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RESIDUAL CURRENT MEASUREMENT

RESEARCH ARTICLE

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Cost-effective sensor for residual current detection in residential DC microgrids

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ABSTRACT

Several developments in the fields of power electronics and materials science have turned direct current (DC) power grids, which have remained in the background until now, into attractive alternatives to the existing alternating current (AC)-based power grids. Although the transition to DC is currently conceivable on a smaller scale as household microgrids, these installations still require reliable and reasonably priced protection devices to ensure electrical safety. The problem is that several existing technologies that have served us well in AC power grids do not work with DC. To ensure the electrical safety of DC networks, several smart power semiconductor switch-based fast DC circuit breakers have appeared on the market, combining the features of a circuit breaker, a smart relay, and an energy meter. However, in most cases, such combined circuit breakers lack the feature of measuring the fault current, which is crucial from the point of view of electrical safety. The reason is the high price of these sensors and their rather large dimensions, which prevent the creation of compact devices. This article examines the possibilities of creating cost-effective residual current sensors, based on integrated magnetometers, and evaluates the usability of such sensors in potential household DC microgrids, based on the prototype created.

1. Introduction

The most important features of modern electrical systems are reliability and safety of use. To ensure electrical safety, it is crucial to measure the leakage currents occurring in the electrical system in order to identify dangerous situations that may have arisen either as a result of a failure of some part of the electrical system or as a result of an electric shock to the user. This task is complicated by the abundance of power electronic devices, which themselves also generate leakage currents and electromagnetic interference, making it difficult to obtain adequate measurement results and distinguish interference from a real dangerous situation. Over time, several sensor solutions operating on different principles have been developed and successfully implemented in practice.

At the same time, the development of power electronics has enabled the increasingly widespread use of direct current (DC) power networks. DC power networks have several advantages over the existing alternating current (AC) power networks. Initially, however, a wider use of DC is expected in residential pure DC microgrids [1–3] and hybrid AC/DC microgrids [4–6]. Similar to AC power networks [7], DC power networks also require reliable methods for detecting leakage (residual) currents [8–10], but not all methods used so far work with DC. Several solutions that have come onto the market are expensive and thus hinder a wider transition to DC technology. A new approach and new technological solutions are needed. Figure 1a shows a typical household DC power network with various loads, accessories, and protection devices. A residual current sensor can be either a stand-alone device or integrated into a solid-state circuit breaker (SSCB) (Fig. 1b).

Low cost is not the only criterion when designing a leakage current sensor [7,11]. These sensors must be able to measure the current difference in milliamperes in electromagnetically "noisy" environments in electrical conductors, with nominal currents up to tens of amperes. During the faults and short circuits [12], the current can briefly increase up to several hundreds of amperes. The general electrical requirements for this type of sensor are shown in Table 1.

This article analyzes various schematic and structural solutions to create a low-cost and relatively compact DC fault current sensor that could be integrated into

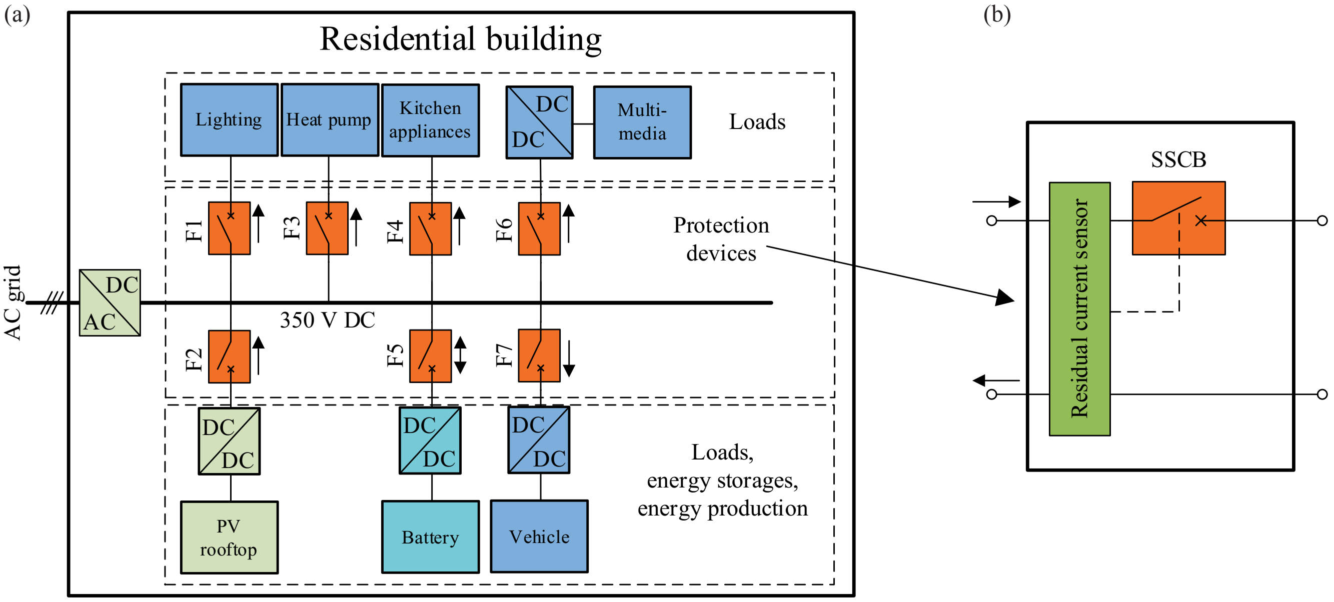

Fig. 1. Protection devices in residential DC microgrid (a) and SSCB-integrated residual current sensor (b).

Table 1. Required parameters for residual current sensors

Resolution of current difference measurement (mA)	Residual overcurrent alarm level (mA)	Nominal current (A rms)	Maximum pulse current (A)	Nominal voltage (V)
1	6	16	150	350

Table 2. Technology analysis of residual current sensors

Sensor technology	Suitable for DC	Advantages	Disadvantages
Current-transformer-based sensor [13]	No	Reliability, precision, galvanic isolation	Saturation of core, dimensions, not suitable for DC
Shunt-resistor-based sensor [14]	Yes	High precision, cost-effectiveness	Not isolated, susceptibility to electromagnetic interferences, losses in measurement circuit
Rogowski-coil-based sensor [15]	No	No saturation effect, compact	Susceptibility to electromagnetic interferences, low precision
Hall-effect-based sensor [16]	Yes	High precision, cost-effectiveness, longevity	External magnetic fields lower the precision, high temperature affects the measurement results
Fluxgate-based sensor [17]	Yes	Less sensitive to external magnetic fields, high precision	Large physical dimensions, high power consumption

multifunctional semiconductor-based circuit breakers used in residential microgrids. Table 2 lists the different leakage current measurement technologies and their suitability for use in AC or DC power grids.

As it can be seen form the above table, the residual current measurement sensor technologies that are well suitable for use in DC microgrids and are galvanically isolated are hall-effect- and fluxgate-based sensors. The fluxgate-based sensors are less sensitive to external magnetic fields and therefore well suitable to be integrated into compact solid-state DC circuit breakers [18–20]. The following article is partially based on the research previously published in [21,22]. The proposed solution described in the article [22] used the standalone residual current sensor Western Automation RCM14-01, while the solution proposed is based on the Texas Instruments integrated magnetometer DRV425 with additional external circuits. The current publication also takes a deeper look at residual current sensor technologies used in DC microgrids and describes the practical challenges of integrating magnetometer-based cost-effective fluxgate sensors with SSCBs, including improving the sensitivity of fault current measuring, degaussing the magnetic core, and optimizing sensor topology for cost-effectiveness.

2. Fluxgate-type residual current sensors

The working principle of the fluxgate sensor is based on Faraday's Law of electromagnetic induction. There are various practical methods for building fluxgate sensors, but the basic version of such a sensor consists of a magnetic core and an excitation coil with a number of turns N_S (Fig. 2). Electrical wires conducting the currents to be measured (I_{pp} and I_{pn})

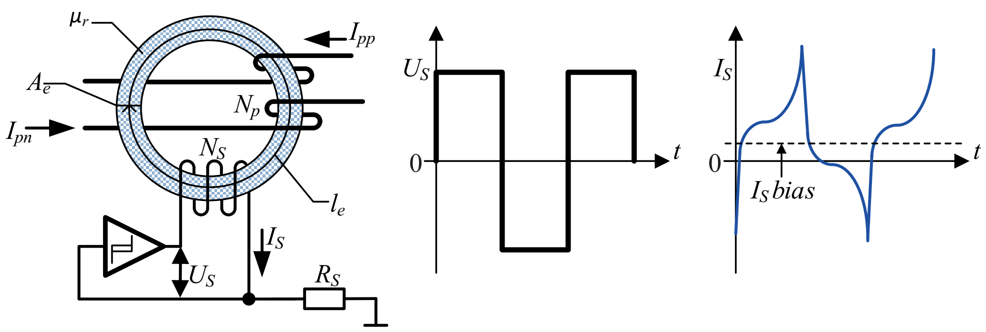

Fig. 2. Basic fluxgate sensor (open loop, no compensation), excitation coil voltage U_S and excitation current I_S waveforms [20].

form a simple one-turn, or sometimes multi-turn, primary winding through the core.

Increasing the primary coil's number of turns N_p can boost sensitivity, but this can be mechanically challenging due to the relatively wide cross-section required for the wires. In addition, the increased inductance of the power circuit must be considered. The design of the primary windings and related problems are discussed at the end of this chapter.

A current I_S is created in the excitation coil by connecting it to a circuit that produces an alternating square-wave voltage signal U_S [20,23]:

$$I_S = \frac{l_e B_{sat}}{\mu_0 \mu_r N_S}, \tag{1}$$

where B_{sat}, is the flux density saturation, l_e is the magnetic path length, μ_r is relative permeability, and μ_0 is the permeability of the empty space [23].

Then the excitation coil's current value is calculated by using the voltage value that is measured across a shunt resistor R_S. One RC (resistor–capacitor) filter, an amplifier, and a microcontroller with an analog input can be used to build a measurement circuit.

The magnetic core is selected with characteristics that cause core saturation and a drop in the excitation coil's inductance L_S, with each half-cycle of the current flowing through it, thus changing the current waveform (Fig. 2). The voltage change on resistor R_S can be used to measure that change. Inductance L_S is expressed as follows:

$$L_S = \frac{\mu_0 \mu_r N_S^2 A_e}{l_e}, \tag{2}$$

where A_e is the cross-section area of the magnetic core [23].

The waveform of I_S is shifted (biased) when current I_{pp} passes through the primary winding, and the second harmonic value of I_S is proportional to the value of I_p (Fig. 3), albeit not exactly linearly.

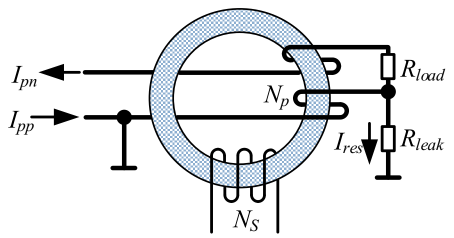

Fig. 3. Measurement of residual current with fluxgate sensor.

The periodic saturation of measurement coils as a result of the fluxgate magnetic core excitation is one of the major drawbacks of such simple fluxgate sensors. The existing sensor design needs to be modified to include a second magnetic core with a secondary winding that displays reversed polarity in order to solve this problem, experienced in basic fluxgate sensors.

When the fluxgate sensor technology is used to measure residual current for electrical safety purposes, then both the positive and negative supply wires of the monitored load R_m are simultaneously passed through the fluxgate sensor's magnetic circuit (primary winding) (Fig. 3). The value of the residual current I_{res} is determined by subtracting the positive conductor current I_{pp} from the negative conductor current I_{pn} [20]. A compensation coil is frequently inserted around the magnetic circuit of fluxgate sensors in order to improve measurement accuracy and eliminate the influence of external magnetic fields:

$$I_{res} = I_{pp} - I_{pn}. \tag{3}$$

3. Practical realization of fluxgate sensors

The practical design of fluxgate-type sensors is facilitated by several factors, including the fact that several well-known electronics manufacturers have come up with integrated solutions. For example, Texas Instruments has come up with a fully integrated ("on-chip") fluxgate-type magnetometer DRV425 [24] and a semi-integrated fluxgate magnetometer DRV421 [25] with some external components. Inside DRV421, a special electrical circuit is integrated into the chip to generate electrical signals in the external compensation coil (Fig. 4a). The advantage of this solution is high measurement accuracy, and the disadvantage is the requirement to use additional coil with a fairly large number of turns and a magnetic core with rather specific properties [26,27].

The advantages of the solution-based DRV425 are simplicity, low cost, and lower requirements for the properties of the magnetic core. The disadvantages are lower measurement sensitivity, greater susceptibility to external interferences, and the need to use a degaussing coil (Figs 4b and 6b) with the corresponding driving circuit.

As mentioned above, it is possible to increase the sensitivity of fault current measuring devices based on both the DRV425 and DRV421 sensors by increasing the number of turns in the primary winding N_p. However, it must be taken

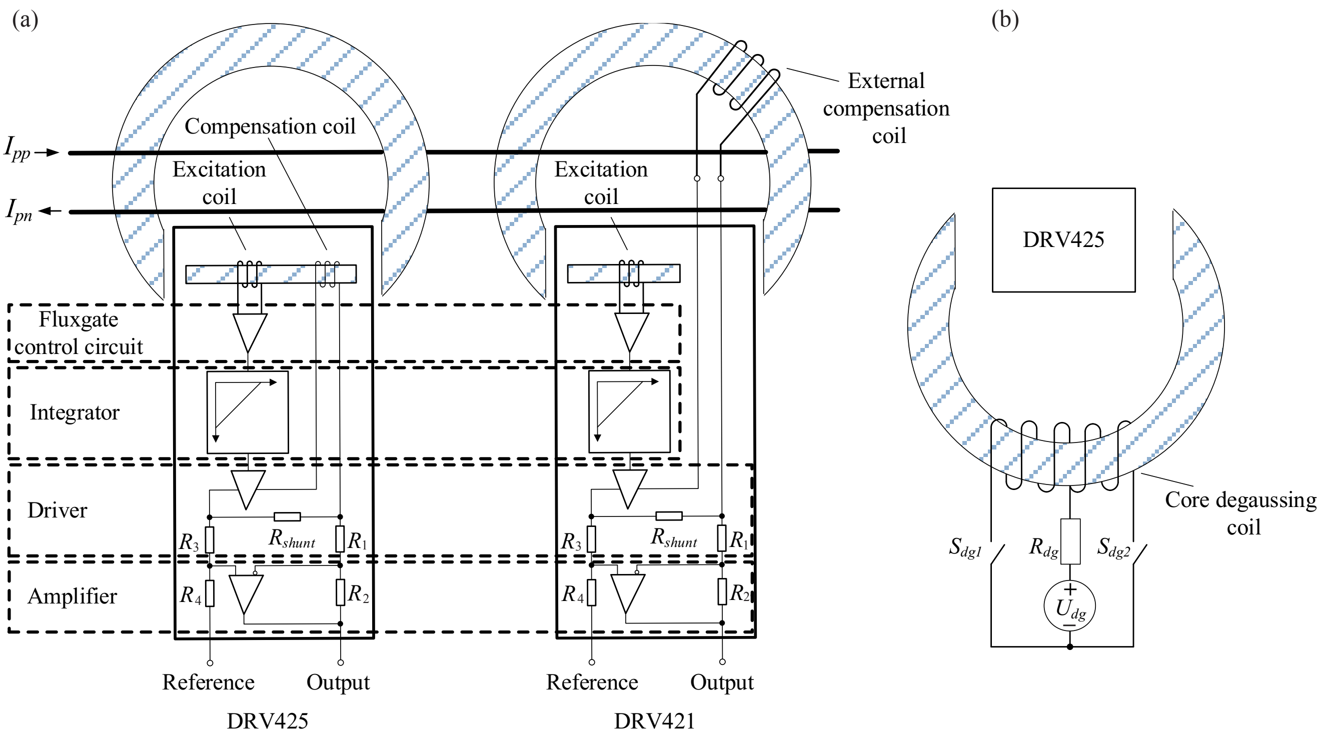

Fig. 4. Texas Instruments DRV425 and DRV421 integrated circuit-based residual current sensors (a) and core degaussing coil (b).

into account that by increasing the number of turns in a given winding, we also increase the inductance of this winding and, consequently, the inductance of the entire protection device. Inductance can be reduced by interleaving the positive and negative circuit current conductors of the primary winding. Interleaving can be practically and economically realized with the utilization of printed circuit board-based windings, as it can be seen in Fig. 6. Design challenges of such planar inductive elements are well covered in [28,29].

4. Cost-effectiveness analysis of proposed sensor design

To assess the cost-effectiveness of the proposed sensor solution compared to existing devices, it is necessary to analyze the main components required to assemble both devices. It is not reasonable to list specific component prices in this article, as component prices are volatile and depend on quantities and confidential agreements between the supplier and manufacturer. A typical commercially available residual current sensor has closed-loop self-oscillating fluxgate topology that is presented in Table 3 compared with the proposed DRV425-based residual current sensor.

The proposed DRV425-based residual current sensor solution has fewer components than commercially available comparable sensors, and those required components have lower parameter requirements. Therefore, it can be stated that the proposed sensor design is a relatively cost-effective solution for the SSCB-integrated residual current detector.

5. Experimental prototype

To evaluate the proposed residual current sensor in conditions close to a real residential DC microgid, a sensor prototype was construed that was integrated with a prototype SSCB (Fig. 5) and tested in a laboratory setup that emulates a real residential small-scale 350 V DC microgid.

A DRV425 fluxgate magnetometer and a ferrite core with a 5 mm air gap (Fig. 6a) make up a low-cost integrated leakage current sensor prototype.

Table 3. Cost-effectiveness analysis of residual current sensor design

Component	Typical commercially available closed-loop self-oscillating fluxgate residual current sensor	Proposed DRV425-based residual current sensor
Magnetic core	Nanocrystalline magnetic core with high relative permeability	Ferrite core with low relative permeability
Excitation coil	External copper wire excitation coil	Internal part of the integrated circuit DRV425
Feedback coil	External copper wire feedback coil	
Excitation circuit	Components: shunt resistor, comparator, voltage divider, and transistor half-bridge coil driver	
Feedback circuit	Components: shunt resistor, operational amplifier, integrator low pass filter, and transistor half-bridge coil driver	
Degauss coil	Not used	20-turn copper wire winding with a current limiting resistor
Control system	Microcontroller-based stand-alone control system	Not used, measurement and control functions are integrated into the control system of the SSCB

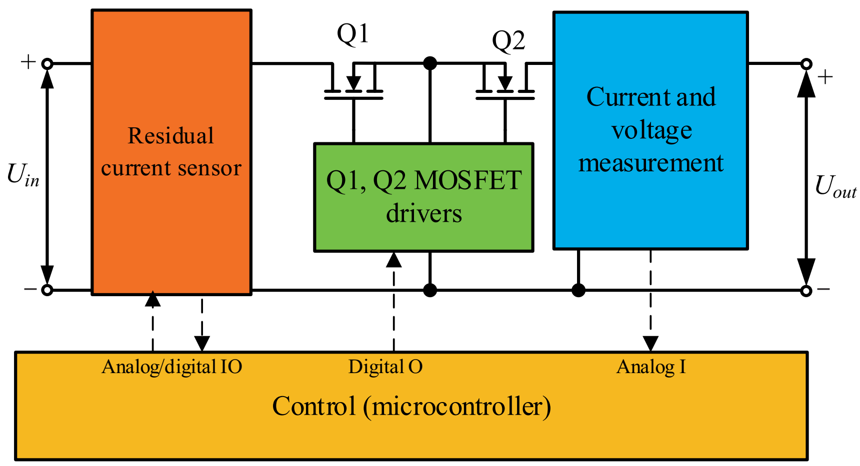

Fig. 5. Experimental SSCB prototype with residual current sensor.

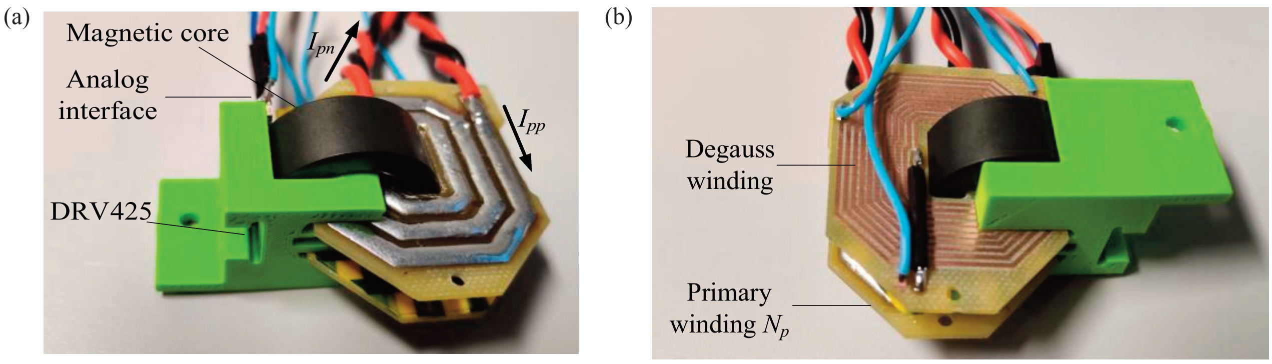

Fig. 6. Residual current sensor prototype top view (a) and sensor prototype bottom view (b).

The residual current sensor is connected to the SSCB prototype. The analo output of the leakage current sensor is linked to the SSCB control system's 12-bit analog-to-digital converter. When the previously set value of the residual current limit has been exceeded, then the SSCB control system will disconnect the SSCB output from the DC grid. The SSCB prototype (Fig. 7) is made up of transistor driver circuits, an auxiliary power circuit, a control system, voltage and current measurement systems, and a bidirectional switching cell, consisting of two MOSFETs (metal–oxide–semiconductor field-effect transistors) and RCD (resistor–capacitor–diode)-type snubbers that are used to supress the overvoltage impulses. Both the short circuit and overload currents are measured using a current-sensing shunt resistor. To measure the DC grid voltage, a voltage divider with a filter and an isolated measurement amplifier are employed.

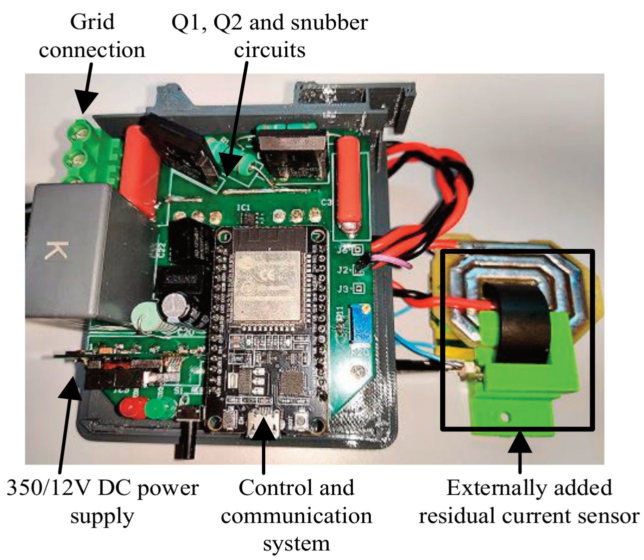

Fig. 7. DC circuit breaker prototype with added residual current sensor.

With a rated current of up to 16 A, the SSCB is designed for use in residential 350 V DC power networks. Through the appropriate software, the user can adjust the residual current, overload, short-circuit, and overvoltage limit values of the SSCB. Table 4 provides the parameters of both the residual current sensor prototype and the SSCB used in the experiments.

A laboratory setup, parametrically similar to a typical 350 V home DC microgrid, was built in order to evaluate the experimental DC grid protection technology. The laboratory setup was formed by the prototype SSCB, an external 350 V DC power supply, a capacitor, an electromechanical switch to initiate a short circuit, a load resistor, a 0.8 mF capacitor, and an external 9 µH inductor to emulate actual DC microgrid parameters and loads, as shown in Fig. 8. To establish two levels of the simulated leakage current and test the sensor's capacity to detect the 6 mA residual overcurrent, resistors R_{L1} and R_{L2} (87.5 kΩ) were connected with the emulated DC grid. Table 5 lists the parameters of the experimental setup.

Table 4. Prototype SSCB parameters

Parameter	Value
Experimental solid-state circuit breaker	
Nominal voltage of SSCB (V)	350 V
Nominal current of SSCB (A)	16 A
Residual current measurement	
Magnetic field measurement sensor	Texas Instruments DRV425
Control/measurement unit	ESP 32 dual-core microcontroller with 12-bit analog-to-digital converter
Magnetic core material	Ferrite
Core magnetic path length l_e (mm)	73
Core cross-section area A_e (cm^2)	0.69
Core internal/external diameter/width (mm/mm)	19/29
Core flux density saturation B_{sat} (T)	0.3
Core material relative permeability μ_r (h/m)	2000

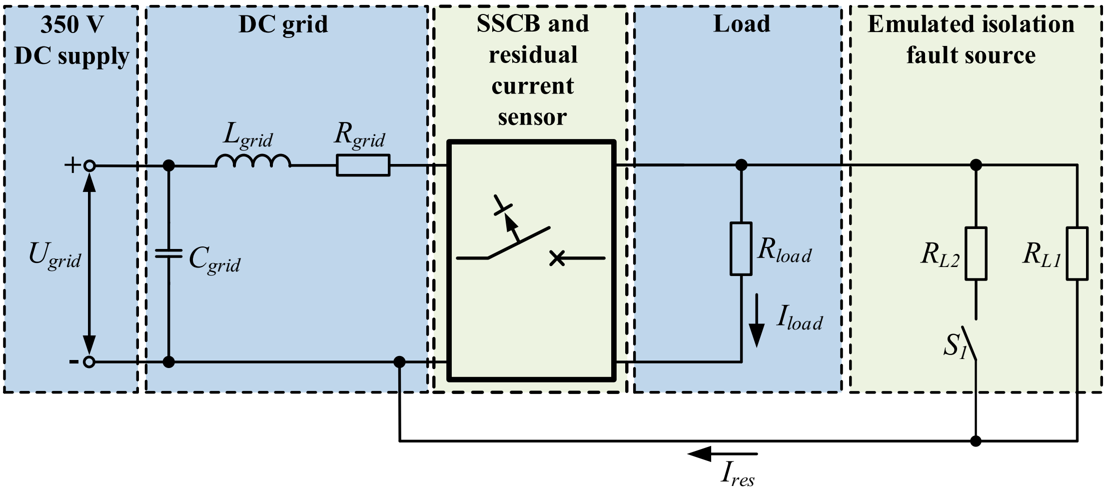

Fig. 8. Schematic of laboratory setup for residual current detection tests.

Table 5. Parameters of experimental setup

Parameter	Value
Supply voltage (emulated DC grid nominal voltage) U_{grid} (V)	350
Emulated DC grid capacitance C_{grid} (mF)	0.8
Emulated DC grid inductance L_{grid} (µH)	9
Resistors R_{L1}, R_{L2} (kΩ)	87.5
Load resistance R_{load} (Ω)	35

6. Experimental results

First, the experimental validation assessed the characteristics and capacity of the low-cost fluxgate residual current sensor to detect comparatively low DC currents. Following that, an insulation fault was simulated in an experimental DC microgrid and the residual current sensor was integrated with a prototype SSCB to show how well the new device can protect both people and equipment. Table 6 presents the plan of experiments along with the initial parameter values.

The initial experiment involved calculating the ratio between the observed current and the output voltage of the residual current sensor. The graph indicates that the sensor output voltage bias is 2.515 V, the signal to noise ratio (SNR) value is between 13.1 dB and 13.14 dB (Fig. 9a), and the ratio of the measured value to the output signal is 0.74 mV/1 mA (Fig. 9b).

The linearity error (Fig. 10) ranges from 0.3% to 2.6%. A look-up table that applies a correction value to the computed current value can be created using the linearity error values.

The measurement results from the DRV425 sensor and an external magnetic circuit were compared with the values measured using a Tektronix PA1000 power analyzer in order to evaluate the sensor measurement error (Fig. 10b). The measurement error is between –1.1% and 1.3%.

The average signal propagation latency of the tested sensor's circuit was 24 µs, demonstrating its capacity to identify variations in the residual current quickly enough for a prompt fault isolation. Fig. 11a displays the response time

Table 6. Plan of experiments

Experiment	Input parameter values
Input current I_{pp} to sensor output voltage measurement	I_{pp} range 0 to 50 mA
Sensor output signal to noise ratio measurement	
Sensor output signal linearity error measurement	
Sensor output signal measurement error measurement	
Sensor output signal propagation delay measurement	I_{pp} = 6 mA
Residual overcurrent test with experimental SSCB	I_{pp} = 16 A, U_{grid} = 350 V DC, $I_{pp} – I_{pn}$ = 8 mA

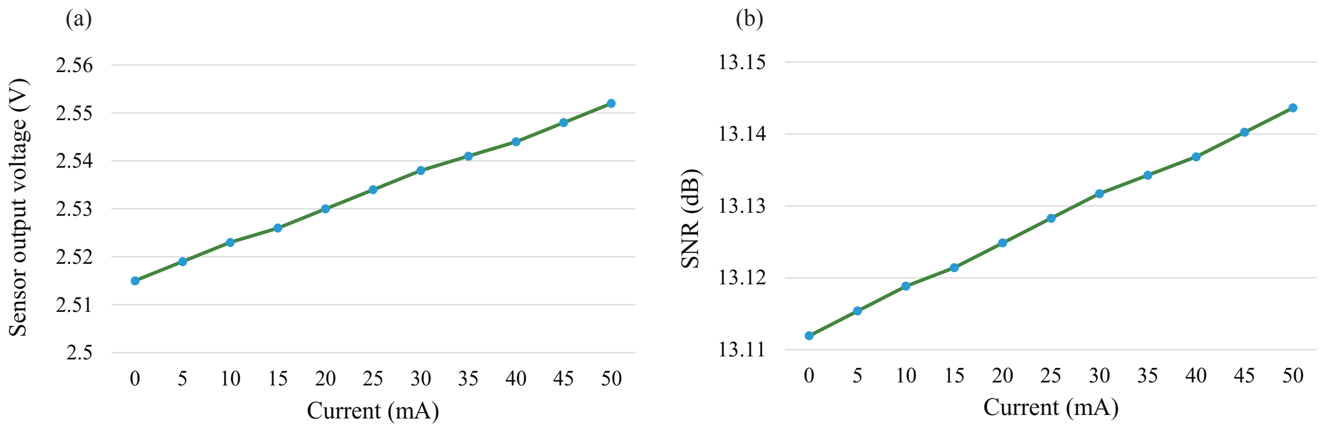

Fig. 9. Measured current to sensor output voltage characteristics (a) and output signal to noise ratio (b) [21].

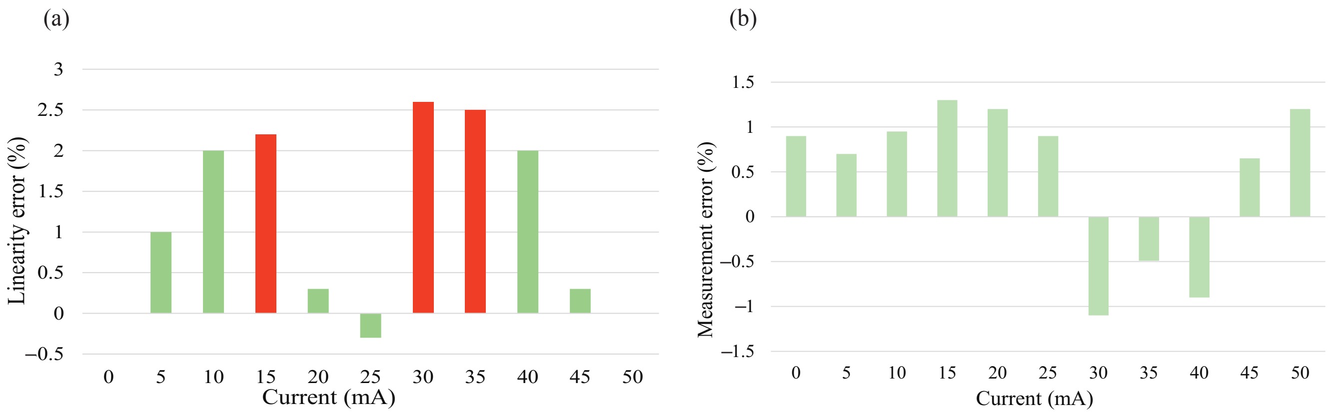

Fig. 10. Linearity error (a) and measurement error (b).

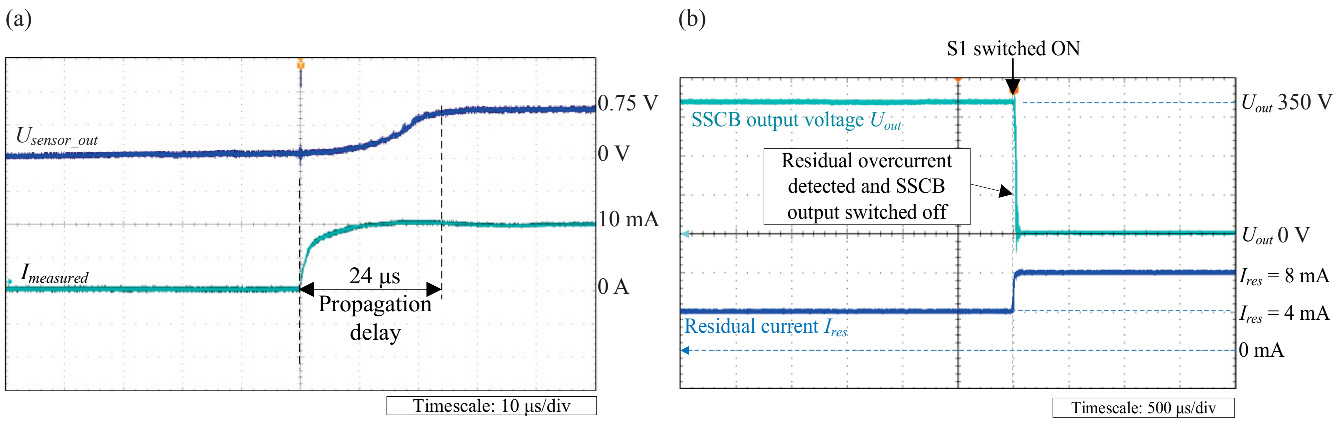

Fig. 11. Residual current sensor step response time (a) and residual overcurrent test with experimental SSCB (b).

of the suggested circuit to step changes in the observed current (the interval between a change in the measured current amplitude and a change in the sensor output voltage), with 0 V bias at 100 times amplification.

More residual current emulating resistors were added to the configuration for the final test (Fig. 11b). A signal amplifier was used to connect the residual current sensor to the analog input of the prototype circuit breaker control system. In order to simulate the inevitable leakage current found in actual DC microgrids (i.e., those produced by power converter EMI filters, etc.), resistor R_{L1} was initially connected between a 350 V DC wire and ground, avoiding the residual current sensor. This resulted in a 4 mA leakage current. In order to simulate an electric shock or an electrical isolation failure, resistor R_{L2} was eventually swapped in parallel to the first leakage simulating resistor, raising the residual current level to 8 mA. In order to isolate the fault source, the integrated residual current sensor measured the current difference between the positive and negative wires of a 350 V DC bus. The measurement result was then sent to the SSCB control system via an analog signal and a measurement amplifier. The SSCB control algorithm responded to the rising residual current level within 20 μs by turning off MOSFETs Q1 and Q2.

7. Conclusions

The current study explains how the safety mechanisms of residential DC microgrids guard against a range of issues, including residual currents, overloads, short circuits, and overvoltages. A number of technologies that are appropriate for AC networks, including Rogowski coils and current transformers, are not directly applicable in DC-based electrical systems, while residual current sensors that are appropriate for DC grids are rather large and costly. However, integrated fluxgate magnetometers make it possible to build appropriate current sensors for leakage current measurement. This paper outlines the design, construction, and testing of a residual current sensor for use in DC solid-state circuit breakers that include residual current detection capabilities. A preliminary sensor prototype was constructed to conduct practical tests. A DRV425-integrated fluxgate technology-based magnetic field sensor, developed by the company Texas Instruments, with an external magnetic core, an open loop design, and an integrated self-oscillating circuit was used to detect the residual current. During the tests, it was determined that this sensor has sufficient characteristics to perform the intended task and is capable of detecting leakage currents of up to 1 mA in DC microgrids, responding sufficiently quickly, withstanding repeated short circuits, and operating long-term with a current of up to 16 A. Several shortcomings were also identified, such as sensitivity to external magnetic fields and the need to improve the design of the primary windings. It can be stated that despite these shortcomings, the proposed sensor is able to perform as required and, after some development work, can be used even in applications where electrical safety is a critical aspect.

Data availability statement

The data used as the basis for the research described in the article are contained within the article.

Acknowledgments

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Majapidamiste alalisvoolu mikrovõrkudes kasutamiseks mõeldud kulutõhus rikkevoolu sensor

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Mitmesugused arengusuundumused jõuelektroonika ja materjaliteaduse vallas on muutnud seni tagaplaanile jäänud alalisvoolu elektrivõrgud atraktiivseteks alternatiivideks senistele vahelduvvoolupõhistele elektrivõrkudele. Kuigi üleminek alalisvoolule on praegu mõeldav eelkõige kodumajapidamiste mikrovõrkude tasandil, on nendes paigaldistes siiski vaja töökindlaid ja mõistliku hinnatasemega kaitseseadmeid elektriohutuse tagamiseks. Probleemina võib välja tuua, et mitmed senised tehnoloogialahendused, mis on meid hästi teeninud vahelduvvoolu elektrivõrkudes, ei toimi alalisvooluga. Alalisvooluvõrkude elektriohutuse tagamiseks on turule toodud nutikaid jõupooljuhtlülititel põhinevaid kiireid alalisvoolu kaitselüliteid, millel on nii kaitselüliti, nutirelee kui ka energiatarbimise mõõtmise funktsioonid. Samas puudub sellistel kombineeritud kaitselülititel enamasti rikkevoolu mõõtmise võimalus, mis on elektriohutuse seisukohalt ülioluline. Põhjuseks on sensorite kõrge hind ja küllaltki suured mõõtmed, mis takistavad kompaktsete seadmete loomist. Artiklis vaadeldakse võimalusi odavate rikkevoolusensorite loomiseks integreeritud magnetomeetrite baasil ning hinnatakse loodud prototüübi põhjal selliste sensorite kasutatavust kodumajapidamiste alalisvoolu mikrovõrkudes.