Device for Testing the Windings of Electrical Machines

Manuel Lonić, Vatroslav Zuppa Bakša, Goran Vujisić
Zagreb University of Applied Sciences / Electrical Engineering, Zagreb, Hrvatska
manuel.lonic@tvz.hr, vatroslav.zuppa.baksa@tvz.hr, goran.vujisic@tvz.hr

***Abstract* - The topic of the paper is the digitization of the process of testing the windings of electrical machines. Windings of electrical machines create a magnetic field in their vicinity. This field should have specific strength allocation in the surrounding area to ensure regular electrical machine operation. By mapping the field strength, it is possible to create a graph of the field strength, which should follow the specified distribution. By checking for deviation, it is possible to detect winding defects. The field is mapped with induction coils, which generate voltage when inserted in the changing electric field. This voltage is then used as an indication of the magnetic field strength. The problem is that the mapping of the field by hand requires many measurements to be made, which is both a time-consuming and an error-prone process. The paper describes the device for testing the windings of electric fields. This device makes the process overall faster and more accurate. Both software and hardware workings are explained in the paper.**

Keywords* – *winding defects; electrical machines; testing; field strength

I. Introduction

During generator and motor production, various methods are used to ensure quality and industrial standards. Therefore, it is necessary to perform serial testing as efficiently as possible to achieve the highest possible time saving and thus increase earnings. This paper is the result of a collaboration with Končar-Generators and Motors d.o.o. The company played a crucial role in facilitating the testing of the device. An opportunity occurred to save time and ease the work of engineers when performing electrical machine winding testing. This test is performed to prevent an error in the early stages of production. An impulse generator is connected to the ends of the winding, which creates voltage pulses on its clamps, thus loading the winding, which in these conditions should create an electromagnet field of a specific shape and symmetry (Figure 1).

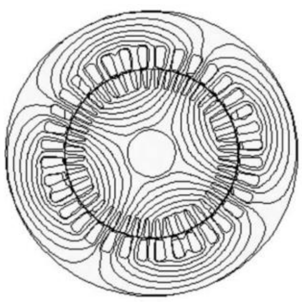

Figure 1. Shape of EMF inside induction rotor [1]

The magnetic field is sampled by a coil in which the signal used for calculations is induced.

Considering the profitability and scalability, the microcontroller was chosen for the A/D conversion of the induced signal. Further, it was necessary to design a computer application to communicate with the microcontroller and process the digital signal sent by the microcontroller. C / C ++ is used within the Visual Studio development environment for that purpose. Necessary conditions were the use of open-source technology, simplicity, and reliability.

II. Determining the health of winding

A. Winding structure

Winding elements are inserted between laminated core teeth according to the winding diagram in Figure 2.

Figure 2 is the stator winding of 2 pole motor with 24 slots. Pole step measured by the number of slots is 12.

According to Ampere's law, a magnetic field will be created in the space around the coil. The shape can be adapted to requirements using various winding methods [2].

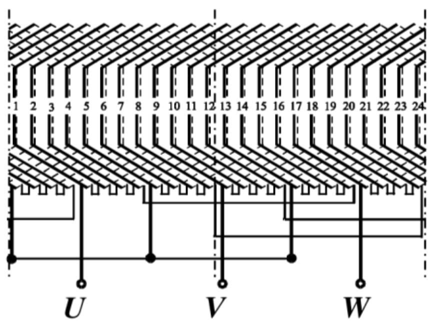

Figure 2. winding diagram [2]

B. Determining the shape of the magnetic field

The EMF (electromagnetic field) is measured using a coil that is placed between each of the teeth on the laminated core in such a way that it covers the slot. Faraday's law, written in expression (1), describes how an induced voltage will be created in the coil proportional to the speed of change of the magnetic flux and the number of loops.

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t} \qquad (1)$$

In which:

- ε - induced voltage
- N - number of loops
- ΔΦ - change in magnetic flux
- Δt - change in time

The voltage induced in the coil serves as an indicator of an EMF intensity inside the laminated core. A low-power voltage pulse generator is used to create EMF inside the core. The device loads the winding with voltage pulses that, depending on the design of the winding, creates EMF of a certain shape and intensity. Impulses are supplied to the phase outputs (U1 – U2, W2 – W1, V1 – V2) of the winding. Each phase (U, W, V) is tested separately so that the impulse generator is connected to each end of a phase that is currently being measured. EMF intensity of each slot is then sampled by placing a coil over a laminated core slot and measuring induced voltage. The process is repeated for each slot and each phase. The data acquired this way can be used to determine pole step, phase shift, and isolation compliancy [3].

C. *Determining the form of compliant winding*

A graphical display of collected data gives a clear picture of the state of the stator and is commonly used in the analysis of results. Figure 3 is a compliant example of a 16-pole rotor with 96 slots. Pole step is 6 slots.

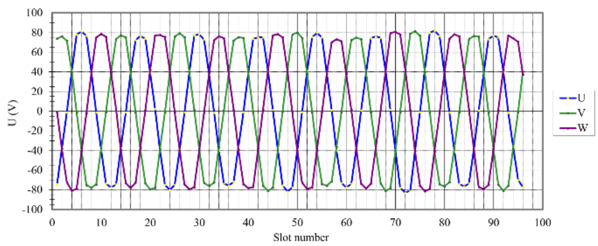

Figure 3. Compliant winding example [4]

Figure 4 shows the non-compliant measurement of incorrectly wound winding.

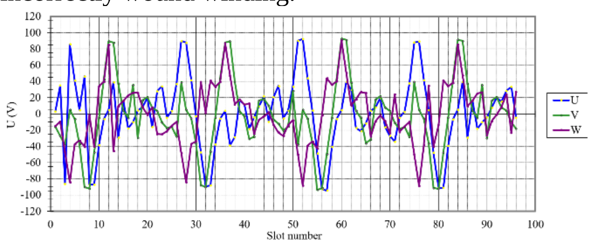

Figure 4. Non-compliant winding [4]

III. HARDWARE WORKINGS OF THE DEVICE

A. *Measurement coil*

Figure 5 shows the characteristic of different types of magnetic field sensors.

There are several types of magnetic field sensors, such as measuring coil and Hall effect sensors. From Figure 5, accuracy and sensitivity characteristics can be obtained.

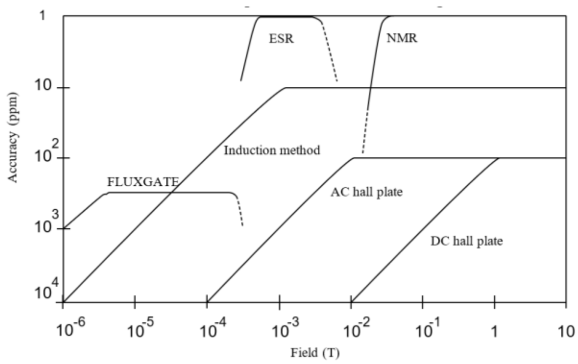

Figure 5. Measurement methods: accuracies and ranges [5]

The pulse-generating device does not supply much energy to the winding, resulting in a very weak field. Therefore, choosing a sensor that can measure a low magnetic flux density is necessary. Measuring coils (Figure 6) are used when testing windings due to their high sensitivity to the magnetic field. Their dimensions must correspond to the size of the slot [5].

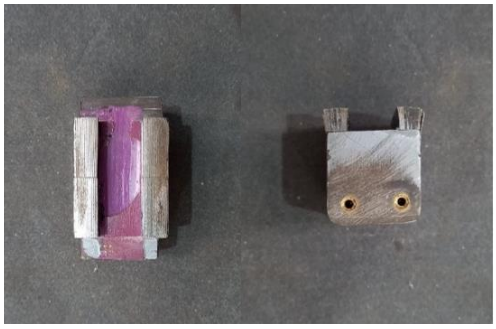

Figure 6. Measurement coil

B. *Signal processing device*

The signal conversion device is shown in Figure 7. It contains a microcontroller and a signal adjustment circuit.

Figure 7. Signal processing device

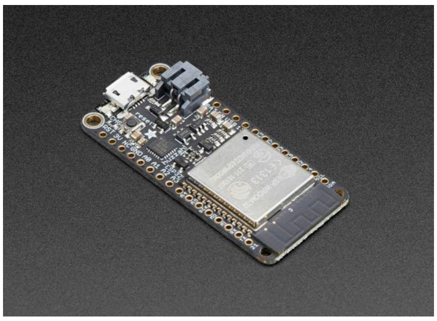

Figure 8. ESP32-based development board [6]

The microcontroller is an ESP32 model built into the Adafruit Huzzah development board (Figure 8).

It was chosen because of its 12-bit A/D converter and built-in Wi-Fi and Bluetooth capabilities, which are necessary if it is decided to modernize the way of connecting to a computer. For example, Bluetooth data transfer. Such a feature would allow the test engineer to move quickly around large stators or rotors.

The development board is insufficient for A/D signal conversion because it requires a maximum 3,3 VDC input signal while the coil's output is in the range of -300 to 300 VAC. Therefore, it is necessary to reduce the value of the signal proportionally and convert it into a DC signal.

For this purpose, a signal adjustment circuit was designed (Figure 9). Voltage reduction is performed via a voltage divider. Rectification of the signal is achieved by directing the positive part of the signal to one input, and the negative portion of the signal to another input of the microcontroller, i.e., to another A/D converter which perceives it as a positively induced signal which is later easily recognized by the software as a negative part of the signal. In this way, the resolution is increased two times compared to the resolution that can be obtained in the case of using the DC offset method.

The biggest challenge of such a circuit is determining the gain and time constant of the system. Since the device needs to work with different winding types, it must be able to cope with a wide range of EMF intensity, which can drive a signal under or over the saturation value of 0-3,3V. Therefore, it is necessary to carefully determine the gain so the device can be used on a wide range of test objects.

Formula (2) calculates the amplification of the voltage divider of the positive part of the signal. Formula (3) calculates the amplification of the voltage divider of the negative part of the signal.

$$K_{10} = R_8 / (R_6 + R_8) \tag{2}$$

$$K_2 = R_9 / (R_7 + R_9) \tag{3}$$

In which:

- K_1 and K_2 - gain of voltage dividers.
- R_8 and R_9 - resistors from which the signal is supplied to the A/D converter.
- $(R_6 + R_8)$ and $(R_7 + R_9)$ - total resistance of the divider.

K_1 and K_2 must be equal; in this case, they amount to 0,0099. However, due to the resistance error problem of non-uniformity between voltage divider R6 - R8 and the voltage divider R_7 - R_9 appears. This results in the circuit amplifying the positive and negative parts of the input signal unequally, which can lead to asymmetric results. Special resistors with a precision of 1% were used to solve this problem. Furthermore, gains of voltage resistors can be compensated in digital signal processing.

The time constant should not be too small due to the accumulation of interference but also not too large because the signal itself would not completely follow the field intensity changes. Expressions (4) and (5) calculate the time constant, which must be the same for both voltage dividers, as in the case of amplification. In this case, the time constants are 0,101 s.

$$\tau_1 = (R_6 + R_8) \cdot C_3 \tag{4}$$

$$\tau_2 = (R_7 + R_9) \cdot C_4 \tag{5}$$

In which:

- τ_1 and τ_2 - time constant.
- $(R_6 + R_8)$ - and $(R_7 + R_9)$ - total resistance of the divider.
- C_3 and C_4 - capacitor capacitance.

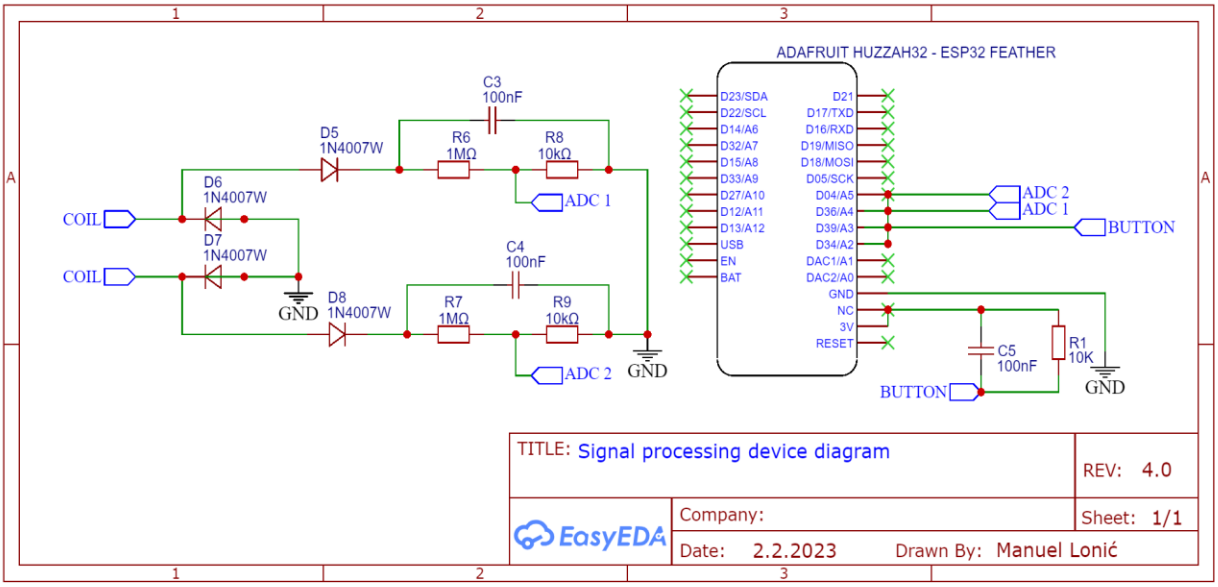

Figure 9. Schematics of signal processing device

Due to the need for system portability, the circuit was redesigned on PCB (Printed Circuit Board) technology (Figure 10).

PCB boards are carriers for electronic components on which conductors are printed, and slots are installed. The components installed on the printed circuit boards have unique housing dimensions adapted for installation on the PCB boards. The most significant advantage is the small dimensions of the final product. The PCB shown in Figure 10 is designed to be compatible with the Adafruit huzzah dimensions, meaning it can be directly installed on the development board itself.

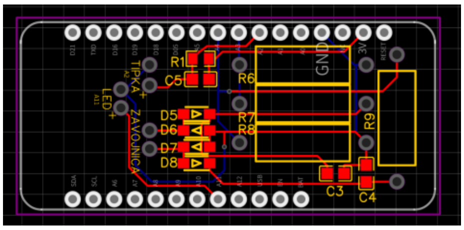

Figure 10. PCB diagram of the signal processing circuit

To achieve the system's resistance to external effects, a case (Figure 11) was designed, the dimensions of which correspond to the Adafruit development board.

Figure 11. Inner workings of signal processing device

IV. SOFTWARE WORKINGS OF THE DEVICE

A. PC application

After the obtained digital signal, it is necessary to process it and obtain values from the magnetic field of the slot, such as in figure 3. The goal is a simple computer application based on available Windows 10 technology that prints data in graphic and textual form. The application consists of a text interface (Figure 12.) for monitoring the measurement progress and a visual graph (Figure 13). The graph shows the values of the induced voltage inside the measuring coil when measuring the magnetic field around the slot.

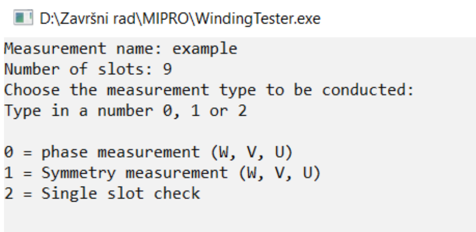

Figure 12. Textual graphics user interface

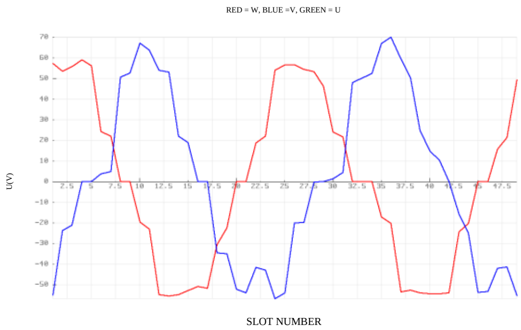

Figure 12. Graphical user interface

B. Code implementation

The software implementation conditions were to build an application on the Windows 10 platform and use open-source technologies listed in table 1. During the program's writing, problems were the creation of a communication channel between the microcontroller and the application, data processing, and display.

TABLE 1. USED LIBRARIES

Microcontroller communication	Graphing tool	Graphical user interface
SerialPort.cpp	pbPlots.cpp	opencv_world454.lib
SerialPort.h	pbPlots.hpp	-
-	supportLib.cpp	-
-	supportLib.hpp	-

Communication with the microcontroller is carried out using the RS 232 protocol, controlled by functions from the SerialPort.cpp library. In this way, the computer application communicates directly with the microcontroller. The library is available under the MIT license.

The tool used to plot the graphs from the data is pbPlots. PbPlots is an open-source plotting library that can be used with many program languages, such as C, C++, Java, JavaScript, and Python. The library is available under the MIT license.

OpenCV is used for the graphical display of results. OpenCV is an open-source library of programming functions mainly focused on real-time computer vision. The software is available under the Apache license.

C. Arduino application

The programming code for the microcontroller is written within the Arduino development environment. The Arduino code digitizes and formats the input signal into a format recognized by the application.

V. DEVICE TESTING

The measurement described below was conducted to prove the device's functionality (Figure 13).

The example below is the excitation system rotor of a hydro generator. This rotor consists of 8 poles and 72 slots.

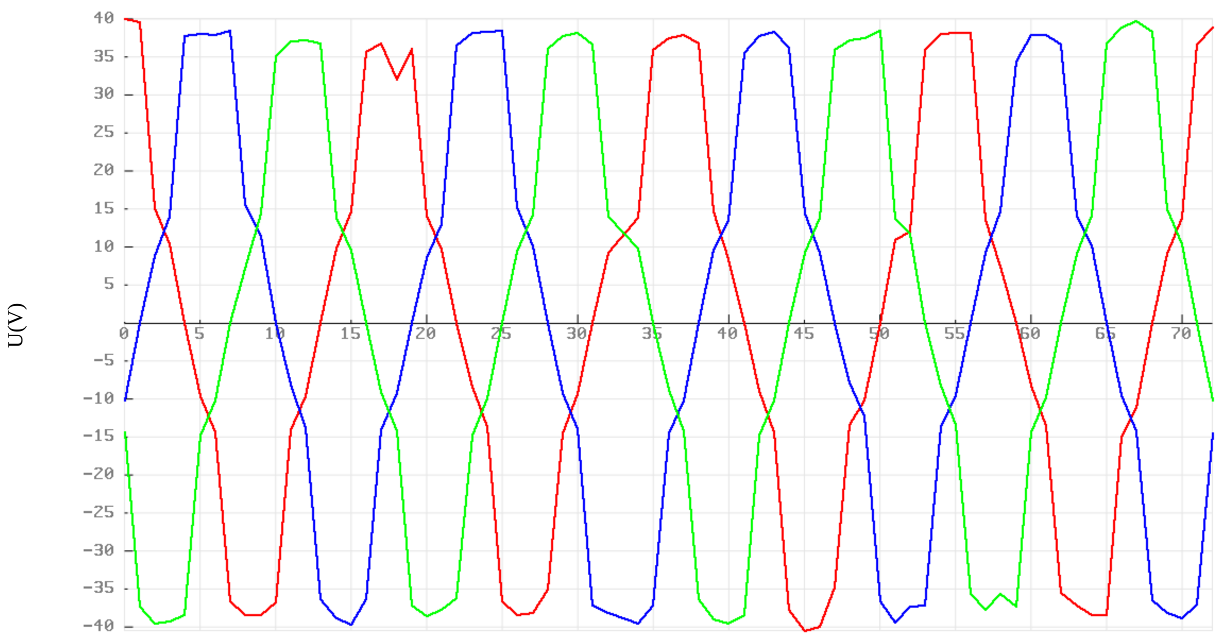

Figure 13. Measurement of the excitation system rotor of a hydro generator

Expected characteristics are a phase shift of 120° and a pole step of 9 slots per pole. Figure 13 can prove the compliancy of the winding. Furthermore, the measured results can be compared with the results obtained by the classic method of measuring each slot's EMF by hand and method, including the testing device, and thus prove the device's validity. Figure 3 shows the measurement results of a similar winding obtained by the classical method of measuring the voltage drop on the coil for each slot. From the comparison of the obtained results, it can be concluded that the results obtained by the winding testing device are credible.

The signal converter's accuracy depends on the voltage divider resistor error and the quantization error of the A/D converter. The error of the voltage divider resistor leads to a systematic error that can be compensated by software.

When calculating the voltage value of a certain point, the method of multiple sampling is applied, and the arithmetic mean of the sampled samples is calculated. The quantization error does not significantly affect the result. Only errors caused by human factors can cause incorrect results.

It is important to note that the high accuracy of the reading of the induced voltage inside the measuring coil is not overly critical because when assessing the validity of the measured object, attention is paid to the symmetry of the poles, the correct arrangement of the phases and the pole step, the case of an inter-winding short circuit results in a significant drop in the intensity of the magnetic field at only 0-20% of the expected value.

VI. Conclusion

Higher production output and increased employee productivity are two of the biggest reasons for implementing automation. Most tasks that are repeated in the same way can usually be automated. In addition to industrial processes, office work like creating reports and protocols can also be the subject of automation. As a result, automation can help engineers do their jobs faster and easier.

The goals of this project are to save time and eliminate errors from the routine of testing electrical machines. This solution removes any copying of data from forms to excel sheets or monotonous data processing. For example, it was estimated that using the classical method by hand when measuring windings with 72 slots takes 10 to 12 minutes more than with the winding testing device. Nevertheless, the most important thing is that there is no further processing of the data, which adds to time-saving, and eliminates the risk of mistakes during filing forms or copying data. While planning the development of the device, the shortcomings of the existing process were considered, and the good sides were retained. Furthermore, the built device is based on open-source technology, which ensures the possibility of constant upgrading and adaptation of the system to all further changes in the process.

References

[1] J. F. A. T. Bashir Ebrahimi, "Losses Calculation in Line-Start and Inverter-Fed Induction Motors Under Broken Bar Fault," *IEEE Transactions on Instrumentation and Measurement*, p. 14, 2013.

[2] I. Mandić, V. Tomljenović i M. Pužar, Sikroni i asnikroni električni strojevi, Zagreb: Tehničko veleučilište u zagrebu, 2012.

[3] C. P, "Fault detection in three-phase rotating machines," *IEEE Transactions on Power Apparatus and System*, 1972.

[4] KONČAR – Generators and motors Inc., *Check of t rotor winding throughput with low impulse voltage.*, Zagreb, 2021.

[5] K. N. Henrichsen, "Overview of magnet measurement methods," 1998.

[6] Adafruit Industries, "Adafruit HUZZAH32 - ESP32 Feather," 2 1 2023. [Online]. Available: https://cdn-learn.adafruit.com/downloads/pdf/adafruit-huzzah32-esp32-feather.pdf. [Accessed 2 2 2023].