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Study of Arcing Processes in Circuit Breakers by Means of Spatially Resolved Magnetic Field Recordings

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Abstract

Magnetic field measurements performed on a circuit breaker in order to study the switching arc processes are presented. Characteristic for these measurements is the spatial two-dimensional recording of the magnetic field with simultaneous high temporal resolution. A sensor head was developed for this purpose, which records the magnetic flux density in an area of 42 mm x 60 mm with a spatial resolution of 12 x 24 measuring points. A highly integrated sensor chip based on the Hall effect was used for the design. The configurability of this sensor chip makes it possible to adapt the time resolution to the measurement task, always in compromise with the amplitude resolution and the number of field components to be measured. Measurements with a sampling rate of 80 kHz were conducted. Also, with the sampling rate reduced to 25 kHz, three axis measurements could be performed. By combining two sensor heads into one measuring system, it was possible to perform simultaneous measurements at the two contacts of a low-voltage circuit breaker with double breaker. As a result, both slow and fast changes in the magnetic field caused by the arcing process were recorded and visualized. The changes in the field distribution measured with the two sensor heads correlated well with the respective arc voltage. With the help of such magnetic field measurements, study of the arcing processes in low-voltage switchgear should be made possible without interference of the arc itself.

1 Introduction

Continuous development is required in the field of switchgears. The increasing demands of current and future electrical distribution grids are driving this development. To be mentioned here are the change from a purely unidirectional to a bidirectional supply structure, the increasing spread of direct current networks or the use of new storage technologies. Continuous improvement of the performance of protective devices such as low-voltage circuit breakers is essential to ensure that they meet upcoming challenges. The arc behaviour during the switching operation is crucial for the switching performance of a breaker. By modifying the contacts and the breaking chamber, the arc behaviour can be optimized.

The use of a high-speed optical camera enables observation of the arc during a switching process lasting only a few milliseconds. This diagnosis method requires an optical access into the breaking chamber. Since low-voltage circuit breakers are usually designed with a moulded case, modifications are necessary to gain optical access. Therefore special laboratory samples are used with housings that are transparent, have cut-outs [1], holes or optical fibres inserted into their housing wall [2]. Such modifications to the laboratory samples make it impossible to rule out influences on the arcing behaviour. Especially the application of other materials in the switching chamber can in turn influence the arcing process. For example, the different gas emission characteristics of the transparent material introduced can change the flow and pressure conditions inside the chamber and thus the behaviour of the arc.

2 Literature on Magnetic Switchgear Diagnosis

With magnetic field measurements, it is possible to test switching devices without influencing the switching behaviour itself. Blaise Pascal University in France published work on this subject between 1990 and 2008. Three different concepts were presented. First, they presented a method called "Magnetic Camera" [3] [4] [5]. Based on a simplified model switch, up to 88 pickup coils attached to the outside of the switch detect the magnetic field. The arc was modelled as a polygon line between the electrodes divided into segments. A nonlinear system of equations based on the law of Biot-Savart was established. The movement of the arc was be reconstructed by inversion and thus e.g. the re-ignition of the arc could be investigated. In a more advanced method, referred to as "Inverse Method", up to 14 Hall effect sensors were used instead of micro coils to detect the magnetic field [6] [7]. The reconstruction was also based on a non-linear system of equations. The influence of the quenching plate configuration, the contact material and the circuit chamber material were investigated. In addition, the current commutation during re-ignition was examined in more detail by modelling two arcs using two separate polygon lines. In a third method, called "Deconvolution Method", the arc was modelled as narrow volume elements between the electrodes instead of a polygon line [8]. The homogeneous current density in each of these elements was reconstructed by inverting a linear system of equations. This method was combined with the "Inverse Method" to investigate the commutation of the current from the moving contact to the electrode. All three methods have in common the use of a simplified model switch, the restriction of the arc movement to two dimensions and the use of Biot-Savart not considering magnetic materials.

Reichert and Berger [9] were also able to determine the arc root movement with pickup coils arranged alongside arc rails. The influence of the current in the rails on the magnetic field measurement was excluded by the arrangement of the coils.

Ghezzi et al [10] theoretically described the current density reconstruction in vacuum circuit breakers by magnetic field inversion. With the help of methods such as singular value decomposition, regularization and temporal filtering, the reconstruction was improved. However, it turned out that this method is only capable of a rough reconstruction of the course of the arc. An exact determination of e.g. the shape of the arc's roots is therefore not possible.

At Jiaotong University in Xi'an, China, a magnetic field sensor array with 8 x 8 Hall effect sensors was presented and used to investigate the influence of quenching plates and ferromagnetic inserts on the arc movement [11] [12]. The sampling rate of the sensors was 20 kHz. Further work describes the reconstruction of three-dimensional current density distributions from magnetic field measurements [13]. The model is based on a simplified switching chamber. A paramagnetic behaviour of the quenching plates and eddy currents in the quenching plates and busbars are considered. In addition, the influence of a real sensor on the reconstruction was examined [14]. The averaging of the magnetic field over the active sensor surface, the tilting and errors in the sensor positioning are taken into account.

3 Measuring System

In order to be able to study fast arcing processes with the help of the magnetic field, a measuring system is required that combines a spatially resolved measurement with a high temporal resolution. Due to the fast arcing process lasting only a few milliseconds, a sampling rate of several kilohertz is required. Commercial measuring devices are available for spatially high-resolution two-dimensional measurements of magnetic fields [15] [16]. However, the sampling rates of about 1 Hz to 100 Hz of these systems are too low for the intended application. For this reason, we developed and built our own magnetic field measurement system particularly designed for this purpose. The developed measuring system consists of several sensor heads, for synchronous measurement at multiple positions. Currently five sensor heads are available to take the measurements. Each sensor head records the magnetic field in a rectangular area, which is equipped with individual sensor ICs (integrated circuits).

3.1 Sensor Technology

For the measurement system, we use the highly integrated sensor IC FH5401 from Fraunhofer IIS [17]. This sensor chip combines six Hall effect sensors, a temperature sensor, the analog and digital signal processing and a sequence control in one IC package. The Hall effect sensors are arranged in two spatially separated measuring points called pixel cells with three sensors each for the three spatial directions as shown in **Fig. 1**. A vectorial detection of the magnetic field is therefore possible. The IC is controlled via a serial peripheral interface (SPI). Due to the configurable sequence control, adaptation to different measuring tasks is possible. For example, you can choose which of the integrated sensors are used and the sampling rate and resolution at which they operate. The integrated temperature sensor allows compensation of the temperature-dependent gain of the Hall effect sensors.

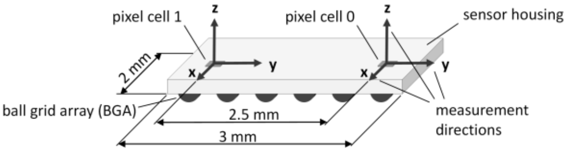

Fig. 1 Packaging of the FH5401 sensor IC.

The two configurations "Single Axis" and "Three Axis" were used for the measurements shown in this paper. **Table 1** lists the data of both configurations. Both use only one measuring point in the IC to achieve the high sampling rates. The "Single Axis" configuration uses only one Hall effect sensor in the IC, which allows a high sampling rate of 80 kHz. The "Three Axis" configuration uses three Hall effect sensors in one measuring point instead. This allows us to record the magnetic flux density in magnitude and direction. Further configurations are possible. Considerable options include increasing the sampling rate to over 100 kHz or using both measuring points in the IC at a reduced sampling rate.

TABLE 1. USED CONFIGURATIONS FOR FH5401.

	Single Axis	Three Axis
Axis:	Bz	Bx, By and Bz
Sampling rate:	80 kHz	25 kHz
Range:	±50 mT	±50 mT
Resolution:	160 µT	270 µT

3.2 Sensor Head

The main components of the sensor head are the sensor board and a control board. The sensor board is equipped with 288 FH5401 sensor ICs. These ICs are arranged in a rectangular 12 x 24 array. The sensor array covers an area of 42 mm x 60 mm, resulting in spatial resolution of 3.5 mm in x-direction and 2.5 mm in y-direction. The sensor board is connected to the control board via board-to-board connectors to form a single unit. The main component of the control board is an FPGA (field programmable gate array), which simultaneously controls and reads out all sensor ICs and temporarily stores the measured data. A plastic housing ensures the targeted airflow from the mounted fan to the sensor board. The rear of the sensor board is cooled to prevent overheating of the sensor ICs on the front of the board. The complete sensor head can be positioned as a unit on the object to be measured. A PC controls the sensor head using a USB interface.

3.3 Measuring Procedure

A command sequence is loaded from the PC into the FPGA to prepare a reading. The command sequence is specific to a sensor IC configuration. Thus, separate sequences are required for the "Single Axis" and the "Three Axis" configurations. After the acquisition duration has been set, you can start the measurement. An auxiliary board to which all camera heads are connected synchronizes the start of the measurement. In addition, this board provides the connection of the peripherals for igniting a thyristor and the control of an auxiliary trigger. After completing the measurement, the magnetic field data temporarily stored in the FPGA is transferred to the PC. There the offset and temperature-dependent gain correction is carried out.

4 Measurements on a Circuit Breaker

4.1 Measurement Setup

The arcing processes in a circuit breaker are studied by performing simulated switch-off operations of a device. The test specimen was a low-voltage circuit breaker with a rated current of 250 A and a rotary double-breaker system. An outer phase of the three-phase device was tested. A test setup was built to conduct the measurements, which is shown in **Fig. 2**. With the contact system initially closed, the switchgear is subjected to a semi-sinusoidal current waveform with an amplitude of up to 3 kA and a duration of 10 ms. This is achieved by discharging a capacitor bank via a choke designed as an air-core coil. During this discharge, the circuit breaker is then remotely tripped by an auxiliary release and the contact system opens. The current flow, driven by the capacitor voltage and the choke, creates an electric arc between the contacts. The time at which the device is tripped can be varied according to the phase of the current.

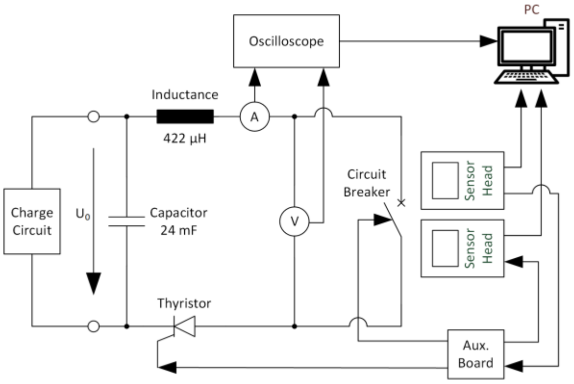

Fig. 2 Schematic of the test setup.

During the arcing process, two sensor heads mounted on the outer wall of the switch detect the magnetic field. **Fig. 3** shows the arrangement. The measuring plane is aligned parallel to the contact system. The two measuring areas are each positioned at the height of the quenching plate arrangement of the two breakers of the double breaker system, as shown in **Fig. 4**. This should allow observation of the arc interaction with the quenching plates, with the focus on the outward and inward movement of the arc. In addition to the flux density, the current and voltage are also measured. A tap on the moving contact piece measures the voltage for both breaker points.

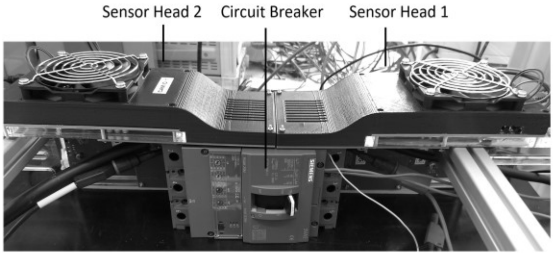

Fig. 3 Picture of the measurement setup.

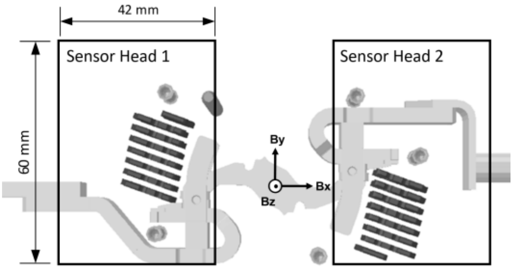

Fig. 4 Location of the measurement areas of the two sensor heads.

4.2 Single Axis Measurement

Fig. 5 shows the current and voltage curve of a measurement. The current reaches a maximum of 1.4 kA. The voltage was measured for both contacts of the double breaker. At t = 1.3 ms the switch opens, which is indicated by an arising voltage across the contacts. The two voltage curves differ mainly by the many high-frequency peaks and drops in the voltage across contact 2 (u2). In contrast, only a few but larger voltage drops can be observed at contact 1 (u1).

The magnetic flux density in the z-direction was measured with the single axis configuration at a sampling rate of 80 kHz during the entire simulated switch-off process. The lower part of Fig. 5 shows a section of the voltage waveforms. Here, the time points of the magnetic field measurements for a range of 225 µs are shown. **Fig. 6** shows the recorded field distributions at these times for both sensor heads. Each pixel in the images represents the measured value of a sensor IC. The field distributions of the two heads show changes during the observed period, each locally limited. The field changes result from the change of the current path within the switching device, which is generated by the opening of the contacts and by the arc movement. Sensor head 1 shows a slow change in the field distribution, which is expressed by a one-time change in the sign of the flux density. A shift in the current density distribution within the switching chamber relative to the sensors can cause such a change in sign. Sensor head 2, on the other hand, detects many fast changes, each of them happening in a few samples. These findings correlate well with the voltage curves, as sensor head 1 is positioned near contact 1 and head 2 near contact 2. Rapid changes in the field always occur with sudden voltage drops.

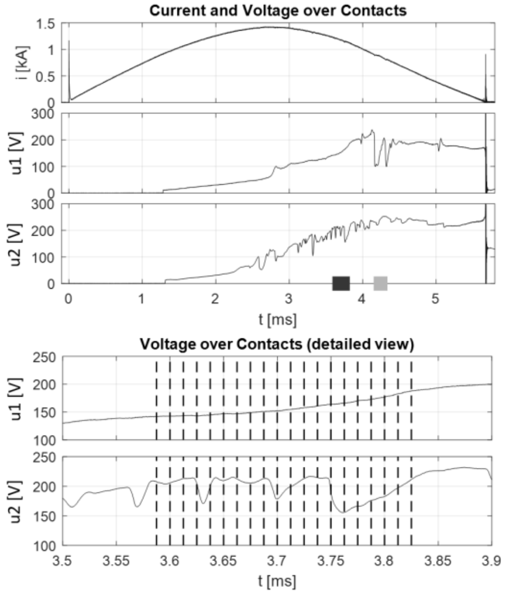

Fig. 5 Current and voltage over contact 1 (u1) and 2 (u2) during single axis measurement (rectangles on the t axis: investigated periods. bottom: detailed view with marked sampling points of the magnetic field).

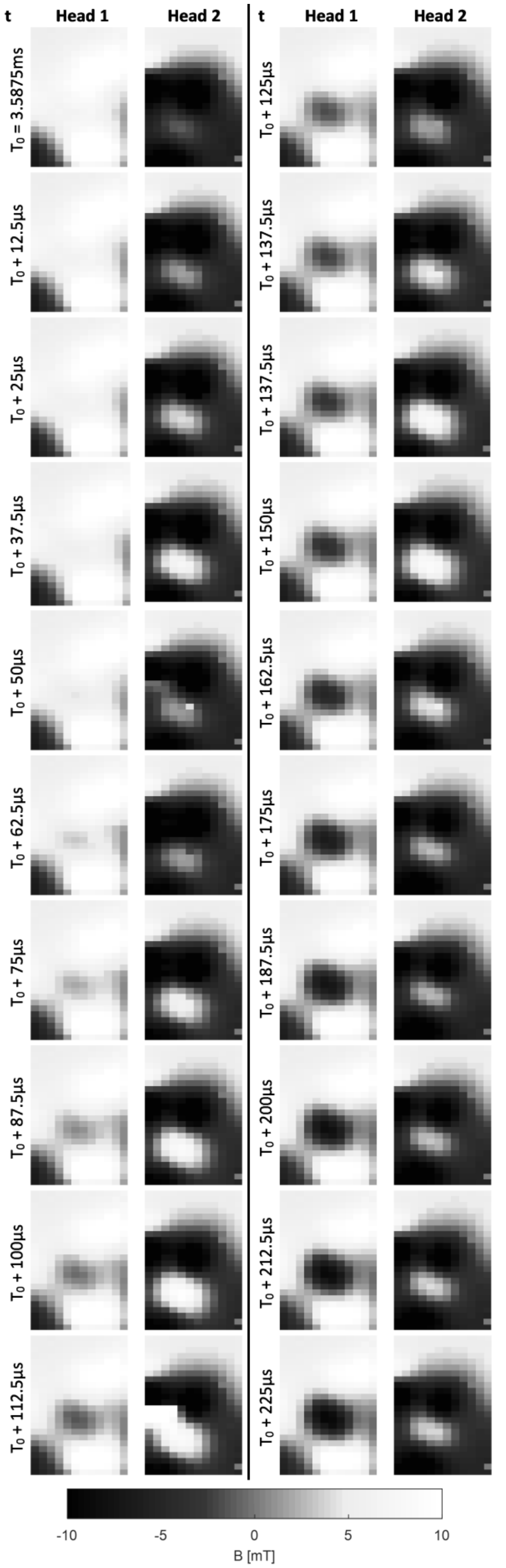

Fig. 6 Magnetic field distribution in z-direction of sensor head 1 and 2 from t = 3.5875 ms to t = 3.825 ms.

Fig. 7 shows a different timeframe of the same single axis measurement. It is noticeable that the voltage across contact 1 now shows large drops. In the field distributions from sensor head 1 shown here, the voltage drops correlate well with changes in the field. In the magnetic field at T_1 + 12.5 µs a strong deflection of some nearby sensors is noticeable, which occurs at the time of a sudden voltage drop. This voltage drop indicates a very fast arcing process. Therefore, it is possible that sensor IC internal effects or interactions with the circuit board cause the deflections shown in the field. Further investigations are necessary to investigate this.

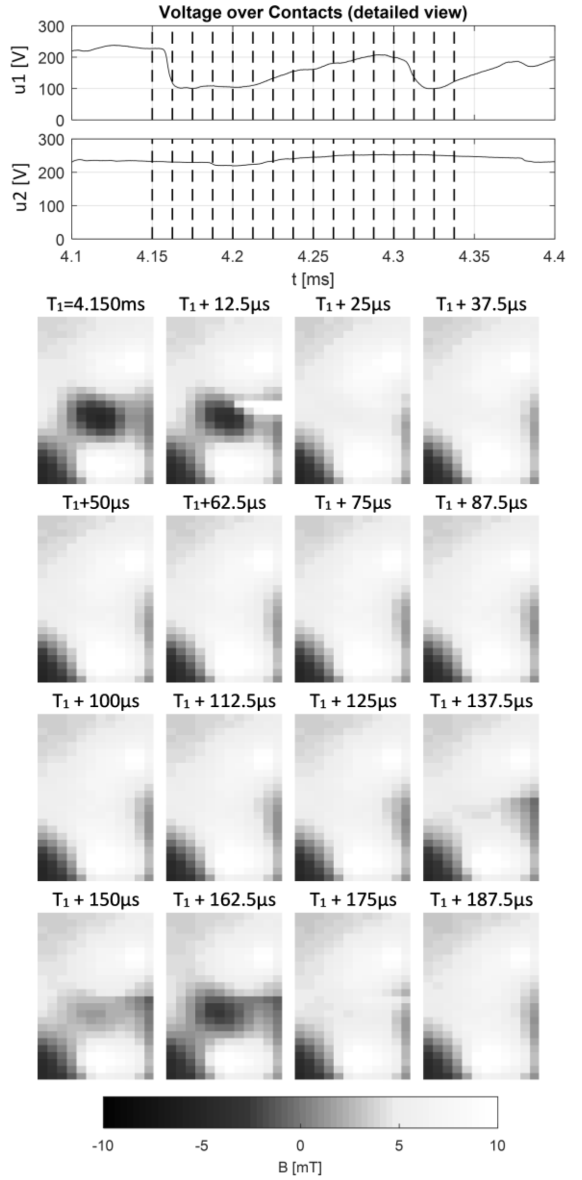

Fig. 7 Magnetic field distribution Bz of sensor head 1 from t = 4.150 ms to t = 4.3375 ms.

4.3 Three Axis Measurement

Fig. 8 and **Fig. 9** show the result of a second measurement. The use of the three axis configuration enables the magnetic flux density to be measured in all directions in space. Here the sensor ICs read the field with a sampling rate of 25 kHz. Fig. 8 shows current and voltage. Larger peaks and dips in the voltages are limited temporally to about 500 µs each. Fig. 9 shows the field distribution at four successive points in time for each spatial direction, for both sensor heads. A larger change, happening abruptly between two samples, can only be observed on sensor head 1. The two samples were taken once before and once after a drop of voltage u1.

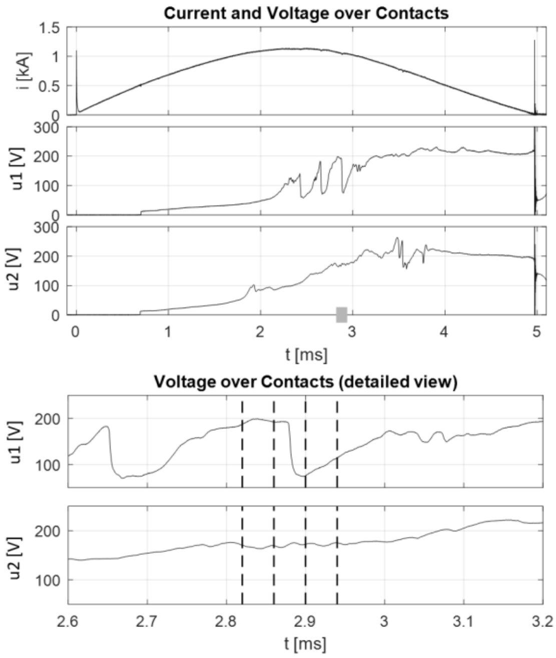

Fig. 8 Result of the three axis measurement (current and voltage).

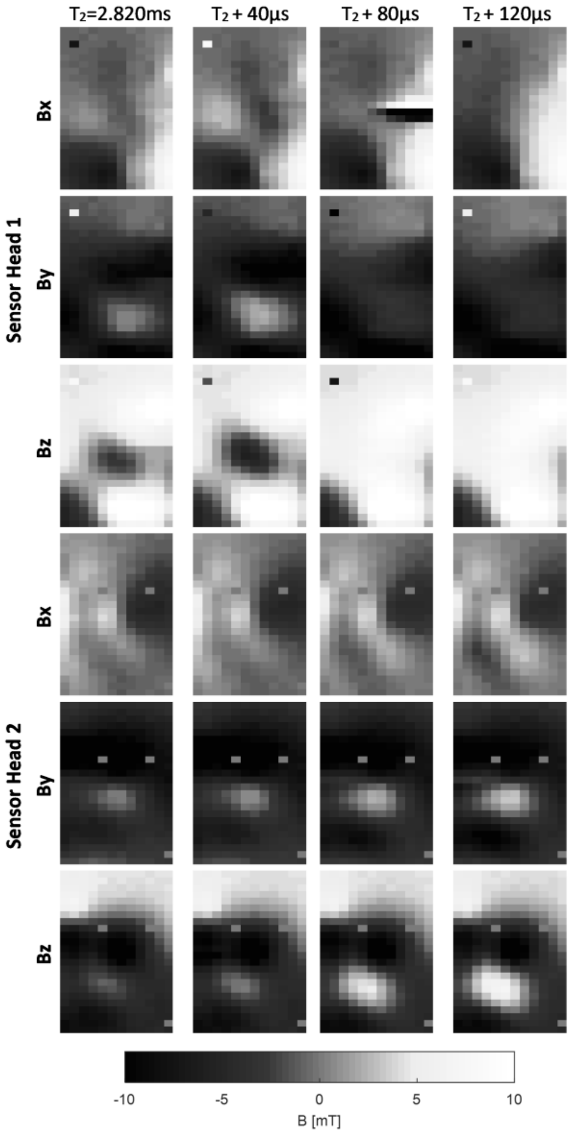

Fig. 9 Result of the three axis measurement (magnetic flux density distribution for the three directions and the two sensor heads).

4 Conclusion

Magnetic field measurements on a circuit breaker during a simulated switch-off process are shown. We used a specially developed magnetic field measuring system. The system is able to detect a field distribution locally resolved with a high sampling rate. Fast as well as slow events showed up in the visualized field distributions. An adaptation of the measuring system to the specific task is possible by using different sensor IC configurations. As shown, a reduction of the sampling rate to 25 kHz allows three axis magnetic field measurements. Using two sensor heads allowed measurements near each contact of the double breaker. The two field distributions measured, correlate well with the corresponding voltage of the contact.

The next step will be a simultaneous measurement of the electric arc with a high-speed optical camera and the magnetic field with the measuring system presented here. Therefore, the presented measuring system shall be verified, supported by numerical magnetic field simulations.

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