Dual Differential Protection of a 240kV Autotransformer

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ABSTRACT

This paper presents a unique transformer protection design consisting of one conventional restraint differential function and one low impedance phase segregated differential function for a 450MVA, 240kV autotransformer. The phase segregated differential protection has the advantage of being immune to inrush current and imbalance current caused by a load tap changer. By combining the two differential elements and optimizing the settings, the dual differential protection has superior performance than conventional transformer differential protection.

The two differential elements were implemented inside one physical micro-processor based relay, which greatly reduced CT requirements, cable connections and panel wiring.

1. INTRODUCTION

The current based transformer differential protection has been in use for many years and is well known. For high and ultra-high voltage autotransformers, some utilities use high impedance differential protection when the transformer neutral side phase CTs are available. (IEEE C37.91-2000, Guide for Protective Relay Applications to Power Transformers, Section 6.2.9).Despite the advantage of being immune to inrush current and the load tap positions, this protection scheme requires that all the CTs have the same ratio. Yet it can not protect winding turn-to-turn fault and fault in the tertiary winding. This paper presents a transformer differential protection design that tries to take the advantages of both the differential schemes, by combining one conventional transformer current differential element, and one low impedance, phase segregated current differential element into a dual differential relay.

2. THE LOW IMPEDANCE PHASE SEGREGATED CURRENT DIFFERENTIAL PROTECTION

Similar to high impedance differential protection, the low impedance version takes current inputs from the autotransformer high voltage side CT, low voltage side CT and the neutral side phase CT. Fig. 1 shows the principle of this differential protection.

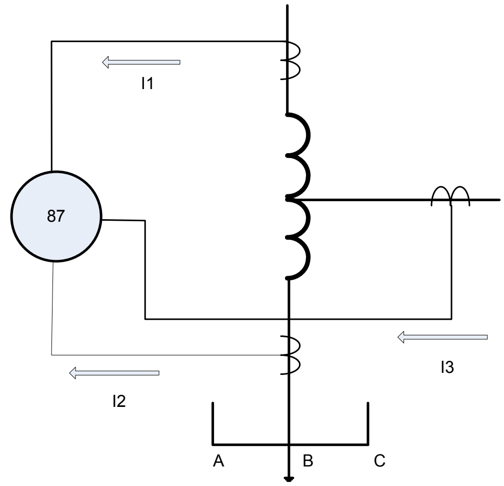

Fig. 1. Phase Segregated Current Differential Protection

The relay measures the differential current Idiff as | I1 + I2 + I3 |, and the restraint current Ires = Max (|I1|, |I2|, |I3|). According to Kirchhoff Law, the Idiff (converted to primary value) is always zero when there is no internal fault on the transformer. This differential scheme is similar to low impedance bus-bar differential protection. The transformer ratio is not a factor that needs to be considered. Compared with the conventional differential protection, the phase segregated differential protection has the following advantages:

1) Immune to the Inrush Current

During transformer energization, the inrush current flows through the transformer high voltage side CT and the neutral side phase CT, therefore, the differential current is always zero. Thus there is no need to restrain the differential element by the inrush current harmonic components.

2) No Imbalance Current Due to Load Tap Changer

An On-Load Tap Changer (OLTC) regulates the transformer load voltage by adjusting the ratio dynamically. For the phase segregated differential element, as discussed above, the transformer ratio does not affect the differential current calculation. This means that only the CT error needs to be considered in setting the differential minimal pickup and the first restraint slope. Settings more sensitive than the conventional differential protection can be achieved. For a typical transformer with OLTC, the imbalance current can be up to 10% of the transformer load. Therefore the phase segregated differential element restraint slope settings can be set 10% lower than that of the conventional one.

3) High Sensitivity for Ground Fault

Since the autotransformer's primary and secondary windings are universally Wye connected, the conventional differential protection must perform the zero-sequence component filtering, which is either performed internally on micro-processor based relays, or externally by connecting the CTs in delta. Consequently, both sensitivity and security of a ground fault are lower than those of a phase-to-phase fault with the same fault current magnitude. This is because the differential and restraint currents are both lowered by a factor after the zero-sequence component is removed. The factor is 1/ sqrt(3) for external zero-sequence current removal and for most micro-processor based relays. On the other hand, the phase segregated differential always calculates the same differential and restraint current regardless the fault phase.

Table 1 calculates and compares the differential and restraint currents for internal and external fault with a magnitude of 2 p.u. in HV and LV windings.

	Internal Fault		External Fault	
	Single Phase Fault	Three Phase Fault	Single Phase Fault	Three Phase Fault
87-1 Conventional Differential	Idiff = 1.15 Ires = 1.15	Idiff = 2.0 Ires = 2.0	Idiff = 0 Ires = 1.15	Idiff = 0 Ires = 2.0
87-2 Phase Segregated Differential	Idiff = 2.0 Ires = 2.0	Idiff = 2.0 Ires = 2.0	Idiff = 0 Ires = 2.0	Idiff = 0 Ires = 2.0

Table 1. Differential and Restraint Currents Comparison

Fig. 2 and Fig. 3 plot the above value on the differential and restraint plane, and compare them with a typical differential restraint characteristic.

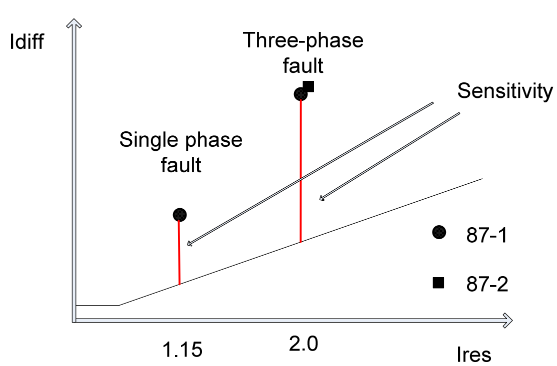

Fig. 2. Internal Fault

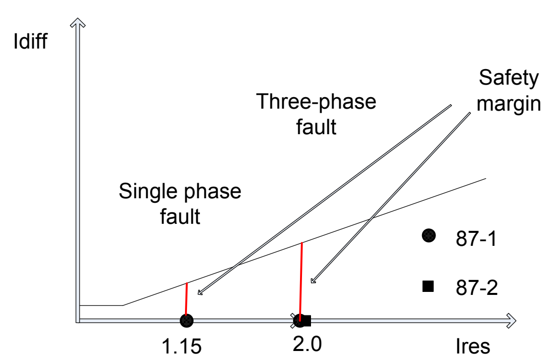

Fig. 3. External Fault

4) Accurate Fault Phase Indication

Due to zero-sequence component filtering, the conventional differential protection always operates more than one differential element for a single-phase fault. The phase segregated differential calculates the differential current independently for phase A, B and C, thus it can always give correct fault phase indication. This feature is particularly important for single-phase transformer group.

The phase segregated differential protection has its limitations. It can not protect turn-to-turn fault, nor can it protect fault in the tertiary winding. That is because there is no differential current that can be sensed by this scheme for the above two types of fault.

3. DUAL TRANSFORMER CURRENT DIFFERENTIAL PROTECTION

The phase segregated differential protection has many advantages. If it can be used to complement the conventional transformer differential protection, better sensitivity and reliability can be expected. Table 2 compares the performance of the conventional, phase segregated and dual differential protections.

Conditions	Conventional Differential	Phase segregated Differential	Dual Differential (Conventional + phase segregated)
Magnetizing inrush current	Need harmonic restraint. Could miss operate due to inrush current with low harmonic component	Immune to inrush current.	Immune to inrush current
OLTC	OLTC can cause imbalance current; Needs higher restraint slope setting	Immune to OLTC	Immune to OLTC
Ground fault	Lower sensitivity and security of ground fault than those of phase-to-phase faults	Ground fault has the sensitivity and security with phase-to-phase fault	Ground fault has the sensitivity and security with phase-to-phase fault
Tertiary winding Fault	Protect the fault in tertiary winding	No protection	Protect the fault in tertiary winding
Winding turn to turn fault	Protect turn to turn fault	No protection	Protect turn to turn fault
Fault phase indication	No accurate	Accurate fault phase indication	Accurate fault phase indication

Table 2. Comparison of Conventional, Phase segregated and Dual Differential Protection

Applying the dual differential protection in the traditional way can be expensive. Two physical relays (for electro-mechanical relays, six relays) will have to be used, and the transformer CTs need to be connected to both relays separately. With an advanced Intelligent Electronic Device (IED) and powerful engineering software, it is much easier and more cost effective to implement the dual differential protection. The two differential elements will be two logical protection functions inside one physical relay. All the autotransformer CTs required by the dual differential protection are connected to this single relay. The currents are shared between the two differential functions internally. Therefore, relay panel wiring is greatly simplified, and the CT secondary side cables are saved as well.

4. THE APPLICATION OF A DUAL DIFFERENTIAL PROTECTION ON A 450MVA / 240KV AUTOTRANSFORMER

The following single line diagram illustrates the implementation of the dual differential protection scheme. The transformer is a 270/360/450MVA, 240/72/13.8kV 3-winding autotransformer, where the third winding is a no-load tertiary winding.

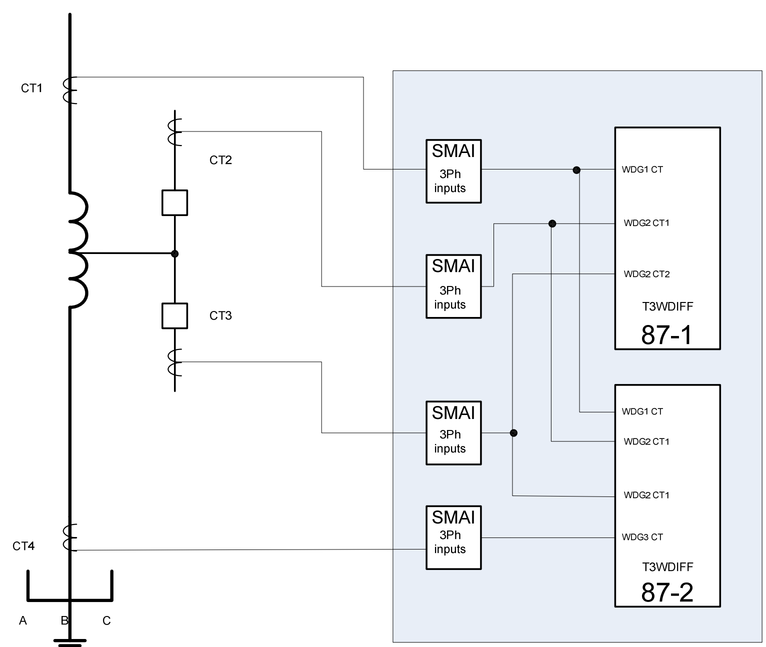

Fig. 4. Simplified Single Line Diagram of the 240kV Autotransformer Protection

As shown in Fig. 4, there are two logical differential function blocks residing in the relay. 87-1 is the conventional differential element, and 87-2 is the phase segregated differential element. The CT1 is the 240kV side transformer bushing CT. The 72kV side is a breaker-and-half connection. CT2 and CT3 are the CTs used for the differential protection. The CT4 is the transformer neutral side CT, and is used only by the phase segregated differential protection. The CT1, CT2, CT3 and the neutral side CT4 are wired into the relay. Internally, the relay's Signal Matrix Analog Input(SMAI) function blocks receive the 3-phase CT currents, then distribute the currents to the two 3-winding Transformer Differential Function blocks.

87-1 receives CT1, CT2 and CT3 to form the conventional differential protection, while the 87-2 receives all the CT currents to form the phase segregated differential protection. The connections from the SMAIs to the T3WDiff functions blocks are engineered with the relay's graphical configuration tool. The T3WDiff function block is designed for 3-winding transformer differential protection with up to six restraint current inputs. By not connecting the third winding current input, it can be used for the two winding transformer application. The 87-1 is a two-winding application, with three restraint current inputs. Bringing both CT2 and CT4 into the differential protection, instead of summing them up externally, provides far better differential protection restraint current for external fault. 87-2 is a 3-winding application, with four restraint current inputs.

CT Connection and Ratio Settings

The T3WDiff differential function performs the calculations in transformer primary values. The CT connection and Ratio settings are used by it to convert the CT currents back into primary values. Tab. 3 shows all the CT settings, which are common to both 87-1 and 87-2.

240kV CT1 Connection Type	Wye
CT1 Ratio	1600:5
72kV CT2 Connection Type	Wye
CT2 Ratio	3000:5
72kV CT3 Connection Type	Wye
CT3 Ratio	3000:5
Tr. neutral side phase CT4 Connection Type	Wye
CT4 Ratio	4000:5

Table 3. Common CT settings

Transformer Configuration Settings

87-1 is set in a regular way to reflect the actual transformer connection type, voltage ratio and CT connection type. For the 87-2, the transformer must be considered as a transformer with 1:1 turn ratio. Furthermore, it must not perform the zero-sequence component removal from the winding current so that the differential is phase segregated. Table 4 lists the transformer configuration settings of the 87-1 and 87-2.

Settings	Conventional Differential 87-1	Phase segregated differential 87-2
Transformer MVA	450	450
Transformer WDG1 Rated Voltage (kV)	240	72
Transformer WDG2 Rated Voltage (kV)	72	72
Transformer WDG3 Rated Voltage (kV)	N/A	72
WDG1 CT 'T' Connection(2 CTs)	No	No
WDG2 CT 'T' Connection(2 CTs)	Yes	Yes
WDG3 CT 'T' Connection(2 CTs)	N/A	No
WDG1 3Io Removal	Yes	No
WDG2 3Io Removal	Yes	No
WDG3 3Io Removal	Yes	No

Table 4. Transformer Configuration Settings

Transformer Differential Characteristic Settings

1. Harmonic Percentage for Inrush Inhibit

As discussed earlier, the phase segregated differential protection is immune to the inrush current and does not require harmonic restraint.

For the stand-alone conventional differential, the 2^{nd} harmonic restraint setting is typically at 15%. Transformers with new core material tend to have lower 2^{nd} harmonic contents in the inrush current. 15% harmonic restraint setting may give the possibility of false tripping for these new transformers, under certain closing angle or remnant transformer core flux level. On the other hand, this harmonic content setting can not be lowered for the fear of excessive delay of fault clearing if the transformer is switched onto fault, unless the protected transformer inrush current 2^{nd} harmonic component is known to be lower than 15%.

With the dual differential scheme, the convention differential protection 2^{nd} harmonic percent setting can be confidently lowered to make it more secure. Transformer switch onto fault will be protected by the phase segregated differential element. The harmonic percentage restraint setting value was setting at 10%, lower than the 15% typical value.

2. Minimal Pickup and Restraint Slope Settings

This autotransformer has a tap changer voltage range of 204kV to 264kV. The imbalance current due to tap changer is up to +(264 – 240) / 240 = 10%, or (204-240)

/ 240 = -15%. Also considering that the maximum CT error is up to 10%, the first slope of the restraint characteristic was set at 30%, and the minimal pickup was at 0.25 for the conventional differential element.

The phase segregated differential is immune to the tap changer position. Therefore, the Slope 1 can be set 5 to 10% lower than the conventional one, to increase sensitivity. We set the 87-2 Slope 1 setting at 25% and the minimal pickup at 0.15.

The restraint Slope2 is designed to increase the security for heavy external fault, where CT may be severely saturated. This setting was set at 85% for both 87-1 and 87-2, because CT saturation affects both elements equally.

3. Turn-to-turn fault protection settings

Because the phase segregated differential does not protect turn-to-turn fault, the conventional differential protection has to provide the protection. For faults that involved more than 10% of turns, the fault current is large enough that the restraint differential characteristic can provide satisfactory protection. If the shorted turns are less than 10% of the winding, then a sensitive turn-to-turn fault protection is necessary. The T3WDiff function has a built-in negative sequence component current protection, specifically designed to detect the winding turn-to-turn fault. Therefore, the sensitive negative sequence element was enabled in 87-1. It was disabled in 87-2.

Tab. 5 lists and compares the settings of the 87-1 and 87-2 differential characteristics

Settings	87-1	87-2
Minimal Pickup	0.25	0.15
Slope 1 starting value	0.8	0.6
Slope 1 percentage	30	25
Slope 2 starting value	3.0	3.0
Slope 2 percentage	85	85
Unrestrained Differential pickup	15	15
2^{nd} harmonic percentage	10	100 (max)
Harmonic cross blocking mode	Yes	No
Sensitive Negative Sequence Element Enable	Yes	No
Negative sequence pickup level	0.04	N/A

Table 5 Differential Characteristic Settings

5. TEST RESULTS

Functional tests were carried out by secondary current injection to test performance and validity of the dual differential design. The following two tests are selected to show the unique advantage of this design.

Test No. 1. Transformer Switch onto Fault

Simulation: The transformer high voltage side Phase A was injected with “inrush current”, consisting of 3 p.u. 60Hz current, superimposed with 25% 2^{nd} harmonic current. This same current also flows through the neutral side phase A. The fault current magnitude was 1 p.u. 60Hz. It was injected only into high voltage side Phase B to simulate an internal fault.

Fig. 5 is the disturbance recording of the fault. The test result analysis is as follows:

The phase segregated 87-2 phase B picked up and operated within one cycle since the fault inception. There were no differential currents for the Phase A or C elements.

All three internal elements of the conventional differential 87-1 picked up by the fault, but all were inhibited by the harmonic restraint. Therefore, the 87-1 did not operate.

The test results proved that the phase segregated 87-2 will correctly clear the fault with high speed. 87-1 is securely blocked by the high 2^{nd} harmonic component contents.

Test No. 2. Transformer Turn-to-Turn Fault

Simulation: The transformer was carrying 1 p.u. load current as the pre-fault condition, then a turn-to-turn fault on phase A was applied. All the currents in the healthy phases did not change.

Fig. 6 is the disturbance recording of the fault. The test result analysis is as follows:

The 87-1 sensitive negative sequence current element detected and cleared the fault in about 2 cycles since the fault inception. The slower speed is necessary because the fault magnitude is small, thus the correct operation is more importance than speed. The differential currents were so small that none of the 87-1 the restraint differential elements picked up.

None of the phase segregated 87-2 differential elements picked up, as the differential currents were always near zero.

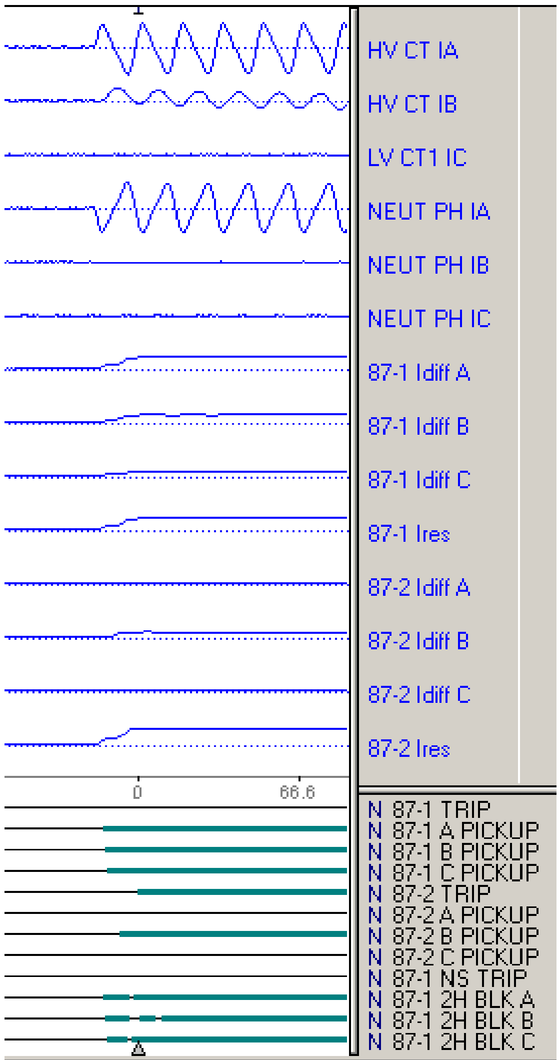

Fig. 5 Switch onto Fault Test

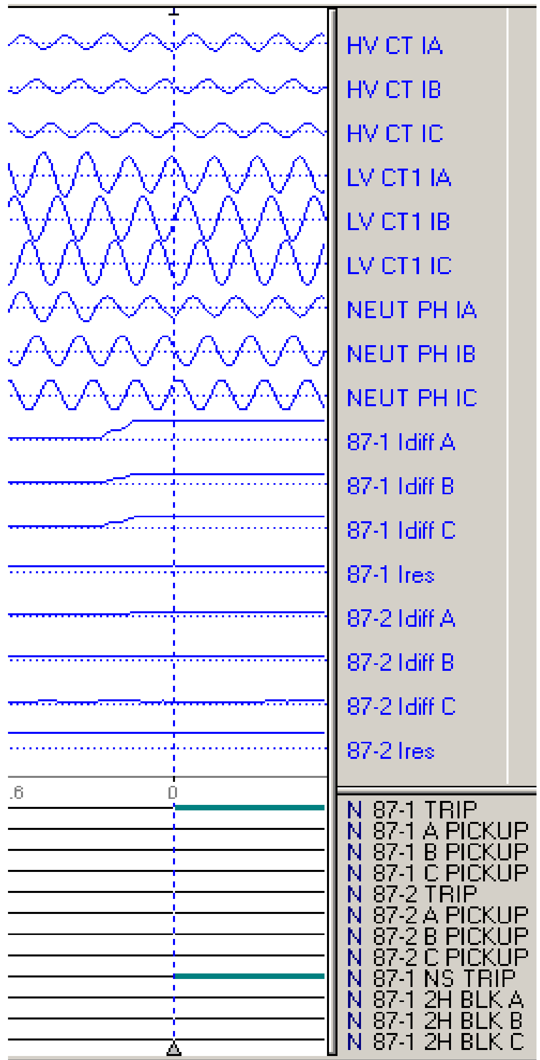

Fig. 6. Turn to Turn Fault Test

6. CONCLUSIONS

Compared with conventional transformer differential protection, phase segregated low impedance differential is immune to magnetizing inrush current, imbalance current caused by load tap changer, and has high sensitivity for ground fault.

Dual Differential, consisting of a conventional differential and a phase segregated differential element, has the advantages of both schemes. By further optimizing the differential setting parameters, the dual differential has greater performance than any of the individual differential element applied alone.

A State of the art IED makes the dual differential implementation simple and cost effective. The two differential elements can reside as function blocks inside one physical IED and share the winding CT currents. Protection panel wiring design is significantly simplified, and fewer cables are required from CTs to the panel

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BIOGRAPHIES

Jonathan Gao received his B. Sc. from North China Electric Power University, Baoding, China in 1993, and M. Sc. from Zhejiang University, Hangzhou, China in 1996. He is a licensed professional engineer in the province of Ontario, Canada, and a member of the IEEE. He joined ABB in 2005, and currently holds the position of Application Specialist with the Substation Automation Product Division. Prior to that, he worked for NARI and Manta Test Systems in the area of protective relaying.

Alin Hasegan received his B.Sc. and M. Eng. from Gh. Asachi University of IASI, Romania in 1989 and 1990 respectively. He is a licensed professional engineer in the province of Alberta, Canada. Currently he is the Principal Engineer at Phasor Engineering Inc., based in Calgary, Alberta. He has 18 years experience in protection and control engineering.

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