EARTH FAULT PROTECTIONS WITH SENSORS

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ABSTRACT

Earth faults are the most common type of fault in medium voltage networks. Earth fault (EF) protection based on residual current detection is therefore the basic protection used in protection systems. Since small isolated and compensated MV networks with low levels of earth fault currents are now increasing in popularity, the use of earth fault protection with residual current detection based on traditional methods and equipment is therefore partly limited. Medium Voltage sensors (low-power stand-alone sensors) based on non-conventional principles provide an alternative method of making the current and voltage measurements required by protection applications. This paper explains how the benefits of MV sensors are utilized in EF protection and describes particular tests carried out to verify this solution.

INTRODUCTION

The sensitive detection of residual current is essential for EF protection, particularly in systems with a low level of earth fault currents. There are many methods for the detection of residual current. In compensated or small isolated systems, a core balanced (ring type) current transformer (CBCT) is typically used. Even though EF protection with a CBCT is widely used, the CBCT represents additional equipment which requires the engineering of its parameters as well as materials and other cost investments.

With the development of digital protection relays, residual current can be easily calculated as a vector sum of three phase currents. However, with traditional current transformers (CTs) this method has a significant drawback due to the limited accuracy caused by the limited size of the CTs. The inaccuracy of this measurement creates an apparent residual current which affects the EF protection function (see Figure 3). Therefore, it is recommended to use the residual current calculated from phase CTs only in systems with high levels of earth fault currents.

Sensors, with their linear characteristics and no saturation, provide highly accurate measurements across the whole operating range. A typical example is the current sensor which can measure accurately phase currents from a few amps (A) up to tens of kilo-amps (kA). This means that the apparent residual current created by measurement inaccuracy can be very low and therefore there might not be limitation in using the calculated residual current from sensor phase current measurements in any system, even with extremely low levels of earth fault current.

MV SENSORS

MV sensors use non-conventional principles such as Rogowski coil or voltage dividers which means that construction is done without the use of a ferromagnetic core. The behaviour of the sensor is therefore not influenced by the non-linearity and width of the hysteresis curve. This fact results in the linear and highly accurate sensor characteristic in the full operating range which provides various benefits.

Accuracy and dynamic range

Due to the absence of a ferromagnetic core the sensor has a linear response over a very wide primary current range, far exceeding the typical current transformer range. Thus, current sensing for both measurement and protection purposes could be realized with single secondary winding. In addition, one standard sensor can be used for a broad range of rated currents and is also capable of precisely transferring signals containing wide range of frequencies different from rated ones.

The typical example of a current sensor can reach the metering class 0.5 for continuous current measurement in the extended accuracy range from 5% of the rated primary current (e.g. 4 A) up to the rated continuous thermal current (e.g. 4000 A). For dynamic current measurement (for protection purposes), current sensors can fulfill the requirements of the protection class up to an impressive value reaching the rated short-time thermal current (e.g. 50 kA).

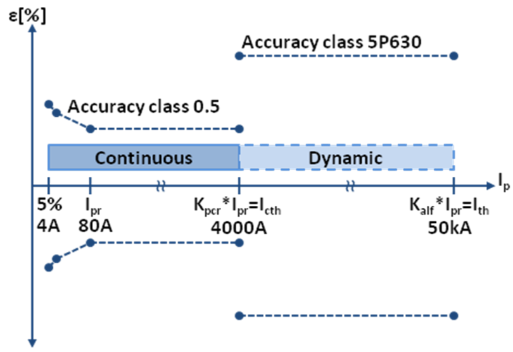

Figure 1: Example of current sensor measurement range

CALCULATED RESIDUAL CURRENT

Modern microprocessor-based protection relays enable calculation of residual current as a vector sum of three phase currents. However there is a limitation for application in systems with low level of earth fault currents if conventional CTs are used for phase current measurements. Due to the measurement error of each CT, it is recommended to use calculated residual current only if the earth fault current is higher than 10% of nominal current. In other cases it is recommended to use CBCT. The recommendation assumes that CTs with protection accuracy class have been used and therefore limited accuracy of such class is considered with additional safety margin.

The amplitude and phase errors of the CTs distort measured phase currents. The Intelligent Electronic Device (IED) then sees the different phase currents than real phase currents in the network. Consequently apparent residual current is created due to measurement inaccuracy.

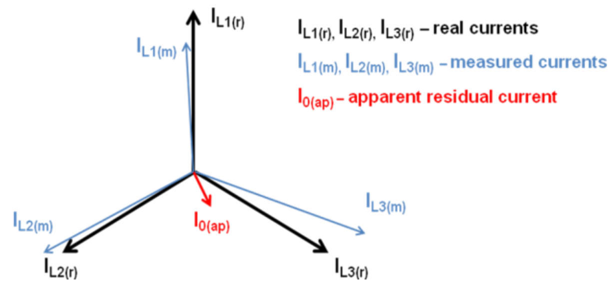

Figure 2: Creation of apparent residual current

The level of apparent residual current is usually quite difficult to determine; moreover, this component could affect the correct function of the EF protection. If the apparent residual current is too high in relation to the earth fault current, it could cause malfunction of EF protection (false operation or failure to operation).

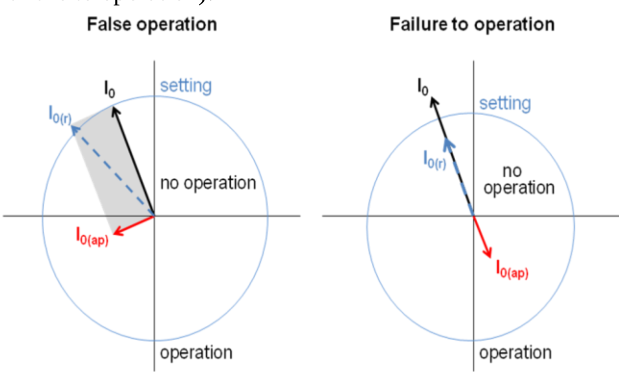

Figure 3: Impact of apparent residual current on EF protection performance

$\mathbf{I_0}$ – real earth fault current in the network
$\mathbf{I_{0(ap)}}$ – apparent residual current
$\mathbf{I_{0(r)}}$ – earth fault current seen by IED

On the other hand, if the measurement is very accurate in the whole operating range provided by the sensors, the apparent residual current could then be very low without significant impact on operation of EF protection.

TESTING IN STEADY-STATE CONDITIONS

The primary tests of EF protection based on calculated residual current in steady-state conditions were done to determine the level of the apparent residual current. The tests were done in a laboratory with the primary current source which supplied the 3-phase current in the range 0-2000 A to the three connected sensors. The testing system was connected as an isolated network (without any connection of neutral to the ground), therefore no real residual current could appear. Consequently the trip of earth fault protection could cause only apparent residual current created by measurement inaccuracy. The level of apparent residual current was detected by a gradual increase of injected primary current (I_p) and by adjusting of EF protection start current. If the EF protection tripped, the apparent residual current was higher than EF protection start current $I_{0(op)}$. Then the setting of EF protection start current was increased by one step up to the value which did not cause the trip $I_{0(inop)}$. The primary current (I_p) was injected in the step 10 A in the range 20 – 1000 A and then in the step 25 A in the range 1000 – 2000 A.

Setting of the EF protection in REF615:
Nominal current: I_n=40A
Start current: from 1% up to 3% of I_n
Time delay: 40 ms

I_p [A]	I_{s1} [A]	I_{s2} [A]	I_{s3} [A]	$I_{0(op)}$ [%]	$I_{0(op)}$ [A]	$I_{0(inop)}$ [%]	$I_{0(inop)}$ [A]
20	19,0	23,2	19,1	-	-	1,0	0,4
310	315,2	310,4	317,8	-	-	1,0	0,4
320	323,8	319,7	326,9	1,0	0,4	1,5	0,6
890	893,7	907,8	928,5	1,0	0,4	1,5	0,6
900	904,5	919,7	941,1	1,5	0,6	2,0	0,8
1400	1397	1416	1458	1,5	0,6	2,0	0,8
1425	1419	1437	1479	2,0	0,8	2,5	1,0
1875	1874	1875	1943	2,0	0,8	2,5	1,0
1900	1903	1902	1972	2,5	1,0	3,0	1,2
2000	2001	1981	2071	2,5	1,0	3,0	1,2

Table 1: Results from the EF protection primary test in steady-state conditions

I_p – injected current set on the primary current source
I_{s1}, I_{s2}, I_{s3} – phase currents read from the IED
$I_{0(op)}$ [%], [A] – start current of the EF protection in [%], [A] when IED tripped
$I_{0(inop)}$ [%], [A] – start current of the EF protection in [%], [A] when IED did not trip
Note: In Table 1 are mentioned only the values where was measured the changed of the apparent residual current.

The primary 3-phase current source was not able to provide exactly 120° phase shift between the phases. This fact resulted in different amplitude values of measured currents in three phases but did not have any impact on measurement accuracy, accuracy of calculated residual current, or EF protection performance since the vector sum of primary phase currents was zero all the time due to the connection of the equipment as an isolated system.

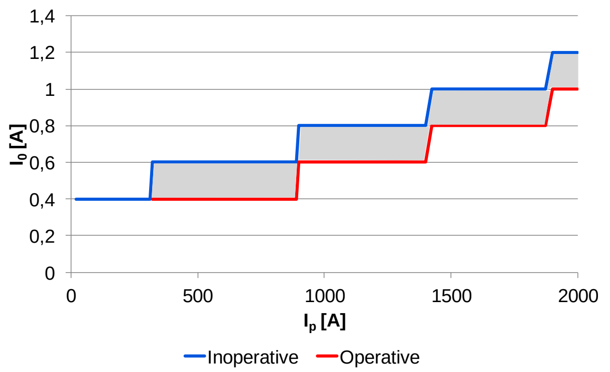

Figure 4: Relation between apparent residual current and injected primary current

The blue curve (Inoperative) on Figure 4 represents the characteristic when EF protection did not trip and the red curve (Operative) represents the characteristic when EF protection was activated by apparent residual current and tripped. Consequently the amplitude of apparent residual current then reached the values between the blue and the red characteristics expressed by the grey zone. From the results it is evident that apparent residual current reached very acceptable values which proved the high accuracy of sensor measurement e.g. for injected current 2000 A was apparent residual current in the range 1-1.2 A.

The results of the test signified very promising precondition to decrease recommended setting of EF protection from 10% of nominal current to lower values if the calculated residual current from sensor measurement is used.

TESTING IN TRANSIENT CONDITIONS

The primary tests of EF protection based on calculated residual current on the model of the network (supply voltage 230 V) were done to prove the behaviour in transient conditions and to verify the positive results from the previous test done in a laboratory in steady-state conditions.

The model of the network consisted of a supply step-up transformer, circuit breaker, transformer which enabled to create required type of network neutral grounding, and different types of burdens e.g. power transformer for stability test on inrush current or capacitors for earth fault tests.

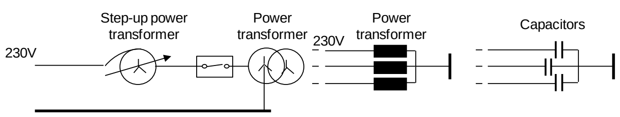

Figure 5: Simplified scheme of network model

Stability test on inrush current

Inrush current represents a problematic element for conventional CTs in case that CTs cannot be designed with appropriate parameters (mainly due to limited size or required low-rated primary current). During switching operation of a power transformer, inrush current could cause saturation of such CTs which would then initiate false trip of EF protection if calculated residual current is used. Therefore, this case was intentionally simulated with the IED RET615 connected to the CTs with very high secondary burden provided by connected resistors $R_b = 500\ \Omega$.

The IED REF615 was connected to the combined sensors for phase current and phase voltage measurements. CBCT connected to the REF615 was used as a reference.

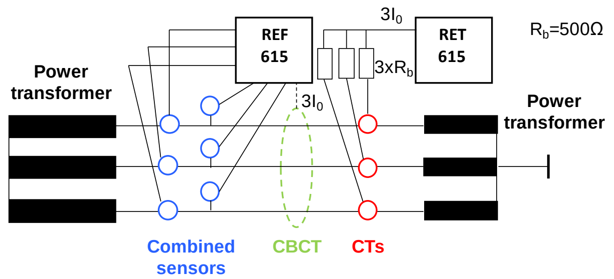

Figure 6: Simplified scheme of connected equipment during the stability test

The EF protection (in REF615) based on calculated residual current from sensor measurements was set on the most sensitive (minimum) settings:

Nominal current: I_n=40A

Start current: 1% of I_n

Time delay: 40 ms

25 tests were simulated to verify stability on inrush current without any false trip of EF protection based on calculated residual current from sensor measurement (in REF615). With the IED RET615 were simulated cases when CTs saturate due to inrush current during switching operation of a power transformer and consequently creates a false trip of the EF protection. Despite the fact that modern IEDs can detect inrush current and therefore avoid unwanted trip of EF protection, such functions are still not often used by users.

Testing of earth faults on the model of network with isolated neutral

Systems with isolated neutral could represent challenges for traditional detection of earth faults particularly in case of small networks where the level of residual current is very low. The purpose of the tests was to verify the behaviour of EF protection in isolated system with low level of earth fault current on the model of the network during transient conditions. The network capacitance was simulated by connected capacitors in all three phases. IED REF615 was connected to the combined sensors. CBCT was used as a reference for residual current measurement.

EF protection (in REF615), based on calculated residual current from sensor measurements, was set on the most sensitive (minimum) settings:

Nominal current: I_n=40A

Start current: 1% of I_n

Time delay: 60 ms

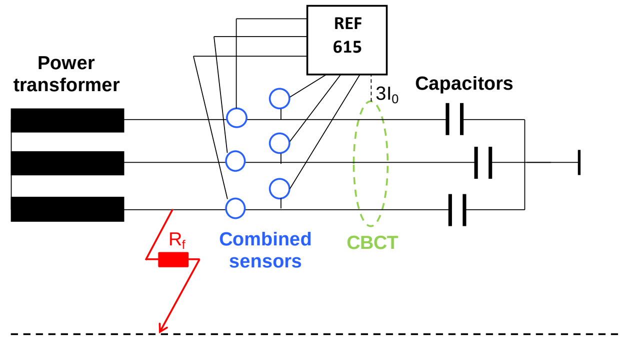

Figure 7: Simplified scheme of connected equipment during the Earth fault tests in the isolated network

Three different types of the earth faults were simulated: solid earth faults, low and high impedance earth faults, and intermittent earth faults.

Solid earth faults in isolated network

During the simulation of solid earth faults, the phase L1 was connected to the ground. In total, six tests were done where correct detection of earth fault currents as well as proper directional function (forward and reverse) were verified.

The phase currents before the earth fault were approximately 0.5 A. The earth fault current was approximately 1.6 A during the tests and EF protection always detected this earth fault current correctly. Maximum amplitude deviation between calculated residual current (from 3-phase current sensor measurement) and directly measured residual current (by CBCT) was about 0.1 A. The deviation could be caused by apparent residual current on the side of calculated residual current but on the other side also accuracy of the reference CBCT could be limited due to measurement of such low currents.

Impedance earth faults in isolated network

During the simulation of impedance earth faults, the phase L1 was connected to the ground via resistors with following resistances: R_f = 1.13 Ω; 50 Ω; 100 Ω; 114 Ω; 115 Ω. In total, five tests were done with positive results and correct detection of earth faults. The earth fault currents were in the range from 1.6 A up to 0.7 A. Maximum amplitude deviation between calculated residual current (from 3-phase current sensor) and directly measured residual current (by CBCT) was again about 0.1 A.

Intermittent earth faults in isolated network

For simulation of intermittent earth faults, 5.4 Ω and 250 Ω rheostats were used. Intermittent EF were simulated by the moving of a pin on the backside of the rheostats where small arcs were created. In total, eleven tests were done where EF protection correctly operated during all these non-standard conditions.

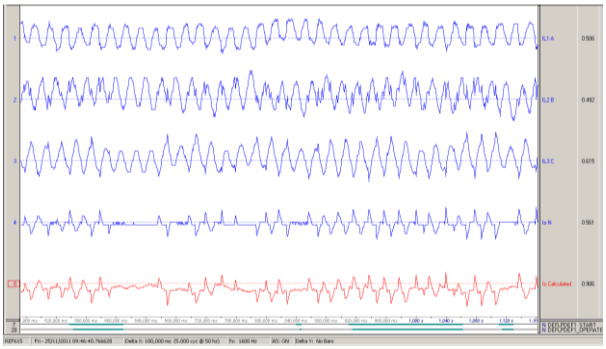

Figure 8: Example of the Disturbance recorder with the record from Intermittent EF in the isolated network

Channel 1 – phase current L1
Channel 2 – phase current L2
Channel 3 – phase current L3
Channel 4 – residual current measured from CBCT
Channel 5 – calculated residual current from sensor measurement

CONCLUSION

MV sensors based on non-conventional principles represent an alternative way how to measure current and voltage for protection and monitoring purposes in MV systems. Due to their compact size, high level of standardization, negligible energy consumption, high reliability, and safety, many advantages for users and applications exist. Their linear characteristic and very accurate measurement in the whole operating range offer new possibilities in the protection schemes. One area where these benefits could be fully utilized is represented by application with EF protection.

The tests in steady state conditions and in transient conditions were performed in order to prove the concept of EF protection based on calculated residual current from sensor measurement.

The results of the tests signified very promising precondition to decrease recommended minimum setting of EF protection, based on calculated residual current from sensor measurement, to lower values than in case of calculated residual current from conventional CTs measurement. This would enable using calculated residual current also in the network with very low level of earth fault current e.g. compensated networks which will contribute to the material and cost savings, further simplify protection schemes, and increase reliability of protection system. The whole concept of EF protection based on calculated residual current from sensor measurement will be further verified with the field tests in the networks.

REFERENCES

[1] R. Javora, V. Prokop, 2011, "Low-Power Current and Voltage Sensors for MV Applications", *Proceedings of International Protection Testing Symposium*, IPTS 2011, 2.1-2.9