Fault Diagnostic and Protection of Power Transformers Grounded with a Common Grounding Resistor

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Abstract. The power transformer is the main and the most expensive component of the power substation, so successful fault diagnostic and protection is an essential part of its maintenance. Protection engineers doing the scheduled maintenance and protection testing need to be familiarized with transient phenomena that can occur in normal operation. Substations with two parallel transformers sharing a common grounding resistor are very frequent in high-voltage networks since a common grounding resistor limits the single-phase to ground-fault current. However, the unfavorable aspect of this type of transformer grounding system is the increased probability of unwanted trips of the transformer protection during the transient operational states, which has the consequence of a supplied low-voltage network outage. Under transformer energization, an appearance of the inrush current can trigger the transformer differential protection as well as circulating current between transformers in parallel operation caused by sympathetic inrush. A single-phase to ground fault in a high-voltage network can cause circulating currents between neutrals of transformers and trip the differential protection too. The paper presents a simulation model of two transformers grounded with a common grounding resistor adequate for transformer transient operational states analysis. Performed simulations of the inrush and sympathetic currents emphasized the diagnosing of the second harmonic distortion dominance in the current spectrum as an efficient tool in the prevention of unwanted trips of differential protection. The analysis of the simulated circulating currents between transformer neutrals in the paper has examined and discussed the proposed solutions for avoidance of unnecessary transformer outage caused by the single-phase to ground fault in a high-voltage network.

Keywords: Power transformer protection · Inrush current · Circulating currents · Common grounding resistor · Single-phase to ground fault

1 Introduction

Most common faults in power systems are line-to-ground faults and therefore the transformer grounding plays a significant role for safe and efficient system operation [1, 2].

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As a compromise of technical and economic demands, the grounding of the two parallel transformers is usually performed with a common grounding impedance as processed in [2–4]. While choosing the type of grounding impedance, it is preferable to obtain as small a current as possible during the ground fault to limit the touch potentials, while on the other hand, the higher current results in lower internal overvoltages that can strain the insulation of the transformer [3, 4]. Grounding impedance should be dimensioned to make the ground fault current higher than steady-state current to ensure fast tripping of the grounding protection device and to keep the voltage of the healthy phase within the limited values [5]. Differential protection is an essential transformer protection function, hence incorrect operation of this protection leads to loss of load. Transformer inrush current can cause unwanted differential protection trips. Under the transformer energization on the primary side, an inrush current can reach ten times the rated primary current and magnetic flux can reach two times nominal value [6, 7]. These currents can last from a few cycles to many seconds and can occur when a transformer is energized, when another transformer in parallel operation is energized or the system recovers from a fault outside of the protection zone as explained in [8]. Application of external voltage can cause the saturation of the transformer core - that is inevitable, and operation of differential protection is unfounded [1, 8–10]. That same current can also cause saturation of the current transformers, hence, internal faults can be misinterpreted as inrush current. The presence of the second harmonic content in the differential current indicates the inrush current and this can be used to prevent incorrect trips of the transformer differential protection [1, 8–10]. Sympathetic inrush occurs during parallel transformers energization [11–13]. In this case, a single transformer is operating while the second transformer is energizing [12] and thus causes the circulating current between the two transformers which remains due to small damping i.e. large time constant – R/X [12, 14]. Any mismatch in impedance or voltage will cause a current to circulate between transformers (to equalize set voltage) [15, 16]. Disturbances such as transformer tap changer switching, three-phase reclosing at the high voltage side can cause circulating current [17] too. Under a single-phase to ground fault in the HV network, circulating current is present between transformer neutrals on the MV- side and can cause protection trips of both transformers [18].

The paper constitutes five chapters. The Introduction is followed by the simulation model of the transformer used for the protection function testing and verifying. The protection performance has been examined simulating the energization process of the transformer and faults on the different locations in Chapters 3 to 5. The results of the simulations are supported by the Conclusion.

2 Simulation Model

In the simulation mode, two three-phase transformers were used. Transformer details are listed in Table 1. Tap changer with 21 position (1,5% additional voltage per tap) was also included in the model. Figure 1 shows magnetization characteristic of the transformer core used in simulation.

Equations (1), (2) and (3) show impedance between individual windings at 35 kV [19, 20]. Neglecting the active resistance, the reactances of individual windings mapped to base voltage are calculated according to (4), (5) and (6).

$$x_{d1-2,35} = \frac{u_{k1-2,d}}{100} \times \frac{U_b^2}{S_n}[\Omega] \tag{1}$$

Table 1. Transformer nameplate details of TR1 and TR2

Voltage ratio (W1/W2): 110/35 kV
Vector group: YNyn0(d5)
Rated power: 40 MVA
Short-circuit voltage: uk = 11,3%
Copper losses: 155 kW
No-load losses: 28 kW

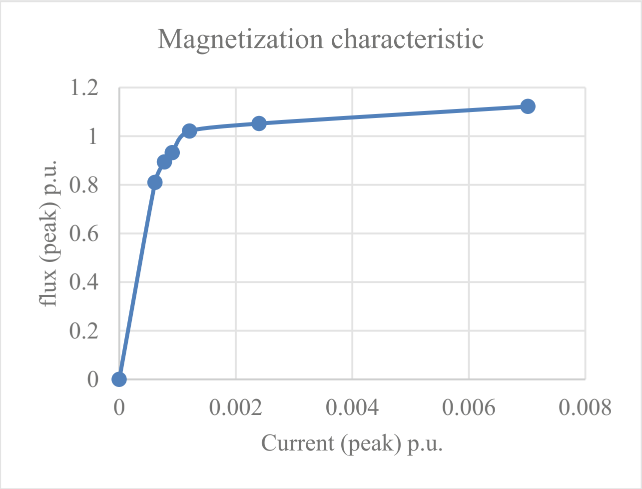

Fig. 1. Magnetization characteristic of the 110/35 kV transformer core

$$x_{d2-3,35} = \frac{u_{k2-3,d}}{100} \times \frac{U_b^2}{S_n}[\Omega] \tag{2}$$

$$x_{d3-1,35} = \frac{u_{k3-1,d}}{100} \times \frac{U_b^2}{S_n}[\Omega] \tag{3}$$

$$X_{d1} = \frac{1}{2}(x_{d1-2,35} + x_{d3-1,35} + x_{d2-3,35}[\Omega] \tag{4}$$

$$X_{d2} = \frac{1}{2}(x_{d1-2,35} + x_{d2-3,35} + x_{d1-3,35}[\Omega] \tag{5}$$

$$X_{d3} = \frac{1}{2}(x_{d1-3,35} + x_{d2-3,35} + x_{d1-2,35}[\Omega] \tag{6}$$

Based on the obtained values, it is possible to display the direct, inverse and zero components scheme of a transformer as it is shown in Fig. 2. As the transformer is a non-rotating element, direct and inverse components are equal [10, 15, 19, 20].

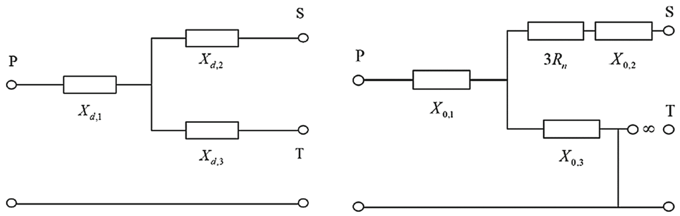

Fig. 2. Direct, inverse and zero component scheme

Figure 3 shows zero component scheme of two parallel transformers. It is shown that a triple value of resistance of resistor is added to the reactance of secondary winding. If a zero component current is injected at point P (primary) i.e. if a single-phase to ground fault occurs at HV side, current will flow between the secondary S-S.

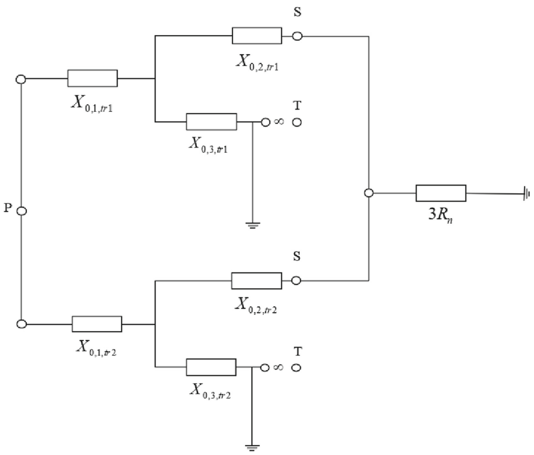

Fig. 3. Zero component scheme of parallel transformers

In the simulation model, a multifunctional protection relay with differential, restricted earth fault (REF) and overcurrent protection was implemented. Emphasis was given to differential and REF protection as two main protection functions of simulated relay. Differential protection provides basic, fast, sensitive and selective protection in the event of short circuit faults within the protection zone (transformer), and is stable during faults outside the protection zone. Protection zone of this protection is the zone between CT of primary winding and the CT of the secondary winding. Differential protection is based on current comparison (Kirchhoff's current law) as it is shown in Fig. 4. [21] Measuring element constantly measures I1 and I2, and if a difference of current marks occurs the relay trips. When switching transformers, high inrush current may occur. Inrush currents can reach ten times rated current, and are characterized by a 2nd harmonic content – this harmonic is not present in the case of a fault so this content is used as a blocking logic for unwanted trips of protection by inrush (Harmonic restraint) [21].

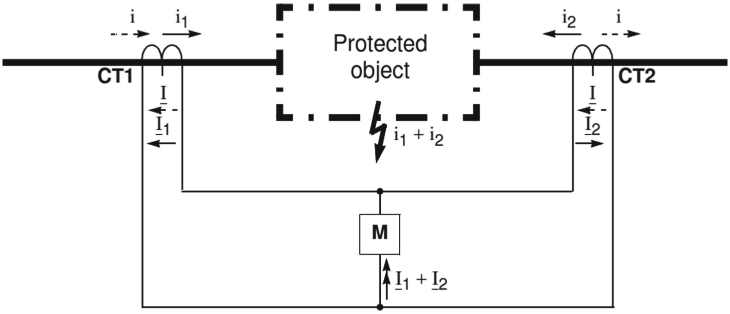

Fig. 4. Principle of differential protection

Restricted earth fault protection (REF) detects earth faults in power transformers, neutral grounding transformers and transformer starpoint (neutral). It is a type of differential protection, as it measures the fundamental wave of the current flowing in the starpoint ($\underline{I}_{SP}$) and the fundamental wave of the sum of the phase currents ($3\underline{I}_0$), and compares them. At Fig. 5 [21], principle of REF protection on a transformer winding was shown. During earth faults in the protection zone, starpoint current $\underline{I}_{SP}$ occurs and flows to the fault location, but also the residual current from the system flows to the fault location – currents are in phase and there is a condition for trip [21].

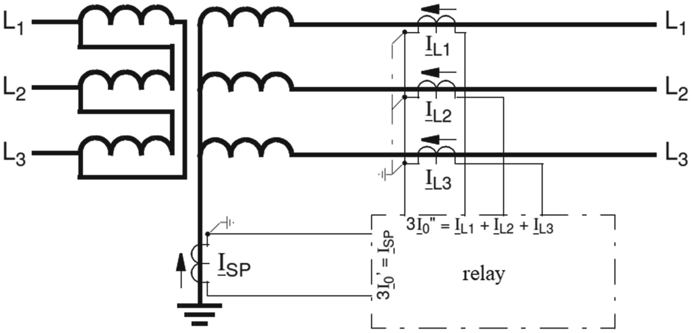

Fig. 5. Principle of REF protection

According to transformers and grounding resistor ratings, following protection settings have been acquired:

Table 2. Protection function settings

Differential	IdMin: 0,30 p.u	IdUnre: 10 p.u	I2/I1 Ratio:15%	I5/I1 Ratio:25%
REF	IdMin:0,10 p.u	time setting: 0,01 s		

Table 2 shows settings of differential and REF protection. *IdMin* represents Sect. 1 sensitivity, which is set by a multiplication of base current (winding 1 current). Section 1 represents the most sensitive part of differential characteristic i.e. minimum operating diff. current. This setting is set in order to avoid unwanted operation for the minimum value of the operating differential current, which includes maximum error of CTs, maximum error due to voltage regulation and additional security factor. *IdUnre* represents unrestricted protection limit, multiplication of base current (W1 current).This part is "instantaneous" part of differential protection, used when the fault is beyond any doubt internal. The reference for this setting is maximum three-phase short circuit current at MV busbars. *I2/I1* represents the maximal ratio of 2nd current harmonic to fundamental current harmonic, *I5/I1* represents the maximal ratio of 5th harmonic to fundamental.

3 Common Grounding Resistor Protection Performance

Performance of the protection of the common grounding resistor has been examined on the simulation model of two parallel 110/35 kV transformers with common low-impedance grounding resistor of 70 Ω to limit the single-phase to ground fault current to maximal value of 300 A on the 35 kV voltage side - Fig. 6. Modeled protection functions are transformer differential and restricted earth fault protection with included auxiliary protection equipment - current transformers (CTs) −150/1 A on the 110 kV side and 600/5 A on 35 kV side and voltage transformers (VTs). Both 110/35 kV transformers are represented with the YN0yn0d vector group.

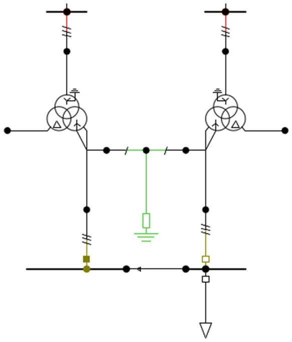

Fig. 6. Simplified schematic presentation of the network model with protection equipment

Differential protection performance has been examined for single-phase to ground fault in case where a single transformer is operating - Fig. 7 – left side or both transformers are operating – Fig. 7 – right side. Protection zone of differential protection includes the zone between two CTs (primary and secondary side) - Fig. 7 - left side, but excludes the substation busbars - Fig. 7- right side.

As shown on Fig. 7, the relay tripped opening the circuit-breakers (labeled as red circles) on high-voltage side and the low-voltage side of the transformer when a fault occurred inside the protection zone and did not trip when the fault occurred outside the protection zone, thus fulfilling the selectivity criterion.

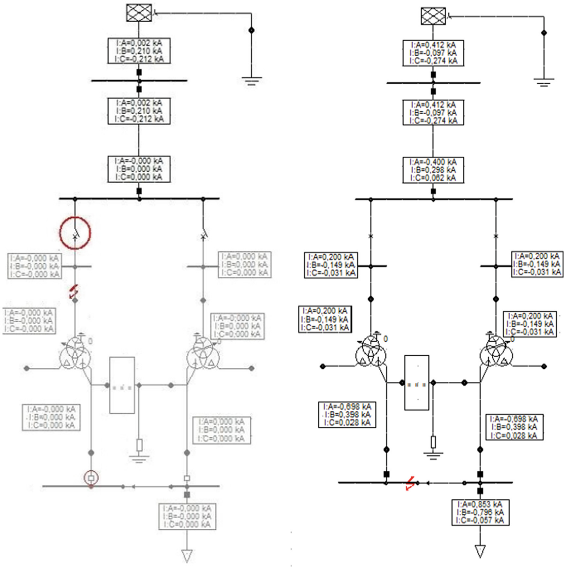

Fig. 7. Single-phase to ground fault inside the protection zone (left side of the figure) and outside the protection zone (right side of the figure)

During internal earth-faults, the sum of phase currents (MV side) and residual current (current at transformer neutral) is different from zero [12], and should trip REF protection. The performance of the REF protection has been examined during the single phase-to ground fault within the protection zone when a single transformer is operating -Fig. 8 - left side and outside the protection zone when both transformers are in parallel operation -Fig. 8 -right side. The simulation diagrams on Fig. 9 indicate on REF protection trip caused by the differential current between the residual current of the secondary side of the transformer and the resistor current during the single-phase to ground fault within the protection zone when a single transformer operates. The trip signal is shown on the upper diagram, the differential current is presented on the second diagram (14 s A (2,5 p.u.) is above the 0,1 p.u. threshold value - Table 2), while the third diagram presents the currents within the protection zone. The last diagram presents the vector sum of the phase and neutral currents at the MV side of the transformer.

The currents during the single-phase to ground fault outside of the protection zone when two transformers are in parallel operation are presented on Fig. 10. Since the differential current of 0,08 p.u. (the second diagram) did not reach the threshold value of the 0,1 p.u. during the simulated fault, the REF protection did not trip. The differential current is presented on the second diagram, the currents within the protection zone are presented on the third diagram, while the last diagram presents the vector sum of the phase and neutral currents at the MV side of the transformer.

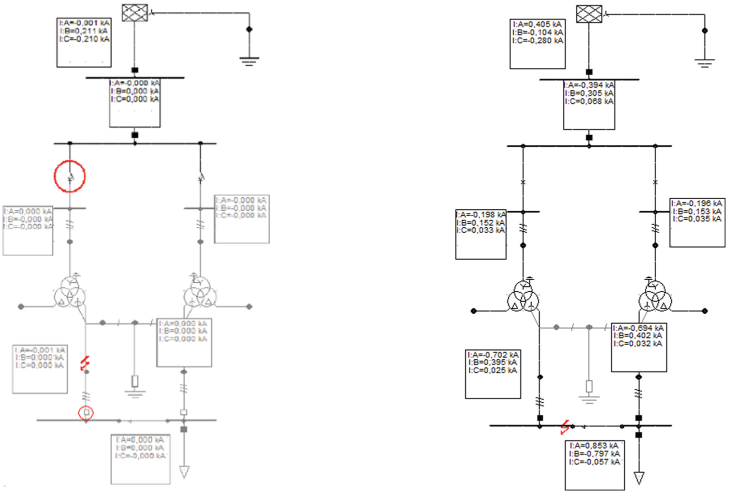

Fig. 8. Single-phase to ground fault inside the protection zone for testing REF protection when a single transformer operates - left side of the figure, single-phase to ground fault outside the protection zone for testing REF protection when both transformers operate - right side of the figure.

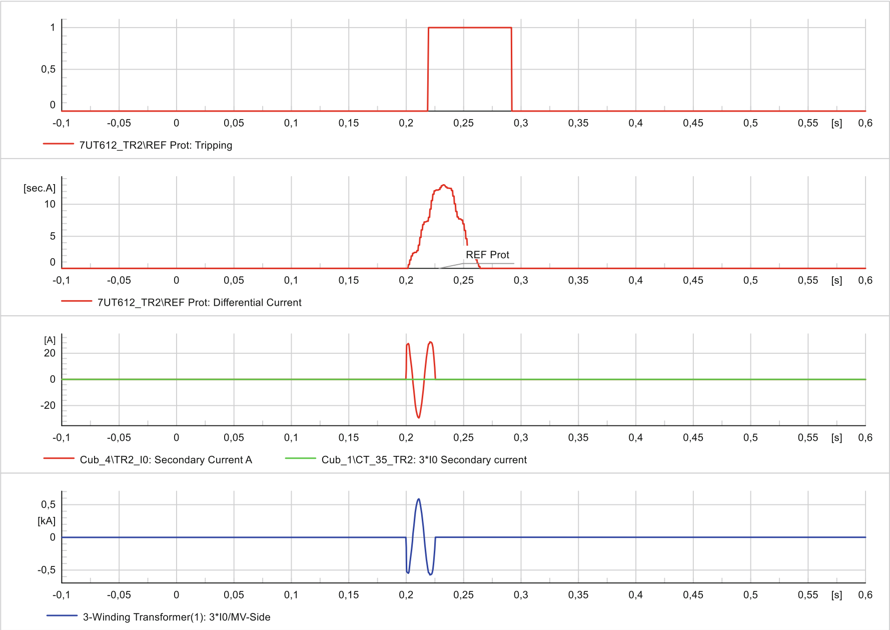

Fig. 9. Diagrams associated with REF protection testing during the single phase-to ground fault inside the protection zone when a single transformer operates

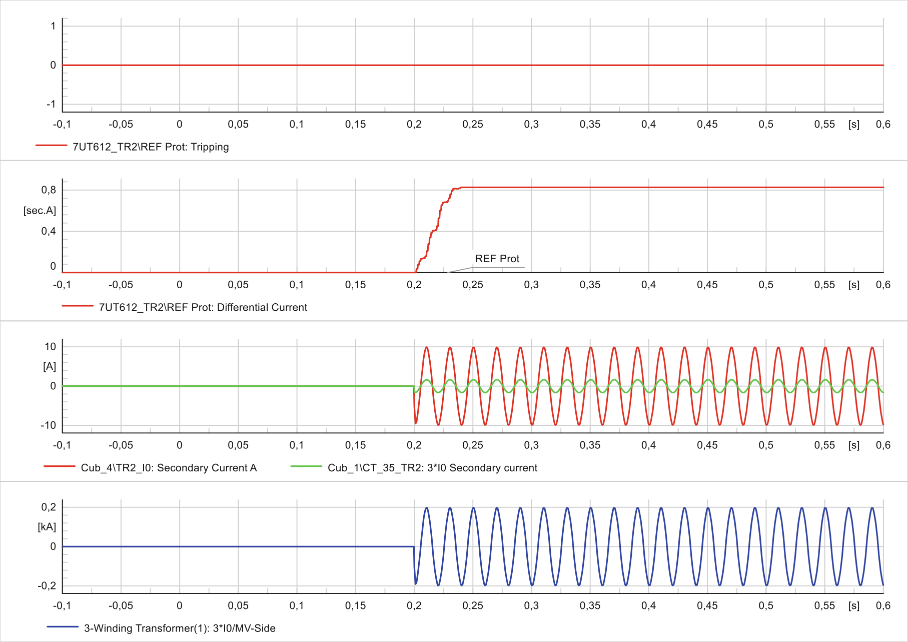

Fig. 10. Diagrams associated with REF protection testing during the single phase -to ground fault outside the protection zone when both transformers operate

4 Inrush Current Influence on Transformer Protection Performance

Simulation of a single transformer energization has been performed at time-instant the worst in terms of possibility of the inrush current occurrence - when the magnetic flux can double the initial value [6–10]. The energization process began at the time instant t = 0, 1 s when the HV-side phase “C” voltage obtained zero value which has resulted in corresponding magnetic flux increase (magnetic flux of phase C) for more than two-times from the initial value Fig. 11 – the third diagram. Phase voltages of all three phases remained within the nominal values during the energization process while the highest value of magnetic flux of phase “C” resulted in the occurrence of the highest in-rush current in phase “C” – Fig. 11. The differential current, because of the transformer in-rush occurrence, obtained the highest value at phase “C” – Fig. 12 second diagram and could lead to an unwanted differential protection trip – dotted line at second diagram of Fig. 12 presents the threshold. However, simulated values do show significant changes during the transformer energization, hence the differential protection did not trip because of settings that block 2nd harmonic shown in Table 2 and the transformer was successfully energized – as it is shown at Fig. 11 and Fig. 12.

The unwanted differential protection trip during the transformer energization process is prevented by analyzing the harmonic spectrum of all three-phase at HV-side of the transformer. The second harmonic presence in phase currents indicates the transformer energization and thus is used for blocking the differential protection tripping as it shows

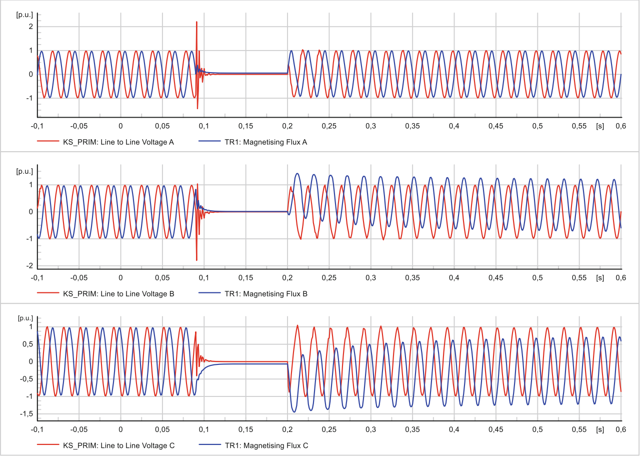

Fig. 11. Phase-voltages and magnetic-fluxes at HV transformer side; phase A -the first diagram, phase B- the second diagram, phase C-the third diagram

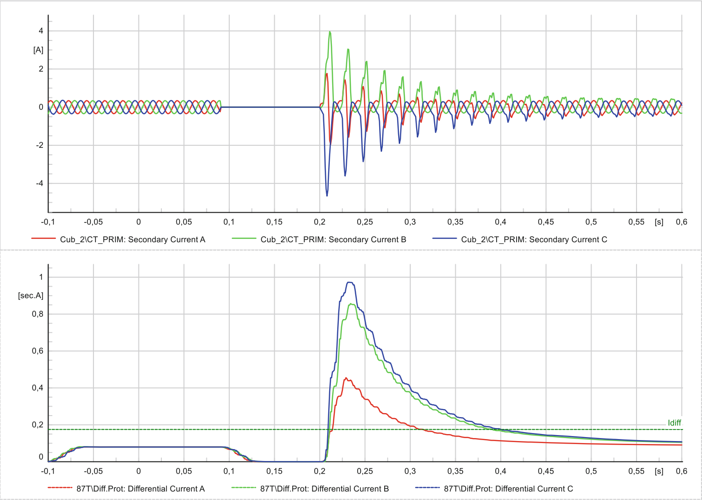

Fig. 12. Inrush currents at the HV - transformer side – the first diagram (values at differential protection CT); differential currents at the HV - transformer side – the second diagram (values at differential protection CT)

on Fig. 13 - 55% of 2nd harmonic presence. This setting is over the threshold setting at Table 2. The manufacturer recommended I2/I1 ratio.

The same differential protection agenda is applied as well when two transformers are in parallel operation. The appearance of the inrush current during the energization of a single transformer causes the inrush current i.e. sympathetic inrush current in the already energized transformer. Figure 14 shows phase currents of TR1 and TR2 during

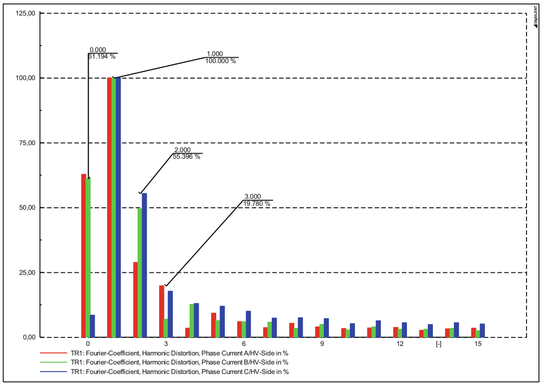

Fig. 13. Harmonic spectrum of the phase currents at the transformer HV - side

TR2 switch-on at the most unfavorable moment because the magnetic flux almost doubles the value. There is an increase in the amplitudes of currents at the switch-on.

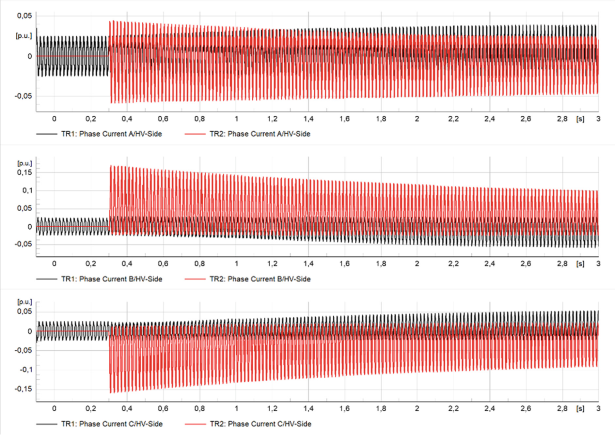

Fig. 14. Waveforms of phase currents at HV transformer side for both transformers; phase A – the first diagram, phase B – the second diagram, phase C – the third diagram

Harmonic spectrum of phase currents at the HV side of both transformers is shown at Fig. 15. The second harmonic presence occurred here as well, but the settings from the Table 2 blocked differential protection trips because the percentage rose above the set threshold. Figure 16 shows differential currents at both transformers. First diagram of Fig. 16 is associated with the first transformer, where the differential current is below the dotted line – setting threshold was not crossed. Second diagram on Figure 16 shows differential currents for the second transformer, where differential current crossed the threshold, but the differential protection trip was blocked by 2nd harmonic I2/I1 ratio shown in Table 2. Second harmonic percentage of the second transformer can be seen at Fig. 15 in the second diagram.

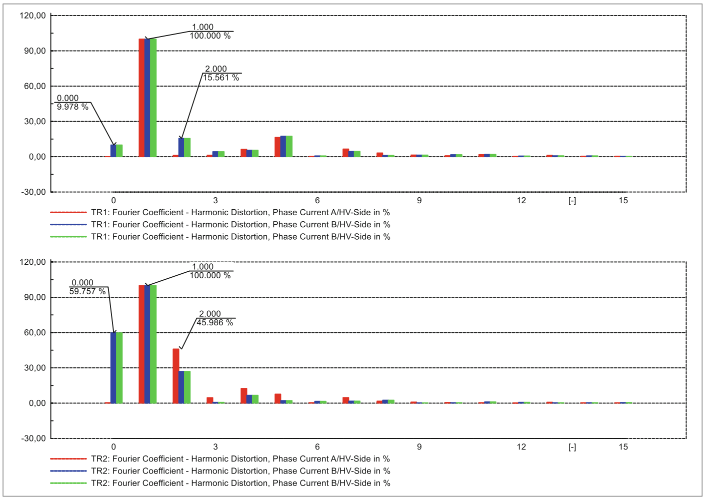

Fig. 15. Harmonic spectrum of the phase currents at the transformer HV side; first transformer - first diagram, second transformer – second diagram

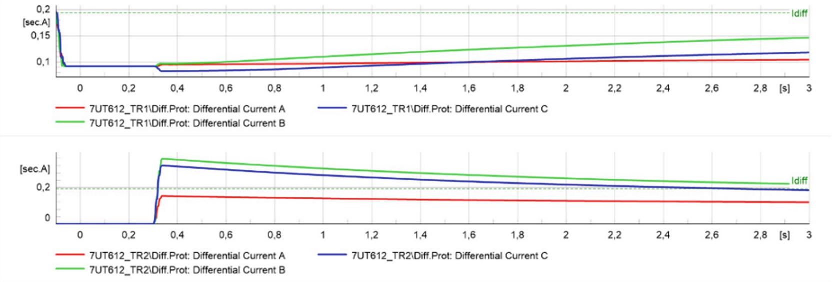

Fig. 16. Differential currents at the HV transformer side; first transformer – first diagram; second transformer – second diagram (values at differential protection CT)

5 Unwanted Circulating Currents Between TR1 and TR2

Single-phase to ground fault was simulated on the HV power line. It can be seen that there is no current through the grounding resistor but there is a circulating current between two transformers - Fig. 17. Current waveforms at HV/MV side during the simulated fault are shown at Fig. 18. First three diagrams of Fig. 18 show phase current and their increase in amplitude when fault occurred, Fourth diagram shows residual current at HV and the fifth one shows there is residual current at MV side – i.e. circulating current.

Figure 19 shows voltage (first diagram) and current waveforms at transformer neutral during fault. As it shows on the first diagram, voltage is minimal and that indicates there is no operating condition. Second diagram shows there is no current through the resistor (CT RN_Io – CT located between resistor and grounding at Fig. 6). Second diagram also shows a circulating current flowing between secondary windings through common grounding recorded by CTs TR1_Io and TR2_Io (located between transformer neutral

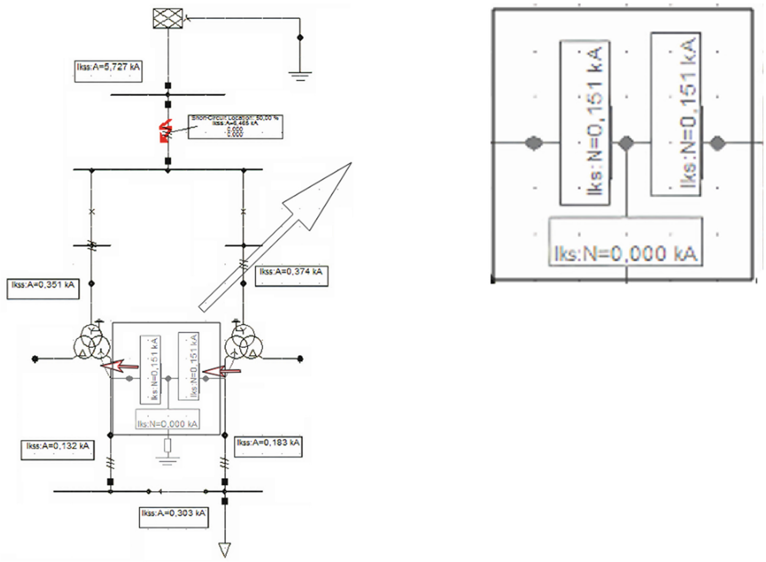

Fig. 17. Single-phase to ground fault at HV network with circulating currents

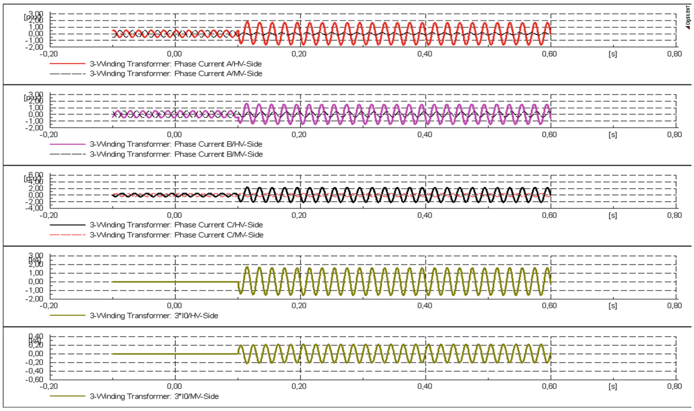

Fig. 18. Current waveforms during single-phase to ground fault

and resistor). That could indicate there is a fault in the 35 kV network that needs to be cleared.

It can be concluded that the occurrence of circulating current between the neutral and secondary windings of two parallel-connected transformers is a very dangerous phenomenon because it can cause unwanted, non-selective trips of short-circuit protection of transformer neutral (resistor protection). This phenomenon was discovered in practice, by unwanted protection trips. Such faults, in 400, 220 or 110 kV - Croatian transmission network, can cause power outages in large areas, even in the whole country depending on voltage level unless the phenomenon is detected and removed in a timely manner.

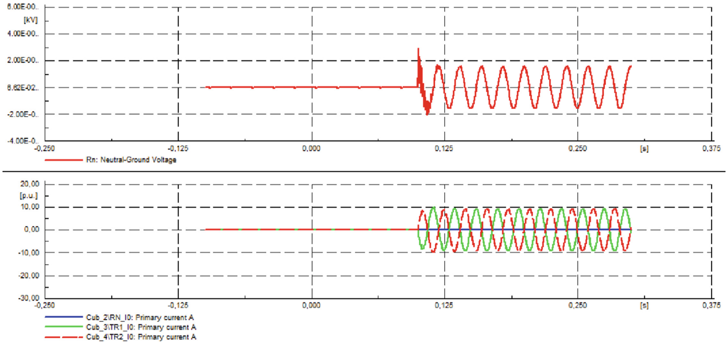

Fig. 19. Voltage and current waveforms at transformer neutral

Resistor protection is used as a backup protection for single-phase to ground faults for 35 kV feeders (distribution network) and coordination between DSO and TSO is necessary for keeping protection settings updated and graded. The most important parameter for quantifying the amplitude of the circulating currents and its occurrence is the zero sequence impedance between the windings [17, 18]. The proposal for solving this problem provides a technical solution with numerical relays, which recommends that the condition for the operation of protection against bridging of resistors is the existence or absence of current flowing through the resistor [17, 18]. A CT built into resistor housing would measure the current through the resistor. With this proposal, it is possible that the resistor can be bridged i.e. no current flows through the CT but the fault is present and it is possible that CT becomes saturated under high magnitudes of current and there will be no conditions for protection to operate [17, 18]. Second solution is to have certain types of protection devices, which have a sufficient number of analog current inputs and filters with the possibility of summing these two analog values (phasors) from different sources [18] i.e. the concept of "differential protection of the resistor". If circulating currents at transformer neutral occur, the sum is equal to zero, but during single-phase to ground fault in a 35 kV network, the summation amount is equal to the current through the resistor and there is a condition for trip. Figure 20 shows the basic concept of this derived protection.

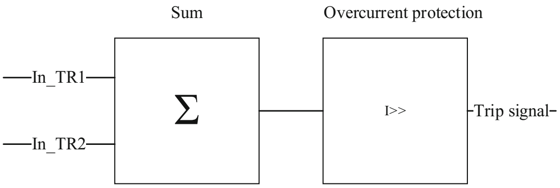

Fig. 20. Basic principle of proposed solution for circulating currents at neutral

6 Conclusion

The transformer can be seen as one of the most important elements of the power system, so it is vital to define and design its protection in order to minimize consequences and to extend its service life. Differential and restricted earth fault protection are the backbone of transformer protection. Nowadays modern protection relays can be programmed to withstand and recognize disturbances, to react quickly and properly. Substations of 110/35 kV connect transmission and distribution networks therefore protection of transformers in these substations is vital for maintaining the stability of the entire distribution network and end customers. Substations with two transformers that share a common grounding resistor are a common practice in Croatia. The choice for a common grounding resistor is the requirement to limit single-phase to ground fault current to a certain value and this construction is economically acceptable compared to other solutions. Transformer inrush current, which occurs under switch on of transformer, can cause an unselective trip of differential protection but solution was given by the detection of second harmonic content in the spectral current separation. In addition, the sympathetic inrush current can occur. Occurrence of circulating currents between neutrals of transformers in parallel operation due to a single-phase to ground fault in the HV network is an unwanted phenomenon. To define the applicable technical solution, it is necessary to analyze each specific and possible situation, taking into account the amount and nominal data of power transformers, available type of protection device, location and characteristics of current transformers and the need and possibility of replacing or upgrading them. The simulation network model is not an actual system but can serve as a model for testing various hazardous operating conditions and faults that may occur within substations that connect transmission and distribution networks and create a power grid.

References

1. Hewitson, L.G., Brown, M., Balakrishnan, R.: Pratical Power System Protection. Elsevier, Oxford (2004)
2. Yu, L., Henriks, R.L.: Selection of system neutral grounding resistor and ground fault protection for industrial power systems. In: Industry Applications Society 38th Annual Petroleum and Chemical Industry Conference, pp. 147–153 (1991)
3. IEEE Recommended Practice for System Grounding of Industrial and Commercial Power Systems. IEEE SA 3003. 1-2019, pp. 1–79 (2019)
4. Ćućić, R., Komen, V., Živić Đurović, M.: Neutral point concept in distribution networks. Eng. Rev. **28**, 77–89 (2008)
5. Fu, Z., Wang, N., Huang, L., Zhang, R.: Study on neutral point grounding modes in medium-voltage distribution network. In: 2014 International Symposium on Computer, Consumer and Control, Taichung, (2014)
6. Chen, N., Wang, C., Zhang, J., Yang, F., Chen, Y., Hong, W.: The inrush current analysis and restraining method of energizing no-load transformer. In: 2016 3rd International Conference on Systems and Informatics (ICSAI), pp. 204–207 (2016)
7. Alibašić, E., Marić, P., Nikolovski, S.: Transient phenomena during the three-phase 300 MVA Transformer energization on the transmission network. Int. J. Electr. Comput. Eng. **6**(6), 2499–2505 (2016)

8. IEEE Guide for Protecting Power Transformers, IEEE SA C37.91-2008 (Revision of IEEE SA C37.91-2000), pp.1–139 (2008)
9. Alstom: Network Protection & Automation Guide (2011)
10. Heathcote, M.: The J & P Transformer Book, 13th edn., Elsevier, Oxford (2011)
11. Bronzeado, H., Yacamini, R.: Phenomenon of sympathetic interaction between transformers caused by inrush transients. Sci. Measur. Technol. IEE Proc. **142**, 323–329 (1995)
12. Ziegler, G.: Numerical Differential Protection. Siemens, Nuremberg (2012)
13. Masle, D., Benović, J., Tolić, I., Marić, P.: The effect of transformer operating conditions on occurrence of inrush current with respect to differential protection settings. In: 12th HRO CIGRE Session, Šibenik (2015)
14. Tsourakis, G., Milis, I., Prousalidis, J.: Transformer sympathetic inrush: a case study. In: 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012), Cagliari (2012)
15. Hong-Ming, S., Tao, Z., Shao-Feng, H., Ou, L.: Study on a Mal-operation case of differential protection due to the interaction between magnetizing inrush and sympathetic inrush. In: 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD (2014)
16. Qi, X., Yin, X., Zhang, Z.: Sympathetic inrush current in a transformer and a method for its identification. IIEEJ Trans. Electr. Electr. Eng. **11**(4), 442–450 (2016)
17. Calzolari, G., Saldana, C.: Power transformers in parallel which share a neutral resistance: how to manage the circulating current between the secondary windings. In: IPST International Conference on Power System Transients, Canada (2005)
18. Masle, D., Rošić, M., Benović, J., Marić, P.: On protection of medium voltage neutral resistor during single phase to ground fault in high voltage grid. In: 12th Symposium on Power System Management, Split (2016)
19. Dommel, H.W.: EMTP Theory Book. Microtran Power System Analysis Corporation, Vancouver (1995)
20. Watson, N., Arrillaga, N.: Power Systems Electromagnetic Transients Simulation. The Institution of Engineering and Technology, London (2003)
21. Siemens. SIPROTEC Differential Protection 7UT612, V4.0 Manual (2002)