DIFFERENTIAL PROTECTION ISSUES FOR COMBINED AUTOTRANSFORMER - PHASE SHIFTING TRANSFORMER

Zoran Gajić
ABB Sweden

Igor Ivanković, Božidar Filipović-Grčić
HEP-Croatian Power Utility

***Abstract*— In the Žerjavinec substation, Croatian Power Company is going to install a special type of power transformer, which has two different modes of operation. The power transformer can be used either as conventional 400MVA, 400/220kV autotransformer with on-load tap-changer or as phase shifting transformer interconnecting 400kV & 220kV networks. When power transformer is de-energized, its operation mode can be changed. This change can be done even remotely, from the network control centre in order to maximize utilization of the electrical network infrastructure. Two different operating modes of the power transformer, as well as remote selection facility, complicate selection of power transformer protection scheme. Especially, proper operation of the power transformer differential protection must be assured during all operating conditions. Necessary calculations for proper selection of power transformer differential relay and final solution for overall power transformer protection scheme are presented in this paper.**

***Index Terms*— Autotransformer, Phase shifting transformer, Protective relaying, Power transformer differential protection**

I. NOMENCLATURE

HEP – Abbreviation for Croatian Power Company
OLTC – On-Load Tap-Changer
PST – Phase Shifting Transformer
AT – Autotransformer

II. INTRODUCTION

THE main Croatian power transmission system consist of 400kV and 220kV networks. Necessary load flow calculations were performed in order to prove effectiveness of PST installation in Žerjavinec substation. It was demonstrated that such device [3] & [4] would help network operators to properly divide power flow between two voltage levels. In addition its installation will allow better utilization of underlying 220kV transmission network infrastructure.

A. Power Transformer Construction

The power transformer is constructed as conventional autotransformer with tertiary delta-connected, equalizer winding [10]. The OLTC winding is located at the autotransformer neutral point [1]. Rated power transformer data are 400/400/(130)MVA; 400/231/(10.5)kV; YNa0(d5).
The main difference from the typical AT construction is a two position switch located in-between the OLTC winding and the common autotransformer winding as shown in Figure 1.

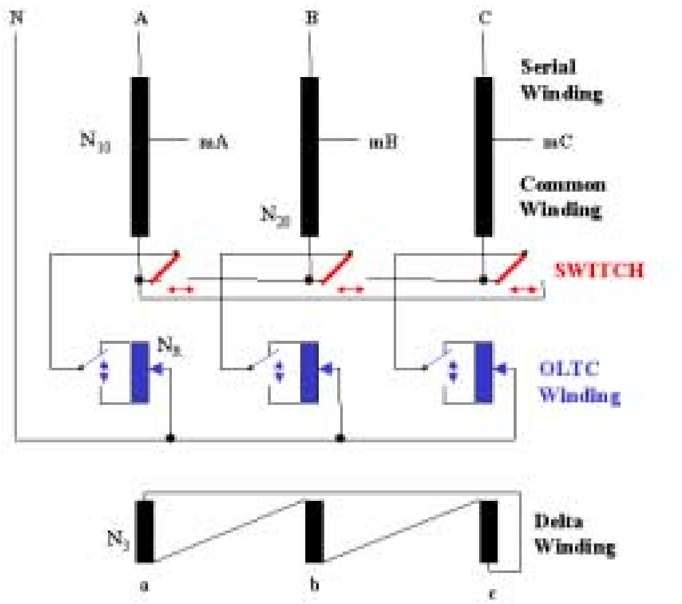

Fig. 1. Power Transformer Simplified Drawing

When this switch position is changed the OLTC winding in one phase (i.e. phase C) is connected in series with the common and serial autotransformer windings in another phase (i.e. phase A) and power transformer becomes the phase shifting transformer [2].

III. POWER TRANSFORMER NO-LOAD VOLTAGES

Phase A winding connections for autotransformer operating mode is shown in Figure 2. For this mode of operation all windings in one phase are located on the same magnetic core lag. Corresponding power transformer no-load voltage phasor diagram is shown in Figure 3.
Phase A winding connections for PST operating mode is shown in Figure 4. For this mode of operation all windings, which are connected in series to form this phase are not located on the same magnetic core lag. This type of connection causes phase shift between 400kV and 220kV no-load voltages as shown in the phasor diagram in Figure 5.

Zoran Gajić is with ABB Automation Technology Products AB, Vasteras, Sweden (e-mail: zoran.gajic@se.abb.com).
Igor Ivanković and Božidar Filipović-Grčić are with Croatian Power Company, District Zagreb, Croatia; (e-mail: Igor.Ivankovic@hep.hr).

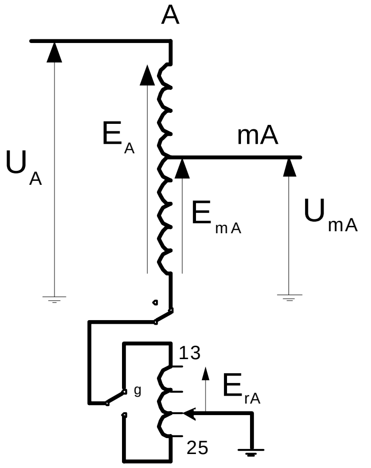

Fig. 2. Phase A Winding Connections for AT Operating Mode

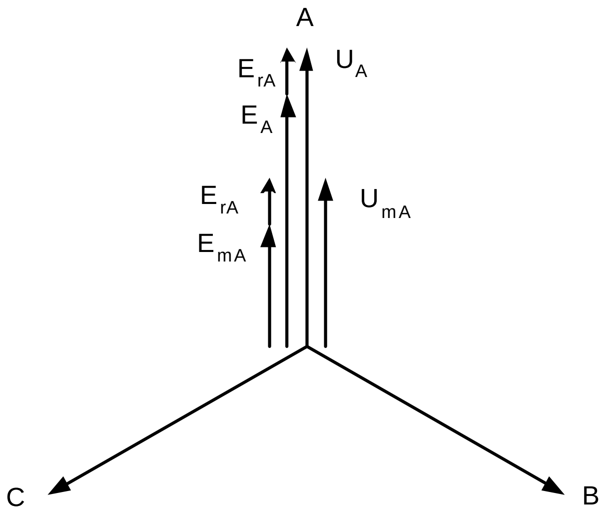

Fig. 3. No-load, Voltage Phasor Diagram in AT Operating Mode

No-load voltage phasor diagrams are shown in Figure 3 & Figure 5 for two different operating modes of the power transformer. From these two pictures the following general equations can be written:

$$U_A = E_A + E_{rX} \tag{1}$$

$$U_{mA} = E_{mA} + E_{rX} \tag{2}$$

where X stands for phase of the OLTC winding connected in series with the main winding in phase A. This actually depends on the position of the switch (i.e. operating mode of the power transformer).

It is well known fact that internal induced emf can be represented as product of the number of turns and emf per each individual turn. This emf per turn, let's mark it as E_{tA} in phase A, is directly proportional to the flux in the magnetic core of the power transformer and it has the same value for all windings located on the same power transformer magnetic core lag.

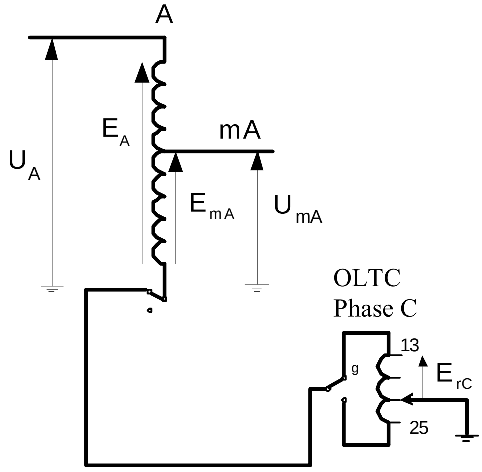

Fig. 4. Phase A Winding Connections for PST Operating Mode

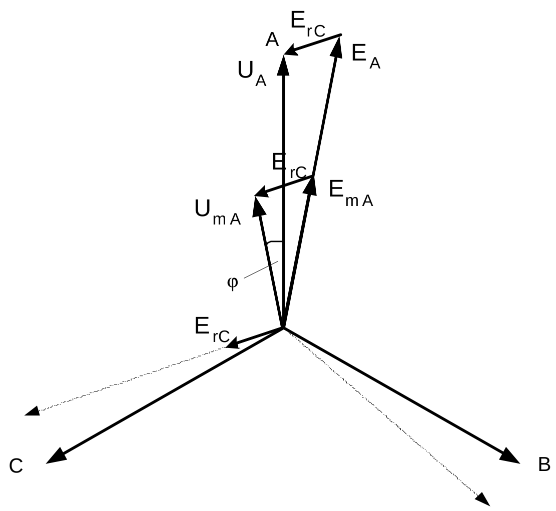

Fig. 5. No-load, Voltage Phasor Diagram in PST Operating Mode

Thus:

$$U_A = N_{10} * E_{tA} + N_R * E_{tX} \tag{3}$$

$$U_{mA} = N_{20} * E_{tA} + N_R * E_{tX} \tag{4}$$

where N_{10} is total number of turns in common and serial winding, N_{20} is total number of turns in common winding and N_R is total number of turns in regulating winding (i.e. tap changer winding). From the power transformer theory it is known fact that for the three phase balanced voltage supply condition this emf per turn will as well form a balanced three phase set of quantities. Therefore the above two equations can be written as follows for both operating modes of the power transformer:

$$U_A = N_{10} * E_{tA} + N_R * E_{tA} * b \tag{5}$$

$$U_{mA} = N_{20} * E_{tA} + N_R * E_{tA} * b \tag{6}$$

where E_{tA} is emf per turn in phase A, and b is operator, which can have one of the following two values:

$b = e^{j0^0} = 1 + j*0$ for Autotransformer operating mode

$b = e^{j120^0} = -0.5 + j*0.866$ for PST operating mode

After multiplication with $\sqrt{3}$ and division of the equations (5) and (6) the following equation is obtained:

$$U\_MV = U\_HV * \frac{N_{20} + N_R * b}{N_{10} + N_R * b} \qquad (7)$$

where U_MV is phase-to-phase voltage on 220kV side and U_HV is phase-to-phase voltage on 400kV side of the power transformers. For a particular power transformer design the only variable in the equation (7) is number of turn in the OLTC winding (i.e. N_R). By using equation (7) the magnitude and the phase angle of the 220kV side, no-load voltage can be calculated for this particular transformer for both operating modes. The derived values are shown in Table 1 and Figure 6 for both operating modes of the power transformer. This way of no-load voltage calculation was confirmed during power transformer acceptance tests.

Power Transformer 400MVA		Autotransformer Operating Mode	PST Operating Mode	
OLTC Position	U_HV [kV]	U_MV [kV]	U_MV [kV]	U_MV Angle [deg]
25	400	253,8	222,2	6,76
23	400	250,4	223,0	5,49
21	400	246,9	224,0	4,28
19	400	243,2	225,4	3,11
17	400	239,4	227,1	2,01
15	400	235,3	229,0	0,97
13	**400**	**231,1**	**231,1**	**0,00**
11	400	226,6	233,3	-0,91
9	400	221,8	235,8	-1,75
7	400	216,8	238,3	-2,52
5	400	211,6	240,9	-3,24
3	400	205,9	243,6	-3,89
1	400	200,0	246,4	-4,48

TABLE 1: 220KV SIDE NO-LOAD VOLTAGE VARIATIONS DUE TO OLTC POSITION

Information about power transformer no-load voltages are critical for operation of the differential protection with automatic OLTC compensation. The differential protection utilizes this data at every individual tap changer position in order to properly estimate magnitude relation between 400kV and 220kV side currents during through-load condition. However differential protection can only compensate for current magnitude variation and not for phase angle difference introduced by the power transformer operating as PST.

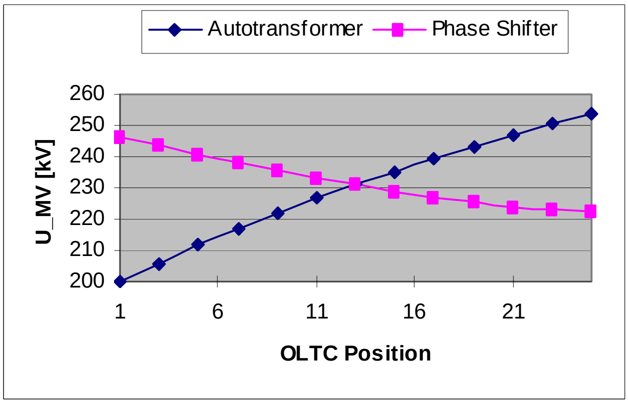

Fig. 6. 220kV Side No-load Voltage Variations due to OLTC Position

IV. DIFFERENTIAL PROTECTION

During 1998 HEP has refurbished biased differential protection for all major autotransformers in the transmission network with new numerical differential protection terminal. Because of excellent performance of this new differential relay [7] it was the natural choice to try and use the same relay type for the differential protection of this special power transformer in the Žerjavinec substation. In the same time this differential relay has the unique but standard features [8] & [9], which makes it superior for this particular application:

- on-line reading, displaying and automatic compensation for OLTC position within differential protection
- bias current is common for all three phases and it is selected as relatively highest current of all currents connected to the differential relay

The OLTC position can be red via mA signal or BCD coded binary signal. However per HEP previous experience with this type of measurements it was decided to utilize the BCD code to transfer tap position to the sensitive differential protection terminal.

In addition to this information, it is as well necessary to provide the position of the switch located within power transformer tank in order to enable the differential relay to automatically change relay setting group in accordance with the operating mode of the power transformer. This change is necessary in order to cope with different 220kV side no-load voltage magnitude variation in two different operating modes of the power transformer as shown in Figure 6.

V. TRANSFORMER DIFFERENTIAL PROTECTION PERFORMANCE

HEP has performed complete short circuit study for this new power transformer [5]. Special attention was given to internal and external single phase to ground faults. Once the currents on all side of the power transformer were calculated for each particular fault the resultant current phasors were fed to MATLAB model of the sensitive differential protection function with automatic OLTC compensation. Proper operation of the differential protection for all calculated

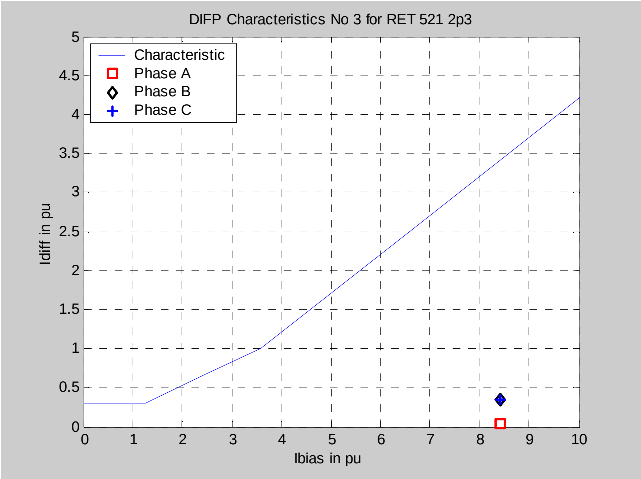

Fig. 7. External Single Phase Fault on 220kV Side

external and internal fault scenarios was confirmed. Resulting differential and bias current for each fault case were plotted against operating characteristic of the relay. The result for one external fault case is shown in Figure 7.

VI. Power Transformer Protection Scheme

In addition to the differential protection HEP has implemented restricted earth fault protection for power transformer common, serial and OLTC winding as well as standard overcurrent and thermal overload protections [6]. Additional protection for tertiary delta-connected, equalizer winding is provided as well. Complete protection scheme for this power transformer is shown in Figure 8.

VII. Conclusion

Transformer differential protection with automatic OLTC position compensation can be used as overall bias differential protection for special power transformer in Žerjavinec substation. From the performed calculation it is obvious that it will remain stable for all external faults for both operational mode of the power transformer and be able to trip correctly for all internal faults. Stability will be maintained even when the tap position reading is lost, but the spill differential current will be much higher during such operating condition.

During the PST operation mode, with correct OLTC position reading, the spill differential current can be estimated by using the following formula:

$$Idiff\,[pu] = 2 * k * Ibias[pu] * \sin\frac{\theta}{2}$$

where θ is phase angle difference between no-load voltages on 400kV & 220kV side for the particular OLTC position, and k is constant, which depends on the type of fault due to zero sequence current reduction performed by the differential relay:

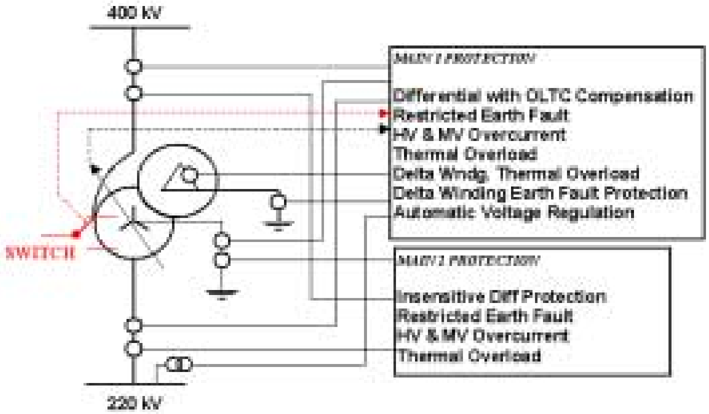

Fig. 8. Overall Power Transformer Protection Scheme

- ♦ k=1.0 for 3Ph and 2Ph faults
- ♦ k=2/3 for 1Ph to Earth faults

Therefore, for this particular power transformer, according to the available design data the maximum spill differential current can be estimated to be approximately equal to 12% of the bias current. This value is within the normal limits for the transformer differential protection that protects the normal power transformer without OLTC position reading. Thus no problems are expected with application of this differential relay in the Žerjavinec Substation.

VIII. References

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