Abstract—This paper is related to the development of an experimental workbench for testing stator cores of fractional horsepower induction motors. The workbench is able to evaluate the quality of the stator core in terms of magnetic material, dimensions, as well as manufacturing faults as short-circuit on laminations. This new tester submits the sample to magnetic flux closer to a real machine compared to traditional testers. In spite of not allowing segregation of the losses components, this workbench compares relative magnetic losses among different electrical steels used in stators. In order to validate the workbench, tests are carried out using the same lamination with three different electrical steels having the same commercial grading. The results are compared to the traditional Epstein Frame, the Ring Coil Tester and the commonly used Dynamometer, which is a very effective process for evaluating the motor quality. The Core Tester proposed in this paper can be used without a total assembly of the machine and mechanical connection with the dynamometer itself. It can detect possible stator troubles during the manufacturing process. Samples with simulation of short circuit on steel sheets are also tested. Results show that the new tester is able to compare materials and indicate manufacturing faults.

Index Terms—Induction motors, iron losses, magnetic materials, non-destructive testing, pulse width modulation inverters, rotating machines, test facilities.

I. INTRODUCTION

In recent years the cost of materials as copper and electrical steel has increased significantly. This scenario also increases the pressure for optimized designs and the correct use of these materials in the development of electrical motors [1], [2]. Electrical steel represents one third of the total material cost of an induction motor. Moreover it also represents 30-40% of the total loss. These facts encourage researchers on effective understanding of the magnetic materials as well as finding models able to simulate and to predict the motor behavior [3]-[8].

The main characteristics of electrical steel, like losses and permeability, can be measured by different methods like Epstein Frame, Single Sheet and Ring-Toroidal tests. Each one has its
advantages and drawbacks. Lamination manufacturers tend to measure core losses more rapidly, while machine designers tend to require more accuracy [8]. In some cases, traditional core loss data (for example, those obtained from Epstein Standard tests) are not suitable to design motor. Moreover, special characteristics like the use of variable speed drives, controls sensitive to motor parameter or highly saturated machines, require core loss data on high frequencies, intense flux densities, non-sinusoidal flux and different sample temperatures [7].

Among these methods, the most popular test to evaluate electrical steel is the Epstein Frame [10]-[13]. It is a standardized test that allows the quantitative comparison of materials from the same or different manufactures. However, it is well known that Epstein Frame has some limitations. It is not able to apply field on all magnetic directions. It only generates alternate flux and does not take into account the manufacturing process of a real lamination [14]-[17]. Many papers have been presented in the way to make this test more reliable, with better material representation and easiness for its preparing [18].

Another well known method to evaluate iron losses is the Ring Coil Test. This is not a standardized test but it is widely used by the machine manufacturers and can provide additional and suitable data for them. The principle is similar to Epstein Frame, but here the primary and secondary windings are directly wound on the sample. Moreover, comparing it to the latter, this test normally is not performed with an air flux compensation. This test allows the use of the stator stack and applies magnetic flux through the whole yoke, taking into account the anisotropy of the material [19]. However, the flux does not cross the stator teeth and the rotational flux is not generated.

A variation of the Epstein Frame is the Single Sheet Test (SST), where only one lamination of the Epstein Frame is used. The SST is less expensive and time consuming. However, it has the drawback of requiring a calibration with the Epstein Frame [9]. Reference [20] shows tests carried out at very low temperature, and [21] shows a SST where rotational flux is applied.

An induction motor stator usually consists of a stack of soft material laminations, an insulation system, copper windings and connectors. Small variations of the manufacturing process result on different performances for the same motor design [22]. For example, laminations can be short circuited if the punching die or stacking process is not well adjusted, reducing the final motor efficiency.

Some papers have investigated methods to evaluate the iron losses in the final lamination form [22]. One way to evaluate the final motor efficiency is performed using a dynamometer. This test allows the designer to compare and check the final performance of the motor. It is a very effective method to evaluate the motor quality. However, it demands a considerable effort: the machine must be totally assembled (stator, rotor, bearings, and electrical connections) and must be mechanically connected to the dynamometer itself. Therefore, the main goal of the proposed tester is that, before the complete assembly above indicated, it can detect possible troubles during the manufacturing process. As a result, when considering a large scale motor production, it represents a considerable economy and
tends to produce devices with a uniform level of quality. In other words, the workbench presented here and called Core Tester, is an effective tool to improve the quality control taking into account, particularly, the fact that steels are provided by different suppliers. Thus, the main goal of this work is to qualitatively evaluate the behavior of a specific stator stack for which the tester is built. It can be seen as a limitation but it is relevant to point out that this specific motor is produced in a very large scale for worldwide appliance applications. The accurate determination of losses cannot be easily obtained with the proposed device whose primary function is to assess the quality control of randomly chosen stators produced on the assembling line.

II. WORKBENCH DEVELOPMENT

The developed Core Tester can be divided into two systems. The first one is the magnetic head where the stator core is inserted and where the magnetic flux is generated. The second one is related to the generation and control of the voltage applied to the exciting windings of the magnetic head.

A. Magnetic head

The purpose of the magnetic head is to create the magnetic flux that passes through the stator core. Many topologies have been considered for its magnetic design. The choice of the material, the number of slots and coils are fundamental to avoid saturation and minimize losses that can interfere on the result. The final design is composed by two exciting windings and two B-coils orthogonally placed in the magnetic head. As can be seen in Fig. 1, it consists of two poles, two phases, 8 slots magnetic head. In Fig.1, “x” and “y” represent the two magnetic axes.

![Magnetic head winding configuration](image)

The exciting windings can generate unidirectional flux or rotational flux in clockwise or counterclockwise direction. The B-coils are secondary windings placed on the head and they are used to supply the system with the feedback of the flux density on the head.

The control set has a power supply and a data processing module to directly control the field. The system cannot ensure or impose a sinusoidal flux in the stator core. Nevertheless, it is able to control the flux waveform in the head and can test all the samples under the same condition. Figure 2 shows the stator core under test (a) and the magnetic head (b). It can be noticed that the stator core is placed externally to the magnetic head. The air gap between the magnetic head and the stator is 0.1 mm. The test can be carried out before or after the stator is wounded.
As it will be shown, the total losses are calculated using the primary currents and the secondary winding voltages. This way, the stator and magnetic head losses are included on the same result. It is not easy to directly segregate the measured losses between the stator and the head. Therefore, to reduce as much as possible the influence of the magnetic head, very low loss electrical steel is used to build it. Moreover when assembling the stack, the laminations are rotated in order to reduce the head magnetic anisotropy.

Simulated losses in the head and the stator set using Finite Element (FE) and iron loss modeling are presented in [23]. The first purpose is to evaluate the ratio between the losses in the magnetic head and the stator core. The second one is to understand the flux density pattern in the sample. Figure 3 shows an example of the FE analyses. It can be seen that the flux passes through the stator teeth and yoke as on a real machine. In [23] the behavior of the magnetic induction in six different points of the magnetically excited stator is also presented. Among these results, as presented in Fig. 4, the radial and tangential magnetic induction evolution as well as their locus in point 6 where one observes the rotational behavior.

Fig. 2. a) Stator core under test; b) Magnetic head.

Fig. 3. Flux density calculation points [23].

Fig. 4. (a) Radial (continuous) and Tangential (dotted) inductions as function of time for point 6. (b) Corresponding Radial and Tangential inductions locus [23].

Losses calculation presented in [23] show that the magnetic head is responsible for 20% of the total losses. This value is almost independent from the primary winding current value.
The second system responsible for feeding the magnetic head has five components: protection, rectification, inverter, controller and signal treatment.

B. Protection

The workbench is connected to a standard three phase 380 V/ 60 Hz power supply with a circuit breaker to protect the system against possible short circuits. As the system has a capacitive bank, it is necessary to use resistances to limit the current peaks, avoiding the circuit breaker opening. The device produces a pre-charge of the system through the resistances that are bypassed after a predefined time. As it is necessary to supply two independent coil sets, two voltage regulators are used, allowing the voltage variation of each set independently. Two transformers are also used to isolate the system, as can be seen in Fig. 5.

![Fig. 5 - Protection block.](image)

C. Rectification

The second block has a three-phase rectifier bridge with power diodes assembled in heat sinks, a filter composed by a capacitors bank of 19.6 mF and an inductor of 28 mH. Using this block, it is possible to supply the inverter with a controlled DC bus. Figure 6 shows only one branch of the rectifier, but an identical one is used for the magnetic head second coil.

![Fig. 6 Rectifier block.](image)

D. Voltage Inverter

Each magnetic axis is associated to a voltage inverter. It has two branches of IGBTs in a full bridge topology. The switches are assembled in independent boards, and capacitors are added in the DC bus to reduce the inductive effect of the cables connecting the blocks. Also some polyester capacitors are used to decouple possible noise, compensating the inertial current on the electrolytic capacitors of the DC bus and the effect of the electrical resistance in series with the capacitors. On the same boards, inductors and capacitors form an output filter that eliminates the PWM contents of the inverter which switches at 80 kHz, keeping the waveform imposed by the reference. A transformer is used between the inverter output and the magnetic head to eliminate a possible DC voltage as well as to increase the voltage magnitude to be applied to the exciting windings. The voltage block is represented in fig. 7.
Fig. 7. Voltage inverter block.

E. Controller

The control stage consists in an analogical controller with a sliding mode strategy [24]-[26]. Its main function is to assure that the voltage waveform across the flux density sensor follows the reference signal, imposing the flux waveform in each axis.

The control loop receives the waveform signal from the induced voltage in the flux sensor and compares it with the reference signal externally generated via software. The signal error between the induced voltage in the sensor and the reference is treated by the controller and added to the reference signal [24]-[26]. At the end of the process the resulting signal is compared with the triangular waveform creating the PWM signal for the adequate driving of the inverter power switches. Reference [24] presents the steps to design the close loop control for a voltage inverter.

The signals from the magnetic head are acquired by a board composed by a resistive attenuator, a buffer and a low-pass filter to remove the noise. The attenuation is necessary to keep the signal level inside the working limits of the control circuit. It is necessary to apply the appropriate attenuation, according to the desired voltage level, or indirectly the flux density. It is possible to choose 10 levels coming from the unity, up to the maximum attenuation of 19 times the input signal. These levels also determine the voltage gains, which are used in the mathematical treatment software of the input signals.

F. Signal treatment

The Core Tester signals treatments have been carried out by developing some software systems called VI (Virtual Instrument) using LabView®. One of them is responsible for generating the voltage reference for the flux density controller. In the case of sinusoidal waveform, it is possible to define the frequency, the magnitude and the phase of the two independent waveforms. Another VI has been developed to treat the output signals, creating an interface that allows the evaluation of the sample quality.

The interface allows the user to enter sample parameters like stator mass \( m \), number of turns \( Nm \) of the exciting windings, number of turns \( Ns \) of the secondary windings, average path \( lm \) and the transversal core section \( S \). Those parameters are used to calculate variables like flux density, magnetic field and losses. One of the most difficult parameters to estimate is the average magnetic path, illustrated in Fig. 8 by red lines. The average path depends on the sample geometry and the flux density level. The influence of this parameter is reduced when comparing samples with the same geometry under the same flux density.
A digital oscilloscope is used to obtain the signals of the winding currents $I_x$ and $I_y$ in both exciting windings as well as the voltages across the windings $V_x$ and $V_y$ in both secondary windings. Those values are treated to calculate the magnetic field $H_x$ and $H_y$, using (1) and (2), and the flux density $B_y$ and $B_x$, using (3) and (4). The lower case latter $x$ or $y$ indicates the axis of the variable. For example, $H_x$ is the magnetic field in $x$ axis.

\[ H_x(t) = \frac{N}{p} m I_x(t) \quad [\text{A/m}] \quad (1) \]
\[ H_y(t) = \frac{N}{p} m I_y(t) \quad [\text{A/m}] \quad (2) \]
\[ B_x(t) = \frac{1}{N_s} \int [V_x(t) dt] \quad [\text{T}] \quad (3) \]
\[ B_y(t) = \frac{1}{N_s} \int [V_y(t) dt] \quad [\text{T}] \quad (4) \]

After calculating the magnetic field and the flux density in both axes, it is possible to create the B(H) locus for each axis as well as the $B_x(B_y)$ and $H_x(H_y)$ ones. It is also important to know the maximum flux density $B_{\text{MAX}}$, calculated by (5). The losses $P_x$ and $P_y$ can be calculated by (6) and (7) for both axes, and the total losses $P$ by (8). It will be shown that all these quantities are important to evaluate the stator core quality.

\[ B_{\text{MAX}} = \sqrt{B_{x_{\text{MAX}}}^2 + B_{y_{\text{MAX}}}^2} \quad [\text{T}] \quad (5) \]
\[ P_x = \frac{1}{n} \sum_{i=0}^{n} V_{x_i} I_{x_i} \quad [\text{W/kg}] \quad (6) \]
\[ P_y = \frac{1}{n} \sum_{i=0}^{n} V_{y_i} I_{y_i} \quad [\text{W/kg}] \quad (7) \]
\[ P = P_x + P_y \quad [\text{W/kg}] \quad (8) \]

A picture of the developed workbench is shown in Fig. 9, where it is possible to observe, from the top, the magnetic head, the signal acquisition stage, the inverters, the voltage regulators and the source with its protection stage.
III. RESULTS

In order to evaluate the workbench, a set of stator cores are produced and tested. The aim of the first test is to evaluate the ability of the system to impose rotating field on the magnetic head. The second test is carried out to evaluate the ability of the system to detect short circuit between laminations. Finally, a third set of measurements is performed to compare stators with the same geometry, but with different materials.

A. Imposing rotating field test

In the first test, a sinusoidal voltage waveform is imposed on the secondary sensor windings of the magnetic head. In other words, the flux density in each axis of the magnetic head follows a sinusoidal reference. The resulting voltage measured in the flux density sensors and the head coil currents of axes Y and X can be seen in Fig. 10. Currents and voltages are presented in the same figure and scale because their values have indeed similar magnitudes. The voltage across the sensor is sinusoidal, consequently the flux density is also sinusoidal, showing that the controller is able to create a rotating sinusoidal field.

![Fig. 9. Experimental workbench.](image)

![Fig. 10. Induced voltage and excitation current of each axes at 1.2T.](image)
The controller is able to keep the magnetic head flux waveform sinusoidal up to 1.80 T. Figure 11 shows the resulting current waveform for this condition, where it can be noticed the effect of the magnetic saturation. The difference of currents is explained by the anisotropy of the core material.

![Figure 11. Excitation current for flux density at 1.80T.](image)

A test to evaluate the repeatability of the measurement is also carried out. The same stator core is assembled, tested and disassembled five times. The workbench is able to adjust the voltage across the magnetic head to have the same flux density in each test. Figure 12 shows the results of the average losses and the standard deviation over the five measurements.

![Figure 12. Average losses and standard deviation.](image)

In order to understand the relationship between the flux density on the magnetic head and the stator core, two coils are placed on the stator teeth and on the yoke to measure the flux density as illustrated in Fig 13.

![Figure 13. Picture of the stator with coils in detail.](image)
The test is carried out with 1.80 T in the magnetic head. The tooth density fluxes along the axes are presented in Fig. 14. One observes that even if the flux is kept sinusoidal in the magnetic head, the flux in the tooth does not follow the sinusoidal waveform.

![Fig. 14. Measured flux density in the stator tooth.](image1)

Figure 15 shows the results for the yoke flux density for both axes, with a peak value of 1.56T. At this point, the flux density in the magnetic head is 1.80T.

![Fig. 15. Measured flux density in the yoke when the magnetic density flux in the head is 1.80T.](image2)

**B. Stator fault test**

A sample is prepared to test the ability of the Core Tester to detect short circuited coils. Coils are wound around the stator teeth, simulating the effect that could happen when all tooth sheets are short circuited by the punching process. Figure 16 shows the eight teeth where these coils are located. They are placed in different teeth in order to localize the short circuit position.

![Fig. 16. Stator core used in short circuit tests.](image3)

Three conditions are tested:

a) All coils opened: this condition is considered as reference;
b) Only coil 5 short circuited;
c) Only coil 3 short circuited.

The coils 3 and 5 are wounded, respectively, along the magnetic flux created by the head in the X and Y axis. Figure 17 shows the voltage waveforms measured in the flux density sensor coils for both axes for the three tests. Condition a) is presented in black line, case b) in red and case c) in blue. It can be observed that the three curves are sinusoidal and superposed, indicating that the bench is able to create and control sinusoidal flux, even when a considerable change occur in the magnetic circuit due to the short circuit. The results are shown in graphics created by the Core Tester VI.

![Fig. 17. Induced voltages on X and Y axes.](image)

Figure 18 shows the current waveforms in the exciting winding for both axes, following the same line color identification of Fig. 17. It can be observed that the short circuit affects only the magnetic axis where it is placed, indicating that it is possible to estimate the position of the fault.

![Fig. 18. Excitation current on X and Y axes.](image)

Figure 19 presents a zoom of the X axis current, where the change on the current created by the short circuit in the coil 5 is more pronounced. The current in the Y axis does not change in this case, showing the effectiveness of the procedure.
Figure 20 shows the current locus for the three cases. As expected, in the absence of a fault, the locus is practically circular for this flux density level. When there is a fault, a current increasing occurs symmetrically and according to the location of the short circuited coil. It is also clear that it is not necessary to saturate the stator core to observe the fault. For this example, the flux density is approximately 0.8 T. An additional result is given in Fig. 21. It shows the circular flux density locus on the magnetic head for the three cases. There is no difference among tests with or without short circuit, since the waveforms of the induced voltages are imposed by the control system.
From the presented results one can conclude that the Core Tester is able to detect differences in the magnetic circuit under test. In a future step of this work, the sensitivity of the workbench to different stator core faults will be evaluated.

C. Different materials comparison

In this third evaluation, a set of materials are tested using Core Tester, and compared with the traditional Epstein Frame, Ring Coil and dynamometer tests. It should be emphasized that the aim of the Core Tester is not to evaluate iron losses but to qualitatively indicate if the stators are within a desired standard of quality. The purpose of this section is to point out that among the used testers, to the Core Tester has the better agreement.

The comparison among the last three tests was already presented in [14]. Now only some results will be given in order to compare them to results obtained with the Core Tester.

Three commercial silicon steels from different manufacturers are chosen. They are denoted M1, M2 and M3. For the Epstein frame test, half of the laminations is cutted lengthwise to the rolling direction, and the second half in crosswise direction, as determined by the standards of this technique.

Figure 22 shows the comparison of iron losses measured on the Epstein Frame. The test is carried out at 60 Hz varying the flux density from 0.05 T to 1.8 T. Taking material M2 as reference (it is on the abscissa axis) a comparison between losses as function of the flux density is presented. It is observed that material M3 has the highest losses of the group.
Fig 22. Epstein Test - relative total iron losses (M2 as reference) at 60Hz [14].

In Fig. 23 the relative iron losses for the Ring Coil test at 60Hz is presented considering again material M2 as reference. Materials M1 and M3 show better performance than material M2. Moreover, for flux densities above 0.6 T, material M3 presents the lowest losses level. One observes that the results of the Ring Test and the Epstein Frame lead to different conclusions.

Fig. 23. Ring Coil test- relative total iron losses (M2 as reference) at 60Hz [14].

The relative losses using the Core Tester are presented in Fig. 24. Again, material M2 is chosen as reference. Similarly to the previous ones, the test was carried out at 60 Hz, varying the flux density level. It is important to remember that the value of flux density is measured on the magnetic head. Thus it cannot be directly compared with the Epstein or Ring test. However, the comparison between materials can be done as the lamination dimensions are exactly the same, and the system imposes the same level of flux density. Based on the Core Tester, both materials M1 and M3 are better than the reference M2. Moreover, for higher flux densities, the material M3 has the best performance of the group. These Core Tester results are in accordance with that obtained using the Ring Test.

Fig 24. Core Tester - relative total iron losses (M2 as reference) at 60Hz [14].
In order to confirm which material has the best performance, motors are produced using the same stack laminations tested in the Ring and Core Tester. The stacks are isolated and wounded using the same material in order to minimize external influences. A standard rotor is used to measure the efficiency of all samples. The test is carried out with three different voltage values for varying the flux density level in the motor. The nominal voltage of the machine is 115V, and it is tested up to 140V. Fig. 25 shows the simulated flux density in the stator tooth and yoke as function of the voltage level. The relative efficiency of the motor using again material M2 as reference is presented in Fig. 26.

From Fig. 26 it can be seen that the materials M1 and M3 have better performance than the reference M2. For higher flux densities, the material M3 is the most efficient of the group. This result confirms that the Core Tester submits the material to a test which simulates a condition close to the dynamometer test.

**IV. Conclusion**

The workbench Core Tester is presented in this paper. It is intended to perform a control quality of a large scale stator production for single phase induction motor. The aim is to evaluate, on the motor manufacturer assembly line, the quality of randomly chosen stators. The quality of the stators can be affected by punching or the electrical steel quality, noticing that steel can be furnished by different material suppliers.

The Core Tester presents a magnetically active head fed by a controlled converter which needs sophisticate techniques.
Tests performed on the Core Tester prototype show that it is able to detect anomalies in the stator core. In spite of the fact that the accurate segregation of losses can not be easily accomplished with this tester, its losses behavior detection follows the same trend of those obtained with a dynamometer. However, the use of the Core Tester does not require a complete assembling of the machine which is financially beneficial when considering large scale productions.

With these characteristics and functionalities, we estimate that the Core Tester here presented is a useful device for stator quality control in the induction motor production line. Finally, we estimate that, even though the development of the Core Tester presented several challenges and multidisciplinary techniques, the results are reliable and useful for achieving a product with constant quality.

REFERENCES


