply frequency must be exactly the same both for the motor under test and the synchronous motor. This condition was easy to be obtained for the tests with sinusoidal supply, while for the inverter supply this condition was not possible due to the impossibility to synchronize the fundamental frequency of the inverter with the sinusoidal power supply of the synchronous motor. After some no-load tests at synchronous speed with inverter supply, it was well evident the impossibility to get a real condition of zero slip. In particular, the test results were not repetitive with a large spread of the prototype absorbed electrical power at the same electrical condition. Since any torque and speed transducer was connected between the two machine shafts, the mechanical power, exchanged between the two machines, was not measurable. So using (14) to determine the iron losses contribution this exchanged power was wrongly attributed to the motor under test iron losses, with significant reduction on the method accuracy. As previously highlighted, the main target of this work is to evaluate the goodness of the proposed method and as a consequence, an alternative solution to the synchronous no-load test has been found. In absence of a conductive rotor cage there are not rotor joule losses. So the locked rotor test on the prototype allows to measure the iron losses as close as possible to the actual iron ones, obviously including the rotor lamination iron losses. In fact, for the considered prototype, the difference between the power balance in the locked rotor test and in the synchronous no-load test is due to the presence of the iron losses in the rotor. As a consequence, if the tests with sinusoidal and PWM supply are performed with the rotor in stand-still condition, all the stator and rotor iron losses can be determined using (14) and the proposed method can be applied considering the iron losses active in the machine as a whole.

IV. MEASURED AND COMPUTED RESULTS: COMPARISON AND DISCUSSION

During the tests with PWM supply, for each measurement point the η and χ values have been measured and used for predicting the iron losses starting from the same value with sinusoidal supply. The measurements have been performed using a three phase digital powermeter (Infratek 305A) with a 800 kHz bandwidth for voltage and current inputs. As previously underlined, the hysteresis and eddy current contributions are not constant with the flux density and the fundamental frequency [21]-[23].

TABLE I
HYSTERESIS AND EDDY CURRENTS LOSS RATIO AS A FUNCTION OF THE FLUX DENSITY (EPSTEIN FRAME, 50 HZ SINUSOIDAL SUPPLY)

Flux density [T]	P_h/P_{ec} [p.u.]
0.245	5.337
0.301	5.2323
0.395	5.097
0.493	4.99
0.606	4.892
0.711	4.8181
0.848	4.737
0.955	4.684
1.002	4.662
1.185	4.5888
1.202	4.5819
1.302	4.546
1.423	4.508
1.512	4.482
1.599	4.457
1.697	4.432

For the magnetic material used in the prototype realization, the ratio P_h/P_{ec} between hysteresis and eddy current losses as a function of the flux density is reported in Table I. The tests, for the hysteresis and eddy current separation, have been done using an Epstein frame and with sinusoidal supply. The results reported in Table I concern to a frequency of 50 Hz. As well known, the flux density in the machine stator and rotor laminations is variable (tooth, tooth root, backiron, etc.). As a consequence, in order to apply the proposed method a constant average value of 4.753 has been adopted for the P_h/P_{ec} ratio.

The tests on the prototype have been carried out using a PWM inverter with a fundamental frequency equal to 50 Hz and a switching frequency of 2 kHz. The tests have been performed with variable modulation index (fixed DC bus voltage) and with variable DC bus voltage (fixed modulation index). In all the tests a sinusoidal modulation waveform was adopted. The maximum value of the DC bus voltage has been selected in order to obtain the prototype rated voltage, with a unitary modulation index. As a consequence, the test results at rated voltage for constant and variable modulation index are coinciding, as shown in Fig.3. Taking into account the complexity of these measurements this result has to be considered as a good flag of the measure accuracy.

Fig. 3 confirms that the iron losses are strongly depending on the PWM inverter voltage regulation strategy, as shown by the authors in [12].

In Fig.4 the comparison between the measured and predicted iron losses for a variable modulation index is reported together with the values measured in sinusoidal supply. Fig.5 shows the comparison between the measured and predicted iron losses for a constant modulation index. In Fig.4 and Fig.5 the x-axis is the rms value of the stator fundamental e.m.f., while an error bars equal to $\pm 5\%$ is used for the measured values.

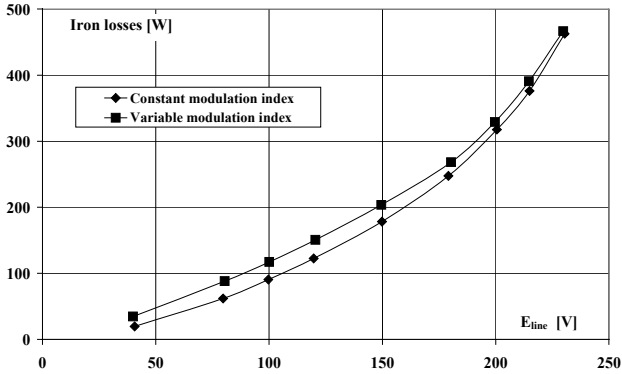


Fig. 3: Measured prototype iron losses with PWM supply (fundamental frequency = 50 Hz, switching frequency = 2 kHz, variable and constant modulation index)

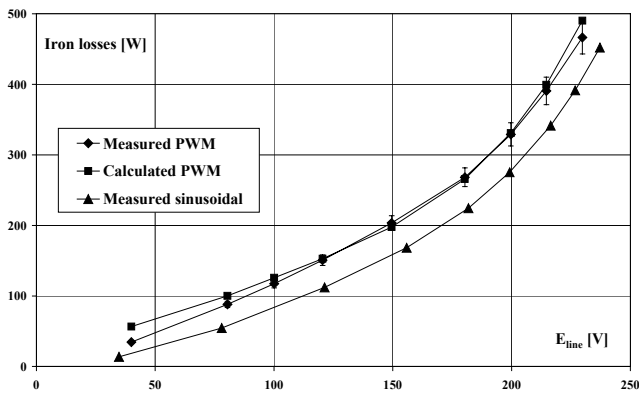


Fig. 4: Predicted and measured prototype iron losses with PWM supply (fundamental frequency = 50 Hz, switching frequency = 2 kHz, variable modulation index, error bars = $\pm 5\%$)

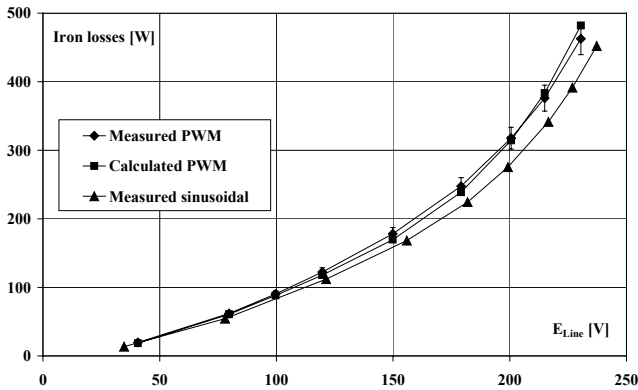


Fig. 5: Predicted and measured prototype iron losses with PWM supply (fundamental frequency = 50 Hz, switching frequency = 2 kHz, constant modulation index, error bars = $\pm 5\%$)

Fig. 4 and Fig. 5 show an excellent agreement between the measured and the predicted values, proving that the proposed method can be successfully used not only for the material, but for the induction motor too. With reference to Fig. 4, a

discrepancy between predicted and measured results is present at voltages lower than 100 V, but, on the contrary, the same discrepancy is not present in Fig. 5. It is an author's opinion that the errors in Fig. 4 are due to lower powermeter accuracy in low voltage test conditions. In particular, it is important to underline that the test results reported in Fig. 4 have been carried out with a variable modulation index. As a consequence, at low voltage, the powermeter has to measure low fundamental voltage values using a high voltage range scale, because the fundamental rms voltage is imposed modifying the modulation index while the DC bus voltage is fixed to its maximum value. For example at low voltage the ratio between the DC bus and output rms fundamental voltage can be higher than 10. This is the main reason because, with extremely distorted voltage waveform, digital powermeters with high crest factor specifications are mandatory.

Beyond the previous considerations, it is an author's opinion that iron loss prediction errors for induction motors with PWM supply lower than 5%, are a good result, in comparison with the obtainable ones using other methodologies reported in literature [9], [16], [18]. In fact, in spite of the complex phenomena involved in the iron losses [19], such as, rotating and unidirectional magnetization in the motor laminations, the proposed approach works well and it is easy to be implemented. In fact, the ratio P_h/P_{ec} and the η and χ values are requested only. In order to play fair, it is important to underline that at now the authors do not have results on induction motor with standard rotor cage. For this reason, the authors are working on industrial induction motors in the power range 4 kW-18 kW to validate the proposed method on several aluminum cage induction machines, and consequently to give more solid results on the proposed method validity.

V. CONCLUSIONS

In the paper the method proposed by the authors for the prediction of the iron losses with PWM supply in magnetic material has been used for the same purpose in induction motors. In order to reduce the iron loss measurement errors a special prototype with rubber rotor cage has been built. The results have proven the method validity, in fact, a percentage error lower than 5%, between predicted and measured results, have been obtained on this induction motor prototype supplied by a PWM inverter. Works are in progress to validate the proposed method on standard induction motors with aluminum rotor cage.

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