

ANALYZING OF RELEVANT FAULT TYPE FOR CALCULATION OF MINIMUM FAULT CURRENT MAGNITUDE ON DISTRIBUTION TRANSFORMER PRIMARY SIDE

Vedran Boras, Tomislav Barić, Alija Muharemović

Original scientific paper

The paper analyses the influence of three-phase transformer connections and several types of bolted shunt faults (short circuits), which occur on a distribution transformer secondary side as well as simultaneous faults in determining of relevant fault type for calculation of minimum fault current magnitude on the transformer primary side, which will be relevant for the selection of fuse-links minimum breaking current of high-voltage fuses for transformer circuit applications. The two transformer connections: delta primary-grounded star secondary (denoted as Dyn) and star primary-grounded interconnected star secondary, also known as zig-zag (denoted as Yzn) are enclosed in the carried out analysis. In this paper a simultaneous fault involves the shunt fault on the transformer secondary side with blown fuse in any phase on the transformer primary side. Calculation of these faults is carried out by means of the symmetrical components method in per-unit.

Keywords: fuse-links minimum breaking current, high-voltage fuses, shunt fault, simultaneous fault, three-phase transformer connection

Analiziranje mjerodavnog tipa kvara za proračun iznosa minimalne struje kvara na primarnoj strani distribucijskog transformatora

Izvorni znanstveni članak

U ovom radu je analiziran utjecaj spoja namota trofaznog transformatora i više tipova izravnih kratkih spojeva, koji se pojavljuju na sekundarnoj strani nekog distribucijskog transformatora kao i simultanih kvarova u određivanju mjerodavnog tipa kvara za proračun minimalnog iznosa struje kvara na primarnoj strani transformatora, koji će biti mjerodavan u odabiru minimalne prekidne struje topljivih umetaka visokonaponskih osigurača za zaštitu transformatora. Ovom analizom obuhvaćene su dvije grupe spoja namota transformatora: trokut na primaru - uzemljena zvijezda na sekundaru (u oznaci Dyn) i zvijezda na primaru - uzemljena izlomljena zvijezda na sekundaru poznata i pod nazivom kao cik-cak (u oznaci Yzn). U ovom radu simultani kvar obuhvata kratki spoj na sekundarnoj strani transformatora uz istodobno pregorjeli osigurač u jednoj od faza na primarnoj strani transformatora. Proračun ovih kvarova izveden je primjenom metode simetričnih komponenti u sustavu jediničnih vrijednosti.

Ključne riječi: minimalna prekidna struja topljivog umetka, poprečni kvar, simultani kvar, spoj namota trofaznog transformatora, visokonaponski osigurači

1

Introduction

Uvod

In many text books and papers such as [1]-[5], it is possible to find descriptions about shunt fault calculations and about the influence of the three-phase transformer connection Dyn on the fault currents distribution through distribution transformers. In [6] is described a method for digitally simulating a three-phase power system which is subjected to a fault at one location with blown fuse or open conductors at another location. The method is applicable when the simultaneous unbalances are on opposite sides of a delta-grounded star transformer. From these books and paper it can be concluded, that in the common case of a delta primary-grounded star secondary connection (Dyn), the currents on the source side of the transformer differ from the corresponding currents on the fault side for the unbalanced secondary shunt fault and for the simultaneous fault.

This paper analyzes influence of three-phase transformer connections (Dyn5 and Yzn5) and several type short circuits and simultaneous faults in determining of relevant fault type for calculation of minimum fault current magnitude on the distribution transformer primary side, which will be relevant for the selection of fuse-links minimum breaking current of high-voltage fuses for transformer circuit applications. In the carried out analysis it is assumed, that a secondary short circuit (shunt) fault occurs between the transformer terminals and the low-voltage side protective device and that the fault must be cleared by the high-voltage side fuses, which are used as transformer primary-side protective devices (incoming protection). In this paper it is considered that a simultaneous fault represents a multiple fault which involves at the same

time a secondary shunt fault and any blown fuse on the transformer primary side. In [7] is noted that the simultaneous fault can lead to a situation where electrical equipment may be overstressed due to the short-circuit duration and thus analyzing of such fault type can be very useful.

According to the IEC Standards [8]-[9], one of ratings which should be specified relating to the protection of a HV/LV transformer circuit is minimum breaking current. This current is defined as minimum value of prospective current that a fuse-link is capable of breaking at a stated voltage under prescribed conditions of use and behaviour. According to [8], fuse-links should be selected so that the value of minimum breaking current is appropriate to the particular application concerned. It should be stressed that the use of a fuse-link having too high a value of minimum breaking current could, under certain circumstances, result in disruptive failure of the fuse-link and consequent damage.

There are two possible cases:

- For applications where low fault levels are unlikely to occur, suitable Back-Up fuses may be used. In this case, it is necessary to ascertain that the rated minimum breaking current of the fuse-link is less than the smallest short-circuit current likely to appear upstream of the low-voltage protecting device (referred to high-voltage side).
- For applications where very low values of fault current occur on the distribution system, the fuse should have minimum breaking current, which is as low as possible. Thus, general purpose fuses should be used for such applications.

Only for the sake of determining the relevant type of fault current, in this paper are made some assumptions, which considerably simplify the longhand calculations.

When the relevant type of fault current is selected, the real minimum fault current magnitude should be determined without these assumptions, taking into account all relevant and required parameters (for example equivalent distribution system impedance, etc.). Like this fault current magnitude can be used by protection engineers to assess the time-current characteristics of high-voltage fuses as incoming protection on the high-voltage side of a distribution transformer.

This paper focuses on three-phase small liquid-immersed distribution transformers with three-legged core-form construction.

The method presented in this paper employs symmetrical component techniques to represent the shunt faults and the faults with blown fuse conditions. A number of methods, which use the method of symmetrical components for computing simultaneous faults involving two faults, have been studied in [1]-[4]. In this paper, each sequence network is described mathematically in appendices in accordance with Kirchhoff's current and voltage law, and the interconnections between the sequence networks at the unbalance locations are expressed in the form of constraint equations. For the calculation of the unknown sequence current and voltages during simultaneous faults, linear matrix equations are presented in appendices.

2 Shunt faults (short circuits) Poprečni kvarovi (kratki spojevi)

This paragraph analyses bolted three-phase fault, bolted phase-to-phase fault and bolted phase-to neutral fault at the fault point F on the secondary side of a Dyn5 or of an Yzn5 transformer in the vicinity of the shunt transformer terminals, as shown in Fig. 1.

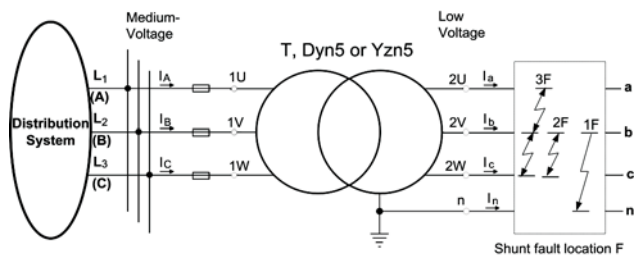


Figure 1 Transformer secondary-side shunt faults (short circuits)
Slika 1. Poprečni kvarovi (kratki spojevi) na sekundaru transformatora

The basic assumptions, which considerably simplify the longhand calculations and comparison, are made:

- The fault currents calculation will be made using per-unit method under no-load conditions neglecting all shunt reactances (loads, charging and magnetizing reactances) and neglecting all mutual reactances.
- Only for the sake of practical examples in this paper, the equivalent distribution system impedance up to transformer medium voltage bus will be neglected. Thus, the short circuit currents will be calculated on the transformer low-voltage side in the vicinity of the transformer terminals assuming that primary winding is connected to an infinitive bus (a system with zero impedance, $\bar{Z}_{1S} = 0 + j0 pu$).
- The source voltage will be assumed to be $1,0 pu$ for fault calculations using per-unit method.
- The transformers will be analyzed on nominal tap

position.

e) In the carried out per-unit analysis, the transformer voltage ratio is assumed 1:1, i.e. it will be for $n = \sqrt{3}$ by a Dyn5 transformer and for $n = \sqrt{3}/2$ by an Yzn5 transformer.

f) Conversion of the transformer impedance magnitude to per-unit value, i.e. $|\bar{Z}_{1T}| = 1 pu$ will be made on a base power $S_b = S_T/u_k$ or $\bar{I}_{3_SCC} = \bar{I}_n/u_k$.

g) In carried fault current calculations it is necessary to take into account both the resistance and reactance values of small distribution transformer impedance. Carried out analysis will be simplified by using the polar representation of the impedance $\bar{Z}_T = |\bar{Z}_T| \angle \varphi$. Phase angle φ can be easy to calculate from data designated by the transformer manufacturer and it lies in range from 47° to 78° . In following examples will be used $\varphi = 60^\circ$ and corresponding ratio $R_T/X_T = 0,577$.

h) The neutral conductor impedance from transformer terminal to fault location is neglected.

I) Zero-sequence reactances of three-phase small distribution Dyn5 and Yzn5 transformers with three-legged core-form construction are lower than their corresponding positive-sequence reactances and usually are equal:

- $X_{T0} \cong 0,95 X_{T1}$ for Dy transformers and
- $X_{T0} \cong 0,1 X_{T1}$ for Yz transformers.

j) Zero-sequence resistances of three-phase small distribution Dyn5 and Yzn5 transformers with three-legged core-form construction are:

- $R_{T0} \cong R_{T1}$ for Dy transformers and
- $R_{T0} \cong 0,4 R_{T1}$ for Yz transformers.

k) Zero-sequence current \bar{I}_{A0} is equal to zero, because the delta connection on the high-voltage side of the Dyn5 transformer or the ungrounded star connection on the high-voltage side of the Yzn5 transformer does not allow the flow of zero-sequence current.

In many text books it is possible to find description about shunt fault calculations by means of the method of symmetrical components. Thus, in this paragraph we will use only final equations of analyzed shunt faults.

2.1 Bolted three-phase fault Izravni trolpolni kratki spoj

Let us consider a bolted three-phase fault at the fault point F on the secondary side of a Dyn5 or of an Yzn5 transformer, as shown in Fig. 1. The method of symmetrical components will allow us to express the bolted three-phase fault current as follows:

$$\bar{I}_{3_SCC} = \bar{I}_{a1} = \frac{\bar{V}}{\bar{Z}_{S1} + \bar{Z}_{T1}}; \quad \bar{I}_{a2} = 0; \quad \bar{I}_{a0} = 0. \quad (1)$$

From (1) it can be concluded that only the positive-sequence network is involved in the three-phase fault.

Substituting above mentioned values by $\bar{V} = j1 pu$, $\bar{Z}_{T1} = 1 \angle 60^\circ pu$ and $\bar{Z}_{S1} = j0 pu$ in (1) we get the following:

$$\bar{I}_{a1} = \bar{I}_{3_SCC} = \frac{1 \angle 90^\circ}{1 \angle 60^\circ} = 1 \angle 30^\circ pu. \quad (2)$$

Substituting the values of \bar{I}_{a1} , \bar{I}_{a2} and \bar{I}_{a0} from (1) and (2) in (A6) we obtain secondary line (winding) currents.

The sequence currents flowing in the leads to the delta winding of the Dyn5 transformer are given in relation to the positive- and negative-sequence secondary line currents (i.e. star winding currents) by means of matrix equation (A9) and (A10). Substituting these in (A7) we obtain Dyn5 transformer primary line currents. Similarly, the sequence currents flowing in the leads to the star winding of the Yzn5 transformer are given in relation to the sequence secondary line currents (i.e. interconnected star winding currents) by means of matrix equation (A17) and (A18). Substituting these in (A7) we obtain Yzn5 transformer primary line currents. The fault analysis results, for the bolted three-phase fault on the secondary side of a Dyn5 or an Yzn5 transformer, are shown in Table 1.

Table 1 Three-phase fault currents analysis
Tablica 1. Analiza struja trofaznog kratkog spoja

| Transformer connections | Primary line currents (pu) | Secondary line currents (pu) |
|-------------------------|------------------------------------|------------------------------------|
| Dyn5 | $\bar{I}_A = 1,0 \angle 180^\circ$ | $\bar{I}_a = 1,0 \angle 30^\circ$ |
| | $\bar{I}_B = 1,0 \angle 60^\circ$ | $\bar{I}_b = 1,0 \angle 270^\circ$ |
| Yzn5 | $\bar{I}_C = 1,0 \angle 300^\circ$ | $\bar{I}_c = 1,0 \angle 150^\circ$ |

Table 1 shows, that for a three-phase secondary fault, the per-unit currents on the primary equal those on the secondary (with the actual currents related by the turns ratio of the transformer). The currents on the primary lead to the corresponding currents on the secondary by 150° .

2.2

Bolted phase-to-phase fault

Izravni dvopolni kratki spoj

Let us consider a bolted phase-to-phase fault, involving phases b and c , at a fault point F on the secondary side of a Dyn5 or of an Yzn5 transformer, as shown in Fig. 1.

The method of symmetrical components will allow us to express the bolted phase b -to-phase c current as follows:

$$\begin{aligned}\bar{I}_a &= \bar{I}_{a1} + \bar{I}_{a2} = 0 \\ \bar{I}_b &= \bar{a}^2 \bar{I}_{a1} + \bar{a} \bar{I}_{a2} = (\bar{a}^2 - \bar{a}) \bar{I}_{a1} = -j\sqrt{3} \bar{I}_{a1} \\ \bar{I}_c &= \bar{a} \bar{I}_{a1} + \bar{a}^2 \bar{I}_{a2} = (\bar{a} - \bar{a}^2) \bar{I}_{a1} = +j\sqrt{3} \bar{I}_{a1},\end{aligned}\quad (3)$$

where

$$\bar{I}_{a1} = -\bar{I}_{a2} = \frac{\bar{V}}{2\bar{Z}_{S1} + 2\bar{Z}_{T1}}; \quad \bar{I}_{a0} = 0. \quad (4)$$

In the event of having $\bar{V} = j1 \text{ pu}$ and $\bar{Z}_{T1} = 1 \angle 60^\circ \text{ pu}$, and substituting this and the basic assumptions $\bar{Z}_{S1} = j0 \text{ pu}$ in (4) we get the following:

$$\bar{I}_{a1} = -\bar{I}_{a2} = \frac{1 \angle 90^\circ}{2 \angle 60^\circ} = 0,5 \angle 30^\circ. \quad (5)$$

Substituting (5) in (3), we will get the following:

$$\begin{aligned}\bar{I}_a &= 0 \text{ pu} \\ \bar{I}_b &= \frac{\sqrt{3}}{2} \angle -60^\circ \text{ pu} \\ \bar{I}_c &= \frac{\sqrt{3}}{2} \angle 120^\circ \text{ pu}.\end{aligned}\quad (6)$$

Thus, we can conclude that the bolted phase-to-phase fault is 0,866 of the bolted three-phase fault.

In the same way as in the case of the bolted three-phase fault, we can determine primary line currents of a Dyn5 or of an Yzn5 transformer for this fault type.

The fault analysis results, for the bolted phase b - to - phase c fault on the secondary side of a Dyn5 or of an Yzn5 transformer, are shown in Table 2.

Table 2 The phase b -to-phase c fault current analysis
Tablica 2. Analiza dvopolnog kratkog spoja (faze b - c)

| Transformer connections | Primary line currents (pu) | Secondary line currents (pu) |
|-------------------------|-------------------------------------|--------------------------------------|
| Dyn5 | $\bar{I}_A = 0,5 \angle 120^\circ$ | $\bar{I}_a = 0,0$ |
| | $\bar{I}_B = 0,5 \angle 120^\circ$ | $\bar{I}_b = 0,867 \angle -60^\circ$ |
| Yzn5 | $\bar{I}_C = 1,0 \angle -120^\circ$ | $\bar{I}_c = 0,867 \angle 120^\circ$ |

It can be seen from Table 2 that bolted phase b - to - phase c secondary fault produce one large primary line current and two smaller primary line currents by both transformer connections. These reduced primary line currents can be a problem in protective relaying. The larger primary line current is approximately 16 % higher than the per-unit secondary line current. If fuse blows in the phase with larger primary line current, then fault will be cleared. The two smaller primary line fault currents are less than the secondary line current. Analyzing these results it can be concluded, that secondary of an Yzn5 transformer, when seen from transformer primary side, behaves as delta connection.

2.3

Bolted phase-to-neutral fault

Izravni jednopolni kratki spoj

Let us consider a bolted single phase-to-neutral fault at the fault point F on the secondary side of a Dyn5 or of an Yzn5 transformer, as shown in Fig. 1. In this fault calculation, the faulted phase is assumed to be phase b , because of the comparison with results of following simultaneous fault analysis. In the event of having $\bar{Z}_{S1} = \bar{Z}_{S2}$ and $\bar{Z}_{T1} = \bar{Z}_{T2}$, the technique of symmetrical components will allow us to express the fault currents as follows:

$$\begin{aligned}\bar{I}_a &= \bar{I}_c = 0,0 \\ \bar{a}^2 \bar{I}_{a1} &= \bar{a} \bar{I}_{a2} = \bar{I}_{a0} \\ \bar{I}_b &= 3\bar{a}^2 \bar{I}_{a1} = \frac{3\bar{a}^2 \bar{V}}{2\bar{Z}_{S1} + 2\bar{Z}_{T1} + \bar{Z}_{T0}}.\end{aligned}\quad (7)$$

If we substitute the basic assumption $\bar{Z}_{S1} = 0 \text{ pu}$ in (7), we can derive from this expression the following:

$$\bar{I}_b = \frac{\bar{a}^2 \bar{V}}{\bar{Z}_{T1}} \cdot \frac{3}{2 + \frac{\bar{Z}_{T0}}{\bar{Z}_{T1}}}. \quad (8)$$

This expression shows that the bolted single phase-to-neutral fault current on line b is the function of: the three-phase bolted fault current (\bar{V}/\bar{Z}_{T1}) and the ratio of the zero-sequence impedance with the positive-sequence impedance.

Using assumptions under bullets i) and j) it is easy to obtain the following expression for a Dyn5 transformer:

$$\frac{\bar{Z}_{T0}}{\bar{Z}_{T1}} = 1 - \frac{0,05}{\left(\frac{R_{T1}}{X_{T1}}\right)^2 + 1} \cdot \left(1 + j \frac{R_{T1}}{X_{T1}}\right). \quad (9)$$

Analogously, the following expression can be obtained for an Yzn5 transformer:

$$\frac{\bar{Z}_{T0}}{\bar{Z}_{T1}} = 0,4 - \frac{0,3}{\left(\frac{R_{T1}}{X_{T1}}\right)^2 + 1} \cdot \left(1 + j \frac{R_{T1}}{X_{T1}}\right). \quad (10)$$

Substituting (9) and (10) in (8) can be obtained values of the bolted single phase-to-neutral fault current on line b , for a Dyn5 and an Yzn5 transformer respectively.

In the event of having $\bar{V} = j1 \text{ pu}$, $\bar{Z}_{1T} = 1\angle 60^\circ \text{ pu}$, $\bar{Z}_{1S} = j0 \text{ pu}$, phase angle $\varphi = 60^\circ$, i.e. $R_{T1}/X_{T1} = 0,577$, and substituting these values in (9) and afterwards in (8) we will get the fault current for phase b of a Dyn5 transformer, as follows:

$$\bar{I}_b = \frac{3\bar{a}^2 \cdot 1\angle 30^\circ}{2,9625 - j \cdot 0,0216} \cong 1,0126 \angle 270^\circ \text{ pu}. \quad (11)$$

Analogously, substituting the values $\bar{V} = j1 \text{ pu}$, $\bar{Z}_{1T} = 1\angle 60^\circ \text{ pu}$, $\bar{Z}_{1S} = j0 \text{ pu}$, phase angle $\varphi = 60^\circ$, i.e. $R_{T1}/X_{T1} = 0,577$ in (10) and afterwards in (8), we will get the fault current for phase b of an Yzn5 transformer, as follows:

$$\bar{I}_b = \frac{3\bar{a}^2 \cdot 1\angle 30^\circ}{2,175 - j \cdot 0,13} \cong 1,377 \angle 273^\circ \text{ pu}. \quad (11a)$$

Thus, it can be concluded that the bolted phase-to-neutral fault current is higher than the bolted three-phase fault current.

In the same way as in the case of the bolted three-phase fault, we can determine primary line currents of a Dyn5 or of an Yzn5 transformer for this fault type.

Table 3 The phase b -to-neutral fault current analysis

Tablica 3. Analiza jednofaznog kratkog spoja (faza b -nulti vodič)

| Transformer connections | Primary line currents (pu) | Secondary line currents (pu) |
|-------------------------|--|--|
| Dyn5 | $\bar{I}_A = 0,0 \angle 0^\circ$ | $\bar{I}_a = 0,0 \angle 0^\circ$ |
| | $\bar{I}_B \cong 0,585 \angle 90,4^\circ$ | $\bar{I}_b \cong 1,013 \angle 270^\circ$ |
| | $\bar{I}_C \cong 0,585 \angle 270,4^\circ$ | $\bar{I}_c = 0,0 \angle 0^\circ$ |
| Yzn5 | $\bar{I}_A = 0,0 \angle 0^\circ$ | $\bar{I}_a = 0,0 \angle 0^\circ$ |
| | $\bar{I}_B \cong 0,795 \angle 91,6^\circ$ | $\bar{I}_b \cong 1,377 \angle 273^\circ$ |
| | $\bar{I}_C \cong 0,795 \angle 271,6^\circ$ | $\bar{I}_c = 0,0 \angle 0^\circ$ |

The fault analysis results, for the bolted phase b - to - neutral fault on the secondary side of a Dyn5 or of an Yzn5 transformer, are shown in Table 3.

Therefore, it can be concluded that the bolted single phase-to-neutral fault currents on the secondary side of a Dyn5 or of an Yzn5 transformer can reach approximately 1,013 or 1,377 times the bolted three-phase fault current value, respectively.

Table 3 shows clearly that the bolted single phase-to-neutral fault on secondary side of a Dyn5 or of an Yzn5 transformer produces the per unit primary-side line currents less than the per-unit secondary line currents.

Thus, it can be concluded that the transformer will not be well protected in this case; because primary-side fuses in phases B and C take longer to clear the bolted phase-to-neutral fault on secondary.

3 Simultaneous faults Simultani kvarovi

In this paragraph have been analysed simultaneous faults which involve single blown fuse on the primary side of a Dyn5 or of an Yzn5 transformer with one of the following shunt faults on the secondary:

- bolted three-phase fault,
- any bolted double phase-to-neutral and
- bolted phase b -to-neutral.

In [7], it is noted that simultaneous faults which involve any phase-to-phase faults without neutral connection on the transformer secondary side with blown fuse in phase A on the transformer primary side cause merely low currents and thus it will not be taken into consideration in this paper.

In this paragraph are used the same basic assumptions as in paragraph 2.

3.1 Bolted three-phase fault on the transformer secondary-side with blown fuse in phase A Izravni trolpolni kratki spoj na sekundarnoj strani transformatora s pregorjelim osiguračem u fazi A

Let us consider a simultaneous fault, which involves a bolted three-phase fault at the fault point F located on the secondary side of a Dyn5 or of an Yzn5 transformer, as shown in Fig. 2 and Fig. 3, with blown fuse in phase A on the transformer primary-side.

When medium-voltage phase A is the reference phase, solving the linear matrix equation (B4) by using the basic assumptions stated above we get for this fault type the following positive- and negative-sequence currents:

$$\begin{aligned} \bar{I}_{A1} = -\bar{I}_{A2} &= \frac{\bar{V}}{2(\bar{Z}_{S1} + \bar{Z}_{T1})} = \frac{1\angle 90^\circ}{2 \cdot 1\angle 60^\circ} = 0,5 \angle 30^\circ \text{ pu} \\ \bar{I}_{a1} = \bar{I}_{A1} \angle -150^\circ &= 0,5 \angle -120^\circ \text{ pu} \\ \bar{I}_{a2} = \bar{I}_{A2} \angle 150^\circ &= -0,5 \angle 180^\circ = 0,5 \text{ pu} \\ \bar{I}_{A0} = \bar{I}_{a0} &= 0,0 \text{ pu}. \end{aligned} \quad (12)$$

The primary line currents \bar{I}_A , \bar{I}_B and \bar{I}_C can be obtained substituting \bar{I}_{A1} , \bar{I}_{A2} and \bar{I}_{A0} in equation (A7), and the secondary line currents \bar{I}_a , \bar{I}_b and \bar{I}_c can be obtained

substituting \bar{I}_{a1} , \bar{I}_{a2} and \bar{I}_{a0} in equation (A6).

Fig. 2 shows results of the simultaneous fault currents on both sides of a Dyn5 transformer.

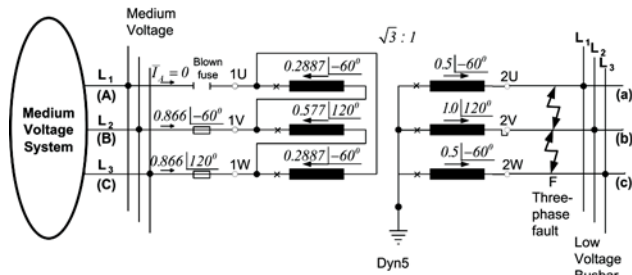


Figure 2 Per-unit fault currents on both sides of a Dyn5 transformer for three-phase fault on transformer secondary-side with blown fuse in phase A on transformer primary-side

Slika 2. Jedinični iznosi struja kvara na obje strane nekog Dyn5 transformatora kod trolpnog kratkog spoja na sekundaru transformatora s pregorelim osiguračem u fazi A na primaru

The fault analysis results for the bolted secondary three-phase fault of an Yzn5 transformer with blown fuse in phase A on primary-side, are shown in Fig. 3.

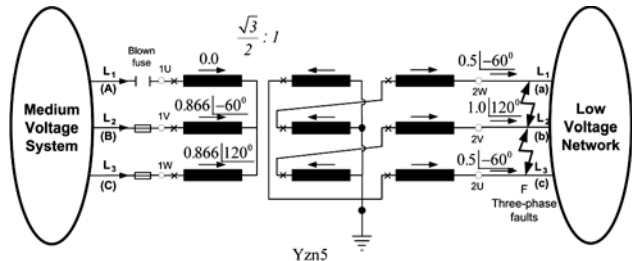


Figure 3 Per-unit fault currents on both sides of an Yzn5 transformer for three-phase fault on transformer secondary-side with blown fuse in phase A on transformer primary-side

Slika 3. Jedinični iznosi struja kvara na obje strane nekog Yzn5 transformatora kod trolpnog kratkog spoja na sekundaru transformatora s pregorelim osiguračem u fazi A na primaru

Fig. 2 and Fig. 3 show that primary-side fuses see lower currents during this simultaneous fault type than those which occur during the three-phase fault only, and thus they take longer to clear this simultaneous fault. However, partial short-circuit currents at the medium-voltage side may not be too small to operate other two medium-voltage fuses.

3.2

Double phase-to-neutral fault on the secondary side with blown fuse in phase A

Dvopolni kratki spoj s istodobnim spojem s neutralnim vodičem na sekundarnoj strani i s pregorelim osiguračem u fazi A

a) First, let us consider bolted double phase-to-neutral fault, involving phases *a* and *c*, at the fault point F located on the secondary side of a Dyn5 or of an Yzn5 transformer, as shown in Fig. 4 and Fig. 5, with blown fuse in phase A on the transformer primary-side.

When medium-voltage phase A is the reference phase and solving the linear matrix equation (C6), the following positive-, negative-, and zero-sequence currents can be obtained:

$$\begin{aligned} \bar{I}_{A1} &= -\bar{I}_{A2} = \frac{\bar{V}}{2(\bar{Z}_{S1} + \bar{Z}_{T1}) + 4\bar{Z}_{T0}} \\ \bar{I}_{a1} &= \bar{I}_{A1} \angle -150^\circ \\ \bar{I}_{a2} &= \bar{I}_{A2} \angle 150^\circ = \bar{I}_{A1} \angle 330^\circ \\ \bar{I}_{a0} &= -a^2 \bar{I}_{a1} - a \bar{I}_{a2} = \frac{\bar{V} \angle -90^\circ}{\bar{Z}_{S1} + \bar{Z}_{T1} + 2\bar{Z}_{T0}} \end{aligned} \quad (13)$$

Substituting the basic assumption $\bar{Z}_{S1} = 0,0 pu$ in (13) and rearranging, the next expression can be derived:

$$\bar{I}_{A1} = -\bar{I}_{A2} = \frac{\bar{V}}{2\bar{Z}_{T1} \left(1 + \frac{2\bar{Z}_{T0}}{\bar{Z}_{T1}}\right)} = \frac{\bar{I}_{3-SCC}}{2 \left(1 + \frac{2\bar{Z}_{T0}}{\bar{Z}_{T1}}\right)}, \quad (14)$$

where $\bar{Z}_{T0}/\bar{Z}_{T1}$ are defined by (9) and (10).

Using the basic assumptions stated above for a Dyn5 transformer, the following positive-, negative-, and zero-sequence per-unit currents can be obtained from (13) and (14):

$$\begin{aligned} \bar{I}_{A1} &\cong 0,171 \angle 30,85^\circ & \bar{I}_{a1} &\cong 0,171 \angle -119,15^\circ \\ \bar{I}_{A2} &\cong 0,171 \angle 210,85^\circ & \bar{I}_{a2} &\cong 0,171 \angle 0,85^\circ \\ \bar{I}_{A0} &= 0,0 & \bar{I}_{a0} &= 0,3418 \angle -59,15^\circ \end{aligned} \quad (15)$$

The primary and secondary line currents can be obtained substituting corresponding positive-, negative-, and zero-sequence currents from (15) in (A7) and (A6), respectively. Fig. 4 shows results of these simultaneous fault currents on both sides of a Dyn5 transformer. In this case, partial short-circuit currents on the medium-voltage side will be too small to operate other two medium-voltage fuses and it can lead to overstressing of electrical equipment.

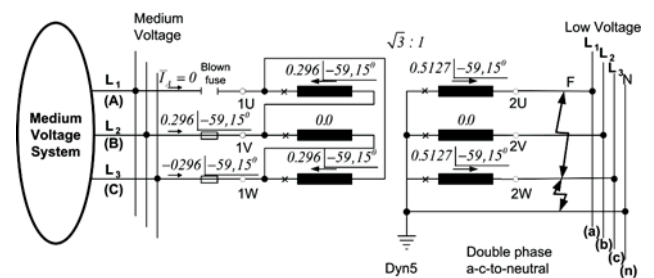


Figure 4 Per-unit fault currents on both sides of a Dyn5 transformer for the simultaneous fault, which involves phase a-phase c-to-neutral fault on the star side and blown fuse in phase A on the delta side

Slika 4. Jedinični iznosi struja kvara na obje strane nekog Dyn5 transformatora kod simultanog kvara koji obuhvata spoj faza a i c s neutralnim vodičem na strani zvijezda namota i pregoreli osigurač u fazi A na strani namota u trokutu

Using the basic assumptions stated above for an Yzn5 transformer, the following positive-, negative-, and zero-sequence per-unit currents can be obtained from (13) and (14):

$$\begin{aligned} \bar{I}_{A1} &\cong 0,364 \angle 31,1^\circ & \bar{I}_{a1} &\cong 0,364 \angle -118,9^\circ \\ \bar{I}_{A2} &\cong 0,364 \angle 211,1^\circ & \bar{I}_{a2} &\cong 0,364 \angle 1,1^\circ \\ \bar{I}_{A0} &= 0,0 & \bar{I}_{a0} &= 0,7275 \angle -58,9^\circ \end{aligned} \quad (16)$$

The primary and secondary line currents can be obtained substituting corresponding positive-, negative-, and zero-sequence currents from (16) in (A7) and (A6), respectively. Fig. 5 shows results of these simultaneous fault currents on both sides of an Yzn5 transformer.

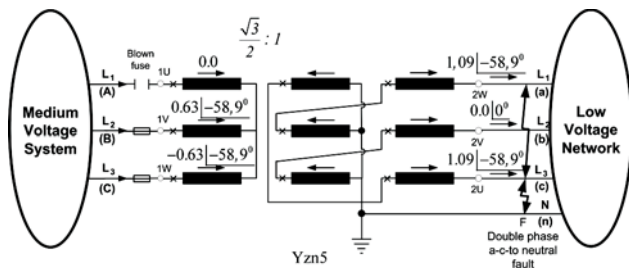


Figure 5 Per-unit fault currents on both sides of an Yzn5 transformer for the simultaneous fault, which involves phase a-phase c-to-neutral fault on the secondary-side and blown fuse in phase A on the transformer primary-side

Slika 5. Jedinični iznosi struja kvara na obje strane nekog Yzn5 transformatora kod simultanog kvara koji obuhvata spoj faza a i c s neutralnim vodičem na sekundarnoj strani i pregorjeli osigurač u fazi A na primarnoj strani transformatora

b) Let us consider bolted double phase-to-neutral fault, involving phases *a* and *b*, at the fault point F located on the secondary-side of a Dyn5 or of an Yzn5 transformer, as shown in Fig. 6 and Fig. 7, with blown fuse in phase A on the transformer primary-side.

When medium-voltage phase *A* is the reference phase and solving the linear matrix equation (C6), the following positive-, negative-, and zero-sequence currents can be obtained:

$$\begin{aligned} \bar{I}_{A1} &= -\bar{I}_{A2} = \frac{\bar{V}}{2(\bar{Z}_{S1} + \bar{Z}_{T1}) + \bar{Z}_{T0}} \\ \bar{I}_{a1} &= \bar{I}_{A1} \angle -150^\circ \\ \bar{I}_{a2} &= \bar{I}_{A2} \angle 150^\circ = \bar{I}_{A1} \angle 330^\circ \\ \bar{I}_{a0} &= -\bar{a}\bar{I}_{a1} - \bar{a}^2\bar{I}_{a2} = \frac{\bar{V} \angle 90^\circ}{2(\bar{Z}_{S1} + \bar{Z}_{T1}) + \bar{Z}_{T0}} \end{aligned} \quad (17)$$

Substituting the basic assumption $\bar{Z}_{S1} = 0,0$ pu in (17) and rearranging, the next expression can be derived:

$$\bar{I}_{A1} = -\bar{I}_{A2} = \frac{\bar{V}}{\bar{Z}_{T1} \left(2 + \frac{\bar{Z}_{T0}}{\bar{Z}_{T1}} \right)} = \frac{\bar{I}_{3-SCC}}{2 + \frac{\bar{Z}_{T0}}{\bar{Z}_{T1}}} \quad (18)$$

Using the basic assumptions stated above for a Dyn5 transformer, the following positive-, negative-, and zero-sequence per-unit currents can be obtained from (17) and (18):

$$\begin{aligned} \bar{I}_{A1} &\cong 0,3375 \angle 30,4^\circ & \bar{I}_{a1} &\cong 0,3375 \angle -119,6^\circ \\ \bar{I}_{A2} &\cong 0,3375 \angle 210,4^\circ & \bar{I}_{a2} &\cong 0,3375 \angle 0,4^\circ \\ \bar{I}_{A0} &= 0,0 & \bar{I}_{a0} &= 0,3375 \angle 120,4^\circ \end{aligned} \quad (19)$$

The primary and secondary line currents can be obtained substituting corresponding positive-, negative-, and zero-sequence currents from (19) in (A7) and (A6), respectively. Fig. 6 shows results of these simultaneous fault currents on both sides of a Dyn5 transformer.

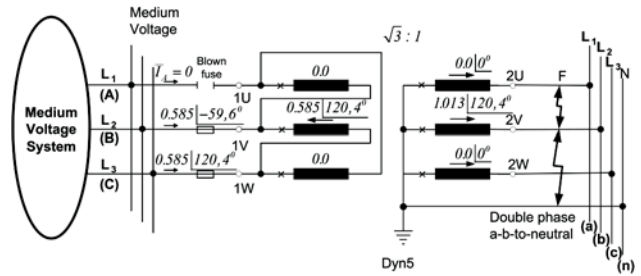


Figure 6 Per-unit fault currents on both sides of a Dyn5 transformer for the simultaneous fault, which involves phase a-phase b-to-neutral fault on the star side and blown fuse in phase A on the delta side
Slika 6. Jedinični iznosi struja kvara na obje strane nekog Dyn5 transformatora kod simultanog kvara koji obuhvata spoj faza a i b s neutralnim vodičem na strani zvijezda namota i pregorjeli osigurač u fazi A na strani namota u trokutu

Using the basic assumptions stated above for an Yzn5 transformer, the following positive-, negative-, and zero-sequence per-unit currents can be obtained from (17) and (18):

$$\begin{aligned} \bar{I}_{A1} &\cong 0,459 \angle 33,4^\circ & \bar{I}_{a1} &\cong 0,459 \angle -116,6^\circ \\ \bar{I}_{A2} &\cong 0,459 \angle 213,4^\circ & \bar{I}_{a2} &\cong 0,459 \angle 3,4^\circ \\ \bar{I}_{A0} &= 0,0 & \bar{I}_{a0} &= 0,459 \angle 123,4^\circ \end{aligned} \quad (20)$$

The primary and secondary line currents can be obtained substituting corresponding positive-, negative-, and zero-sequence currents from (20) in (A7) and (A6), respectively. Fig. 7 shows results of these simultaneous fault currents on both sides of an Yzn5 transformer.

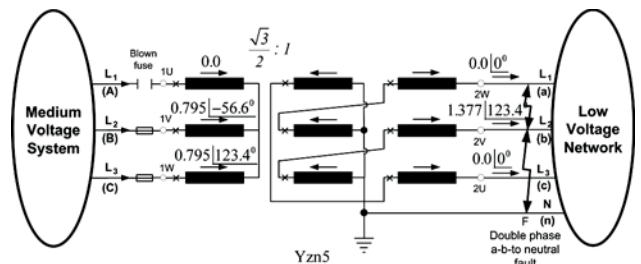


Figure 7 Per-unit fault currents on both sides of an Yzn5 transformer for the simultaneous fault, which involves phase a-phase b-to-neutral fault on the secondary-side and blown fuse in phase A on the transformer primary-side

Slika 7. Jedinični iznosi struja kvara na obje strane nekog Yzn5 transformatora kod simultanog kvara koji obuhvata spoj faza a i b s neutralnim vodičem na sekundarnoj strani i pregorjeli osigurač u fazi A na primarnoj strani transformatora

c) Let us consider bolted double phase-to-neutral fault, involving phases *b* and *c*, at a point F located on the secondary side of a Dyn5 or of an Yzn5 transformer, with blown fuse in phase A on the transformer primary-side.

When medium-voltage phase *A* is the reference phase, by solving the linear matrix equation (C6) can be obtained the positive-, negative-, and zero-sequence per-unit currents, which are equal to those in previous case, i.e. they are defined by means of equation (17), too. Thus, all primary and secondary currents are equal to those shown in Fig. 6 and Fig. 7.

3.3 Phase b-to-neutral fault on the secondary side with blown fuse in phase A

Kratki spoj faze b s neutralnim vodičem na sekundarnoj strani i s pregorjelim osiguračem u fazi A

In [1] it is noted, that in case of single phase-a-to-neutral fault and blown fuse in phase A or in the case of single phase-c-to-neutral fault and blown fuse in phase A, the resulting low currents are stipulated by the transformer open-circuit impedances and they may be neglected. Thus, we will consider bolted phase-b-to-neutral fault at the fault point F located on the secondary-side of a Dyn5 or an Yzn5 transformer, as shown in Fig. 8 and Fig. 9, with blown fuse in phase A on the transformer primary-side.

When medium-voltage phase A is the reference phase and solving the linear matrix equation (D6), the following positive-, negative- and zero-sequence currents can be obtained:

$$\begin{aligned} \bar{I}_{A1} &= -\bar{I}_{A2} = \frac{\bar{V}}{2(\bar{Z}_{S1} + \bar{Z}_{T1}) + \bar{Z}_{T0}} \\ \bar{I}_{a1} &= \bar{I}_{A1} \angle -150^\circ \\ \bar{I}_{a2} &= \bar{I}_{A2} \angle 150^\circ = \bar{I}_{A1} \angle 330^\circ \\ \bar{I}_{a0} &= \bar{a}^2 \bar{I}_{a1} = \frac{\bar{V} \angle 90^\circ}{2(\bar{Z}_{S1} + \bar{Z}_{T1}) + \bar{Z}_{T0}} \end{aligned} \tag{21}$$

Once when the sequence currents are determined by means of equation (D6), the primary and secondary line currents can be determined from (A7) and (A6), respectively.

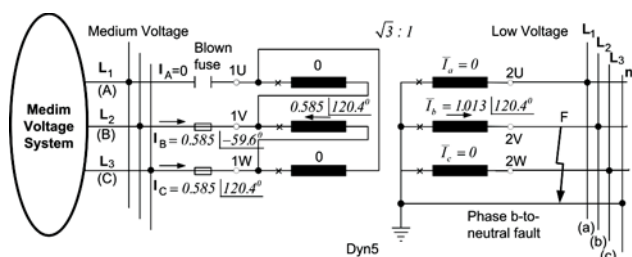


Figure 8 Per-unit fault currents on both sides of a Dyn5 transformer for the simultaneous fault, which involves phase b-to-neutral fault on the star side and blown fuse in phase A on the delta side
Slika 8. Jedinični iznosi struja kvara na obje strane nekog Dyn5 transformatora kod simultanog kvara koji obuhvata spoj faze b s neutralnim vodičem na strani zvijezda namota i pregorjeli osigurač u fazi A na strani namota u trokutu

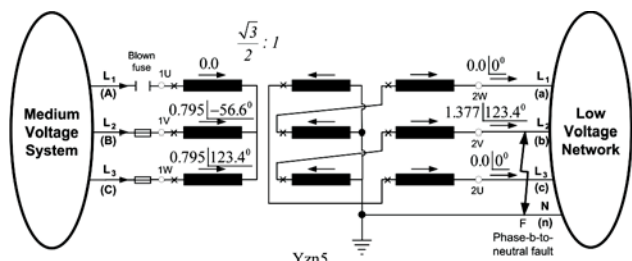


Figure 9 Per-unit fault currents on both sides of an Yzn5 transformer for the simultaneous fault, which involves phase b-to-neutral fault on the secondary-side and blown fuse in phase A on the primary-side
Slika 9. Jedinični iznosi struja kvara na obje strane nekog Yzn5 transformatora kod simultanog kvara koji obuhvata spoj faze b s neutralnim vodičem na sekundarnoj strani i pregorjeli osigurač u fazi A na primarnoj strani transformatora

Fig. 8 and Fig. 9 show results of the simultaneous fault currents on both sides of a Dyn5 and an Yzn5 transformer, respectively.

4 Conclusion Zaključak

From previous analysis we can conclude that the fault current on each side of a Dyn5 and an Yzn5 three-phase transformer can differ in magnitude and phasing, depending on the type of fault and the fault location. Excepting three-phase secondary fault and blown fuse in phase A, the analyzed simultaneous fault currents can be equal to or lower than the minimum shunt fault current and thus they can directly affect coordination of transformer protective devices.

For a delta-grounded star (Dyn5) transformer, substantially the lowest fault current on the transformer primary-side occurs for double phase-to-neutral fault on the secondary-side, involving phases a and c, with blown fuse in phase A. This current magnitude equals 0,296 pu.

For a star-grounded zig-zag (Yzn5) transformer, substantially the lowest fault current on the transformer primary-side occurs for double phase-to-ground fault on the secondary-side, involving phases a and c, with blown fuse in phase A. This fault current magnitude equals 0,63 pu.

Finally, we can conclude that:

- when faults occur on the secondary-side of a delta-grounded star or a star-grounded zig-zag transformer, the per-unit fault current magnitude in each phase depends on the type of faults,
- Dyn5 and Yzn5 distribution transformers could not be well protected, if we do not take into consideration these minimum simultaneous currents,
- determining minimum simultaneous fault currents could be necessary for selection of fuse-links minimum breaking current of high-voltage fuses for transformer circuit applications,
- taking the minimum simultaneous fault currents into account we can be sure that the high-voltage fuses can adequately protect the transformer for the various fault types and ensure proper coordination.

Final expression for the simultaneous fault currents on both sides of a Dyn5 or an Yzn5 transformer, obtained in this paper, confirms the generalized equation given in [7]. These final expressions for the simultaneous fault currents have been checked and are confirmed by means of the fault simulation on the three-phase transformer, model 61-107 manufactured from Feedback, too.

The authors suggest that the operating current of the high-voltage fuse in transformer applications should be determined so that it is less than the minimum (shunt or simultaneous) fault current of the transformer as limited by the combination of distribution system impedance and transformer impedance. But, this operating current should not be so low to cause circuit interruption due to the inrush excitation current of the transformer or normal current transients in the secondary circuits.

According to the analysis carried out in this paper, it is shown that protection schemes of utility substations could be designed by taking into account minimum fault currents during simultaneous faults, too.

Appendix A

Dodatak A

a) Sequence phase shift through three-phase two winding Dyn5 transformer

a) Fazni pomaci sustava simetričnih komponenti kroz trofazni dvonamotni transformator Dyn5

Let us consider a Dyn5 three-phase two winding transformer as shown in Fig. A1.

According to [2] and [3], two basic rules of transformer polarity are used in this paper for making and analyzing the proper three-phase transformer connections.

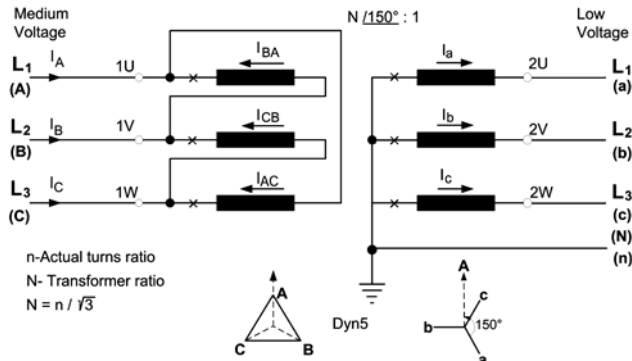


Figure A1 Transformer phase relationships- Dyn5 connection
Slika A1. Uzajamni odnos faza transformatora-Dyn5 spoj

Throughout this analysis, three distinct sets of symmetrical components are defined: positive-, negative-, and zero-sequence for both currents and voltages. Positive-sequence sets consist of the balanced (symmetrical) three-phase currents or three-phase line-to-neutral voltages, which can be designated like these:

- for medium-voltage currents or voltages as

$$\begin{aligned} \bar{I}_{A1} &= \bar{I}_{A1} & \bar{V}_{A1} &= \bar{V}_{A1} \\ \bar{I}_{B1} &= \bar{a}^2 \bar{I}_{A1} & \bar{V}_{B1} &= \bar{a}^2 \bar{V}_{A1} \\ \bar{I}_{C1} &= \bar{a} \bar{I}_{A1} & \bar{V}_{C1} &= \bar{a} \bar{V}_{A1} \end{aligned} \quad (A1)$$

and for low-voltage currents or voltages as

$$\begin{aligned} \bar{I}_{a1} &= \bar{I}_{a1} & \bar{V}_{a1} &= \bar{V}_{a1} \\ \bar{I}_{b1} &= \bar{a}^2 \bar{I}_{a1} & \bar{V}_{b1} &= \bar{a}^2 \bar{V}_{a1} \\ \bar{I}_{c1} &= \bar{a} \bar{I}_{a1} & \bar{V}_{c1} &= \bar{a} \bar{V}_{a1}, \end{aligned} \quad (A2)$$

where \bar{a} is unit phasor, so that:

$$\begin{aligned} \bar{a} &= 1 \angle 120^\circ = -0,5 + j \frac{\sqrt{3}}{2} \\ \bar{a}^2 &= 1 \angle 240^\circ = -0,5 - j \frac{\sqrt{3}}{2} \\ 1 + \bar{a} + \bar{a}^2 &= 0. \end{aligned} \quad (A3)$$

Negative-sequence sets are also balanced (symmetrical) with three-phase currents or three-phase line-to-neutral voltages, but with the phase rotation or sequence reversed in relation to positive-sequence sets. Negative-sequence sets can be designated like these:

- for medium-voltage currents or voltages as

$$\begin{aligned} \bar{I}_{A2} &= \bar{I}_{A2} & \bar{V}_{A2} &= \bar{V}_{A2} \\ \bar{I}_{B2} &= \bar{a} \bar{I}_{A2} & \bar{V}_{B2} &= \bar{a} \bar{V}_{A2} \\ \bar{I}_{C2} &= \bar{a}^2 \bar{I}_{A2} & \bar{V}_{C2} &= \bar{a}^2 \bar{V}_{A2} \end{aligned} \quad (A4)$$

and for low-voltage currents or voltages as

$$\begin{aligned} \bar{I}_{a2} &= \bar{I}_{a2} & \bar{V}_{a2} &= \bar{V}_{a2} \\ \bar{I}_{b2} &= \bar{a} \bar{I}_{a2} & \bar{V}_{b2} &= \bar{a} \bar{V}_{a2} \\ \bar{I}_{c2} &= \bar{a}^2 \bar{I}_{a2} & \bar{V}_{c2} &= \bar{a}^2 \bar{V}_{a2}. \end{aligned} \quad (A5)$$

It is well known, that any unbalanced currents or voltages can be determined from sequence components from the following basic equations:

$$\begin{aligned} \bar{I}_a &= \bar{I}_{a1} + \bar{I}_{a2} + \bar{I}_{a0} & \bar{V}_a &= \bar{V}_{a1} + \bar{V}_{a2} + \bar{V}_{a0} \\ \bar{I}_b &= \bar{a}^2 \bar{I}_{a1} + \bar{a} \bar{I}_{a2} + \bar{I}_{a0} & \bar{V}_b &= \bar{a}^2 \bar{V}_{a1} + \bar{a} \bar{V}_{a2} + \bar{V}_{a0} \\ \bar{I}_c &= \bar{a} \bar{I}_{a1} + \bar{a}^2 \bar{I}_{a2} + \bar{I}_{a0} & \bar{V}_c &= \bar{a} \bar{V}_{a1} + \bar{a}^2 \bar{V}_{a2} + \bar{V}_{a0}. \end{aligned} \quad (A6)$$

$$\begin{aligned} \bar{I}_A &= \bar{I}_{A1} + \bar{I}_{A2} + \bar{I}_{A0} & \bar{V}_A &= \bar{V}_{A1} + \bar{V}_{A2} + \bar{V}_{A0} \\ \bar{I}_B &= \bar{a}^2 \bar{I}_{A1} + \bar{a} \bar{I}_{A2} + \bar{I}_{A0} & \bar{V}_B &= \bar{a}^2 \bar{V}_{A1} + \bar{a} \bar{V}_{A2} + \bar{V}_{A0} \\ \bar{I}_C &= \bar{a} \bar{I}_{A1} + \bar{a}^2 \bar{I}_{A2} + \bar{I}_{A0} & \bar{V}_C &= \bar{a} \bar{V}_{A1} + \bar{a}^2 \bar{V}_{A2} + \bar{V}_{A0}. \end{aligned} \quad (A7)$$

From the connection of Fig. A1, it can be written that:

$$\bar{I}_A = \bar{I}_{AC} - \bar{I}_{BA} \quad \bar{V}_a = \frac{\bar{V}_B - \bar{V}_A}{n_{Dy}}. \quad (A8)$$

According to the first rule of transformer polarity, as it is noted in [2] and [3], and in accordance with Fig. 1, it can be seen that delta currents \bar{I}_{BA} , \bar{I}_{CB} and \bar{I}_{AC} are in phase with corresponding winding currents \bar{I}_a , \bar{I}_b and \bar{I}_c on the transformer secondary side. Thus, the positive- and negative-sequence primary line currents can be given in relation to the positive- and negative-sequence secondary line currents by the next matrix equations:

$$\begin{aligned} \begin{bmatrix} \bar{I}_{A1} \\ \bar{I}_{B1} \\ \bar{I}_{C1} \end{bmatrix} &= \frac{1}{n_{Dy}} \cdot \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_{a1} \\ \bar{a}^2 \bar{I}_{a1} \\ \bar{a} \bar{I}_{a1} \end{bmatrix} = \\ &= \frac{1}{n_{Dy}} \cdot \begin{bmatrix} \bar{a} - 1 \\ 1 - \bar{a}^2 \\ \bar{a}^2 - \bar{a} \end{bmatrix} \begin{bmatrix} \bar{I}_{a1} \\ \bar{I}_{a1} \\ \bar{I}_{a1} \end{bmatrix} = \frac{\sqrt{3}}{n_{Dy}} \cdot \begin{bmatrix} e^{j150} \\ e^{j30} \\ e^{j270} \end{bmatrix} \begin{bmatrix} \bar{I}_{a1} \\ \bar{I}_{a1} \\ \bar{I}_{a1} \end{bmatrix}. \end{aligned} \quad (A9)$$

$$\begin{aligned} \begin{bmatrix} \bar{I}_{A2} \\ \bar{I}_{B2} \\ \bar{I}_{C2} \end{bmatrix} &= \frac{1}{n_{Dy}} \cdot \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_{a2} \\ \bar{a} \bar{I}_{a2} \\ \bar{a}^2 \bar{I}_{a2} \end{bmatrix} = \\ &= \frac{1}{n_{Dy}} \cdot \begin{bmatrix} \bar{a}^2 - 1 \\ 1 - \bar{a} \\ \bar{a} - \bar{a}^2 \end{bmatrix} \begin{bmatrix} \bar{I}_{a2} \\ \bar{I}_{a2} \\ \bar{I}_{a2} \end{bmatrix} = \frac{\sqrt{3}}{n_{Dy}} \cdot \begin{bmatrix} e^{-j150} \\ e^{-j30} \\ e^{j90} \end{bmatrix} \begin{bmatrix} \bar{I}_{a2} \\ \bar{I}_{a2} \\ \bar{I}_{a2} \end{bmatrix}. \end{aligned} \quad (A10)$$

The delta connection on the medium-voltage side of the Dyn5 transformer and the ungrounded star connection on the medium-voltage side of the Yzn5 transformer do not allow the flow of zero-sequence current, i.e. it will be equal to zero ($\bar{I}_{A0} = \bar{I}_{B0} = \bar{I}_{C0} = 0,0 pu$).

b) Sequence phase shift through three-phase two winding Yzn5 transformer

b) Fazni pomaci sustava simetričnih komponenti kroz trofazni dvonamotni transformator Yzn5

Let us consider an Yzn5 three-phase transformer as shown in Fig. A2.

According to Fig. A2 we get the following:

$$\bar{I}_A = \frac{\bar{I}_a'' - \bar{I}_a'}{n_{Yz}} \quad \bar{V}_a = \frac{\bar{V}_B - \bar{V}_A}{n_{Yz}} \tag{A11}$$

$$\bar{I}_B = \frac{\bar{I}_b'' - \bar{I}_b'}{n_{Yz}} \quad \bar{V}_b = \frac{\bar{V}_C - \bar{V}_B}{n_{Yz}} \tag{A12}$$

$$\bar{I}_C = \frac{\bar{I}_c'' - \bar{I}_c'}{n_{Yz}} \quad \bar{V}_c = \frac{\bar{V}_A - \bar{V}_C}{n_{Yz}} \tag{A13}$$

From the connection of Fig. A2, it can be written that:

$$\bar{I}_a' = \bar{I}_a, \quad \bar{I}_a'' = \bar{I}_c \tag{A14}$$

$$\bar{I}_b' = \bar{I}_b, \quad \bar{I}_b'' = \bar{I}_a \tag{A15}$$

$$\bar{I}_c' = \bar{I}_c, \quad \bar{I}_c'' = \bar{I}_b \tag{A16}$$

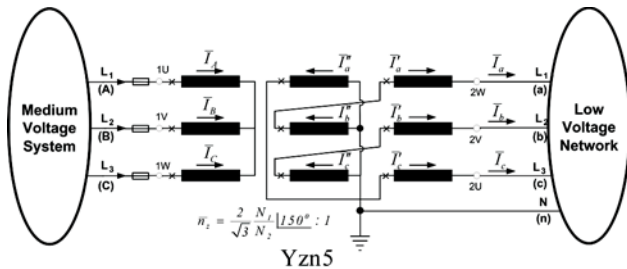


Figure A2 Transformer phase relationships- Yzn5 connection
Slika A2. Uzajamni odnos faza transformatora-Yzn5 spoj

According to (A1)-(A5) and (A14)-(A16), the positive- and negative-sequence primary line currents can be given in relation to the positive- and negative-sequence secondary line currents by the next matrix equation, respectively:

$$\begin{aligned} \begin{bmatrix} \bar{I}_{A1} \\ \bar{I}_{B1} \\ \bar{I}_{C1} \end{bmatrix} &= \frac{1}{n_{Yz}} \cdot \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_{a1} \\ \bar{a}^2 \bar{I}_{a1} \\ \bar{a} \bar{I}_{a1} \end{bmatrix} = \\ &= \frac{1}{n_{Yz}} \begin{bmatrix} \bar{a} - 1 \\ 1 - \bar{a}^2 \\ \bar{a}^2 - \bar{a} \end{bmatrix} \begin{bmatrix} \bar{I}_{a1} \\ \bar{I}_{a1} \\ \bar{I}_{a1} \end{bmatrix} = \frac{N_2 \sqrt{3}}{2 \cdot N_1} \begin{bmatrix} e^{j150} \\ e^{j30} \\ e^{j270} \end{bmatrix} \begin{bmatrix} \bar{I}_{a1} \\ \bar{I}_{a1} \\ \bar{I}_{a1} \end{bmatrix} \end{aligned} \tag{A17}$$

Equations (A9) and (A17) show that for the Dyn5 and the Yzn5 transformer connections, the positive-sequence currents on medium-voltage side (MV) lead to corresponding positive-sequence currents on low-voltage side (LV) by 150°. Equations (A10) and (A18) show that for the Dyn5 and the Yzn5 transformer connections, the negative-sequence currents on medium-voltage side (MV)

$$\begin{aligned} \begin{bmatrix} \bar{I}_{A2} \\ \bar{I}_{B2} \\ \bar{I}_{C2} \end{bmatrix} &= \frac{1}{n_{Yz}} \cdot \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_{a2} \\ \bar{a} \bar{I}_{a2} \\ \bar{a}^2 \bar{I}_{a2} \end{bmatrix} = \\ &= \frac{1}{n_{Yz}} \begin{bmatrix} \bar{a}^2 - 1 \\ 1 - \bar{a} \\ \bar{a} - \bar{a}^2 \end{bmatrix} \begin{bmatrix} \bar{I}_{a2} \\ \bar{I}_{a2} \\ \bar{I}_{a2} \end{bmatrix} = \frac{\sqrt{3}}{n_{Yz}} \begin{bmatrix} e^{-j150} \\ e^{-j30} \\ e^{j90} \end{bmatrix} \begin{bmatrix} \bar{I}_{a2} \\ \bar{I}_{a2} \\ \bar{I}_{a2} \end{bmatrix} \end{aligned} \tag{A18}$$

lag with respect to the corresponding negative-sequence currents and voltages on low-voltage side (LV) by 150°.

In the same way, we can find the phase shift between positive-sequence primary and positive-sequence secondary phase-to-neutral voltages and the phase shift between negative-sequence primary and negative-sequence secondary phase-to-neutral voltages of a Dyn5 or an Yzn5 transformer.

Appendix B
Dodatak B

Three-phase short circuit on transformer secondary with any blown HV fuse

Tropolni kratki spoj na sekundaru transformatora i pregorjeli bilo koji VN osigurač

Let us consider a simultaneous fault, which involves a bolted three-phase fault at the fault point F located on the secondary side of a Dyn5 or an Yzn5 transformer with blown fuse in any phase on the primary.

The calculation of this simultaneous fault is carried out by means of per-unit method selecting the phase with blown fuse as the reference.

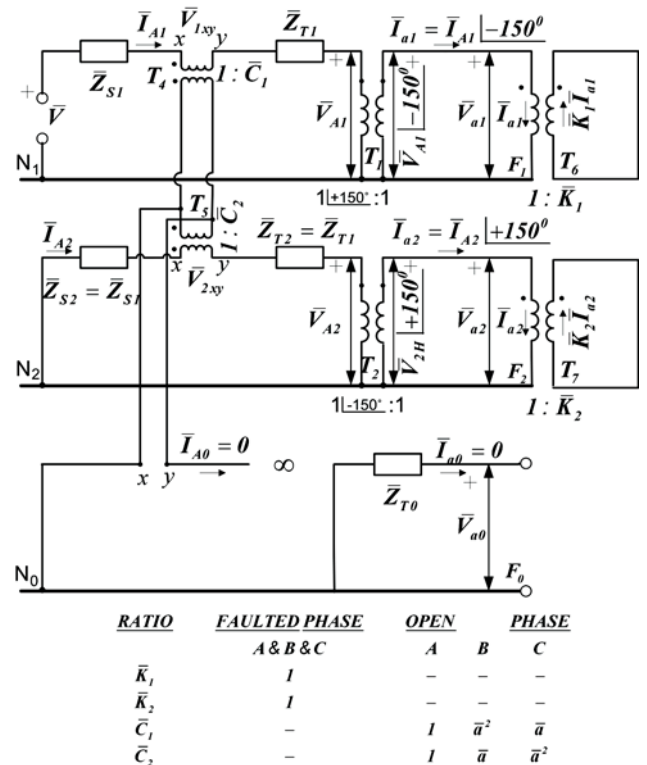


Fig. B1 Sequence networks interconnection for bolted three-phase fault on the transformer low-voltage side with any blown fuse on the transformer primary-side

Sl. B1 Interkonekcija sustava simetričnih komponenti za izravni trofazni kratki spoj na niskonaponskoj strani transformatora i pregorjelim osiguračem u bilo kojoj fazi na primarnoj strani transformatora

This shunt fault location and the fuse location are on opposite sides of the Dyn5 or the Yzn5 transformer and thus the calculation of this simultaneous unbalance should involve the phase shift caused by these transformers as explained in Appendix A. Also, for this phase shift, ideal (perfect) transformers T_1 , and T_2 are required in the sequence connection diagram, as shown in Fig. B1.

Since the sequence networks are interconnected at more than one location to represent such simultaneous unbalances, the connections must satisfy the sequence constraint equations at both unbalance points.

To draw the sequence network for any blown fuse situation (open phase), two constraints have to embed into the network. The first of these is a voltage constraint and the second is a current constraint.

The sequence voltages between points x and y are given in matrix form by:

$$\begin{bmatrix} \bar{V}_{1,xy} \\ \bar{V}_{2,xy} \\ \bar{V}_{0,xy} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & \bar{a} & \bar{a}^2 \\ 1 & \bar{a}^2 & \bar{a} \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \bar{V}_{Axy} \\ \bar{V}_{Bxy} \\ \bar{V}_{Cxy} \end{bmatrix} \quad (\text{B1})$$

If we assume that blown fuse is in phase A (i.e. A -phase is open), then values for \bar{V}_{Bxy} and \bar{V}_{Cxy} are equal to zero, and substituting these values in (B1) we obtain the sequence voltages $\bar{V}_{1,xy}$, $\bar{V}_{2,xy}$, and $\bar{V}_{0,xy}$ in relation to \bar{V}_{Axy} . Similar consideration can be carried out for the other two cases.

According to the condition that the current in open phase must be equal to zero, the current constraint can be

expressed by means of (B2):

$$\bar{C}_1 \bar{I}_{A1} + \bar{C}_2 \bar{I}_{A2} + \bar{I}_{A0} = 0. \quad (\text{B2})$$

The value of the ideal transformer constants, \bar{C}_1 and \bar{C}_2 will depend upon the phase in which the fuse is blown. These values are given in the table in Fig. B1. Fig. B1 shows that the two ideal transformers T_4 and T_5 are connected between points x and y in the positive- and negative-sequence network, because they implement the two voltage and current constraints, which are given by means of (B1) and (D1), respectively. When medium-voltage phase A is the reference phase, the sequence constraint equations for three-phase short circuit at a fault point F on low-voltage side are:

$$\bar{V}_{a1} = \bar{V}_{a2} = \bar{V}_{a0} = 0,0 \text{ pu}. \quad (\text{B3})$$

Note that the ideal transformers T_6 and T_7 in Fig. B1 are not necessary, but they are shown because they are required in general for the other fault types. According to [6], Fig. C1 shows the interconnection of the resulting equivalent sequence networks for this simultaneous fault type. From sequence networks interconnection as is shown in Fig. B1, it can be concluded that current can flow through the transformer without connected load.

If the three sequence networks of Fig. B1 are described mathematically in accordance with Kirchhoff's current and voltage law, we can resolve the interconnected sequence networks for the unknown sequence currents and voltages by solving the next linear matrix equation (B4):

$$\begin{bmatrix} \bar{Z}_{S1} + \bar{Z}_{T1} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & \bar{C}_2/3 \\ 0 & \bar{Z}_{S1} + \bar{Z}_{T1} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & \bar{C}_1/3 \\ \bar{C}_1 & \bar{C}_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1\angle -150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1\angle 150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1\angle -150^\circ & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1\angle 150^\circ & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{I}_{A1} \\ \bar{I}_{A2} \\ \bar{I}_{a1} \\ \bar{I}_{a2} \\ \bar{I}_{a0} \\ \bar{V}_{A1} \\ \bar{V}_{A2} \\ \bar{V}_{a0} \\ \bar{V}_{xy} \end{bmatrix} = \begin{bmatrix} \bar{V} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (\text{B4})$$

$$*\bar{V}_{xy} = \bar{V}_{Axy} \quad \text{when fuse in phase } A \text{ is blown}$$

$$*\bar{V}_{xy} = \bar{V}_{Bxy} \quad \text{when fuse in phase } B \text{ is blown}$$

$$*\bar{V}_{xy} = \bar{V}_{Cxy} \quad \text{when fuse in phase } C \text{ is blown}$$

Once when the sequence currents are determined from equation (B4), the primary and secondary line currents can be determined from (A7) and (A6), respectively.

The calculation of this simultaneous fault is carried out in this paper by means of per-unit method selecting the phase with blown fuse as the reference.

Appendix C Dodatak C

Double phase-to-neutral fault on transformer secondary with any blown HV fuse

Dvopolni kratki spoj s istodobnim spojem s neutralnim vodičem na sekundaru transformatora i pregorjeli bilo koji VN osigurač

Let us consider any bolted double phase-to-neutral fault at the fault point F located on the secondary side of a Dyn5 or of an Yzn5 transformer with blown fuse in any phase on the primary.

This shunt fault location and the fuse location are on opposite sides of the Dyn5 or the Yzn5 transformer and thus the calculation of this simultaneous unbalance should involve the phase shift caused by these transformers as explained in Appendix A. Also, for this phase shift, ideal (perfect) transformers T_1 , and T_2 are required in the sequence connection diagram, as shown in Fig. C1.

According to [6], Fig. C1 shows the interconnection of the resulting equivalent sequence networks for this simultaneous fault type. This sequence networks interconnection shows that current can flow through the transformer without load and that the zero-sequence network is connected in parallel with positive- and negative-sequence network at the fault point F.

Since the sequence networks are interconnected at more than one location to represent such simultaneous unbalances, the connections must satisfy the sequence constraint equations at both unbalance points.

To draw the sequence network for any blown fuse situation (open phase), two constraints into the network have to be embed. The first of these is a voltage constraint and the second is a current constraint.

Equation (B1) gives the sequence voltages between points x and y, which fulfil the voltage constraint.

According to the condition that the current in open phase must be equal to zero, the current constraint can be expressed by means of (C1):

$$\bar{C}_1 \bar{I}_{1H} + \bar{C}_2 \bar{I}_{2H} + \bar{I}_{0H} = 0, \tag{C1}$$

where values of the \bar{C}_1 and \bar{C}_2 are given in Fig. C1.

The two ideal transformers T_4 and T_5 , which are connected between points x and y in the positive- and negative- sequence network as shown in Fig. C1, are used to implement the two voltage and current constraints.

On the other side, the sequence constraint equations, which must be satisfied at the shunt fault point for a double phase-to-neutral on any two low-voltage phases, are:

$$\bar{K}_1 \bar{I}_{1L} + \bar{K}_2 \bar{I}_{2L} + \bar{I}_{0L} = 0 \tag{C2}$$

$$\bar{K}_1 \bar{V}_{1L} = \bar{K}_2 \bar{V}_{2L} \tag{C3}$$

$$\bar{K}_1 \bar{V}_{1L} = \bar{V}_{0L} \tag{C4}$$

$$\bar{V}_{0L} = -\bar{I}_{0L} \bar{Z}_{0T}. \tag{C5}$$

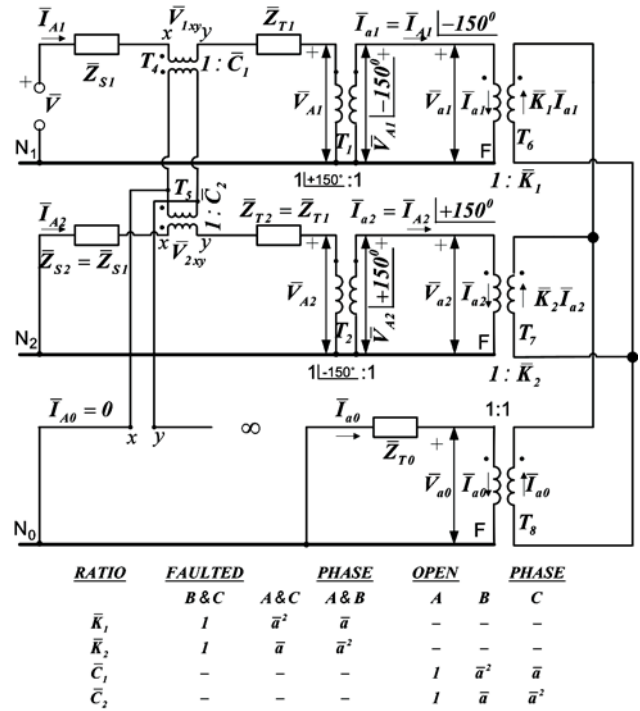


Figure C1 Sequence networks interconnection for any double phase-to-neutral fault on the transformer low-voltage side with any blown fuse on the transformer primary-side

Slika C1. Interkonekcija sustava simetričnih komponenti za dvopolni kratki spoj s neutralnim vodičem na niskonaponskoj strani transformatora i pregorjelim osiguračem u bilo kojoj fazi na primarnoj strani

Fig. C1 shows values of the \bar{K}_1 and \bar{K}_2 .

When making the connections to the positive-, negative-, and zero-sequence networks, ideal transformers T_6 , T_7 , and T_8 with the input-output relationships must be used to implement voltage and current constraints given in (C2)-(C4). The value of the ideal transformer constants, \bar{K}_1 and \bar{K}_2 will depend upon phases, which are faulted and their values are given in Fig. C1.

If the three sequence networks of Fig. C1 are described mathematically in accordance with Kirchhoff's current and voltage law, we can resolve the interconnected sequence networks for the unknown sequence currents and voltages by solving the next linear matrix equation (C6):

$$\begin{bmatrix} \bar{Z}_{S1} + \bar{Z}_{T1} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & \bar{C}_2/3 \\ 0 & \bar{Z}_{S1} + \bar{Z}_{T1} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & \bar{C}_1/3 \\ \bar{C}_1 & \bar{C}_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 \angle -150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 \angle 150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \bar{K}_1 \angle -150^\circ & \bar{K}_2 \angle 150^\circ & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{K}_1 \angle -150^\circ & -\bar{K}_2 \angle 150^\circ & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{K}_1 \angle -150^\circ & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \bar{Z}_{T0} & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \bar{I}_{A1} \\ \bar{I}_{A2} \\ \bar{I}_{a1} \\ \bar{I}_{a2} \\ \bar{I}_{a0} \\ \bar{V}_{A1} \\ \bar{V}_{A2} \\ \bar{V}_{a0} \\ \bar{V}_{xy} \end{bmatrix} = \begin{bmatrix} \bar{V} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{C6}$$

- * $\bar{V}_{xy} = \bar{V}_{Axy}$ when fuse in phase A is blown
- * $\bar{V}_{xy} = \bar{V}_{Bxy}$ when fuse in phase B is blown
- * $\bar{V}_{xy} = \bar{V}_{Cxy}$ when fuse in phase C is blown

Once when the sequence currents are determined from equation (C6), the primary and secondary line currents can be determined from (A7) and (A6), respectively.

The calculation of this simultaneous fault is carried out in this paper by means of per-unit method selecting the phase with blown fuse as the reference.

Appendix D
Dodatak D

Single phase-to-neutral fault on transformer secondary with any blown HV fuse

Kratki spoj jedne faze s neutralnim vodičem na sekundaru transformatora i pregorjeli bilo koji VN osigurač

Let us consider any bolted single phase-to-neutral fault at a Fault F on the secondary of a Dyn5 or of an Yzn5 distribution transformer with blown fuse in any phase on the transformer primary-side. This shunt fault location and the fuse location are on opposite sides of the Dyn5 or the Yzn5 transformer and thus the calculation of this simultaneous unbalance should involve the phase shift caused by these transformers as explained in Appendix A. Also, for this phase shift, ideal (perfect) transformers T_1 and T_2 are required in the sequence connection diagram, as shown in Fig. D1. It should be pointed out, that ideal transformers must be used with positive- and negative-sequence networks at both the shunt fault and fuse locations.

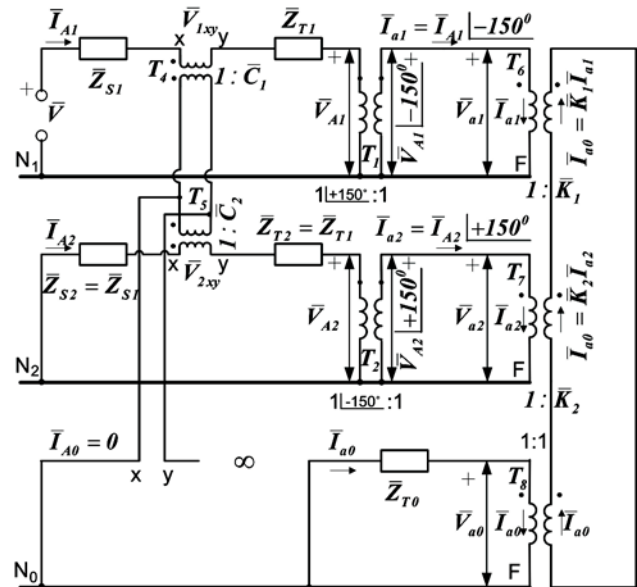
Since the sequence networks are interconnected at more than one location to represent such simultaneous unbalances, the connections must satisfy the sequence constraint equations at both unbalance points.

To draw the sequence network for any blown fuse situation (open phase), two constraints into the network have to be embed. The first of these is a voltage constraint and the second is a current constraint. Equation (B1) gives the sequence voltages between points x and y, which fulfil the voltage constraint. According to the condition that the current in open phase must be equal to zero, the current constraint can be expressed by means of (D1):

$$\bar{C}_1 \bar{I}_{1H} + \bar{C}_2 \bar{I}_{2H} + \bar{I}_{0H} = 0. \tag{D1}$$

Values of the \bar{C}_1 and \bar{C}_2 in equation (D1) are given in Fig. D1. Fig. D1 shows that two ideal transformers T_4 and T_5 are connected between points x and y in the positive- and negative- sequence network, because they implement the voltage and the current constraints, which are given by means of (B1) and (D1), respectively.

On the other side, the sequence constraint equations, which must be satisfied at the shunt fault point for a single



| RATIO | FAULTED | PHASE | OPEN | PHASE |
|-------------|---------|-------|------|-------|
| \bar{K}_1 | A | B | A | B |
| \bar{K}_2 | B | C | B | C |
| \bar{C}_1 | C | A | C | A |
| \bar{C}_2 | A | B | A | B |

Fig. D1 Sequence networks interconnection for a single phase-to-neutral fault on the transformer low-voltage side with any blown fuse on the transformer primary-side

SI. D1 Interkonekcija sustava simetričnih komponenti za kratki spoj jedne faze s neutralnim vodičem na niskonaponskoj strani i pregorjelim osiguračem u bilo kojoj fazi na primarnoj strani

phase-to-neutral on any low-voltage phase, are (D2):

$$\bar{K}_1 \bar{V}_{1L} + \bar{K}_2 \bar{V}_{2L} + \bar{V}_{0L} = 0 \tag{D2}$$

$$\bar{K}_1 \bar{I}_{1L} = \bar{K}_2 \bar{I}_{2L} \tag{D3}$$

$$\bar{K}_1 \bar{I}_{1L} = \bar{I}_{0L} \tag{D4}$$

$$\bar{V}_{0L} = -\bar{I}_{0L} \bar{Z}_{0T}. \tag{D5}$$

When making the connections to the positive-, negative-, and zero-sequence networks, ideal transformers T_6 , T_7 , and T_8 with the input-output relationships must be used to implement voltage and current constraints given in (D2)-(D4). The value of the ideal transformer constants, \bar{K}_1 and \bar{K}_2 will depend upon phase which is faulted and their values are given in Fig. D1.

If the three sequence networks of Fig. D1 are described mathematically in accordance to Kirchhoff's current and voltage law, we can resolve the interconnected sequence networks for the unknown sequence currents and voltages by solving the next linear matrix equation (D6):

$$\begin{bmatrix} \bar{Z}_{S1} + \bar{Z}_{T1} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & \bar{C}_2/3 \\ 0 & \bar{Z}_{S1} + \bar{Z}_{T1} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & \bar{C}_1/3 \\ \bar{C}_1 & \bar{C}_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 \angle -150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 \angle 150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{K}_1 \angle -150^\circ & \bar{K}_2 \angle 150^\circ & 1 & 0 & 0 \\ \bar{K}_1 \angle -150^\circ & -\bar{K}_2 \angle 150^\circ & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \bar{K}_1 \angle -150^\circ & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{Z}_{T0} & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \bar{I}_{A1} \\ \bar{I}_{A2} \\ \bar{I}_{a1} \\ \bar{I}_{a2} \\ \bar{I}_{a0} \\ \bar{V}_{A1} \\ \bar{V}_{A2} \\ \bar{V}_{a0} \\ * \bar{V}_{xy} \end{bmatrix} = \begin{bmatrix} \bar{V} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{D6}$$

$^*\bar{V}_{xy} = \bar{V}_{Axy}$ when fuse in phase A is blown

$^*\bar{V}_{xy} = \bar{V}_{Bxy}$ when fuse in phase B is blown

$^*\bar{V}_{xy} = \bar{V}_{Cxy}$ when fuse in phase C is blown

Once when the sequence currents are determined from equation (C6), the primary and secondary line currents can be determined from (A7) and (A6), respectively.

The calculation of this simultaneous fault type is carried out by means of per-unit method selecting the phase with blown fuse as the reference.

List of Symbols

Popis oznaka

\bar{V} - Per unit line-to neutral driving voltage

$\bar{I}_a, \bar{I}_b, \bar{I}_c$ - General unbalanced three-phase currents on the transformer secondary side

$\bar{I}_A, \bar{I}_B, \bar{I}_C$ - General unbalanced three-phase currents

\bar{I}_{3-SCC} - Three-phase short circuit current

\bar{I}_n - Transformer three-phase full-load current on the transformer primary-side

$\bar{V}_a, \bar{V}_b, \bar{V}_c$ - General unbalanced three-phase low-voltage phase-to-neutral voltages

$\bar{V}_A, \bar{V}_B, \bar{V}_C$ - General unbalanced three-phase high-voltage phase-to-neutral voltages

\bar{Z}_{S1} - Positive-sequence equivalent network per unit impedance

\bar{Z}_{S2} - Negative-sequence equivalent network per unit impedance

\bar{Z}_{T1} - Positive-sequence transformer per unit impedance

\bar{Z}_{T2} - Negative-sequence transformer per unit impedance

\bar{Z}_{T0} - Zero-sequence transformer per unit impedance

\bar{Z}_F - Per unit fault impedance

S_b - Base power in kVA

S_T - Rated apparent power of distribution transformer in kVA

u_k - Short-circuit voltage at rated current in per unit

N_1 - Number of turns in primary winding set

N_2 - Number of turns in secondary winding set

$N_2/2$ - Number of turns in each of six secondary winding in zig-zag winding set

$n_{Dy} = N_1/N_2$ - Actual winding turns ratio by a Dyn5 transformer

$n_{Yz} = \frac{N_1}{N_2/2}$ - Actual winding turns ratio by an Yzn5 transformer

$N = V_A/V_a$ - Transformer ratio (V_A and V_a - phase-to-neutral voltages), where

$\bar{I}_{A1}, \bar{I}_{B1}, \bar{I}_{C1}$ - Positive-sequence high-voltage currents

$\bar{I}_{A2}, \bar{I}_{B2}, \bar{I}_{C2}$ - Negative-sequence high-voltage currents

$\bar{I}_{a1}, \bar{I}_{b1}, \bar{I}_{c1}$ - Positive-sequence low-voltage currents

$\bar{I}_{a2}, \bar{I}_{b2}, \bar{I}_{c2}$ - Negative-sequence low-voltage currents

$\bar{I}_{a0}, \bar{I}_{b0}, \bar{I}_{c0}$ - Zero-sequence low-voltage currents

$\bar{V}_{A1}, \bar{V}_{B1}, \bar{V}_{C1}$ - Positive-sequence high-voltages

$\bar{V}_{A2}, \bar{V}_{B2}, \bar{V}_{C2}$ - Negative-sequence high-voltages

$\bar{V}_{a1}, \bar{V}_{b1}, \bar{V}_{c1}$ - Positive-sequence low-voltages

$\bar{V}_{a2}, \bar{V}_{b2}, \bar{V}_{c2}$ - Negative-sequence low-voltages

References

Literatura

- [1] Das, J. C. Power System Analysis, Marcel Dekker, Inc., 2002.
- [2] Blackburn, J. Lewis. Symmetrical Components for Power Systems Engineering, Marcel Dekker, Inc., 1993.
- [3] Blackburn, J. Lewis. Protective Relaying-Principles and Applications, Second Edition, Marcel Dekker Inc., 1998.
- [4] Anderson, P. Analysis of Faulted Power Systems, Iowa State University Press, Ames, IA, 1973.
- [5] Short, T. A. Electric Power Distribution Handbook, CRC Press LLC, 2004.
- [6] Smith, D. R. Digital Simulation of Simultaneous Unbalances Involving Open and Faulted Conductors. // IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, No. 8, November/December 1970, pp 1826-1835.
- [7] IEC Std. 60909 (1988): Short-circuit current calculation in three-phase A.C. systems.
- [8] IEC STANDARD Publication 787, 1983: Application Guide for the selection of fuse-links of high-voltage fuses for transformer circuit applications.
- [9] IEC Std. 282-1, 1984: High-voltage fuses-Part 1: Current-limiting fuses.
- [10] IEEE Std. 242-2001: IEEE Recommended Practice for Protection and Coordination Industrial and Commercial Power Systems.
- [11] ANSI/IEEE Std. C37.91-1985: Guide for protective relay Applications to power transformers.

Authors' addresses

Adrese autora

Vedran Boras, D.Sc. Associate Professor

University of Split
Faculty of Natural Sciences and mathematics
Department for Polytechnic
Teslina 12
21000 Split, Croatia

Tomislav Barić, D.Sc. Assistant Professor

University of Osijek
Faculty of Electrical engineering
Kneza Trpimira 2b
31000 Osijek, Croatia

Alija Muharemović, Ph.D

University of Sarajevo
Faculty of Electrical Engineering
Zmaja od Bosne bb
71000 Sarajevo, Bosnia and Herzegovina