Technical Note

Impulse Winding Tester ST4030A

Masami Kitazawa
DB Unit

***Abstract*—The Impulse Winding Tester ST4030A provides high-speed sampling and high-resolution measurement functionality, enabling it to detect even minuscule shorts. It expands conventional waveform comparisons with numerical comparisons to generate even higher-precision pass/fail judgments. This paper provides an overview of the product, discusses its functionality and features, and provides several examples of measurements carried out with it.**

I. Introduction

The recent transition to electric drivetrains for vehicles and the development of self-driving technologies has created demand for high-reliability onboard motors, which are intimately related to vehicle performance and safety. There is particularly high demand for more compact designs for drive motors used in electric vehicles, and the stator wiring space factor (i.e., the percentage of a coil's cross-sectional area that is occupied by wire) is increasing.

Due to the high voltages at which drive motors operate, the inverters used in controlling them produce surge voltages. When there are insulation defects in motor windings, these surge voltages produce partial discharges that cause the insulation to further deteriorate. Such deterioration can lead to shorts between windings (layer shorts) and insulation breakdown, causing the motor to burn up and posing the risk of serious accidents.

Winding insulation performance must be maintained over the long term in order to fulfill demand for high motor reliability. However, with impulse testing using the conventional approach of response waveform comparison, there is little difference between windings with minuscule layer shorts and non-defective windings, making it difficult to generate pass/fail judgments.

Hioki developed the Impulse Winding Tester ST4030A to resolve this problem. Fig. 1 depicts the appearance of the instrument.

Fig. 1. Appearance.

II. Overview

Testing techniques typically used to evaluate the quality of motor windings include winding resistance testing, withstand voltage testing (hipot test), insulation resistance testing, impulse testing, and partial discharge testing. The ST4030A is an impulse tester.

In impulse testing, an impulse voltage is applied to both ends of a winding, and the voltage waveform across the winding (the response waveform) is observed. That response waveform is then compared to the response waveform obtained from a known-good winding to generate a pass/fail judgment. This test method offers exceptional utility because it is able to detect wire breaks in windings, shorts between phases, and variations in inductance.

However, it suffers from one disadvantage: when the difference between the response waveform from a defective winding and the response waveform from a known-good winding is too small, it becomes difficult to detect the underlying defect. To carry out this testing in a more reliable manner requires a tester with a high level of detection precision and resolution so that it can distinguish minuscule waveform variations.

The ST4030A expands conventional waveform comparison with the numerical comparison of LC and RC values, which serve as judgment feature values. By quantifying response waveforms and treating them in a quantitative manner, this approach makes it possible to detect minuscule variations in response waveforms, for example one-turn shorts in windings, that would be difficult to identify using waveform comparison.

Hioki also developed the Discharge Detection Upgrade ST9000, which is available as a factory option for the ST4030A, by combining high-precision waveform detection with newly developed digital signal processing technology. The ST9000 can detect weak discharges without the need to add other equipment such as discharge detection antennas. Thanks to this capability, it is possible to detect insulation defects between motor windings with a high degree of precision. The instrument also provides insulation breakdown voltage (BDV) testing functionality.

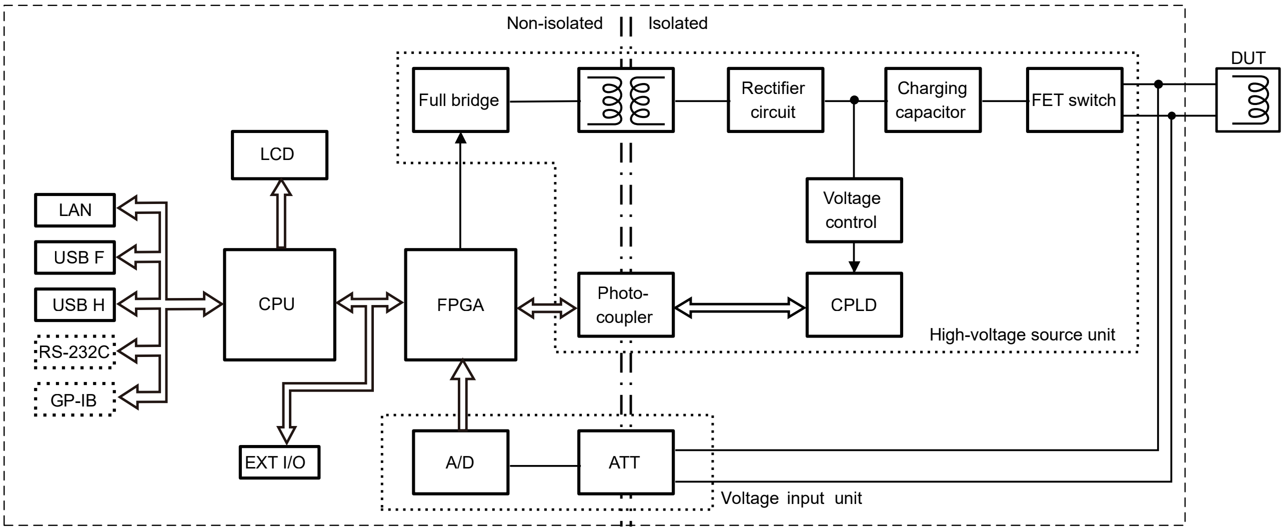

Fig. 2. Overall block diagram.

An abbreviated list of the ST4030A's specifications follows:

- Applied voltage: 100 V to 4200 V (setting resolution: 10 V)
- Testable inductance range: 10 µH to 100 mH
- Maximum sampling frequency: 200 MHz
- Sampling resolution: 12 bit

III. Functions and Features

A. *Architecture*

Fig. 2 provides a block diagram for the ST4030A. A charging capacitor is charged at the set test voltage. Then, when the pulse voltage is applied to the coil under test by a high-speed FET switch, the coil's inductance and parasitic capacitance result in a damped oscillation waveform. This waveform is sampled at high speed and compared to known-good data to produce a pass/fail judgment.

B. *Output Waveform Characteristics*

Reports in scientific literature indicate that the partial discharge inception voltage (PDIV) of drive motors used in hybrid and electric vehicles depends on factors such as the impulse voltage rising time. IEC standards define the rising time as t_r = 300 ns ±200 ns. The ST4030A is designed to ensure that the rising times for its output waveforms in all voltage ranges falls within the range of 100 ns to 500 ns (under no-load, open conditions). Figs. 3 and 4 provide impulse voltage rising waveforms for the ST4030A.

C. *High-Speed Sampling and High Resolution*

The ST4030A's voltage input unit incorporates a high-resolution 12-bit A/D converter that performs high-speed sampling at 200 MS/s. An impulse voltage of 4200 Vp can be

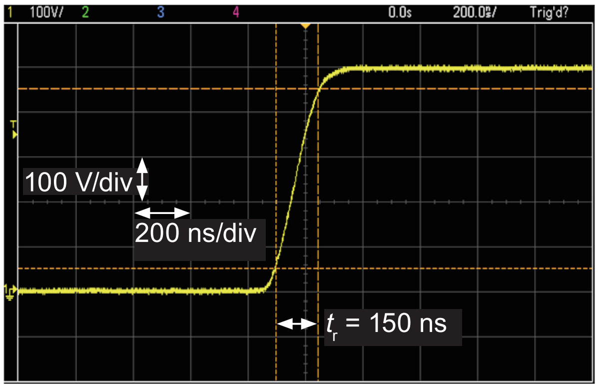

Fig. 3. Example of a rising waveform (500 V).

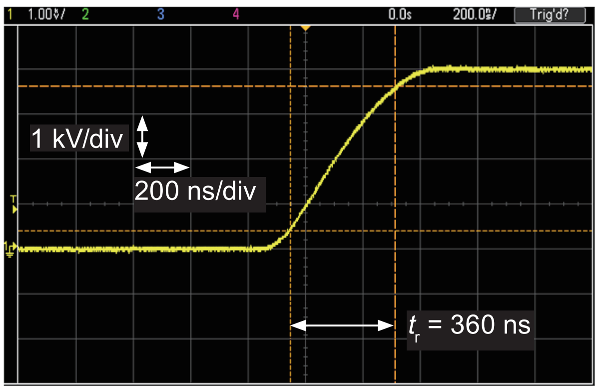

Fig. 4. Example of a rising waveform (4.2 kV).

directly input to the front end of the instrument, which can detect minuscule variations in impulse response waveforms. Additionally, multiple detection ranges are provided so that the appropriate gain circuit can be selected based on the output voltage, allowing the instrument to maintain high resolution. The impulse generation unit incorporates a dedicated 16-bit D/A converter whose test voltage can be set in a fine-grained manner, allowing the output voltage to be adjusted at a resolution of 10 V.

D. Quantification of Response Waveforms

The ST4030A provides functionality that can be used to quantify impulse response waveforms and generate judgments based on them [1]. The LC and RC values that describe an LCR series equivalent circuit consisting of the coil under measurement and the ST4030A's measurement unit are calculated from the response waveform (Fig. 5). If the calculated values are mapped on a two-dimensional plane consisting of LC and RC values, there will be a difference in the distributions of LC and RC values for a known-good motor and a motor with a layer short. By generating judgments based on a numerical comparison of LC and RC values in addition to a conventional comparison of the impulse response waveforms, the ST4030A is able to broaden its judgment range. In short, adding the numerical method using the LC and RC values to the conventional single-parameter comparison has improved judgment precision. Additionally, this approach can be used to generate judgments even when the response waveforms differ due to the rotational angle between the motor's stator and rotor.

In instances where the core material and structure of the inductor or motor causes high iron loss, the resonance waveform will rapidly attenuate, making it difficult to calculate LC and RC values. In such cases, the ST4030A uses the voltage waveform at the time of impulse voltage application to automatically calculate LC and RC values. Although these values lose their meaning as LCR series equivalent circuit constants, they can nonetheless be used to generate pass/fail judgments.

E. High Repeatability

By incorporating a proprietary charging circuit and high-voltage switching circuit into its high-voltage generation unit, the ST4030A achieves high impulse output waveform repeatability. Fig. 6 illustrates the variability in peak values observed when a 1000 V impulse voltage was output 100 times while the instrument's output terminals were in the open state.

F. ST9000 Discharge Detection Upgrade

Figs. 7 and 8 provide examples of the ST9000 display. Response waveforms are processed by a high-pass filter without using the partial discharge detection circuit. This approach eliminates applied signal components from the response waveform so that the instrument can separate and detect discharge components. This proprietary filter processing allows the ST9000 to detect partial discharge phenomena that would be difficult to detect using conventional flutter analysis or Laplacian analysis with a high degree of precision. Although its capability does not

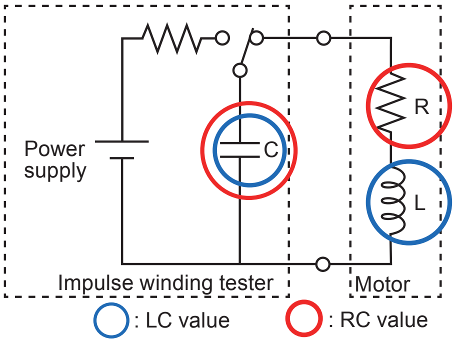

Fig. 5. LC and RC values.

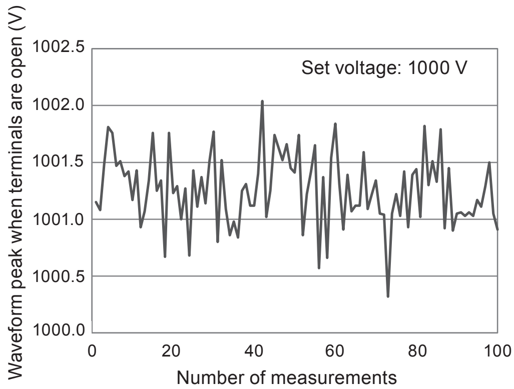

Fig. 6. Variability in impulse waveform peak values.

Fig. 7. Waveform graph display screen (with discharge).

Fig. 8. Waveform graph display screen (without discharge).

HIOKI

reach the level of dedicated partial discharge testers, the ST9000 can detect the presence of partial discharges of a certain magnitude when the impulse voltage is applied, making it well suited to use in screening applications.

Inductance, which is measured by the ST4030A, includes frequency components ranging from a maximum of several hundred kilohertz to several megahertz in impulse waveforms. The ST4030A's filter processing does not completely eliminate applied signal components, leaving the impulse waveform's frequency components to a certain extent. This approach improves detection sensitivity compared to simple filter processing. Furthermore, the instrument eliminates the need to set thresholds by normalizing filter output using the standard deviation of the thermal noise occurring in the circuit.

G. Breakdown Voltage (BDV) Test Function

Fig. 9 provides an example of the BDV test screen. The ST4030A's breakdown voltage (BDV) test function measures the response waveform while gradually increasing the impulse voltage. Partial discharge and spark discharge phenomena cause changes in the waveform, even in low-frequency bands that are eliminated by the discharge detection function's high-pass filter. Consequently, the instrument detects discharges and measures the breakdown voltage by taking into consideration not only the amount of discharge at each voltage, but also LC and RC values, waveform area values, waveform area differences, response waveform oscillation periods, and crest values.

Since the algorithm does not require a response waveform (master waveform) from a known-good winding, this test can be carried out even when there is no reference winding.

H. Support for Judgment Area Creation

In order to generate pass/fail judgments based on the distribution of LC and RC values, it is necessary to create judgment areas. To assist in this task, the ST4030A provides functionality for creating such areas automatically from known-good winding data. The function can be used not only when LC and RC values exhibit uniform distributions, but also when they exhibit belt-like distributions.

I. Faster Production Line Development

1) EXT. I/O testing: Fig. 10 provides an example EXT. I/O test screen. This functionality makes it possible to easily check operation of external control terminal (EXT. I/O) input and output signals, reducing the number of man-hours that must be spent on debugging when building a production line.

- I/O OUT
  The user selects the name (PASS, ERR, etc.) of a signal that the user would like to output from the I/O output pins. The user can then check whether the output signal is being generated properly.

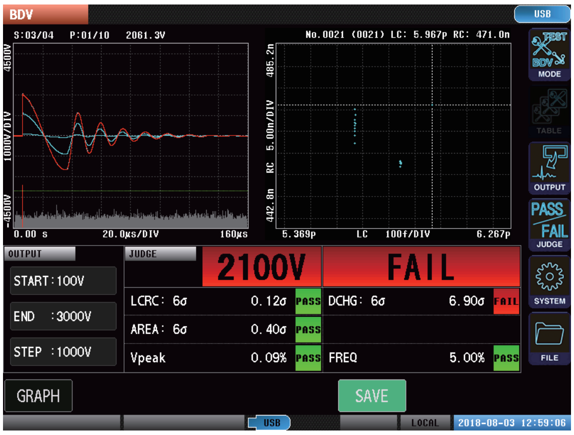

Fig. 9. BDV test screen.

Fig. 10. EXT. I/O test screen.

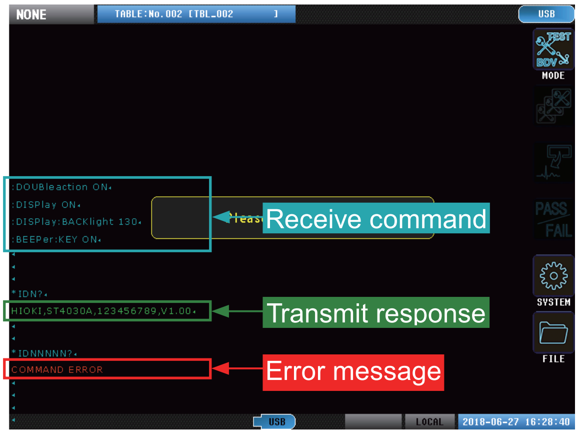

Fig. 11. Communication monitor screen.

- I/O IN
  When a signal is received by the I/O input pins, the corresponding signal name turns green on the EXT. I/O test screen (START, STOP, etc.). In this way, the user can verify that the input signal is being properly recognized by the ST4030A.

2) Communication monitor: Fig. 11 provides an example screen of the communication monitor function. Communication commands and query responses can be displayed on the screen, allowing operation to be checked in real time while building testing lines.

Verification work is simplified by the fact that the commands and messages displayed by the communication monitor are color-coded.

J. Physical Design

The ST4030A is designed to fit in half a rack so that it takes up less room in testing systems.

The product has the following features:

- The voltage input and output connectors adopt a compact design that nonetheless satisfies dielectric strength specifications.
- The instrument's 8.4-inch color TFT display with touch panel provides excellent operability and visibility.
- Operation is controlled via a simple layout of three physical buttons (power, voltage start, and voltage stop).
- Vents on the back dissipate heat and allow the instrument to be installed in a wider range of orientations.

IV. Example Measurements

A. Testing after Rotor Installation

In most motors, once the rotor is installed, the stator and rotor operate in tandem and are capacitance-coupled. Because the waveforms used in impulse testing vary with the position of the rotor, judgments based on conventional waveform comparisons cannot be made once the rotor has been installed. Fig. 12 illustrates a pair of impulse waveforms captured for different motor rotor positions. The response waveform clearly changes with the position of the rotor. Fig. 13 illustrates the distribution of LC and RC values between a motor's phases (U-V, U-W, and V-W) when its W-phase has been shorted. The figure shows how the distribution of LC and RC values changes depending on whether the phase in question is properly insulated or shorted, even if the rotor is rotated. Since judgments of the response waveforms are done numerically (LC and RC values), the ST4030A can generate pass and fail judgments even after the rotor has been installed. This capability is extremely useful when it comes to maintenance, since it means that the instrument can test motors that have been embedded in other systems without requiring disassembly.

B. Low-Voltage Impulse Testing

In impulse testing that uses waveform comparison, it is generally necessary to apply a high voltage in order to produce a sufficient difference between pass and fail response waveforms. By contrast, when judgments are based on LC and RC values obtained by quantifying response waveforms, the pass and fail distributions differ even at low applied voltages. Fig. 14 illustrates the distribution of LC and RC values for a number of applied voltages. The distributions of values for defective and non-defective coils remains clear, even at a low applied voltage of 500 V. As a result, the applied voltage can be lowered if using an impulse tester that generates judgments based on numerical value comparison, allowing damage to the circuit under test to be reduced.

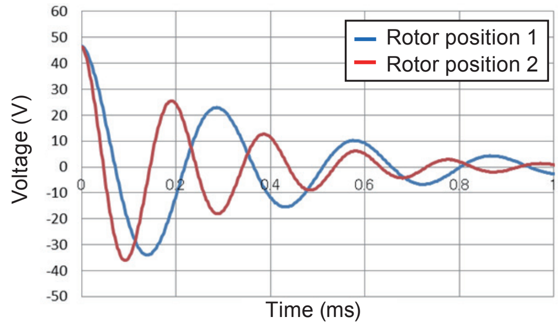

Fig. 12. Voltage waveform variation when rotor is rotated.

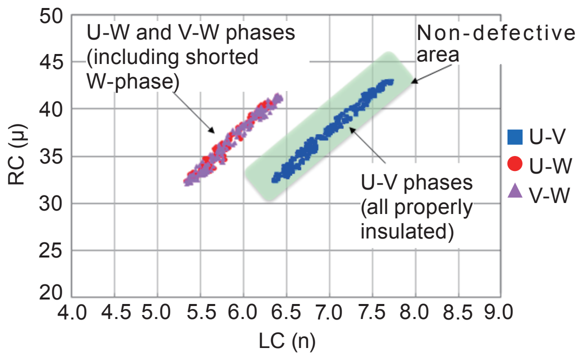

Fig. 13. Distribution of LC and RC values between each phase of a motor whose W-phase is shorted.

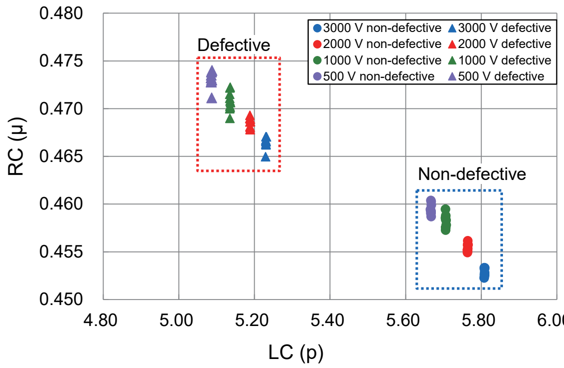

Fig. 14. Differences in LC and RC values caused by applied voltage.

C. Use of Accumulated Data to Improve Test Quality

Quantifying response waveforms generates data that can be quantitatively managed and statistically analyzed. By accumulating such data based on LC and RC values obtained from testing, it is possible to infer trends in how devices under test exhibit shorts. Fig. 15 illustrates the LC and RC value distributions for a non-defective coil and defective coils with shorts involving various numbers of turns. Since the distributions of values differ for 1-turn, 2-turn, and 3-turn shorts, it is possible to ascertain the nature of the shorts in the defective coils. This data can be used to prevent recurrences of defects and to improve the quality of testing.

V. Conclusion

The ST4030A generates quantitative judgments using characteristics values known as LC and RC values, allowing it to detect even 1-turn shorts that would be difficult to detect using conventional waveform judgment. Furthermore, the ST9000 option allows the ST4030A to clearly detect discharge components that could not be detected by the conventional numerical calculation methods. Demand for motors for use in vehicles continues to rise as automobile powertrains are electrified and as self-driving technologies progress. Hioki expects the ST4030A to contribute to the improvement of such components' reliability.

Tadashi Iijima[1], Hironori Sakurai[1], Yukinori Hayashi[1], Yuki Maita[1], Shunichi Miyamoto[1], Tsuneo Ogawa[2], Yusuke Sato[3], Megumi Yuki[4]

Reference

[1] Japanese Patent No. 5721581, TOENEC CORPORATION

[1] DB Unit
[2] MN Unit
[3] Field Design Division, Engineering Planning Department
[4] Production Engineering Division, Manufacturing Department

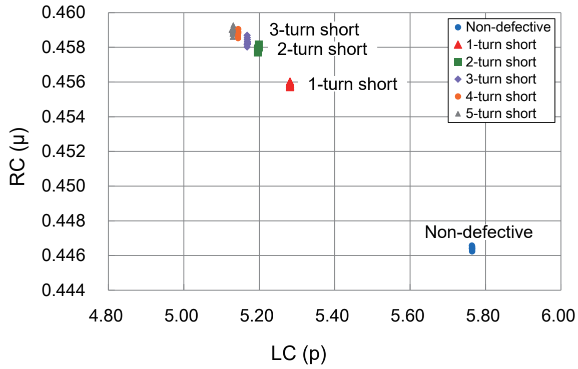

Fig. 15. Distribution of LC and RC values for a non-defective coil and coils with shorts involving various numbers of turns.