Yuriy VARETSKY[1,2], Zbigniew HANZELKA[1], Volodymyr KONOVAL[2], Beata KUSHKA[2]

AGH University of Science and Technology (1), Lviv Polytechnic National University (2)

doi:10.15199/48.2021.03.05

Considerations regarding the parallel operation of transformers - an example case in the mining industry

***Abstract**. During the operation of industrial supply power systems, sometimes it becomes desirable paralleling transformers, the characteristics of which do not quite correspond to such a procedure. When transformers are connected in parallel, any difference between their parameters causes the load to be redistributed between them compared to the previous operating mode they had been running separately. The paper deals with the problem of different capacity transformers paralleling within a mine power supply system.*

***Streszczenie.** Podczas pracy przemysłowych systemów zasilania pożądana jest czasami równoległa praca transformatorów, których charakterystyki nie są w pełni przystosowane do takich warunków. Gdy transformatory są połączone równolegle, każda różnica pomiędzy ich parametrami powoduje zmianę ich obciążenia w porównaniu z indywidualną pracą każdego z nich. W artykule omówiono problematykę równoleglej pracy transformatorów różnej mocy w systemie zasilania kopalni. (**Rozważania dotyczące równoległej pracy transformatorów — przykład w górnictwie**).*

Keywords: transformer, parallel operation, power flow, simulation.
Słowa kluczowe: transformator, praca równoległa, przepływ mocy, symulacja.

Introduction

Sometimes appear on operating conditions in which are required parallel connection of transformers, characteristics of which do not quite correspond to such a procedure. According to the IEEE Standard [1], two or more transformers connected to common load buses should be considered as operating in parallel. All types of load, as well as capacitor banks, shunt reactors, or power sources, can be connected to those buses. The primary windings of these transformers can be connected to common buses or buses that receive power from different lines.

The IEEE Standard also describes general requirements to the paralleling transformers - general paralleling application (GPA) - when two or more regulated transformers are connected in parallel to the common source buses:

- transformer ratios should be the same;
- relative impedances of transformers should be the same and should have the same ratio of the reactance to the equivalent resistance of the windings;
- transformers should have the same polarity of the secondary windings;
- three-phase transformers should have the same phase sequence;
- there should be no phase shift between the voltages of the secondary windings of the transformers.

Obviously, under practical operating conditions, it is almost impossible to meet the above requirements due to possible differences in characteristics of the transformers and configurations of the electrical networks [1-6]. The problem of parallel operation of transformers under the following conditions is of particular practical interest:

- power supply of transformer primary windings from different power lines;
- difference of relative impedances of parallel transformers under change of transformer ratios.

In this case, the parallel operation of transformers should meet the requirements of voltage control on the load buses and minimize the circulating current due to inappropriate transformer ratios [6]. Also, these conditions should be provided regardless of the power system configuration changes.

A lot of studies are dedicated to the problem of paralleling power transformers and their control [1-9]. But the authors did not find studies on the impact of the power supply system configuration and types of power consumers on loading the paralleled transformers.

The paper discusses paralleling transformers in the existing mine power supply system with the load connected to the substation buses through current-limiting reactors. Modeling the power supply system operating conditions has been carried out on the platform of the DAKAR software [10].

Basics of paralleling transformers

In the case when there is needed to ensure the parallel operation of transformers T_1 and T_2 of different nominal powers by different power lines W_1 and W_2, it is necessary to take into account the change in a load of both transformers. The simplified case of the paralleling is shown in Fig.1.

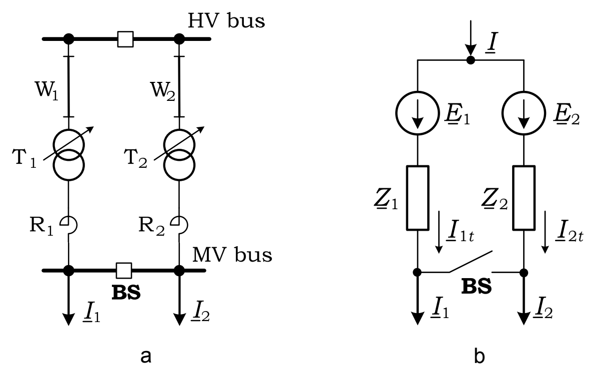

Fig.1. Paralleling transformers: a – simplified layout, b – equivalent circuit

In this diagram, $\underline{Z}_1 = r_1 + jx_1$ and $\underline{Z}_2 = r_2 + jx_2$ are the equivalent impedances of the HV supplying lines, transformers, and MV current-limiting reactors reduced to a common base voltage. The electromotive forces (e.m.f.) $\underline{E}_1$ and $\underline{E}_2$ of the transformers take into account the actual transformation ratios before switching on for parallel operation. After closing the switch BS, the divide of resulting load current $\underline{I} = \underline{I}_1 + \underline{I}_2$ between transformers T_1 and T_2 will change according to the following expressions:

(1) $$\underline{I}_{1t} = \frac{\underline{E}_1 - \underline{E}_2 + \underline{Z}_2 \cdot \underline{I}}{\underline{Z}_1 + \underline{Z}_2};$$

and

(2) $$\underline{I}_{2t} = \frac{\underline{E}_2 - \underline{E}_1 + \underline{Z}_1 \cdot \underline{I}}{\underline{Z}_1 + \underline{Z}_2} .$$

Three main features affect the redistribution of the currents $\underline{I}_{1t}$ and $\underline{I}_{2t}$ after paralleling transformers with the same winding connections:

1) the magnitudes of the equivalent e.m.f.'s, which depend on the T1 and T2 transformation ratios and voltage drops in the HV lines;

2) the phase shift between the equivalent e.m.f.'s, which depends on the voltage drops in the HV lines;

3) the values of the equivalent impedances $\underline{Z}_1$ and $\underline{Z}_2$, which depend on the transformer nominal powers, line and reactor parameters as well as on the transformation ratios.

In approximate calculations, when the impact of the system resistances and the phase shift between e.m.f.'s are not essential, the redistribution of currents is evaluated solely based on the difference in magnitudes of the e.m.f.'s and the values of the equivalent reactances. Due to different reactances of transformers and power sources, and equal transformer e.m.f.'s the load current divides in inverse proportion to the path impedances:

(3) $$\underline{I}_{1t} = \underline{I}\frac{x_2}{x_1 + x_2} ;$$

and

(4) $$\underline{I}_{2t} = \underline{I}\frac{x_1}{x_1 + x_2} .$$

If the reactances are equal and $\Delta E = E_1 - E_2$, the load current divides as following:

(5) $$\underline{I}_{1t} = \frac{\underline{I}}{2} - j\frac{\Delta E}{2x} ;$$

and

(6) $$\underline{I}_{2t} = \frac{\underline{I}}{2} + j\frac{\Delta E}{2x} .$$

The second part in equations (5) and (6) is the circulating current that is added to the path having a smaller e.m.f. and is subtracted from the path that has a larger e.m.f.

These examples show the key impact of the described features on the load currents redistribution under the parallel operation of transformers. But in the practice of industrial power supply systems for verification of the feasibility paralleling transformers the following features are essential: change in circuit configurations and power flows in HV and MV systems, the aggregate effects of other intertie transformers of the system, the initial load of the paralleled transformers and their overload capacity, as well as the actual parameters of all system components.

To study the paralleling transformers in a typical mine power supply system, the authors developed a model that takes into account these features.

Power supply system description

Figure 2 shows a part of the existing mine power supply system layout. Mine loads are supplied through transformers T1 and T2, T3 from the 110 kV buses of substations SS1 and SS2 located in different places.

Under normal operating conditions, the mine loads of TS1… TS6, which are connected to the bus section C1 of the switchgear SG1 and mine loads of TS7… TS11, which are connected to the bus section C2 of the switchgear SG2, are supplied from the transformer T1.

The mine loads of TS12… TS16, which are connected to the bus section C1 of the switchgear SG2, are supplied from the transformer T3. The bus circuit breaker (BS) is opened under normal operating conditions. The total load of the transformer T1 varies from 6 to 16 MVA with a power factor of 0.88. Dividing the transformer T1 total load between switchgear SG1 and switchgear SG2 in operating conditions of the mine may vary in the ratios from 20%:80% to 80%:20%, respectively. The load of the transformer T3 remains constant - 1.2 MVA with a power factor of 0.87.

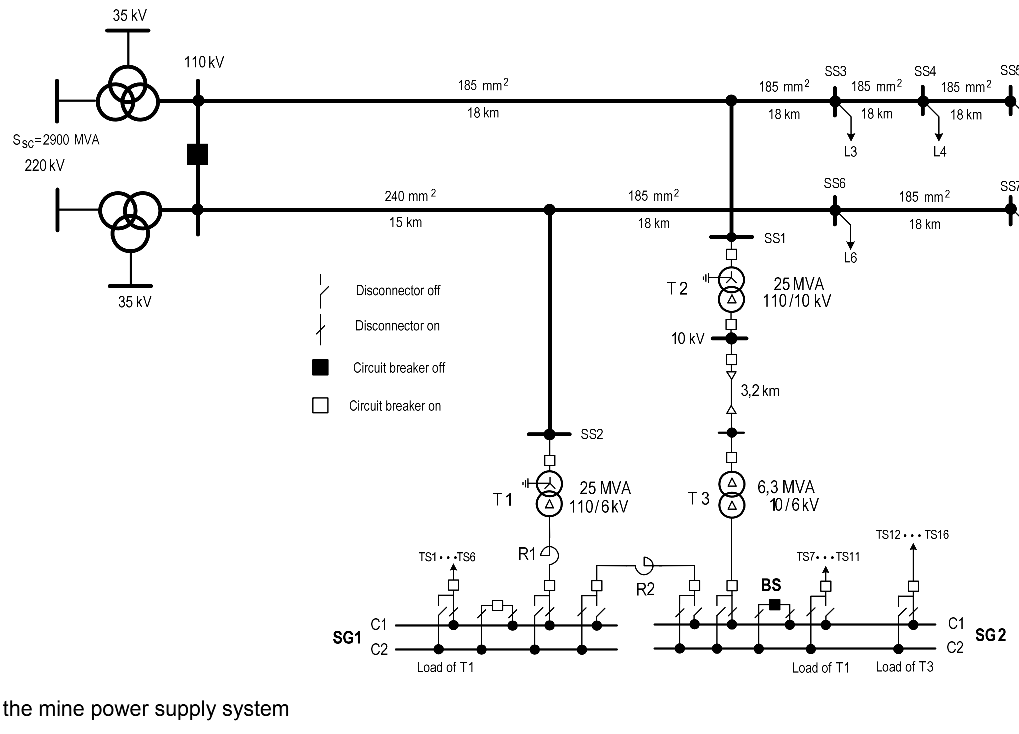

Fig.2. Layout of the mine power supply system

The study aims at analyzing the feasibility of temporary paralleling transformers T1 and T3 in the different operating conditions to ensure the transfer of the critical mine consumers between the sections of the switchgear SG2 without interrupting their power supply. A feature of the power supply system is the presence of current-limiting reactors R1 and R2, which affect the load sharing between transformers T1 and T3 under their parallel operation. Catalog data of transformers and reactors for the investigated power supply system are presented in Table 1 and Table 2.

Table 1. Power supply system transformers

Symbol	Nominal power, windings connection	Nominal voltage [kV]	Equivalent impedance [Ω]
T1	25 MVA Y/Δ -11	115 ± 8×1.25%/6.3	63.48+j2.33
T2	25 MVA Y/Δ -11	115±8×1.25%/10.5	95.22+j2.54
T3	6.3 MVA Δ/Δ-0	10 ± 2×2.5%/6.3	2.50+j0.39

In the considered power supply system, the amplitudes and mutual phase angle shift of the voltages on the buses SG1 and SG2 also depend on the operating conditions of the 110 kV grid, which affects the sharing of the common load between parallel-connected transformers. Changes of the loads L3...L7 in the 110 kV grid cause variations in the voltage drop in the lines, and as a result, this causes a change in voltage levels on the secondary windings of the transformers before their paralleling.

Table 2. Power supply system reactors

Symbol	Nominal voltage [kV]	Nominal current [A]	Reactance [Ω]
R1	10	2500	0.25
R2	10	2500	0.25

Modeling the supply system

The model of the examined supply system within DAKAR software [10] is presented in Fig. 3. Using the internal object library, the adequate models of the system transformers, lines, cables, and loads there were chosen.

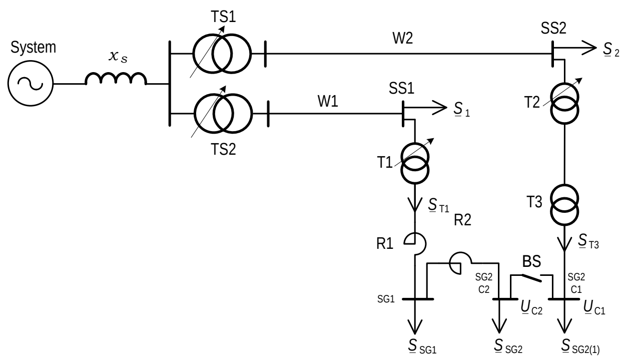

Fig. 3. Model of the power supply system

Symbols of the model components are adequate to the symbols of the power supply system layout in the Fig.2. Load of the transformer T1 $\underline{S}_{T1}$ before closing bus circuit breaker BS is the sum of loads $\underline{S}_{SG1} + \underline{S}_{SG2}$, and the load of transformer T3 $\underline{S}_{T3}$ before closing bus circuit breaker BS is the load of $\underline{S}_{SG2(1)}$. Loads $\underline{S}_1$ and $\underline{S}_2$ are equivalents of the 110 kV line loads of the examined grid. Transformers T1 and T2 are equipped with on-load tap changing systems (LTC), and by modelling the different settings of the transformer tap changers it may be possible to simulate power flow in the system depending on the voltage levels on the switched buses. Because the bus voltage level depends on not only the tap changer setting, the comparative power flows in the study are analyzed within the possible changes of the operating voltages on the MV buses of switchgear SG1 and switchgear SG2.

Simulation of operating conditions

Impact of operating conditions of the 110 kV grid. The results of comparative simulations of the 110 kV grid operating conditions are shown in Table 3 and Table 4. Load sharing between the switchgear SG1 ($\underline{S}_{SG1} = P_{SG1} + jQ_{SG1}$) and switchgear SG2 ($\underline{S}_{SG2} = P_{SG2} + jQ_{SG2}$) of the transformer T1 is equal. One can observe a different loading the transformers at different voltage moduli on the sections C1 (U_{C1}) and C2 (U_{C2}) of the switchgear SG2 before paralleling transformers T1 and T2.

Table 3. Maximum load of the transformer T1, equal load sharing between SG1 and SG2 and maximum loads of the110 kV grid

No.	BS state	$\underline{U}_{C1}$ [кV]	$\underline{U}_{C2}$ [кV]	$\underline{S}_{T1}$ [MVA]	$\underline{S}_{T3}$ [MVA]
1	off	$6.23e^{-j2.8^\circ}$	$6.15e^{-j10.0^\circ}$	13.73+j7.43	0.90+j0.50
2	on	$6.17e^{-j7.0^\circ}$	$6.17e^{-j7.0^\circ}$	10.03+j7.55	4.55+j0.04
3	off	$6.08e^{-j2.8^\circ}$	$6.15e^{-j10.0^\circ}$	13.73+j7.43	0.90+j0.50
4	on	$6.10e^{-j7.0^\circ}$	$6.10e^{-j7.0^\circ}$	10.09+j8.31	4.50-j0.64

Table 3 and all the following ones contain rows with odd numbers which refer to the operating conditions before paralleling transformers T1 and T3. The rows with even numbers refer to the same values when paralleling transformers T1 and T3.

Table 4. Maximum load of the transformer T1, equal load sharing between SG1 and SG2 and minimum loads of the110 kV grid

No.	BS state	$\underline{U}_{C1}$ [кV]	$\underline{U}_{C2}$ [кV]	$\underline{S}_{T1}$ [MVA]	$\underline{S}_{T3}$ [MVA]
5	off	$6.30e^{-j1.7^\circ}$	$6.23e^{-j8.8^\circ}$	13.72+j7.46	0.90+j0.50
6	on	$6.25e^{-j5.8^\circ}$	$6.25e^{-j5.8^\circ}$	9.99+j7.56	4.59+j0.02

Comparing rows 1 and 2 (Table 3) to rows 5 and 6 (Table 4) when the ratio of the switchgear SG2 bus voltages before the bus circuit breaker switching-on is $U_{C1} > U_{C2}$, it can be stated that 110 kV grid operating conditions have no significant impact on power flows after paralleling the transformers T1 and T3.

At the same time, the voltage moduli at the contacts of the bus circuit breaker before paralleling the transformers change the nature of the power flows. Comparing rows 1 and 2 to rows 3 and 4 (Table 3) it can be seen, that after paralleling, the reactive loads of the transformers T1 and T3 are changed, due to different ratios of the voltages on the bus C1 and bus C2 before paralleling.

After paralleling, the transformer T1 will be unloaded and the transformer T3 will be additionally loaded. When under initial operating conditions the separated transformers were loaded as:

$$T1 – 13.73+j7.43 = 15.64e^{j29^\circ} \text{ MVA};$$

$$T3 – 0.9+j0.5 = 1.03e^{j29^\circ} \text{ MVA},$$

then after switching-on the bus circuit breaker, the loads will change to the following values:

$$T1 – 10.03+j7.55 = 12.55e^{j37^\circ} \text{ MVA};$$

$$T3 – 4.55+j0.04 = 4.55e^{j0.5^\circ} \text{ MVA}.$$

Analyzing the results of the simulations, it can be concluded that it is feasible the parallel operation of transformers T1 and T3 in the examined supply system, when the voltages at the bus circuit breaker are in the operating limits before it paralleling and loads of switchgears SG1 and SG2 for transformer T1 are equal.

Operating conditions of the 110 kV grid have not noticeable impact on the paralleling of the transformers.

Impact of bus voltage moduli. As the results of further simulating showed, changes in the reactive power flows in transformers under the operating conditions of the examined power system can be more significant. Paralleling transformers T1 and T3 will change their load compared to their separate operation depend on the LTC settings and system configuration.

Table 5 shows the results of simulations for the minimum loads of the 6 kV grid consumers under the condition when loads of switchgears SG1 and SG2 for transformer T1 are equal and the voltage moduli on the bus C1 and bus C2 vary in the operating limits before paralleling transformers.

Table 5. Minimum load of the transformer T1, equal load sharing between switchgears SG1 and SG2 ($\underline{S}_{SG1} = \underline{S}_{SG2}$)

No.	BS state	$\underline{U}_{C1}$ [кV]	$\underline{U}_{C2}$ [кV]	$\underline{S}_{T1}$ [MVA]	$\underline{S}_{T3}$ [MVA]
7	off	$6.17e^{-j1.4°}$	$6.19e^{-j3.7°}$	5.42+j2.73	0.90+j0.50
8	on	$6.17e^{-j2.8°}$	$6.17e^{-j2.8°}$	4.23+j3.01	2.09+j0.17
9	off	$6.01e^{-j1.4°}$	$6.42e^{-j3.6°}$	5.42+j2.71	0.90+j0.50
10	on	$6.23e^{-j2.9°}$	$6.23e^{-j2.9°}$	4.51+j4.96	1.84-j1.68
11	off	$6.49e^{-j1.4°}$	$5.96e^{-j3.9°}$	5.42+j2.74	0.90+j0.50
12	on	$6.16e^{-j2.7°}$	$6.16e^{-j2.7°}$	3.89+j0.54	2.44+j2.60

The following loads on the transformers can be obtained from the Table 5:

before switching on the bus circuit breaker:

T1 – 5.42+j2.73 = $6.07e^{j28°}$ MVA;
T3 – 0.9+j0.5 = $1.03e^{j29°}$ MVA,

after switching on the bus circuit breaker:

$U_{C1} \approx U_{C2}$ T1 – 4.23+j3.01 = $5.19e^{j36°}$ MVA;
T3 – 2.09+j0.17 = $2.10e^{j5°}$ MVA,
$U_{C1} < U_{C2}$ T1 – 4.51+j4.96 = $6.70e^{j48°}$ MVA;
T3 – 1.84 - j1.68 = $2.49e^{-j42°}$ MVA,
$U_{C1} > U_{C2}$ T1 – 3.89+j0.54 = $3.93e^{j8°}$ MVA;
T3 – 2.44+j2.60 = $3.57e^{j47°}$ MVA.

According to the obtained results, it can be concluded that the minimum load on the transformer T3 after paralleling transformers will be in the case of approximately the same voltage moduli at the open contacts of the bus circuit breaker ($U_{C1} \approx U_{C2}$) before their closing. If the voltage moduli at the contacts of the bus circuit breaker satisfy the condition $U_{C1} < U_{C2}$, then the load on the transformer T3 increases after paralleling the transformers, at the same time the load on the transformer T1 also increases due to the circulating reactive power between the transformers. In the last case, when $U_{C1} > U_{C2}$, it is observed the maximum load on the transformer T3 after paralleling the transformers and the minimum load on the transformer T1.

Table 6 shows the results of simulations for the maximum loads of the 6 kV grid consumers under the condition when loads of switchgears SG1 and SG2 for the transformer T1 and the voltage ratios at the C1 and C2 buses before closing the bus circuit breaker are similar to the previous case.

For the described case:

before switching on the bus circuit breaker:

T1 – 13.73+j7.43 = $15.64e^{j29°}$ MVA;
T3 – 0.9+j0.5 = $1.03e^{j29°}$ MVA,

after switching on the bus circuit breaker:

$U_{C1} \approx U_{C2}$ T1 – 10.03+j7.55 = $12.55e^{j37°}$ MVA;
T3 – 4.56+j0.06 = $4.56e^{j0.5°}$ MVA,
$U_{C1} < U_{C2}$ T1 – 10.21+j9.72 = $14.10e^{j44°}$ MVA;
T3 – 4.40 - j1.92 = $4.80e^{-j24°}$ MVA,
$U_{C1} > U_{C2}$ T1 – 9.79+j5.82 = $11.39e^{j31°}$ MVA;
T3 – 4.78+j1.67 = $5.06e^{j19°}$ MVA.

Table 6. Maximum load of the transformer T1, equal load sharing between switchgears SG1 and SG2

No.	BS state	$\underline{U}_{C1}$ [кV]	$\underline{U}_{C2}$ [кV]	$\underline{S}_{T1}$ [MVA]	$\underline{S}_{T3}$ [MVA]
13	off	$6.19e^{-j1.7°}$	$6.15e^{-j9.2°}$	13.73+j7.43	0.90+j0.50
14	on	$6.17e^{-j6.0°}$	$6.17e^{-j6.0°}$	10.03+j7.55	4.56+j0.06
15	off	$5.99e^{-j1.7°}$	$6.35e^{-j8.6°}$	13.72+j7.43	0.90+j0.50
16	on	$6.16e^{-j5.9°}$	$6.16e^{-j5.9°}$	10.21+j9.72	4.40-j1.92
17	off	$6.49e^{-j1.7°}$	$6.0e^{-j9.1°}$	13.73+j7.43	0.90+j0.50
18	on	$6.18e^{-j5.8°}$	$6.18e^{-j5.8°}$	9.79+j5.82	4.78+j1.67

Under the maximum load of the 6 kV grid consumers and even load sharing between the switchgears SG1 and SG2 for the transformer T1 can be observed the similar trend of the loading transformers after paralleling as in the previous case, but the load on the transformer T3 increases. Figure 4 shows the dependencies of loading transformers on the relation of the bus voltages under the maximum load of the 6 kV grid consumers.

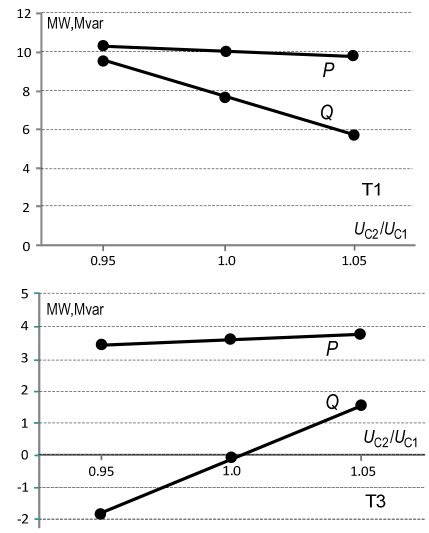

Fig.4. Dependencies of transformers loading on the bus voltages

Impact of T1 load sharing. Table 7 shows the results of simulations for the maximum loads of the 6 kV grid consumers under the condition, when loads of switchgear SG1 and switchgear SG2 for transformer T1 are dividing in the ratio of 20% and 80%, respectively. In this case, there are the following transformer loads after switching on the bus circuit breaker:

$U_{C1} < U_{C2}$ T1 – 9.46+j9.55 = $13.44e^{j45°}$ MVA;
T3 – 4.97 - j1.60 = $5.22e^{-j18°}$ MVA,
$U_{C1} > U_{C2}$ T1 – 9.10+j6.35 = $11.10e^{j35°}$ MVA;
T3 – 5.29+j1.29 = $5.45e^{j14°}$ MBA.

As can be seen, for these operating conditions, the load on the transformer T3 significantly increases.

Table 8 shows the results of simulations for the maximum loads of the 6 kV grid consumers when loads of switchgears SG1 and SG2 for transformer T1 are shared in the ratio of 80% and 20%, respectively.

Table 7. Maximum load of the transformer T1 and load sharing is $\underline{S}_{SG1} = 0.2\underline{S}_{T1}$, $\underline{S}_{SG2} = 0.8\underline{S}_{T1}$

No.	BS state	$\underline{U}_{C1}$ [кV]	$\underline{U}_{C2}$ [кV]	$\underline{S}_{T1}$ [MVA]	$\underline{S}_{T3}$ [MVA]
19	off	$5.99e^{-j1.7°}$	$6.24e^{-j9.7°}$	13.56+j7.78	0.90+j0.50
20	on	$6.11e^{-j6.5°}$	$6.11e^{-j6.5°}$	9.46+j9.55	4.97-j1.60
21	off	$6.30e^{-j1.7°}$	$5.88e^{-j10.2°}$	13.58+j7.44	0.90+j0.50
22	on	$6.10e^{-j6.5°}$	$6.10e^{-j6.5°}$	9.10+j6.35	5.29+j1.29

Table 8. Maximum load of the transformer T1 and load sharing is $\underline{S}_{SG1} = 0.8\underline{S}_{T1}$, $\underline{S}_{SG2} = 0.2\underline{S}_{T1}$

No.	BS state	$\underline{U}_{C1}$ [кV]	$\underline{U}_{C2}$ [кV]	$\underline{S}_{T1}$ [MVA]	$\underline{S}_{T3}$ [MVA]
23	off	$6.15e^{-j1.7°}$	$6.12e^{-j7.7°}$	13.50+j7.11	0.90+j0.50
24	on	$6.12e^{-j5.2°}$	$6.12e^{-j5.2°}$	10.39+j7.38	3.99+j0.02
25	off	$6.0e^{-j1.7°}$	$6.34e^{-j7.5°}$	13.49+j7.07	0.90+j0.50
26	on	$6.16e^{-j5.2°}$	$6.16e^{-j5.2°}$	10.61+j9.27	3.78-j1.75
27	off	$6.31e^{-j1.7°}$	$6.0e^{-j7.8°}$	13.50+j7.14	0.90+j0.50
28	on	$6.12e^{-j5.1°}$	$6.12e^{-j5.1°}$	10.24+j6.13	4.12+j1.22

For these load sharing of the transformer T1:

$U_{C1} < U_{C2}$ T1 – 10.61+j9.27 = $14.09e^{j41°}$ MVA;
T3 – 3.78 - j1.75 = $4.17e^{-j25°}$ MVA,
$U_{C1} > U_{C2}$ T1 – 10.24+j6.13 = $11.94e^{j31°}$ MVA;
T3 – 4.12+j1.22 = $4.30e^{j16°}$ MVA.

Compared to the previous case of load sharing for transformer T1, it can be seen that the load on the transformer T3 is reduced. The simulation results show that the more of the total load on transformer T1 is connected to switchgear SG2, the greater the load of transformer T3 will be. The reactive powers of transformers T1 and T2 are weakly dependent on load sharing, but the active powers have a significant dependence, as shown in Fig. 5.

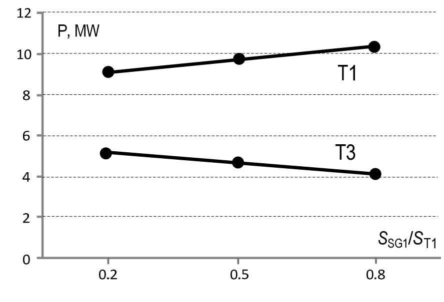

Fig.5. Dependencies of active powers of transformers T1 and T3 on the load dividing between SG1 and SG2 for transformer T1

Conclusion

The model to analyze loading transformers within a complex power supply system under their paralleling has been developed out on the platform of DAKAR software. Based on simulation results it was shown the impact of the power supply system circuit and compound of consumers on the loading transformers under their paralleling. Under planning parallel operation of transformers within an industrial power grid, it should be taken into consideration not only regulating possibilities of the transformers, but also all possible system conditions. This will prevent any of the problems under the system operation.

Simulation results for the examined mine power supply system show that within the operating voltage limits on the buses of the 6 kV switchgears and the operating load changes, it is feasible paralleling transformers T1 and T3. Under the parallel operation, transformer T1 will be unloaded and transformer T3 will be additionally loaded compared to their separate operation. The nature of the load sharing between the transformers depends on the voltage moduli on the bus C1 and bus C2 before switching on the bus circuit breaker. The maximum load of the transformer T3 under the parallel operation does not exceed its nominal power.

The minimum values of circulating currents between transformers operating in parallel will be in case of close values of voltages on the bus C1 and bus C2 before switching on the bus circuit breaker. The load of the transformer T3 under the paralleling transformers depends on the load sharing between the switchgears SG1 and SG2 for the transformer T1. The higher the relative load on the switchgear SG1, the lower the additional load on the transformer T3.

Acknowledgments

These studies were funded by the Polish Ministry of Science and Higher Education (Grant AGH 16.16.210.476)

***Authors**: prof. dr hab. inż. Yuriy Varetsky, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 E-mail: jwarecki@agh.edu.pl; prof. dr hab. inż. Zbigniew Hanzelka, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 E-mail: hanzel@agh.edu.pl; dr inż. Volodymyr Konoval, Lviv Polytechnic National University, ul. S.Bandera 12, 79013 E-mail: Volodymyr.Konoval@eleks.com ; dr inż. Beata Kushka, Lviv Polytechnic National University, ul. S.Bandera 12, 79013 E-mail: BeataKushka22@gmail.com.*

REFERENCES

[1] IEEE Std C57.153™-2015. IEEE Guide for Paralleling Regulating Transformers. - 107 P, (2015).
[2] Introduction to Paralleling of LTC Transformers by the Circulating Current Method, *Tapchanger Control Application Note #11, Beckwith Electric Co., Inc.* (1998).
[3] Harlow J. H., The Electric Power Engineering Handbook, CRC Press LLC, (2000).
[4] Harlow J. H., Electric Power Transformer Engineering, CRC Press, 2nd ed., (2007).
[5] Loading Considerations when Paralleling Transformers, *Ed. Zientek, PE. Schneider Electric USA,* (2011).
[6] Jauch E. T., Factors in Choosing Transformer Paralleling Methods, *Proceedings of 2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition Note, Beckwith Electric Co., Inc.*, pp.1-6, (2006).
[7] Zhu Z., Sun S., Mou X., and Zhang C., Qualitative Calculation and Simulation Analysis of Transformer Parallel Operation, *Proceedings of 2nd International Symposium on Instrumentation and Measurement, Sensor Network and Automation*, pp.1027-1030, (2013).
[8] Wang F., She X., Wang G., Huang A., and Burgos R., Parallel operation of solid state transformer, *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE,* Sept 2012, pp. 1433–1438.
[9] Hampson B., Power System Operation and Control Solutions Using IEC 61850. *Proceedins of 22nd Conference of the Electric Power Supply Industry, Kuala Lumpur,* pp. 1-15 (2018).
[10] Power design and analysis solution – DAKAR, www.dakar.eleks.com.