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Impact of MV sensors on differential protection performance

***Abstract**. Differential protection provides basic protection for power transformers, motors, generators, overhead lines, cables and other important equipment used in Medium Voltage (MV) systems. The main advantages of differential protection are selectivity and fast operation. However for proper operation differential protection needs to receive reliable information about primary currents. Therefore differential protection places special requirements on current transformers (CTs). Consequently CTs generally need to be designed with very high parameters that are not practical to achieve in all cases. MV sensors represent an alternative way for measuring currents and voltages in MV networks. Due to their linear characteristics, sensors are very accurate across the whole operating range and in particular do not have a problem with saturation. The paper introduces the latest development in sensors used for differential protection applications and offers new views on how sensors could improve differential protection performance.*

***Streszczenie.** Zabezpieczenia różnicowe mogą wprowadzać ograniczenia. Dlatego w artykule przedstawiono czujniki określające precyzyjnie prąd I napiecie w sieci, bez ryzyka nasycenia. (**Wpływ czujników średniego napięcia na właściwości zabezpieczeń różnicowych**).*

Keywords: Differential protection, MV sensors, Current transformers, Saturation
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

The behaviour of a differential protection system depends on the quality of the current measurement. In the case of CT saturation, the current measurement values could be distorted to such a level that the differential protection could falsely trip due to a fault outside the protection zone, or with time delay during a fault inside the protection zone. That is why it is necessary for the CT to meet certain requirements defined by the particular differential protection. Unfortunately there are cases where it is very difficult or even impossible to meet differential protection requirements using CTs. This situation could arise in cases where a high short circuit current could occur but the rated primary current of the application is very low. A typical example is a motor application where the rated primary current is tens of Amperes, but the maximum short circuit current supplied from the MV network could be in tens of kA. In this case is impossible to fulfil the requirements of differential protection and malfunctions caused by CT saturation should be analysed and possibly considered in protection relay coordination study.

MV sensors based on non-conventional principles provide very accurate measurement from a few Amperes up to tens of kA (e.g. class 5P for current measurement up to 50 kA). This means that is no saturation because they do not use an iron core. Consequently there is no need for any calculation to verify the correct performance of the differential protection if current sensors are used.

Differential protection

Differential protection is a current comparison scheme for the protection of a component with two ends, such as the two windings of a power transformer; therefore the incoming and outgoing currents through the component to be protected are compared with each other. If no fault exists in the protection zone, the incoming current and the outgoing current must be identical. Therefore the difference between those currents, the differential current, can be used as the criteria for fault detection. The operation level is increased at through faults to ensure stability. Generally the CT cores should not saturate for any through fault current but the percentage stabilization and an internal stabilization for current transformer saturation means that the requirement can be limited. Specifically, modern microprocessor-based differential protection uses algorithms to detect current transformer saturation and is able to recognize if the fault is inside or outside the protection zone. This means that the requirement to prevent CT saturation can be applied less strictly nowadays. On the other hand, as indicated above there could be cases where is not possible to fulfil differential protection requirements on CTs at all [1].

Consequence of CT saturation

In a few cases, a saturated CT that fails to deliver a true representation of a primary fault current may cause the undesirable operations of the differential protection described below.

- **False trip**

At first, it might seem rather uncommon for a saturated CT to cause a false trip. Sometimes during a high through fault current one CT could be saturated and the differential protection could cause a false trip. A current differential is most likely to misoperate when one CT saturates. Partial or full saturation of one CT will allow the other CT to deliver the necessary operating current to the differential relay for a through fault condition, thus causing a false trip by not producing the expected balancing current. Such a situation is most likely to occur when a small load is connected to a relatively high-voltage distribution system. CT performance with a low ratio at the high-voltage side of the power transformer will be poor and the through fault current for a low-voltage side fault may cause an undesirable trip of the transformer differential protection. Operating current will be supplied by the low-voltage circuit high ratio CT and the severely saturated high-voltage circuit low ratio CT will not provide a matching current [1].

- **Delayed trip**

When the power supply is only on the one side, during a short circuit in the protection zone, the saturation of the CT on the power supply side could cause an undesirable delayed trip. The level of secondary current saturation is so high that differential protection could not recognize the short circuit in the protection zone within the correct time [1].

CT influence on differential protection performance

For correct operation of differential protection it is necessary to obtain undistorted or at least not heavily distorted information about the primary current. However, there are now differential protection systems designed with a partial stabilization feature which provides lower sensitivity on CT saturation. The stabilization is done by bias current (Ib) which results in a differential protection characteristic including slopes – see Fig. 1.

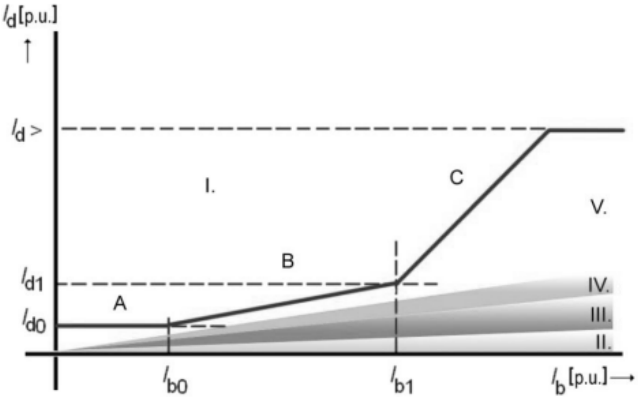

Fig.1. Typical example of differential protection characteristic including slopes

Unfortunately, the slopes can make differential protection less sensitive on fault detection and consequently it could detect the faults in the protection zone at a late stage when the fault current could reach high values.

Further differential protection systems based on CT measurement require the verification of CT parameters according to particular differential protection requirements. As indicated above, there are cases where it is not possible to design CTs with appropriate parameters due to size limitations. In that case, the performance of the differential protection should be verified as well as its impact on false trip or delayed operation.

MV sensors

MV sensors use non-conventional principles such as a Rogowski coil or voltage dividers, meaning that they are constructed 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 results in linear and highly accurate sensor characteristics across the full operating range which provides various benefits [2].

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 a 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 a wide range of frequencies.

A typical 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 fulfil the requirements of the protection class up to an impressive value reaching the rated short-time thermal current (e.g. 50 kA).

Fig. 2 shows the curve of current accuracy measurement corrected by use of correction factors in the IED (intelligent electronic device) across a typical current dynamic range in MV networks. Standalone Rogowski coil current measurement can achieve very accurate current measurement across the entire dynamic range; however, the possibility to use correction factors in the IED can even improve accuracy of current measurement both in amplitude and phase [3].

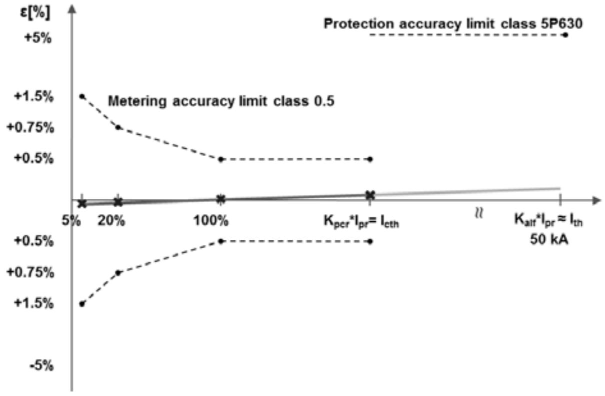

Fig.2. Typical example of combined current accuracy class corrected by use of correction factors in IED

Differential protection based on sensor measurement

The linear and very accurate dynamic measurement range of MV sensors could provide significant improvement for differential protection applications. In particular, there is no need to consider the saturation issue. There is therefore no need for high stabilization of differential protection on the high bias currents. Consequently fault detection sensitivity could be increased. The other advantage is the high accuracy of the sensor measurement. Measurement errors are reduced to a minimum due to utilization of signal conditioning by correction factors in the IED. This extends measurement accuracy which could be utilized in differential protection and could again lead to higher sensitivity of fault detection [4]. The improved differential protection characteristic which utilizes benefits of sensors measurement is expressed in Fig. 3.

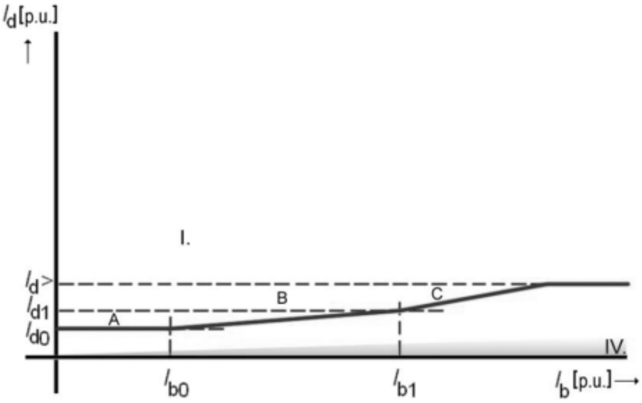

Fig.3. Improved differential protection characteristic utilizing advantages of sensor measurement

Basically, there could be two applications of differential protection based on sensor measurement. The first possible application requires sensors with long secondary cables on one side to be able to connect them to the IED from the remote end. This application represents protection of motors, generators, power transformers etc. The estimated maximum length for the sensor's secondary cable is 100 m in this case.

The second possible application is line differential protection where sensors are connected to the IEDs on both sides and the IEDs are interconnected via a fibre optic protection communication link which can be used at distances up to 20 km. This application represents protection of overhead lines or long cables.

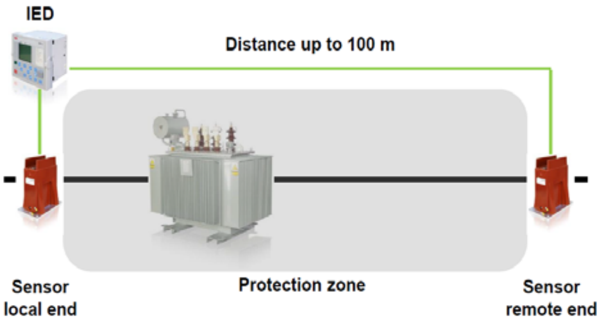

Fig.4. Example of differential protection based on sensor measurement where a long secondary cable is required

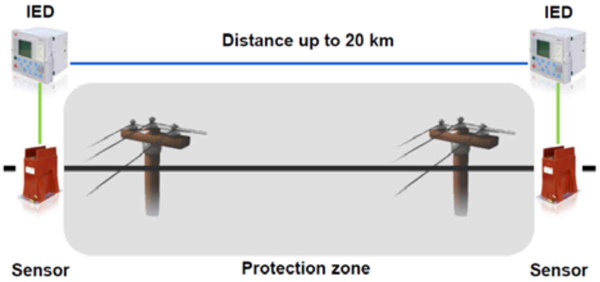

Fig.5. Example of differential protection based on sensor measurement where IEDs are interconnected via a fiber optic protection communication link

Differential protection and long sensor cables

The application of sensors for differential protection requires sometimes long sensor cables. Sensors have not been previously used in this application as it was believed that they cannot work reliably with long cables. However, the high accuracy and dynamic measurement range of sensors could bring many benefits to differential protection application. Since the only obstacle to sensor utilization in differential protection applications was the presumption that sensors with extended cable length could be used, tests have been carried out to refute this opinion.

Type test setup

The current sensors were measured using a type test setup based on the commercial system from ZERA Gmbh but with a different generator and with a TETTEX current transformer as reference. The current sensors were based on existing products using Rogowski coil technology. The test circuit for accuracy measurements in steady state corresponds to that described in IEC 60044-8, 2002. The burden of sensors was in all cases set to 10 MΩ.

Results

The influence of four different cable lengths on the accuracy of the current sensor has been investigated. Cable lengths used were: 6.5 m, 20 m, 50 m and 100 m. Three sensor samples have been used with each cable length. Measured results of amplitude and phase error are nearly identical for all sensors and are summarized in Fig. 6.

It must be considered that the sensor used was originally designed for operation with 6.5 m cable length. It is evident that for different cable lengths the current sensor does not need any correction of amplitude accuracy to be introduced to a given IED, in order to reach high accuracy. However, if very high accuracy is of concern, the corrections detailed in Tab. 1 could be used.

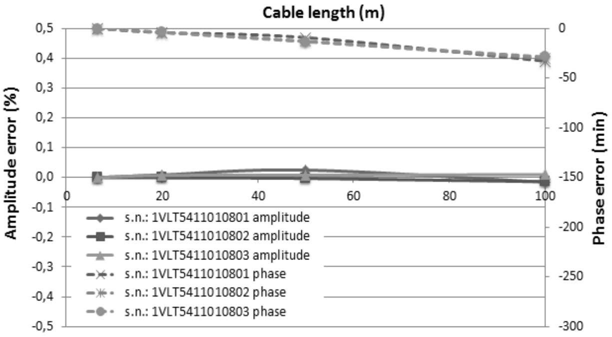

Fig.6. Amplitude and phase error variation of current sensor with different cable lengths

Table 1. Correction factor adjustments required for use with different sensor cable lengths

Cable length	Correction factor adjustment			
	V-sensor		I-sensor	
	amplitude	phase	amplitude	phase
6,5m	1,0000	0	1,0000	0
20m	1,0007	34	1,0000	4
50m	1,0025	113	0,9999	12
100m	1,0066	242	1,0001	31
	Correction factors - available limit range in IEDs			
	0,9000-1,1000	± 300	0,9000-1,1000	± 300

Since modern IEDs enable secondary signal correction by correction factors, the influence of different cable lengths could be easily corrected within an IED. Therefore, the total measurement error of the whole chain IED and sensor would be significantly less than shown in Fig. 6.

EMC test

In order to verify the performance of sensors with different cable lengths in harsh environments, EMC tests have also been performed, for all current sensors and all cable lengths investigated, in order to prove their suitability for application in power systems. EMC tests have been performed on a sensor connected to the IED, which fully corresponds to the real application in service. An example of the electromagnetic field immunity test setup is shown in Fig. 7.

Fig.7. Electromagnetic field immunity test

It has been proved that connection of such sensors together with IEDs does not cause any EMC issues, which confirms suitability for differential protection applications, showing significant benefits in setting up of the IED and the use of standardized sensors [5].

Conclusion

The challenging situation for traditional differential protection based on measurements from conventional CTs is mainly CT saturation. This could happen during faults outside or inside the protected zone when a high fault current occurs in primary system. To avoid false operation during faults outside the protected zone, the traditional differential protection uses stabilized characteristic with slopes. Thanks to the slopes the differential protection could be less sensitive when the CT is saturated. Unfortunately the slopes can make differential protection less sensitive on fault detection and consequently differential protection could detect the faults in the protection zone at a late stage when the fault current could reach high values. Moreover use of CTs with differential protection requires verification of CT parameters which sometimes results in a complex procedure.

On the other hand, sensors with their linear characteristics without saturation could change dramatically differential protection characteristic, and the slopes which should stabilize the differential protection on CT saturation could be removed. Therefore utilization of sensors for accurate measurement for differential protection could bring significant improvements in making it more sensitive and reliable. Moreover there is no need to calculate any sensor parameters since they are very well standardized.

In the past, it was believed that sensors cannot be used for differential protection since they cannot work reliably with long secondary cables. The accuracy and EMC tests were performed with positive results to disprove this fallacy. The project will continue with field tests which should verify the behaviour of sensors with long secondary cables in real applications.

Acknowledgements

The authors gratefully acknowledge financial support from the Technology Agency of the Czech Republic under project No. TA03010444.

This work has been partly supported by the Czech Science Foundation under the project 102/09/1842 and by the Ministry of Education, Youth and Sports of the Czech Republic (ENET No. CZ.1.05/2.1.00/03.0069) and also project SP2013/68.

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