Generator Stator Intermittent Ground Fault Test Instrument - Version 2.0

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***Abstract*—The paper describes an improved design and fabrication of a novel intermittent ground fault (IGF) test instrument used in industrial generator stator ground protection. The improved instrument allows staging and acquisition of IGF data with higher precision and reliability. The instrument also enables more effective testing and validation of IGF detection algorithms contributing to the prevention of catastrophic generator stator ground faults and enhancing grid reliability.**

***Index Terms*—Generator stator ground fault protection, and subharmonic voltage injection-based (64S) scheme.**

I. Introduction

Synchronous generators are critical to the stability and reliability of the power grid, making their protection against electrical faults essential for national security.

The most common generator fault is the stator single-phase ground fault which often begins as an IGF. IGFs are characterized by high transient currents and overvoltages that can cause severe damage to insulation and generator components, potentially escalating into more severe faults and resulting in costly repairs and downtime [1] - [5].

Reports of stator IGF have sparked a renewed interest to develop reliable IGF detection schemes [6] - [8]. Specifically, [8] reports on development of a novel test instrument called 64S/87S-TI Version 1.0 by which stator IGF can be safely emulated on real-world generator stator windings resulting in valuable fault data. Acquisition of such fault data enables protective relay engineers to analyze the performance of IGF detection schemes and assess their reliability.

The goal of this paper is to report on the upgrades enhancing the functionality of the 64S/87S-TI Version 1.0. The primary upgrades include redesigning the electronic circuitry to incorporate a custom power supply, battery management system, and improved load switch topology. The Arduino UNO microcontroller (MCU) in the 64S/87S-TI Version 1.0 is replaced with an STM32 MCU, offering increased processing power and flexibility. Additionally, the instrument enclosure is completely redesigned using a combination of extruded aluminum and CNC machined panels to ensure resilience to physical stresses.

II. IGF Test Instrument - Version 1.0

The IGF test instrument named the 64S/87S-TI is an instrument designed and manufactured for stator insulation condition diagnosis in high-impedance grounded (HIG) generators [8]. Fig. 1 shows the typical schematic of the neutral grounding circuit equipped with the subharmonic voltage injection protection scheme 64S [9]. The 64S scheme is implemented using a subharmonic injection source, a bandpass filter, a 64S protective relay [10], a current transformer (CT) [11], and a neutral grounding transformer and resistor.

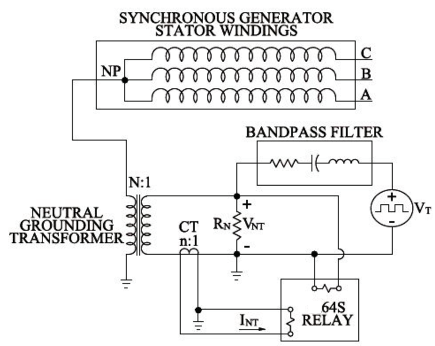

Fig. 1. Implementation of the 64S scheme in HIG generators

The instrument's main function is to stage stator ground faults and measure the *primary neutral grounding current* on the grounding transformer low voltage side [8]. Two types of ground faults can be staged using the instrument: solid ground fault (SGF) and intermittent ground fault (IGF). Fig. 2 displays the front panel of the instrument.

Fig. 2. IGF Test instrument - Version 1.0

A. SGF/IGF Test Setup

Fig. 3 shows the wiring diagram from the 64S/87S-TI to the generator neutral point. The setup is used for staging a solid or intermittent ground fault on the neutral side of the generator. When it is desired to stage a solid or intermittent ground fault on the terminal side of the generator, the AC IN connection is moved to one of the phases A, B, or C. The AC IN, EARTH, CT IN, and CT OUT connections are bundled in one plug-in port, respectively. The CT IN/OUT are, respectively, the input and output of a high-fidelity CT inside the 64S/87S-TI. The CT is capable of measuring high frequency neutral grounding current activity during intermittent ground fault [12].

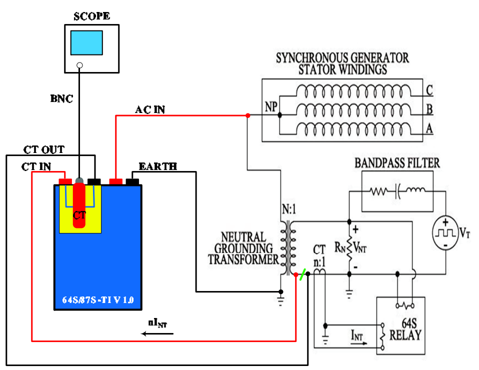

Fig. 3. 64S/87S-TI wiring connection diagram for fault staging

The principal component of the 64S/87S-TI is a single-channel AC bidirectional switch with a pair of MOSFETs, a gate driver IC and an Arduino UNO MCU. Moreover, a rotary switch is used for fault resistance selection. The complete assembly is referred to as the *load switch circuit* and is shown in Fig. 4.

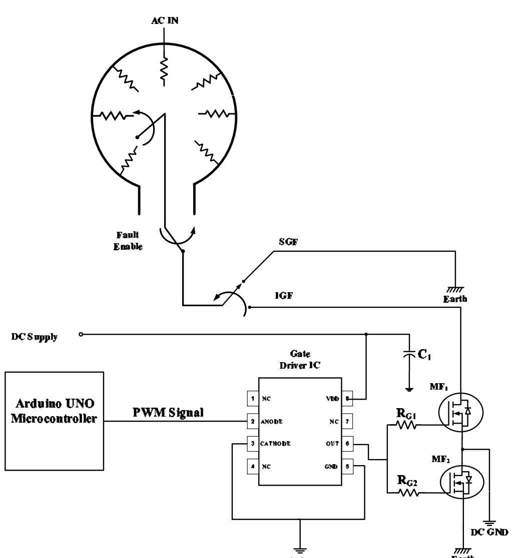

Fig. 4. Load switch circuit in 64S/87S-TI - Version 1.0

III. IGF Test Instrument - Version 2.0

The Version 1.0 of the instrument has been successfully implemented on a lab model of HIG generators to verify the reliability of a novel IGF detection scheme called the 87S [8]. However, in the process of this verification, a number of upgrades have been deemed necessary to improve the instrument's functionality and performance. Specifically, the simple rechargable lithium-ion battery in Version 1.0 has been upgraded to an electronic circuitry for regulated power supply at 5VDC and 15VDC. In addition, a battery management system has been added to provide information on the state of battery charge. Moreover, the load switch circuit topology has been completely redesigned for optimal performance and its Arduino UNO MCU has been replaced with an STM32 MCU, offering increased processing power and flexibility. Finally, the instrument's enclosure is completely redesigned using a combination of extruded aluminum and CNC machined panels to ensure resilience to physical stresses. The subsequent sections provide further details on all the upgrades.

A. Load Switch Circuit Module

The load switch circuit has seen significant improvements over the previous version. Version 2.0 retains the core design of the AC bidirectional switch shown in Fig. 4, but replaces the single-channel configuration and rotary switch for load selection with eight parallel switching channels as shown in Fig. 5.

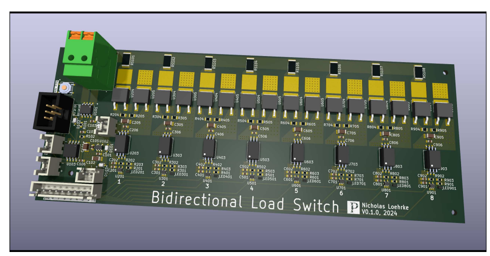

Fig. 5. Upgraded load switch circuit

This upgrade allows for a much wider range of fault resistances, as each channel can be independently controlled [resistance range figure]. The previous design faced reliability issues due to the rotary switch, a problem now eliminated with the solid-state implementation. Additionally, the new load switch integrates a microcontroller that reads an onboard Hall effect current sensor, providing overcurrent protection. The board maintains full compatibility with the previous version, supporting a single pulse-width modulation (PWM) input while also allowing up to eight PWM inputs for independent channel control. Each of the switching channels features galvanically isolated gate drivers with a working isolation voltage of 3.75 kVrms. The board logic side is powered by 5 VDC and the gate drivers are powered by an isolated 15-20 VDC supply. The onboard microcontroller provides either a simple GPIO interface, or UART.

B. Power Supply Module

The power supply module (PSM) has two primary functions: generating voltage rails and charging the battery. It utilizes two buck-boost converters to produce 5 VDC and 15 VDC power rails, with the 15 VDC rail isolated via a flyback converter. Texas Instruments TPS552872 buck-boost converters were selected for their wide input voltage range, enabling compatibility with various battery configurations. These converters also feature built-in protections, including output overvoltage protection, output short-circuit protection, and thermal shutdown. Designed to support $1-3$ cell lithium-ion batteries, the PSM integrates a switch-mode battery charger from Monolithic Power Systems, offering configurable charge current and end-voltage settings. An onboard STM32U5 microcontroller negotiates power from any USB-C Power Delivery-compatible supply for charging.

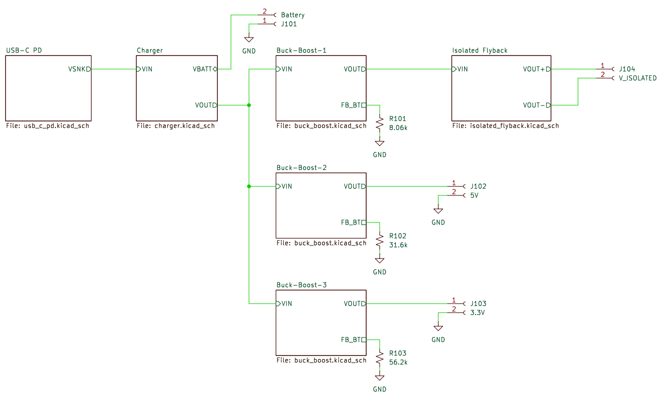

Fig. 6. Schematics of the power supply module

C. Battery Management System Module

D. Microprocessor Unit

The microcontroller unit is built around an STM32U5, handling user input, display control, load switching, and USB communication. Menu navigation is achieved using three rotary encoders, allowing precise control of settings displayed on a 3.5-inch capacitive touch screen. The display operates over an SPI interface, while touch inputs are processed separately via an I2C bus to ensure smooth and responsive interaction.

To control the load switch, the microcontroller generates PWM signals with adjustable frequency and duty cycle. Additionally, USB functionality supports firmware updates, allowing end-users to upgrade the system without requiring specialized programming tools. This ensures long-term maintainability and easy deployment of software improvements or feature enhancements. Fig. 7 shows the STM32U5 and the ancillary subsystems of the instrument.

IV. Enclosure Redesign and Fabrication

V. Functional Testing

VI. Conclusion

The paper describes the detailed steps to manufacture an enhanced version of an intermittent ground fault testing instrument by which generator stator intermittent and/or solid ground fault data can be simulated and stored. The stored data aid the relay setting calculations of generator stator ground protective relays which use the subharmonic voltage injection scheme. At present, there are no commercial ground fault testing devices by which such data can be collected.

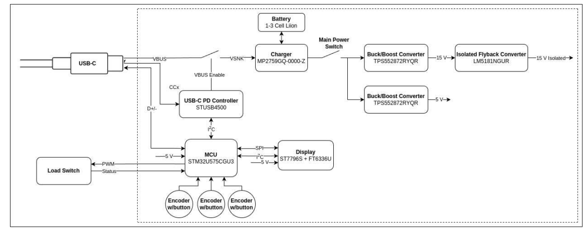

Fig. 7. Block diagram of the controller and the ancillary subsystems

Packaging the required components in accordance with industrial standards has been the main objective of this undergraduate research endeavor.

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