CONDITION MONITORING OF SURGE PROTECTIVE DEVICES BY MEASURING THE MAGNETIC FIELD OF DISCHARGE CURRENTS IN POWER DISTRIBUTION SYSTEMS

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ABSTRACT

In order to increase the equipment availability and operating safety in industrial processes, strategies for the maintenance and servicing of plants supported by condition monitoring are getting more and more into focus. The increasing number of sensitive electrical equipment provides system protection with major challenges. Therefore, the correct function of all safety-relevant overvoltage protection devices is of elementary importance. This paper presents techniques for a newly developed condition monitoring system for power distribution protection, including sensor and processing, based on the quantitative measurement of the discharge current up to 40 kA passing through active conductors of a Surge Protection Device (SPD). In addition, it is possible to measure qualitative electromagnetic disturbances by specifically designed capacitive couplings. This allows preventative measures before actual failures of components and offers the possibility to investigate surge currents and their splitting in the individual areas of distribution systems.

I. INTRODUCTION

Due to the increasing number of sensitive electrical equipment, Surge Protective Devices (SPDs) become an important part of power distribution systems. The protection is based on components, which becomes a low-ohmic state in case of a surge event. The SPD discharges the current associated with surge voltages and limit the load voltage and the lightning-induced voltages to an acceptable level. There are different types of damaging overvoltages, which are differentiated by their duration and energy, for example, electrostatic discharges and lightning surges. The integration of SPDs in Industrial Internet of Things (IIoT) is in contrast to most of the common devices an unsolved subject in power distribution systems. Monitoring functions in commercially available SPDs are often only equipped with relatively simple means of monitoring. Surge protective devices usually have a floating remote indication contact which switches in case of a failed component. Thus, the signalling occurs only when no protection exists anymore. Another common method is to count surge events without any information of the allowable stress level. Condition monitoring is, in contrast, a preventative measure before it comes to the actual failure of a component. In this way, unnecessary risks can be avoided and the equipment availability can be increased. Condition Monitoring is based on four general challenges. These are divided into the following tasks:

- Search for suitable measuring points and sensors
- Find meaningful state variables for the damage of components of interest
- Targeted application of signal analysis and pattern recognition
- Handling big amounts of data

The concept envisages that the state of health (SoH) of the overvoltage components is built by the galvanic isolated measurement of the discharge current passing through the active conductors of a SPD. The processed surge current is digitized by analog-to-digital A/D converter and forwarded to a data cloud with big data processing. Results show that the signal is digitized with a high accuracy for the monitoring of SPDs to permit condition-oriented and predictive maintenance. One of the major technical challenges of the new developed measurement system is the strong electro-magnetic environment in the case of a discharge current and the concept and design of a current sensor, which needs to be compact and simultaneously related to its costs. Intensive feasibility studies lead to a concept shown in Fig. 1. [1, 2]

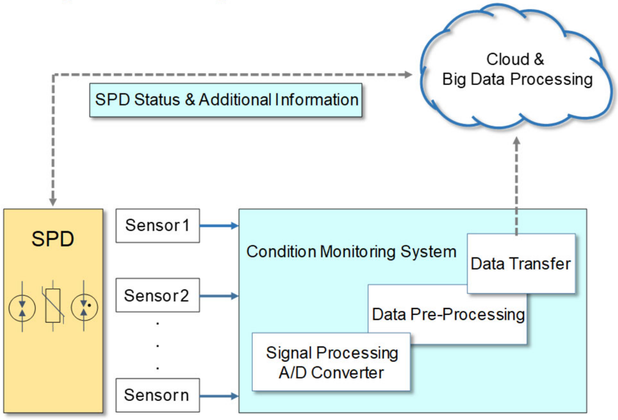


Fig. 1. Simplified diagram of condition monitoring for SPDs with cloud-based data evaluation

This paper focuses on the developed measurement techniques of the discharge current passing through SPDs and the measuring of electromagnetic disturbances, which can damage all components of distribution systems.

II. DESIGN OF PCB CURRENT SENSOR

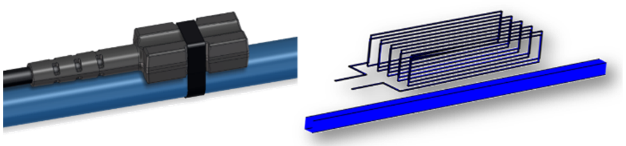
The demands of the measuring system are on its costs, high measuring dynamic range, wide frequency linearity and simultaneous slim design for the application to international standard horizontal pitch (HP) rack mounted equipment. An electric current passing through a connecting wire of an SPD generates a magnetic field around the wire. This allows a galvanically isolated measurement of the current. Isolated current transformer like Hall-Effect sensors or magnetoresistance MR-Sensors do not have the necessary dynamic range. The further investigated processes method is to measure the Faraday's law of induction voltage by a conductor loop:

$$\boldsymbol{\Phi_B = \iint_A \vec{B} \cdot d\vec{A}} \qquad (1)$$

The total voltage U_i induced within a loop is obtained by integration over the loop:

$$\boldsymbol{\oint \vec{E_i} \cdot d\vec{s} = U_i = -\frac{d\Phi}{dt}} \qquad (2)$$

The best-known application with wide dynamic and high frequency range is the Rogowski-Coil, which is inapplicable for this application because of its size and costs. The induction voltage senses the *di/dt* so that an integration circuit has to be implemented. Another geometric design of a conductor loop is a solution represented by a printed circuit board (PCB). The demanded bandwidth and dynamic are comparable to wire-wound Rogowski-Coils but without the advantage of position independence. Nevertheless, with the knowledge of fixed sensor position, it is possible to develop a retrofittable current transformer with a PCB. Wire-wounds and through-hole plating design the PCB coil in Fig. 2. This allows a compact design and the possibility of the attachment of the sensor directly fixed to the cable. By overmolding the PCB with a cable-adapted geometry, it is possible to design a retrofittable sensor with the postulated requirements.



(a) (b)

Fig. 2. Retrofittable PCB current sensor (a) over-molded 3D model, (b) simulation model by MATLAB

The development of the coil geometry is based on numerical simulation with the Partial Element Equivalent Circuit (PEEC) method [3] and is executed via Matlab program code (Fig. 2.b). In this case, the mutual coupling of two inductances is calculated by a function of the relative spatial positioning $\vec{r}$ within a two-port network expression (Fig. 3). The symmetry of the flux linkages of the mutual inductance from L_1 to system L_2 is the same as the opposite case. With the calculation of $M(\vec{r})$ and the value of the inductances with their cooper resistance, it is possible to calculate the coupling coefficient: [3]

$$\boldsymbol{k = \frac{M(\vec{r})}{\sqrt{L_1 L_2}}} \qquad (3)$$

This coefficient is used for another embedded simulation program with integrated circuit emphasis (SPICE). The coupling capacitance can be neglected in the first step. Through a variety of experiments, a suitable geometry has been developed.

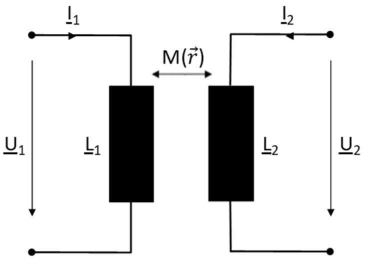


Fig. 3. Simplified mutually coupled inductances $M(\vec{r})$

For a specially designed prototype (sample), the simulation is compared to measuring result (Fig. 4.) The difference error is situated in a tolerance band around 3 % and consistent for different measurement as a function of amplitude and frequency. Thus, the comparison of the measurement and simulation proves a sufficient accuracy for further processing.

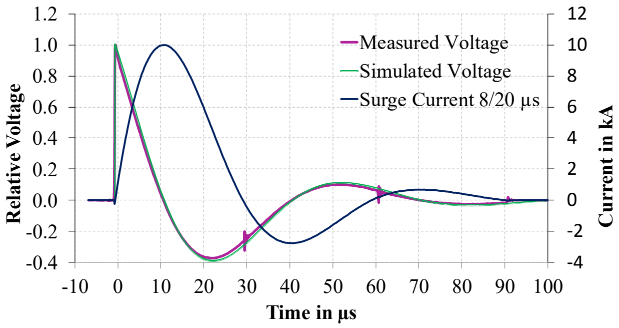


Fig. 4. Verification results of simulation data

III. CIRCUIT DESIGN PROCESS

The developed PCB coil measures a voltage, which is proportional to the current change *di/dt*. For getting the relation to *i(t)*, it has to be integrated. To achieve the required linear bandwidth and dynamic, an active integration and filter circuit has been designed. By the transfer of the current coil simulation setting into SPICE, it is also possible to combine the values with further signal transformation simulation. The main component, the operational amplifier (OPA), is selected by its high linearity and frequency response. For an active integration with continuous resetting, that means a parallel resistor to the OPA capacitor in the negative feedback coupling, it is also important to select a high common-mode rejection ratio (CMRR). Otherwise, the difference signal completely integrates itself. The result of the processing circuit design for the simulation including sensor and processing is divided in the following parts:

- primary inductance as the current carrying wire
- secondary inductance as the PCB current sensor
- protective circuit
- burden resistance
- second order filters
- integration circuit with continuous resetting

By a careful selection of suitable active and passive components, the following frequency response has been reached.

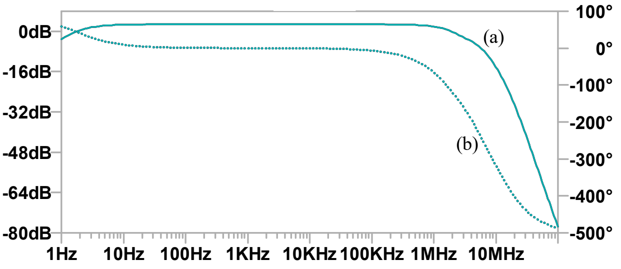


Fig. 5. Frequency response of the sensor and processing circuit (a) magnitude plot (b) phase plot

The frequency response bode diagram shows the magnitude and phase plot of a ramp-up frequency from the current carrying wire, over the induced voltage of a PCB coil with a subsequent integration circuit. The PCB sensor can be assumed as differentiator with the transfer function s/ω_0 with +20 db/decade and a phase of +90 deg. That means a linearly increasing induction voltage with rising current change *di/dt*. The integrator circuit with the transfer function ω_0/s with -20 db/decade and a phase shift of -90 deg is the exact opposite. By combining these function, the sensor and processing circuit receives a proportional behavior of i(t) ~ u(t) with a compensated phase. Low pass filters ensure, that in higher frequency areas the magnitude is dampened. The bode plot of the final circuit design is presented in Fig. 5. The magnitude plot shows a wide linearity in the area of interest. With reference to the international standards [4, 5] and for all defined current test impulses the necessary frequency range up to 250 kHz is given.

IV. SYSTEM PERFORMANCE

The overall concept in Fig. 1 shows, that an analog-to-digital converter digitises the processed voltage signal. This allows an exhaustive transfer of the recorded surge current to cloud services with pre- and post-processing. The signal is digitised with a sampling rate of 500 kHz and a resolution 12 bit. The result for a waveform, measured by a full-fabricated prototype including the cloud transfer is shown in Fig. 6. The digitised processing data is downloaded from the cloud platform and compared with the time-recorded data of an oscilloscope, measured with a Pearson current transformer.

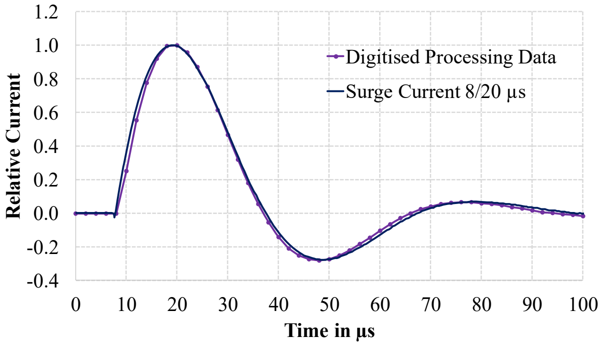


Fig. 6. Comparison of the digitization with the measured current

In contrast to the almost position-independence of a Rogowski-Coil, the newly developed sensor depends on the distance to the cable center. With the knowledge of the different coupling factors *k*, data can be recorded with a tolerant range of less than 5 % in its amplitude and frequency behavior. This fact also allows measuring higher currents by increasing the distance. The measuring system is designed for standard connecting cables with cross-section around 1.5–35 mm² and its wide ranges of outer diameter depending on its isolation width. This enables amplitudes with a dynamic from 0.2 kA to 40 kA. With an increasing distance and an adaption of the coupling factor, measurements were realized up to 200 kA with an 8/20 µs shape. For such current amplitudes, a precise electromagnetic compatibility EMC has to be prepared. As the frequency response in Fig. 5. shows, the measurement of different curve progression as 10/350 µs or 10/1000 µs is feasible. This practical proofed and evaluated system concept is expandable to different application of surge current measurement and offers the basis for further developments.

V. EMI DISTURBANCE DETECTION

Due to the increasing use of semiconductor technologies or switching operations in the low-voltage distribution systems, transient low energy disturbances are also increasingly occurring. The additional miniaturization of electrical components increases the sensitivity further to the interference of all kinds. The high number of low-energy transients additionally increases the stress of overvoltage protection components. A high repetition rate can lead to damage in the system. In order to monitor these continuous influences of electromagnetic interferences, further development is needed. The approach has been solved due to previous problems with capacitive coupling between PCB traces that are next to each other. There is an exchange of displacement current by the change of electric flux. In order to create the transition to displacement current, this is explained based on the time-varying electrical flux. These forms, similar to the induction voltage with time-varying magnetic flux, a displacement current. The electric flux is defined as.

$$\boldsymbol{\psi} = \iint_{A} \vec{\boldsymbol{D}} \cdot \boldsymbol{d}\vec{\boldsymbol{A}} \qquad (4)$$

It follows from the definition that the electrical flux D, which mathematically normal intersects an area A, results in an electric flux ψ. That change generates a displacement current i_D.

$$\boldsymbol{i_D} = \frac{\boldsymbol{d\psi}}{\boldsymbol{dt}} \qquad (5)$$

That means also a displacement current between the cable and sensor in Fig. 2a. in case of high frequency electromagnetic interferences depending on the geometry and material as permittivity ε. The coupling capacity is within a range of several pF between the inductances. The continued signal is of opposite polarity to the induced voltage a common-mode signal current with the same polarity at the end of both sensor cable conductors. This signal has a magnetic flux density, which can be measured. In the practical design, a supplementary loop is inserted (Fig. 7.). Important in the high frequency range is a low-resistance connection to the functional earth. By means of a suitably dimensioned capacitor as a high frequency bridge, a common mode signal can be detected on both conductors. Depending on the dimensioning, the capacitor even represents a short circuit for certain frequencies. Thus, the magnetic flux density of both conductors is amplified. By adding, a planar coil over several PCB layer inside, the magnetic flux induces a voltage in turn.

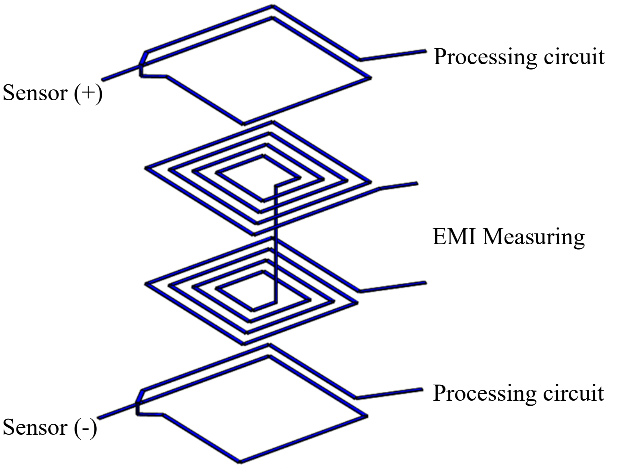


Fig. 7. Simplified PCB layer design of EMI measuring coil used from simulation data

The induced voltage has a sufficient level for triggering a switch. This binary state can be recorded and controlled by microprocessors. The results of a technical improved prototype demonstrate that it is possible to record a number of a 15,000 burst transients with a curve progression of 5/50 ns during a test procedure according EN 61000-4-4 [6] with voltages of about 500 V to 6000 V. The repetition frequency is of the 5/50 ns is 5 kHz and the burst period duration is 300 ms. The summation of the individual pulses result the number of 15,000. First field tests on solid-state AC-to-AC converters also show evaluable measurements and thus highly vulnerable distribution areas.

VI. ADVANTAGES AND APPLICATIONS

The exchange of information about the status of SPDs in power distribution systems provides advantages about preventive maintenance. Unnecessary service assignment can be prevented specially for exposed locations with a high demand on technical reliability for example electronic control systems of wind power plants offshore as well as onshore. Apart from the knowledge of the status of installed SPDs, the detailed information about the surge current, charge or specific energy of detected disturbance can provide needs-oriented services with controlling of alleged damages of other parts of the whole facility. By intelligent visualization of EMI disturbance detection, pattern recognition of vulnerable distribution areas can spot hidden problems. A new test environment offers also the increasing development of DC power grids in industrial manufacturing with unknown challenges for power signal quality in error cases. Figure 8 shows an application example for a monitoring of a class I surge protective device with three developed sensors. The application is based on the n-1 principle. The total current is calculated by Kirchhoff's current law, where the sum of currents result to zero. This allows investigating and understanding surge currents and their splitting in the individual areas of distribution systems for future interpretation.

Fig. 8. Application example of a cloud-based condition monitoring on class I SPD

VII. CONCLUSION

Cloud based monitoring on SPDs permit condition-oriented and predictive maintenance. The measurement of high energy discharged current and the measurement of electromagnetic interferences provides an opportunity for determining the state of health of all kinds of overvoltage protective elements. The presented solutions form the basis for the development of further applications. A newly developed sensor fulfils the requirements of high measuring dynamic range, wide frequency linearity and a slim design. In combination with circuit design processes, a scalable possibility for the measurement of impulse currents has been presented in this paper. In addition, this sensor and system can be used as a capacitive coupling path for the detection of electro-magnetic interferences. Besides the knowledge of the condition of SPDs, conclusions can be drawn on vulnerable areas of the entire facility. Cloud-based data collections help to create an early-warning monitoring and emerging aging models for unwanted and unexpected system failure. Thus, the integration of SPDs in the new generation of Industrial Internet of Things (IIoT) offers an increasing system reliability and advanced potential applications for the future. Through the close cooperation between industry-research and university-science it is possible to use findings participatively.

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