Commissioning a test for a differential protection scheme for a three-winding transformer

Mr Lee Wai Meng shares some of his experience in the protection of transformers, through a case study.

The transformer is one of the most important items of hardware in the electrical power system. An important consideration in transformer protection is the high cost of the transformer and the relatively long outage times that occur, when a transformer fails. The most common form of transformer protection is 'differential protection', where the zone of protection is determined by the location of the protection current transformers (CTs) between the transformer's high voltage and low voltage terminals. The differential protection scheme will operate when there is a fault within the zone of the CT, and will not operate when there is a fault outside the zone of the CT. The major advantage of differential protection is the speed with which a fault is detected, as compared to transformer protection based on overcurrent relays. The use of overcurrent relays will result in comparatively longer operational time, to detect a fault, because of the need to co-ordinate with upstream overcurrent relays. Differential protection does not require co-ordination with other protection schemes, and its operation is essentially instantaneous for all in-zone faults. The CT ratio, polarity, and connection, must all be correct, in order to ensure the correct operation of the differential protection scheme. Hence it is imperative that the differential protection scheme be commissioned before first-time energisation of the transformer. Figure 1 shows the electrical transformation at a power station.

Three-winding transformers

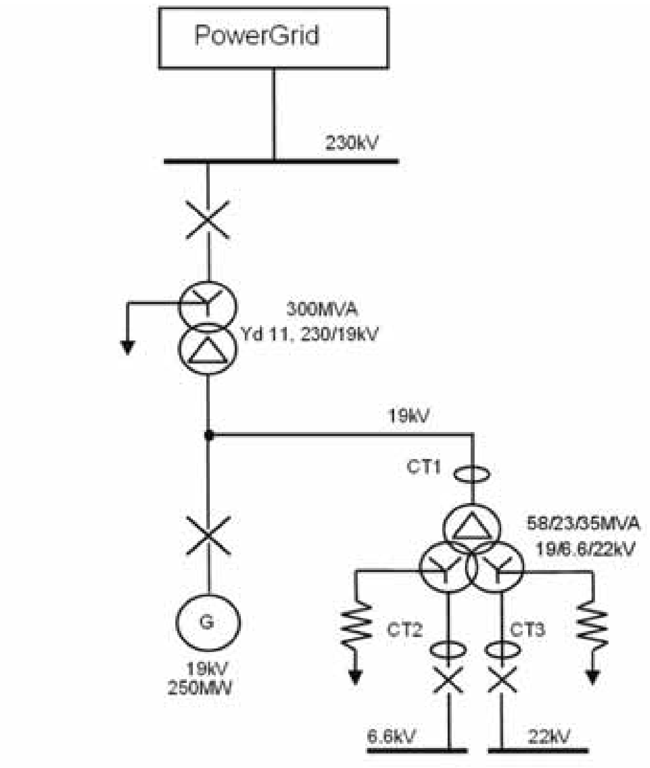
The equivalent circuit for a three-winding transformer can be represented by an impedance star, as shown in Figure 2. The impedance of any of these branches can be determined by considering the short circuit impedance between any pairs of windings, with the third winding in open circuit. Therefore, as shown below:

☐ Z_{ps} - impedance at primary with secondary short-circuit and tertiary open circuit.

☐ Z_{pt} - impedance at primary with tertiary short-circuit and secondary open circuit.

☐ Z_{st} - impedance at secondary with tertiary short-circuit and primary open circuit.

The impedance values Z_{ps}, Z_{pt}, and Z_{st} have physical meaning and can be measured. However, the equivalent circuit values Z_p, Z_s, and Z_t are fictitious and cannot be measured. It is possible to have negative values for one of the impedances. The values Z_{ps}, Z_{pt}, and Z_{st} may be based on different base values and hence these impedance values must be converted to the same base value before the start of any calculation. The capacity of the primary winding is often chosen as the common base value. Table 1 shows the nameplate data and the normalised impedance values Z_{ps}, Z_{pt} and Z_{st}.



19kV Primary CT1 - located at transformer
6.6kV Secondary CT2 - located at 6.6kV switchgear
22kV Tertiary CT3 - located at 22kV switchgear

Figure 1: Single line diagram.

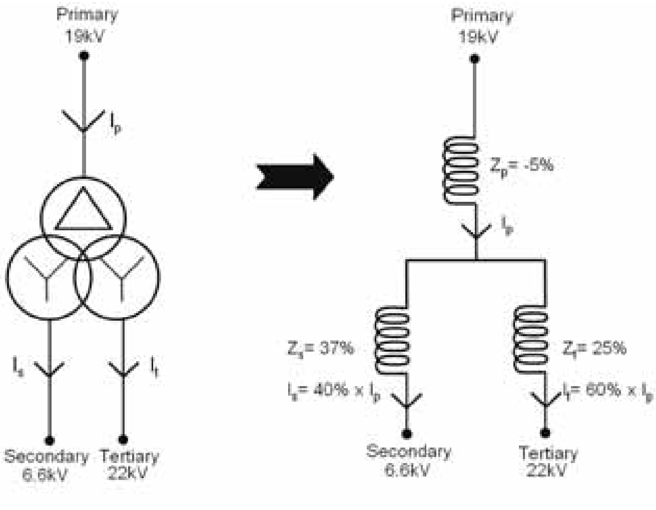


Figure 2: Equivalent circuit of three-winding transformer.

Capacity	Voltage	Nameplate Impedance	Impedance at 58MVA Base	Phase angle Difference
Primary 58MVA	Primary = 19kV	Z_{ps} = 12.5%, 23MVA	Z_{ps} = 32%	Primary to Secondary = 30°
Secondary 23MVA	Secondary = 6.6kV	Z_{pt} = 12.0%, 35MVA	Z_{pt} = 20%	Primary to Tertiary = 30°
Tertiary 35MVA	Tertiary = 22kV	Zst = 62.0%, 58MVA	Zst = 62%	Secondary to Tertiary = 0°

Table 1: Impedance and vector group data.

The values of the impedance, normalised to a 58 MVA base are:

☐ $Z_{ps} = Z_p + Z_s = 32\%$

☐ $Z_{pt} = Z_p + Z_t = 20\%$

☐ $Z_{st} = Z_s + Z_t = 62\%$

Solving the three equations

$Z_p = -5\%$; $Z_s = 37\%$; $Z_t = 25\%$

Commissioning

An external 3 phase, 400 volt diesel generator was connected at the 19 kV side, with three different combinations of open/short circuits, at the 6.6 kV and 22 kV sides.

The three combinations were:

Connection	19 kV Primary	6.6 kV Secondary	22 kV Tertiary
Figure 3	Generator connection	Short circuit	Open circuit
Figure 4	Generator connection	Open circuit	Short circuit
Figure 5	Generator connection	Short circuit	Short circuit

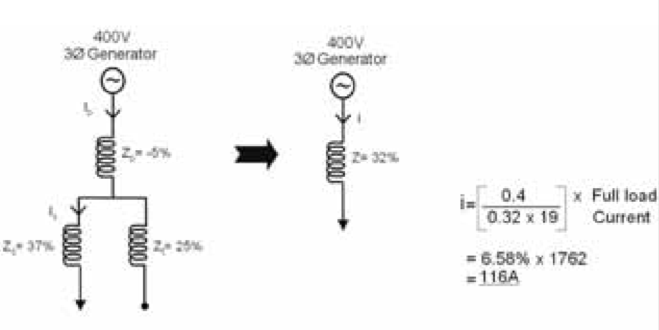


Figure 3: Short circuit at 6.6kV Secondary.

The KVA rating of the external generator was calculated using the impedance data for the three-winding transformer, from Table 1. The required KVA rating of the external generator for the three different connections were:

Connection	KVA rating of Generator	Percentage of Full Load Current
Figure 3	√3 x 400 x 116 = 80 KVA	6.6%
Figure 4	√3 x 400 x 185 = 128 KVA	10.5%
Figure 5	√3 x 400 x 375 = 260 KVA	21.3%

A 3 phase, 400 volt, 300 KVA generator was selected for the commissioning test. Table 2 is the summary of the measured values for Figure 3, Figure 4, and Figure 5, under external fault conditions. Incorrect CT polarity at the 22 kV CT was suspected because of the following reasons:

☐ High value of differential current in the case of Figures 4 and 5.

☐ 2 I_{Bias} = differential current in the case of Figure 4.

The star point of the 22 kV CT was reversed, to rectify the incorrect CT polarity. Table 3 is the summary of the measured values with the correct CT polarity. The differential protection was considered stable for the 'out of zone' fault because the differential current was zero. The short circuit at the 22 kV side, was relocated to create an in-zone fault and the differential current was non-zero and of high value. The differential relay was considered commissioned.

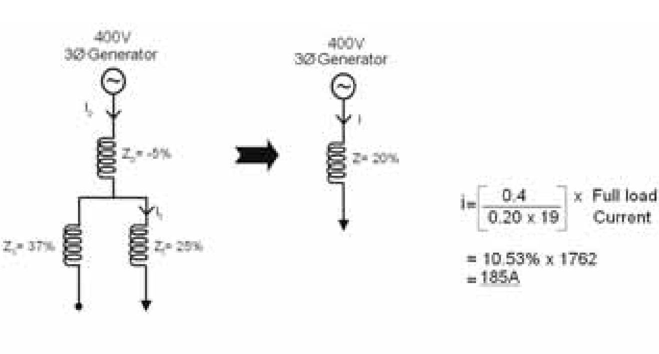


Figure 4: Short circuit at 22kV Tertiary.

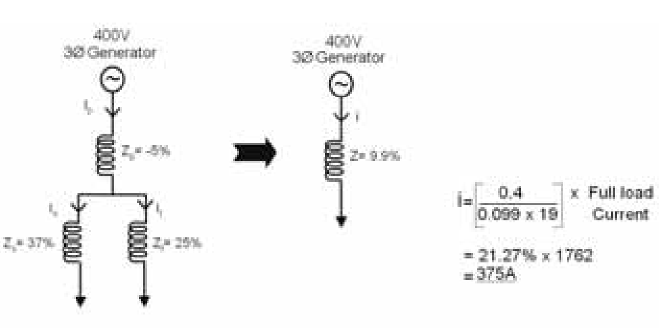


Figure 5: Short circuit at 6.6kV Secondary and 22kV Tertiary.

External Generator Connected to 19kV side		**Out of Zone Fault**	**Out of Zone Fault**	**Out of Zone Fault**
		6.6kV Short Circuit and 22kV Open Circuit (Fig. 3)	**22kV Short Circuit and 6.6kV Open Circuit (Fig. 4)**	**22kV and 6.6kV Short Circuit (Fig. 5)**
19kV Primary	I_{red}	105A	162A	344A
	I_{yellow}	105A	162A	344A
	I_{blue}	105A	162A	344A
6.6kV Secondary	I_{red}	289A	0A	421A
	I_{yellow}	289A	0A	421A
	I_{blue}	289A	0A	421A
22kV Tertiary	I_{red}	0A	137A	169A
	I_{yellow}	0A	137A	169A
	I_{blue}	0A	137A	169A
Bias	I_{red}	59mA	91mA	197mA
	I_{yellow}	59mA	91mA	197mA
	I_{blue}	59mA	91mA	197mA
Diff.	I_{red}	0A	183mA	226mA
	I_{yellow}	0A	183mA	226mA
	I_{blue}	0A	183A	226mA

Table 2: Measured value with incorrect CT polarity.

External Generator Connected to 19kV side		**In-Zone Fault**	**In-Zone Fault**	**In-Zone Fault**	**Out of Zone Fault**	**Out of Zone Fault**	**Out of Zone Fault**
		Short Circuit at 22kV	**Short Circuit at 6.6kV**	**Short Circuit at 22kVand 6.6kV**	**Short Circuit at 6.6kV and 22kV Open Circuit (Fig. 3)**	**Short Circuit at 22kV and 6.6kV Open Circuit (Fig. 4)**	**Short Circuit at 22kV and 6.6kV (Fig. 5)**
19kV Primary	I_{red}	344A	344A	344A	105A	162A	344A
	I_{yellow}	344A	344A	344A	105A	162A	344A
	I_{blue}	344A	344A	344A	105A	162A	344A
6.6kV Secondary	I_{red}	421A	0A	0A	289A	0A	421A
	I_{yellow}	421A	0A	0A	289A	0A	421A
	I_{blue}	421A	0A	0A	289A	0A	421A
22kV Tertiary	I_{red}	0A	169A	0A	0A	137A	169A
	I_{yellow}	0A	169A	0A	0A	137A	169A
	I_{blue}	0A	169A	0A	0A	137A	169A
Bias	I_{red}	140mA	154mA	97mA	59mA	91mA	197mA
	I_{yellow}	140mA	154mA	97mA	59mA	91mA	197mA
	I_{blue}	140mA	154mA	97mA	59mA	91mA	197mA
Diff.	I_{red}	113mA	81mA	194mA	0A	0A	0A
	I_{yellow}	113mA	81mA	194mA	0A	0A	0A
	I_{blue}	113mA	81mA	194mA	0A	0A	0A

Table 3: Measured value with correct CT polarity.

Conclusion

In this case study, the polarity of the 22 kV CT was incorrect and fortunately it was discovered during the commissioning test. If such a commissioning test was not done, the differential relay would have operated under normal loading of the transformer, or during an external fault condition.

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