Alternative Coupling Method for Immunity Testing of Power Grid Protection Equipment

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***Abstract*— Modern electric power distribution networks require flexible and cost effective solutions for measurement and grid protection purposes. Because conventional instrument transformers cannot always keep up with the changing demands, electronic instrument transformers are increasingly being used for the current and voltage measurements. Due to the different working principle of such sensors, the standardized type test for protection devices should be adapted in order to ensure the electromagnetic immunity, especially during switching operations. This contribution points out the differences between the conventional and the new technology from the EMC point of view. It is shown by measurement that the standardized test procedure is not suitable for protection relays with electronic instrument transformers. The experimental coupling network proposed in this paper is evaluated based on the disturbance voltages occurring at the input terminals of the protection device during real switching operations and the new type test.**

Keywords*— *electronic instrument transformer; current sensor; EMC; transients; medium voltage; switchgear

I. Introduction

In power networks, medium voltage switchgears allow a change in the network topology, respectively the selective protection of the network in case of failure. Due to grid extension and distributed generation the demands on switchgear applications are subject to continuous change, which requires reinforcements in the installed base of electrical distribution equipment, e.g. switchgear, cable networks, as well as control and protection functions. The possibility to adapt switchgears to a higher short circuit current depends mostly on the operating range of the current transformer (CT). Because of the nonlinear magnetization characteristic of the iron core (see Fig. 1b), the accuracy of such CTs is limited to a certain range of the primary current and the burden. A higher short circuit current than what it was originally designed for, would saturate the core material and lead to an inaccurate image of the primary current at the secondary terminals. However, changing the CTs is usually not practicable, due to additionally required space and heat dissipation. An alternative to the conventional CT solution could be Rogowski Sensors, which are classified as electronic current transformers and defined by the IEC standard 60044-8. They do not have a ferromagnetic core, are not prone to saturation effects and can therefore provide an accurate image of the primary current in a much wider range. While in a conventional CT the secondary current $i_2(t)$ corresponds directly to the primary current $i_1(t)$, the Rogowski sensor provides an output voltage $u_2(t)$ which is a scaled time derivative of the primary current. This results in a phase shift of 90° for harmonic currents. An accurate image of the original input current can be obtained by performing an integration of the signal. In order to minimize the influence of external magnetic fields, the winding wire is returned to the starting point along the central axis of the winding (see Fig. 1a).

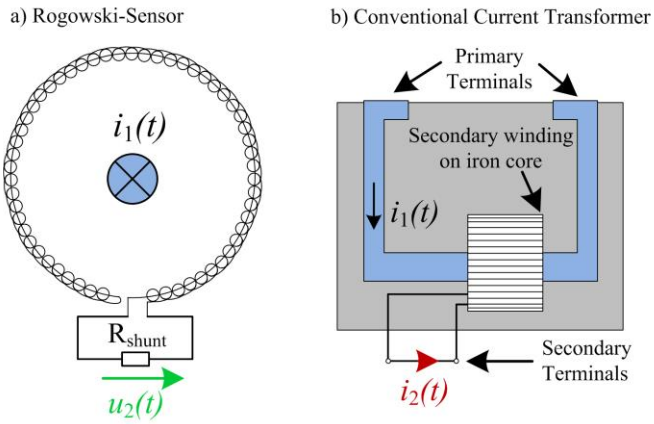

Fig. 1 Disturbance voltages during Disconnector breaking operation

For the consideration of the electromagnetic immunity it is especially important to prevent unintended operation of the protection functions, caused by transients generated in the switchgear itself. Switching operations in the medium voltage circuits cause pre- and restrike arcs which result in transient overvoltages with short risetimes. These broadband transients can transfer to the measuring circuits on the low voltage side and cause interference on the electronic protection relays. The disturbance propagation path of the Rogowski Sensor and the conventional CT is presented in section II. In order to minimize the risk of malfunction, IEC standard 60255-26 [1] provides specific type tests for the analog inputs of protection relays. In section III it is shown why the test method described is not suitable for electronic CTs with a high impedant termination and how other existing coupling methods fail to reproduce the disturbance levels which occur during real

978-1-5090-1416-3/16/$31.00 ©2016 IEEE

switching operations. Subsequently, section IV presents an experimental coupling network as an attempt to adequately reproduce the actual coupling path and thus the occurring disturbance voltage in the time and frequency domain.

II. Disturbance Propagation in Switchgear

The amplitude of the transient common mode disturbance at the analog measurement inputs of the protection relay primarily depends on the operating voltage of the switchgear, the coupling path, and the input impedance of the protection relay. For the comparison of the conventional CT and the Rogowski sensor, two measurements made under the same ancillary conditions are plotted in Fig. 2 whereas the measurement points are also indicated in Fig. 3 und Fig. 4. The plot shows the disturbance voltages at the terminals of a protection relay during a disconnector breaking operation for a conventional CT input and a Rogowski sensor input. The ignition voltage rises, causing higher wave fronts and higher disturbance amplitudes as the distance between the switch contacts increases. Due to the different coupling paths and input impedances, the disturbance level at the Rogowski sensor input is approximately 20 times lower than at the CT input.

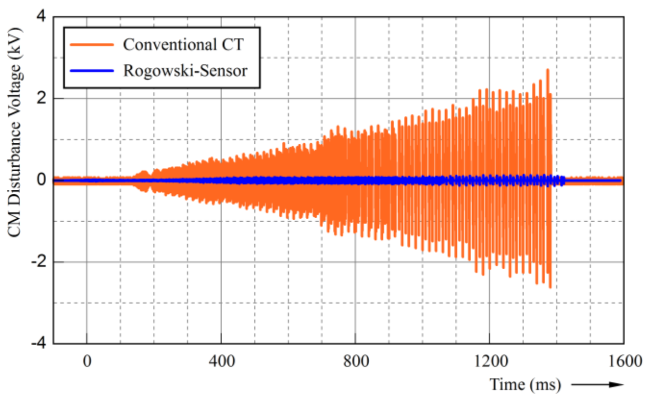

Fig. 2 Disturbance voltage in conventional and Rogowski application

A. *Conventional CT Application*

In conventional CTs, the disturbance propagates mostly capacitive via the stray capacitance between the primary conductor and the secondary winding (see Fig. 3). A high capacitance value causes stronger coupling, which results in higher disturbance voltages at the input of the protection relay. Even though shielding of the secondary winding is a proven method for disturbance reduction, it is often dispensed due to high costs and difficulties in insulation coordination. The signal wiring, which is made up from unshielded single wires is grounded in only one spot via impedance Z_{E1} in order to avoid high current injection in case of a fault event (see Fig. 3). Assuming that those wires can be described as transmission lines, a variation of the line lengths changes the impedance conditions of the system and leads to different disturbance voltage distributions.

The secondary transformer inside of the protection relay is often shielded to protect the ADC from conducted interference. In the case of high frequency common mode disturbances, the input impedance is mostly determined by the inductive component of $Z_{E2.}$ Because the reference potential for the ADC is the signal ground inside the relay, the earthing impedance is negligible and therefore not shown in Fig. 3.

B. *Electronic Instrument Transformer (Rogowski-Coil)*

In Rogowski Coils (see Fig. 4) the stray capacitance is usually low, due to their small dimensions and rather great distance to the primary conductor. They can also be shielded more easily, since they do not have to isolate the primary voltage. Furthermore, they are mostly applied onto bushings, containing coupling layers for voltage indication systems. Those layers close to ground potential create an additional shielding effect which eliminates most of the stray capacitance. However, the inductive parts of the impedances Z_{VI} and Z_{ES1} become more critical for high frequencies, so that a small common mode current is still coupled into the sensor.

The shielding of the twisted pair sensor cable affects the disturbance current by providing a capacitive bypass to ground. The impedances Z_{ES1} and Z_{ES2} in the ground connection of that shield are limiting its effectiveness at high frequencies [2].

The input impedance of the analog sensor input has to be rather high, due to the limited output power of the sensor [3]. Consequently, for high frequency common mode disturbances, that input impedance is primarily defined by the low pass filters in the analog input circuit. The cut-off frequency of such filters is usually more than 5 kHz.

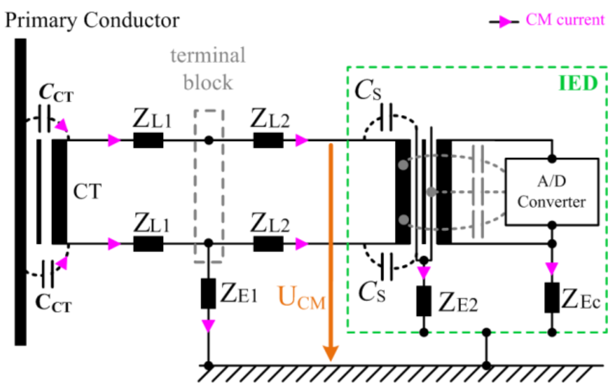

Fig. 3 Coupling Path Conventional CT

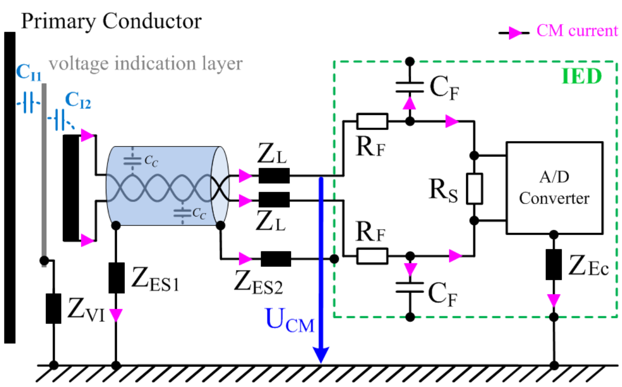

Fig. 4 Coupling Path Rogowski Sensor

III. Current State in Immunity Testing

In order to cover the transient disturbances caused by switching operations, the Burst test is especially relevant. The test equipment and the test techniques are specified in the basic standard IEC 61000-4-4. The immunity requirements themselves are specified within the generic standards and the more specialized product family standards. Table I lists the requirements for the Fast Transient /Burst test of a protection relay's analog input terminals. The more specialized standard has a higher priority.

TABLE I. TABLE I REQUIREMENTS FOR FAST TRANSIENT / BURST TEST

Requirements for signal ports	Generic standard (switchgear environment) *IEC 61000-6-5*	Product family standard switchgear *IEC 62271-1*	Product family standard Protection rel. *IEC 60255-26*
Generator charging Voltage	4 kV	2 kV	4 kV
Pulse Repetition Rate	2,5 kHz	5 kHz	5 kHz
Coupling Method	not specified	Capacitive coupling clamp	Coupling decoupling network

The product family standard for protection relays IEC 60255-26 provides different coupling methods for each interface category. For input terminals provided for instrument transformers, a coupling decoupling network (CDN) – as described in IEC 61000-4-4 (see Fig. 5) – shall be used.

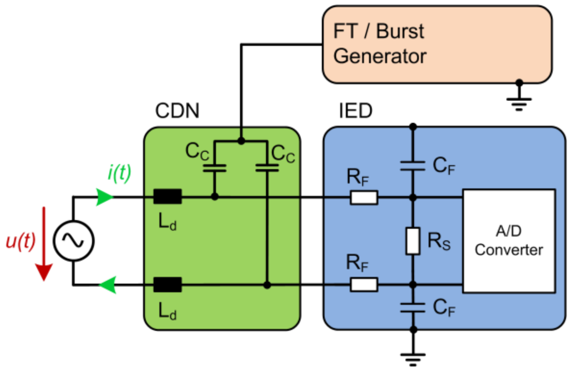

Fig. 5 Burst test according to IEC 61000-4-4

The test voltage is applied by the coupling capacitance $C_C = 33$ nF between the generator output and each of the signal lines. The decoupling inductance $L_D > 100$ µH protects the signal source, respectively the power supply, from the test voltage since it is not subject to the test. However this coupling method is not suitable for testing of high impedant sensor inputs. The impedance of the low pass filter - made of R_F and C_F (see Fig. 5) - inside the relay is much higher than the generator output impedance and the coupling impedance. Therefore, almost the entire test voltage drops across the input terminals of the relay. This leads to immunity requirements, which exceed the practical needs by far. In the case of a conventional CT, the disturbance is – as described in section II – reduced by the shielding of the secondary transformer. In a sensor input, this type of coupling would cause flashovers at the connector of the relay or within the input circuit.

In order to counter this problem in praxis, the capacitive coupling clamp is used for the type tests, even though this method cannot be derived from IEC 60255-26. While it is appropriate e.g. for communication ports, it cannot be used for interfaces directly linked to the medium voltage circuits. Voltage and current sensors are passive components and shall be treated as voltage and current input ports, even though they have RJ-45 connectors. The reference to IEC 62272-1 [4] – where such a test is specified – is also not valid at this point, because that test is meant to reproduce the effects of transient electromagnetic fields on the sensor wiring. However this type of coupling does not match the actual coupling path described in section II. Not only does the coupling take place primarily in the sensor itself, the coupling capacitance is also very low, due to the cable shields. Fig. 6 shows the result of a Burst immunity test on a current sensor input using the capacitive coupling clamp.

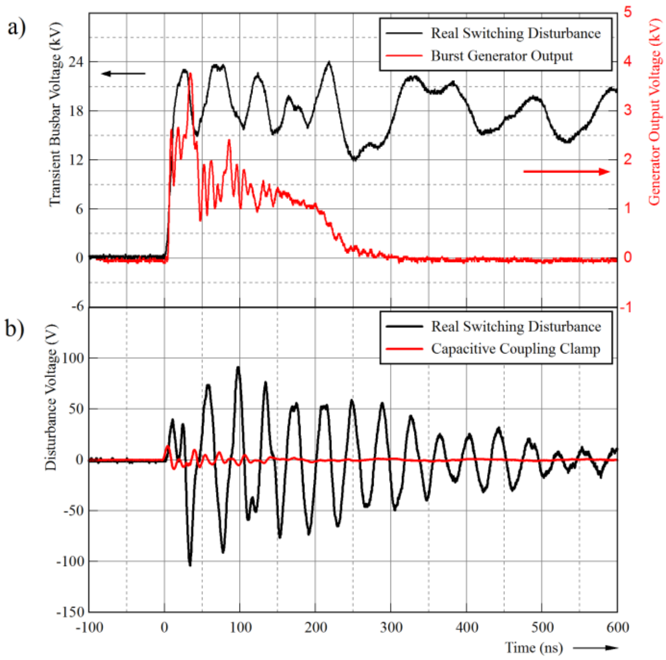

Fig. 6 Fast Transient / Burst Test with capacitive coupling clamp

As can be seen from Fig. 6a, the transient wave front of a Burst impulse is very comparable to a real ignition at the disconnector switch. Since both can be seen as a broad-band stimulation of the input under test, the frequency content of the test voltage is also very comparable. However, the comparison of the CM voltages at the input terminals shown in Fig. 6b reveals a significant difference in the voltage levels during a real switching operation and the type test. This deviation shows that a test with the capacitive coupling clamp leads to insufficient test levels and is therefore not suitable for type tests according to IEC 60255-26. As a conclusion from this, a new test method has to be found, in which test levels are not unrealistically high while the real electromagnetic stress of a protection relay in service is adequately covered.

IV. NEW COUPLING METHOD FOR FAST TRANSIENTS

In order to perform a realistic electromagnetic immunity test, the coupling path has to be adequately reproduced. The setup with the coupling network according to Fig. 7 allows the testing of the input port including the original signal cable by using the standard test generator and test levels.

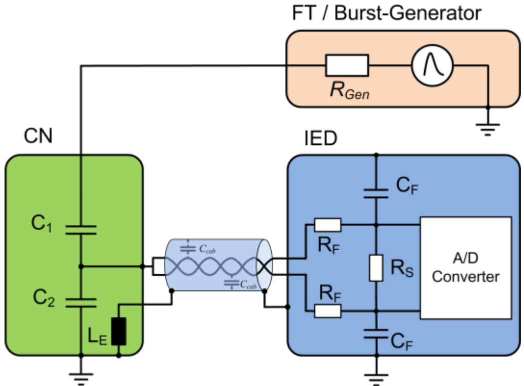

Fig. 7 Burst Test using Experimental Coupling Network

The experimental coupling network (CN) is basically a capacitive divider, which is made up from a multilayer PCB. It is connected to the test generator by a short coaxial cable and to the device under test by the original shielded twisted pair sensor cable. The impedance of the ground connection of the sensor cable is reproduced by the inductance L_E.

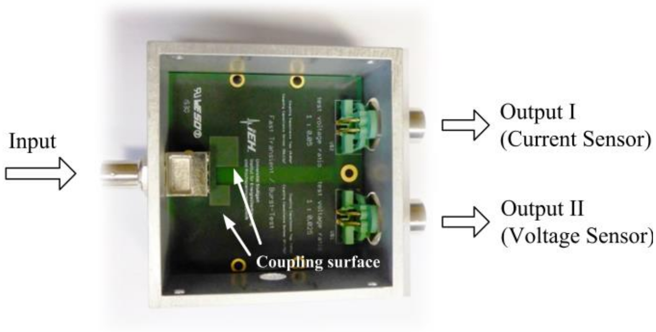

Fig. 8 Experimental Coupling Network

The amplitude of the test voltage can be adjusted to a pre-defined worst case for the specific sensor type by choosing different divider ratios. A resistive voltage sensor has usually a smaller stray capacitance to the medium voltage circuit and can therefore be tested with lower levels than current sensors or capacitive voltage sensors. The design of the divider as stray capacitances on a PCB ensures the required dielectric strength and keeps the parasitic inductances small at the same time. Due to the shielded housing, other coupling paths than the one described in section II can be neglected.

By a direct comparison of the disturbance voltage at the current sensor input (see Fig. 9b) it becomes clear that the real switching disturbance is well covered by the Burst Immunity Test, as regards to amplitude and signal shape. For the latter is especially important, that the bandwidth, respectively the risetime of the stimulation is nearly the same (see Fig. 9a).

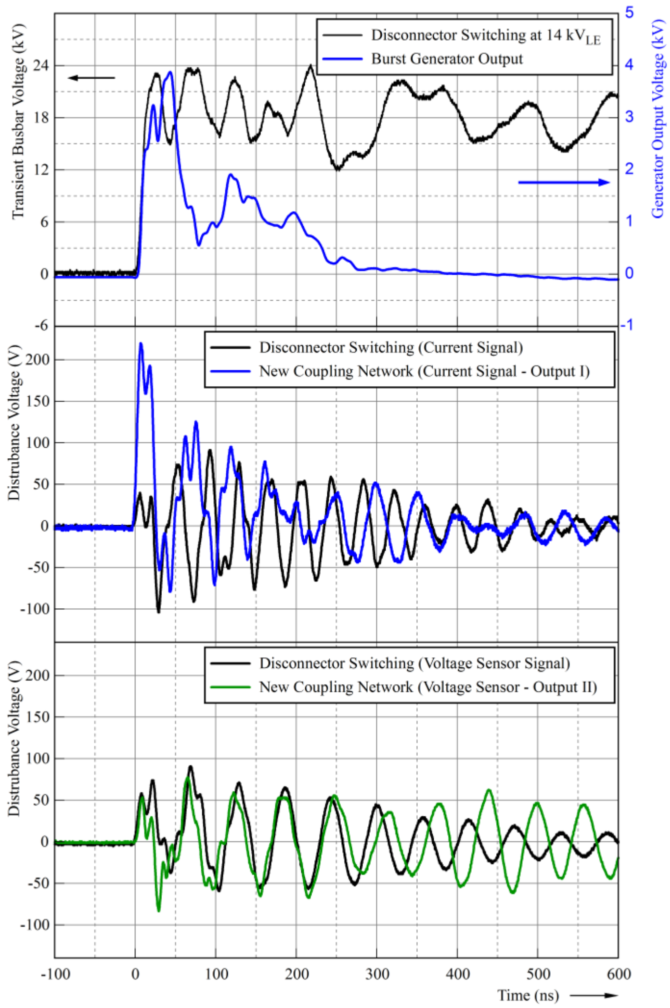

Fig. 9 Fast Transient / Burst Test with Experimental Coupling Network

The comparison of the coupled interference voltages in the frequency domain (see Fig. 10) shows that in the case of current senor input, the actually occurring spectral components are much better covered in the experimental coupling method as in testing with the capacitive coupling clamp.

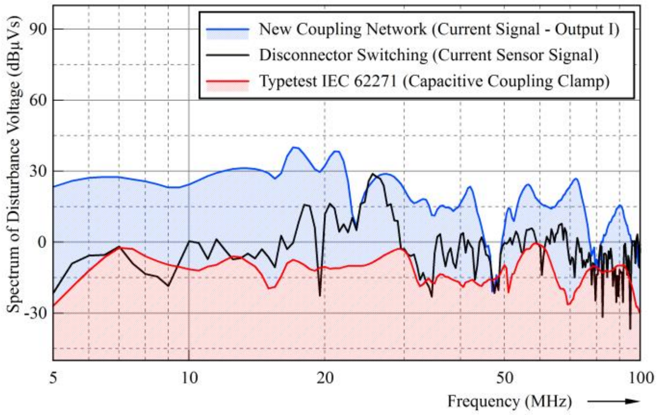

Fig. 10 Frequeny content of test voltage at current sensor input

In the case of the voltage sensor input, the analysis in the frequency domain (see Fig. 11) shows that in the immunity test with the capacitive coupling clamp there are deviations between tested voltage and actual interference of up to 30 dB. The test with the experimental coupling network provides better coverage, especially in the critical frequency range between 5 MHz and 30 MHz. Nevertheless there are still areas, between 28 MHz and 42 MHz, which are not yet adequately covered.

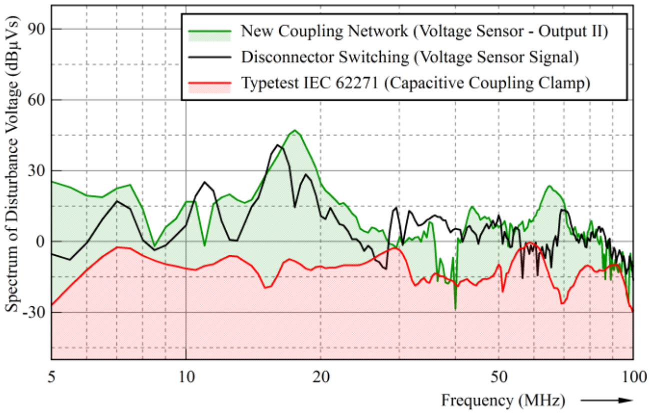

Fig. 11 Frequeny content of test voltage at voltage sensor input

V. Conclusion

The need for cost effective and flexible measurement solutions in power distribution grids has led to an increasing spread of electronic instrument transformers. In order to rule out unintended protection function operation, the electromagnetic immunity to switching operations needs to be tested. Due to other impedance conditions, the test procedure standardized in IEC 60255-26 is not transferable from conventional to electronic CTs. The test method from IEC 62271-1 can also not be applied, because of the different coupling path. Therefore, a new test method is proposed which is – except for the network - based on standard components. It is shown by measurement that the experimental coupling network can adequately reproduce the disturbance voltage caused by actual switching operations in the time and frequency domain.

In the next step, a worst case will be determined for the common mode disturbance voltage at the analog inputs of the protection device, which covers all sensor types and voltage levels and to which the divider ratio is adapted.

The applicability of the new coupling method on other test voltage shapes, e.g. damped oscillatory wave will also be subject to further investigations.

VI. References

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