PERFORMANCE ANALYSIS AND ASSESSMENT OF A TRANSFORMER DIFFERENT PROTECTION RELAY SEL387 AT 110KV LANG CO SUBSTATION

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Abstract - Based on the influences of current transformer connection type, CT errors, magnetizing inrush current, errors because of tap changing and fault conditions on differential protection function, the paper establishes and assesses the performance of a numerical relay SEL387 model concerning the protection of the 115/24kV transformer at Lang Co Substation by Matlab/Simulink. The paper also calculates the setting value of two actual slope characteristics (O87P = 0.3, U87P = 10, SLP1 = 25%, SLP2 = 50% and IRS1 = 3). The results can be applied to increase the accurate and reliable performance of the differential transformer protection relay against internal faults. Simulation has simplified the process of selecting relay and protection system. This can improve the quality of the protection system design early, thereby reducing the number of errors found later in the operation.

Key words - Different protection relay; transformer; two slope characteristics; Matlab/Simulink; SEL387.

1. Introduction

Nowadays, there are a variety of numerical transformer different protective relays on the market such as Siemens 7UT613, SEL387, Schneider P632, Toshiba GRT200, ABB RET670, which include many functions in one unit, as well as providing metering, communication, and transformer protection. These protective relays help us to simplify implementation of the protection in circuit design and setting calculations.

The connection diagram is used for the numerical protective relay SEL387 (shown in Figure 1) that provides protection of two transformer windings (HV, LV) as well as differential function (F87T) for sensitive detection of inter turn faults within the transformer winding. Both HV CTs and LV CTs are wye connected. The F87T obtains three phase current inputs from them. This function compares the currents entering and leaving the protected zone of the windings of the transformer.

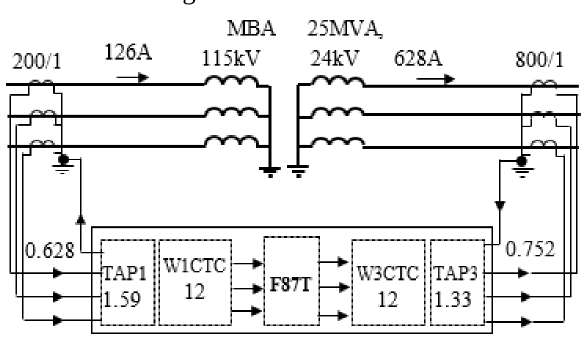


Figure 1. *Secondary current in HV and LV side at normal condition*

As with most false trips involving F87T in Central Power Grid, checking the relay should be done first, and can be done by inspecting the LED indicators, cable connections, auxiliary relay and so on. The main cause shown in Figure 2 is CT secondary wire connected to the incorrect tap on the CT, Crossed phases, Incorrect CT polarity in design or construction [2]. In addition, there is a general lack of understanding the ground differential protection principle. In most cases, inadequate or no verification test is performed to check the correctness of the secondary current circuit. So, these errors depend on skill of testers. If the hardware has no issues, then it is very likely to be a setting problem. Unlike hardware issues, setting issues cannot be assessed by the naked eyes, so the universal relay test set and commissioning tool are required. It performs to check wiring and setting of relays, by using primary/secondary injection of currents from the test set.

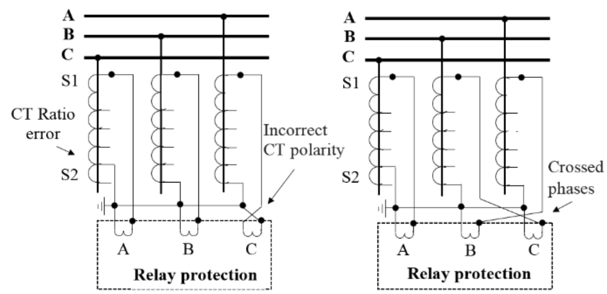


Figure 2. *Incorrect CT Ratio, CT Polarity, or Crossed Phases*

But even in a no fault situation, the magnitude and the phase of the currents in both sides of the transformer will not have the same value. This is often the case that mis-operation on relay does not become apparent immediately. One possibility is CT errors, magnetizing inrush current during initial energization, CTs mismatch and saturation. Another possibility is that the transformation ratio changes due to Tap changer. These have already been introduced to the different currents by devices that have not yet caused any problems, but will cause significant disruption to the transformer in the future. Besides, the possibility is that someone with unauthorized access infiltrates the relay and reconfigures incorrect setting to a relay, instructing it to release a false trip signal without the existence of any fault. When these types of mis-operation risks go undetected, it is very easy for substation operators to mistakenly believe that their relay protection is secure. The question substation operators need to ask is, “How confident am I that my relay protection is reliable and secure?”

After this introduction, the rest of the paper is organized as follows. The section 2 describes the transformer different protection function and provides instructions for setting calculation SEL387 in Lang Co substation. The section 3 builds the power system and the relay protection on Matlab Simulink. The section 4 simulates the testing normal/fault conditions. The section 5 gives the conclusions related to the transformer different protection.

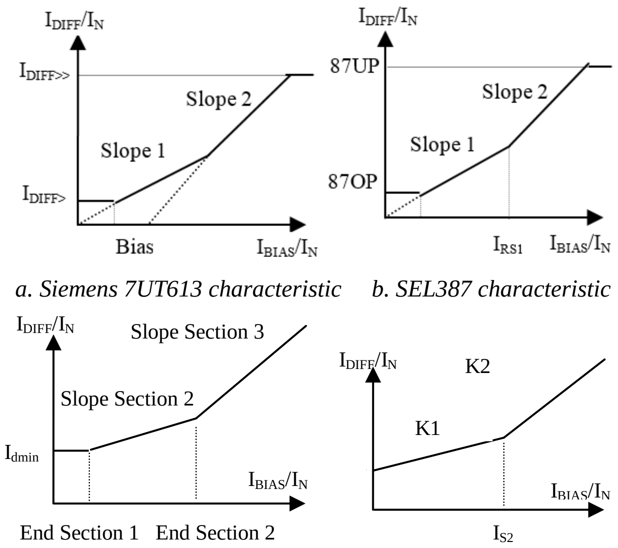
2. Transformer different protection function

The main operation of a current differential protection relay is made by comparing the vector current in both sides of the transformer: $I_{DIFF} = |I1 + I2|$ (1)

Restraint current:

$I_{BIAS} = |I1| + |I2|$ (Siemens, Sel, Abb) (2)

$I_{BIAS} = 0.5(|I1| + |I2|)$ (Schneider) (3)



a. Siemens 7UT613 characteristic *b. SEL387 characteristic*

c. ABB RET670 characteristic *d. Schneider P632 characteristic*

Figure 3. *Differential protection characteristic*

Based on these values of I_{BIAS} and values of I_{DIFF}, the trip/restrain characteristics offer from vendors of protection relay such as Siemens, Sel, Abb, and Schneider which has a three-step shape (two slopes and one pickup level) as in Figure 3 and defined by the following settings as in Table 1. The F87T operates when I_{DIFF} exceeds a minimum operate current threshold and a percentage of I_{BIAS}, defined by a slope setting (slope 1, slope 2). Consider matlab code of this matter in subsection 3 below.

Table 1. *Parameter characteristic of relay vendors*

Parameter	Siemens	Sel	Abb	Schneider
Minimum pickup	$I_{DIFF>}$	87OP	Idmin	IS1
Slope 1	Slope 1	Slope 1	Slope Section 2	K1
Slope 2	Slope 2	Slope 2	Slope Section 3	K2
Unrestraint tripping	$I_{DIFF>>}$	87UP	$I_{D>>}$	
Points of intersection	Base Point 2	IRS1	End Section1, End Section 2	IS2

To help us understand a setting calculation for relays, we use SEL 387 to protect a 25MVA, 50Hz, (115/24) kV, Y/y0 Vina Takaoka transformer in Lang Co Substation that has CTHV = 200/1, CTLV = 800/1, and an OLTC with tapping range from 1 to 19 positions. It has satisfied the following requirements from Decision No. A3-06-2015/LCO110 by the Central Region Load Dispatch Centre of Vietnam [3, 6].

Windings 1 and 3 are validated for differential protection. Settings will be: E87W1 = Y, E87W3 = Y.

The voltages for winding 1 and 3 are 115kV and 24kV, respectively: VWDG1 = 115, VWDG3 = 24.

The internal compensation (ICOM = Y) for the wye-wye transformer with a wye-wye CT can be set to 12 to remove the zero sequence currents.

Winding 1 CT Conn.Compensation W1CTC =12

Winding 3 CT Conn.Compensation W3CTC =12

The following settings refer to the CTs connection and to the current ratio for each winding: W1CT = Y; CTR1 =200; W3CT = Y; CTR3 = 800.

The secondary current of CT HV side under normal operating condition is:

$I_{HV} = MVA/(1.732 \times VWDG1 \times CTR1)$

$I_{HV} = 25\times106/(1.732\times115\times103\times200) = 0.628$ [A]

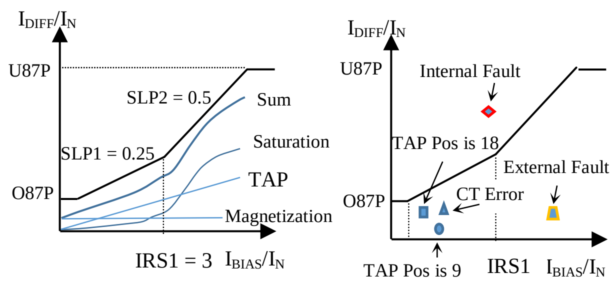
and requires ratio compensation TAP1 = 1/0.628 = 1.593

Under normal condition, secondary current in LV side is:

$I_{LV} = MVA/(1.732 \times VWDG3\times CTR3)$

$I_{LV} = 25\times106/(1.732\times24\times103\times800) = 0.752$ [A]

and requires ratio compensation TAP3 = 1/0.752 = 1.33



a. Setting characteristic *b. Test point in Normal/ Fault conditions*

Figure 4. *SEL 387 setting characteristic in Lang Co Substation*

As shown in Figure 4a, dual slope characteristics can be used with a minimum pickup setting. This can be mathematically represented as follows:

The minimum pickup O87P should be set as sensitively as possible while considering the steady state CT error and transformer magnetizing current. The O87P setting must yield an operating current value of at least $0.1\times I_N$, at the least tap. In this case O87P $\geq 0.1 I_N/TAP_{MIN}$ = 0.1x1/ 1.33 = 0.0752. The typical O87P range is 0.3 to 0.5. Therefore, the O87P setting of 0.3 is valid.

The instantaneous unrestrained current element is intended to react quickly to very heavy current levels that clearly indicate an internal fault. Set the pickup level (U87P) about 10 times TAP. The unrestrained differential element only responds to the fundamental frequency component of the differential operating current. It is not affected by the SLP1, SLP2, IRS1, PCT2, PCT5, or IHBL settings. Thus, it must be set high enough so as not to react to large inrush currents.

Slope 1 region is used between the minimum pickup region and the slope 2 breakpoint. Slope 1 provides security against false tripping due to the following factors: Excitation current = 2 %, CT accuracy = 3%, NLTC = 5%, LTC = 10%, Tap mismatch = 0%, and Relay accuracy = 5%. All these percentages sum to 25 %, thus a setting of SLP1 = 25% can be used.

Slope 2 is used to prevent false tripping caused by saturation of the CTs. A setting of SLP2 = 50 % for slope 2 covers all the situation.

IRS1 = 3 is restraint current slope 1 limit.

Operate time (restrained function): 20 to 35 ms.

Operate time (unrestrained function): 5 to 20 ms.

PCT2 = 15% (the F87T is going to be blocked if the second harmonic is higher than 15% from fundamental).

PCT5 = 35% (the F87T is going to be blocked if the fifth harmonic is higher than 35% from fundamental) and TH5P = OFF (the 5th harmonic alarm is deactivated).

3. Building of the differential protection function using Matlab Simulink

For the purpose of testing reliability of the relay protection from SEL vendor to test the algorithm of different protection, the power system model has been simulated in the Matlab Simulink and it is depicted in Figure 5. It consists of a 115 kV, 1000 MVA system, a 25MVA, 50Hz, (115/24) kV, Y/y0 OLTC regulating transformer, two CT (200/1A and 800/1A), 24 MW /1Mvar loading and SEL 387 relay protection. All fault conditions are created to transformer via the three phase fault block.

A relay SEL387 model shown in Figure 6 combines functions of vector group compensation, TAP factor compensation, different and bias current calculation, inrush harmonic blocking and slope characteristics. Firstly, current signals have been simulated in Matlab, which combines vector group value of current throw S-function, which is used to correct the phase shift across the YNy0 transformer. Since the HV, LV side of the transformer are wye connected, they require and will use the same ϴ = 0^0. The identity matrix is shown below:

$$CTC0(\theta)=\frac{2}{3}\times\begin{vmatrix}\cos(\theta) & \cos(\theta+120^0) & \cos(\theta-120^0)\\ \cos(\theta-120^0) & \cos(\theta) & \cos(\theta+120^0)\\ \cos(\theta+120^0) & \cos(\theta-120^0) & \cos(\theta)\end{vmatrix}$$

$$\begin{vmatrix}I_{A\_COMP}\\ I_{B\_COMP}\\ I_{C\_COMP}\end{vmatrix}=CTC0(0^0)\times\begin{vmatrix}I_A\\ I_B\\ I_C\end{vmatrix}=\frac{1}{3}\times\begin{vmatrix}2 & -1 & -1\\ -1 & 2 & -1\\ -1 & -1 & 2\end{vmatrix}\times\begin{vmatrix}I_A\\ I_B\\ I_C\end{vmatrix}$$

After that it sends to the subsystem combined TAP factor compensation (TAP1 = 1.59, TAP3 = 1.32). Secondly, the subsystem different value and bias of current are calculated for each phase separately according to the relation of the equation (1) and (2). Similarly, in the harmonic subsystem the F87T is going to be blocked if the second harmonic is higher than 15% from fundamental. Finally, S-Function Builder checks the position of operating point described by currents (for each phase separately) with respect to the pick-up characteristic I_{DIFF} = f(I_{BIAS}) and decision tripping the pulse, which opens a circuit breakers located on both sides of the protected transformer. The following Matlab code is written for phase A:

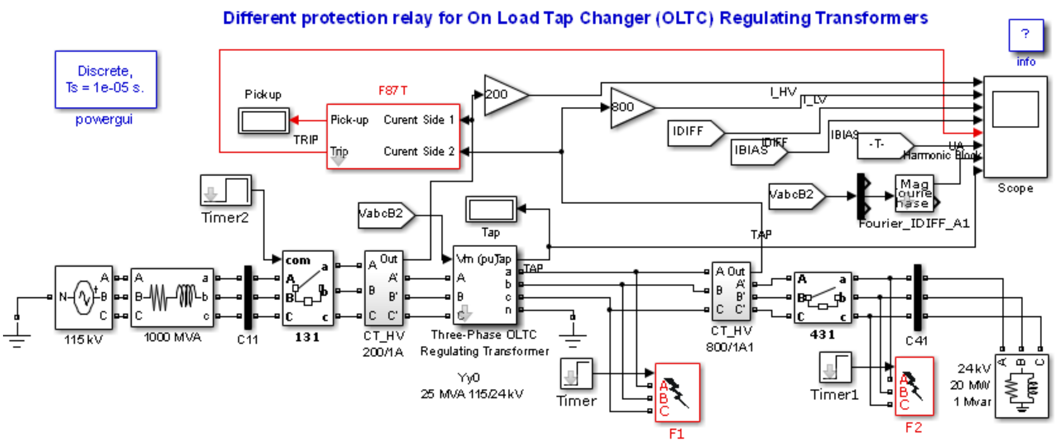


Figure 5. *Matlab/Simulink Model of the proposed system*

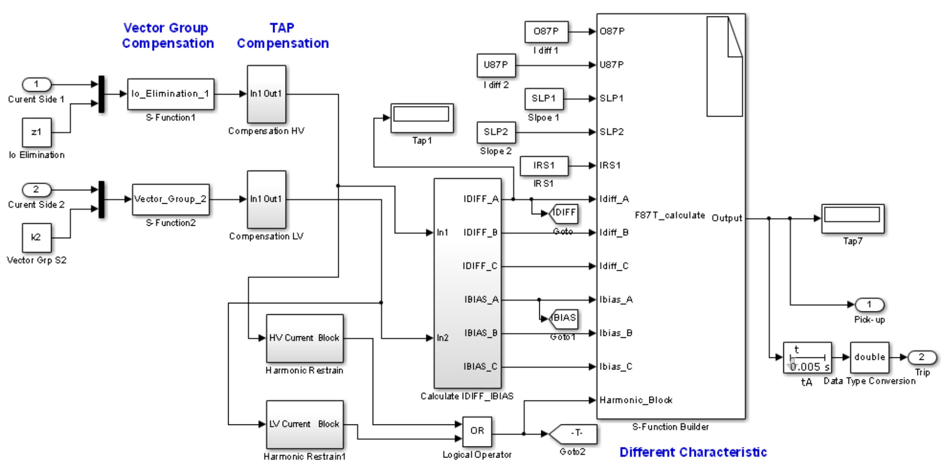


Figure 6. *Overview of the function blocks of the F87T*

```
double IRT = (*O87P) / (*SLP1);/* starting point of SLP1*/
double IRT2 = (*U87P) / (*SLP2); /* ending point of SLP2*/
if ((*Ibias_A <= IRT) && (*Harmonic_Block == 0))
{
if (*Idiff_A > (*O87P))
  *Output = 1;
    else
  *Output=0;
}
else
{
if (*Idiff_A > (*U87P))
  *Output = 1;
else
  *Output=0;
}
if ((*Ibias_A > IRT) && (*Ibias_A <= *IRS1) && (*Harmonic_Block == 0))
{
if (*Idiff_A > ((*Ibias_A) * (*SLP1)))
  *Output = 1;
else
  *Output=0;
}
if ((*Ibias_A > *IRS1) && (*Ibias_A <= IRT2) && (*Harmonic_Block == 0))
{
 if (*Idiff_A > ((*Ibias_A) * (*SLP2)))
    *Output = 1;
else
   *Output=0;
}
```

4. Simulation results and discussion

The main goal of the simulation is either to obtain or calculate waveforms such as currents on both sides of transformer, TAP position, voltage at bus C41, I_{DIFF}, I_{BIAS}, trip signal, and harmonic block signal during normal/fault conditions for analysis of the behavior of relay.

4.1. Case.1. Normal Condition

When the transformer is operating normally, TAP position is 9 and the resulting voltage at bus C41 is 0.99pu. The differential currents in all the phases (I_{DIFF} = 0.028) are well below pick up value O87P = 0.3, I_{BIAS} = 1.35 and the relay does not issue any trip signal. Figure 7 shows I_{DIFF} and I_{BIAS} in any one phase (phase A) and relay output.

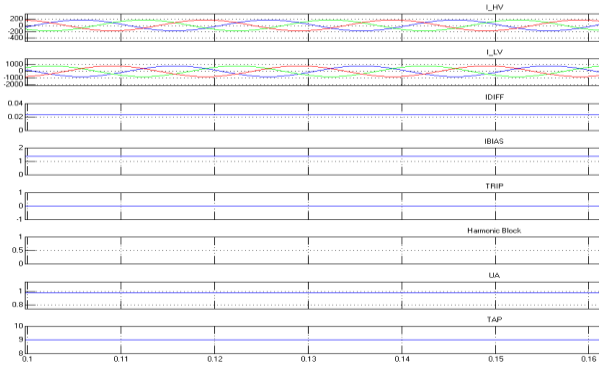


Figure 7. *TAP position at 9*

As the transformer taps further from the balance position (9), i.e. TAP position is 18 and voltage at bus C41 is 0.855pu, so the magnitude of the different current increases I_{DIFF} = 0.14, I_{BIAS} = 1.08. However, the differential current is still smaller than 0.2, the relay will not trip (shown in Figure 8).

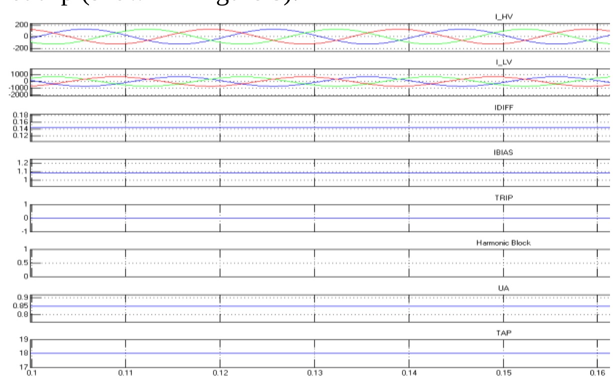


Figure 8. *TAP position at 18*

There are other ways to increase I_{DIFF} by the CT errors. It makes secondary current on two sides, not equation under healthy conditions; for example a 15VA - 5P20 CT has a guaranteed error of less than ± 5% when it is subjected to 20 times its nominal current and delivers into its nominal load (15 VA to In). At TAP = 9, current in HV side is (CT error +5%) and current in LV side is (CT error -5%), then I_{DIFF} = 0.11, I_{BIAS} = 1.35. Relay does not issue any trip signal as shown in Figure 9.

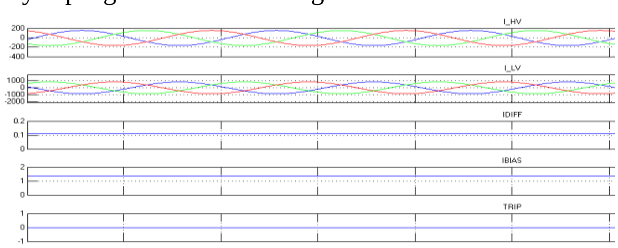


Figure 9. *TAP position at 9, CT_{HV} error +5%, CT_{LV} error -5%*

At TAP = 9, the transformer is energized from the HV side, magnetizing currents appear due to its core magnetization and saturation. Figure 10 shows the waveform of a magnetizing inrush current with transformer energized at 0.1s. The I_{DIFF} is = 0.88, I_{BIAS} = 0.44 but the relay does not issue any trip signal because harmonic blocking signal is = 1.

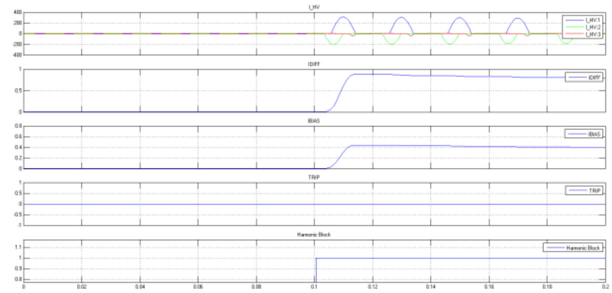


Figure 10. *Harmonic block for energization condition*

4.2. Case.2. Fault Condition

There are various types of faults, such as single phase to ground, double phase, double phase-to-ground, and three phases. If a fault is detected, i.e. the start signals will be set by the differential protection (the measured I_{DIFF} > O87P), and at the same time the internal/ external fault discriminator will determine the relative phase angle between them.

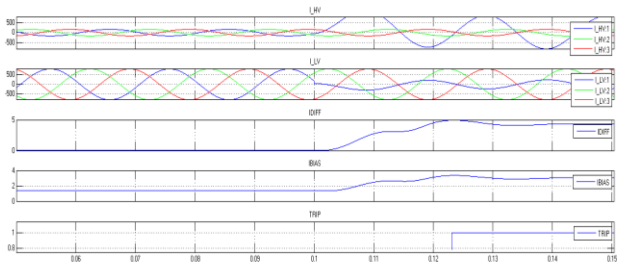


Figure 11. *Internal fault at phase A to ground*

For an internal AG fault is performed on F1, it is located within the differential protection zone. Therefore, the fault currents will flow out from the faulty power transformer on both sides. The fault currents on the HV and LV sides will have the same direction as shown in Figure 11. In the figure immediately after the fault is applied, we can observe that fault current in HV side is increased enormously, I_{DIFF} is = 4.35, I_{BIAS} = 3.1 and the trip signal occurs at 0.12s.

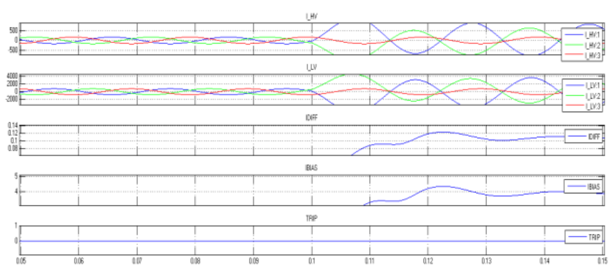


Figure 12. *External fault at phase AB*

For an external AB fault is performed on F2, it is located in the LV side of the transformer model. The fault current contributions from the HV and LV side are 180 degrees out of phase as shown in Figure 12. I_{DIFF} is = 0.106, I_{BIAS} is = 3.76 and relay does not trip.

Reviews: By using numerical relays, problems like CT ratio mismatches and phase shift compensation can be solved mathematically in the software of the relay. Besides, the test point results of relay SEL387 (shown in Figure 4b) demonstrate the stable operation during cases of normal conditions (CT error, the change in tap position of a power transformer, and magnetizing inrushes), external fault and higher sensitivity during internal faults.

5. Summary

This paper provides a detailed description of a transformer different protection function based on a two-slope characteristic. It also provides valuable tips on how to guide the setting calculation and troubleshooting process. Furthermore, the power system model simulates numerous test cases for an existing power transformer of Lang Co Substation, Viet Nam using Matlab/Simulink software package. These test cases save time by immediately indicating whether the issue has occurred on the SEL387. As a result, protection engineers can easily analyze the mis-operation to determine the root cause and can fulfill very demanding requirements set by power utilities.

REFERENCES

[1] Sandro Gianny Aquiles Perez, "Modeling relays for power system protection studies", *the Degree of Doctor of Philosophy in the Department of Electrical Engineering University of Saskatchewan Saskatoon, Saskatchewan Canada*, July 2006.

[2] Casper Labuschagne and Normann Fischer, "Relay-Assisted Commissioning", *59th Annual Conference for Protective Relay Engineers College Station*, Texas, April 4–6, 2006.

[3] SEL, "*SEL-387 Relay Current Differential Instruction Manual*", 2010.

[4] Zoran Gajić, "Differential Protection for Arbitrary Three-Phase Power Transformers", *Doctoral Dissertation Department of Industrial Electrical Engineering and Automation, Lund University*, SWEDEN, 2008.

[5] M. Tanveer Ahmad, "Differential Protection of Transformer using Harmonic Restraint Circuitry", *The 12th GCC Cigre International Conference, Doha, Qatar, 8-10 November*, 2016.

[6] Decision No. A3-06-2015/LCO110 by the Central Region Load Dispatch Centre of Vietnam.

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