

## Info Letter No. 10

### Voltage regulation with step transformers in parallel to busbars (Part 2)

The following considerations apply to a symmetrical operation of a three-phase network, so that the entire three-phase network can be modelled by a single-system equivalent circuit diagram. It should however be noted that the nominal voltage and the short-circuit voltage at the three-phase transformer are still specified as external conductor voltages. The nominal voltages  $U_{10}$  and  $U_{20}$  indicated on the rating plate (upper and lower voltage) always refer to the off-load operation. The nominal transmission ratio is  $U_N = U_{10} / U_{20}$ .

The fundamental considerations in Part 1 for the parallel operation of DC sources can be transferred to the parallel operation of transformers.

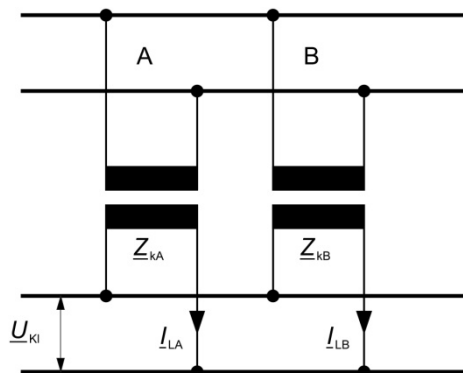


Figure 2 Parallel circuit of the transformers at the bus bars

#### Requirements for efficient parallel operation

The main tasks for parallel operation are therefore:

- Avoidance/minimization of the circulating current
- Avoid unequal relative loading of the transformers

These tasks can be fulfilled if the following conditions are met:

- same nominal voltages, same transmission ratio (the same off-load voltages)
- same nominal value of the short-circuit voltages
- Ratio of the rated outputs is not greater than 1:2. If the rated output is exceeded, the dependent values of  $u_k$  are so far apart that at the parallel connection too great differences occur between the relative loads.

#### Distribution of the load current

If the primary side and secondary side respectively of transformers A and B are placed directly on the same busbar, both the magnitude and angle of the voltage vector of the two input voltages and output voltages must be the same. It is assumed that the impedance of the connecting lines between A and B is equal to 0! For the voltage drop  $U_F$  across the windings, the following must therefore apply.

$$U_F = I_{LA} Z_{kA} = I_{LB} Z_{kB}$$

It follows that the sum of all voltage drops in the short-circuit impedances for each of the transformers working in parallel must be identical; even with different values for  $u_k$  and  $\varphi_k$ .

For the complex values of one circuit the following relations thus result

$$\frac{I_{LA}}{I_{LB}} = \frac{Z_{kB}}{Z_{kA}} = \frac{Z_{kB}}{Z_{kA}} e^{j(\varphi_B - \varphi_A)}$$

#### Example 3

| Transformer A         | Value  | Angle  |
|-----------------------|--------|--------|
| $I_{LA}$ [A]          | 197.12 | -41.41 |
| $Z_{kA}$ [ $\Omega$ ] | 3.12   | 79.76  |
| $I_{LA} Z_{kA}$ [V]   | 614.56 | 38.35  |

| Transformer B         | Value  | Angle  |
|-----------------------|--------|--------|
| $I_{LB}$ [A]          | 322.56 | -43.29 |
| $Z_{kB}$ [ $\Omega$ ] | 1.91   | 81.64  |
| $I_{LB} Z_{kB}$ [V]   | 614.56 | 38.35  |

When  $\varphi_B - \varphi_A = 0$ , these relations also apply to the values (effective values) and the impedance of the load currents and also for the relative short-circuit voltage/rated outputs of the transformers.

$$\left| \frac{I_{LA}}{I_{LB}} \right| = \left| \frac{Z_{kB}}{Z_{kA}} \right| = \frac{S_{rA}}{S_{rB}} \cdot \frac{u_{kB}}{u_{kA}}$$

There is proportionality between the load currents, impedances and output ratings when  $u_{kB} = u_{kA}$ . With unequal short-circuit voltages these direct relationships no longer apply!

We take care of it.

The value of the short-circuit impedance (per phase) can be calculated from the characteristics of the transformer.

$$Z_k = \frac{u_{kr} \cdot U_r}{I_r \sqrt{3}} = \frac{u_k \cdot U_r^2}{S_r}$$

### Relative loads, limiting the degree of utilisation

The distribution of the load current  $I_L$  across the transformers is dependent on the ratio of the impedances.

Transformer A

$$I_{LA} = I_L \frac{Z_{kB}}{Z_{kA} + Z_{kB}}$$

Transformer B

$$I_{LB} = I_L \frac{Z_{kA}}{Z_{kA} + Z_{kB}}$$

Only with  $u_{kA} = u_{kB}$  is the load current proportional to the nominal output  $S_{rA}$  and the load current  $I_{LB}$  is proportional to the nominal output  $S_{rB}$ . When  $u_{kB} \neq u_{kA}$  this relationship no longer applies. The transformer with the smaller impedance takes the larger load current, which is then no longer proportional to the rated output  $S_r$ . This also concerns the distribution of the active power and reactive power drawn from the network by the two transformers.

The disproportionate distribution of the load current with high duty cycles can result in overloading one of the two transformers. The total power available with unequal short-circuit voltages is therefore less than the arithmetic sum of the two rated outputs.

### Circulating current

With unequal off-load voltages, the difference voltage  $\Delta U = U_A - U_B$  drives as EMF a current through the windings of the parallel operation transformers that is independent of the load current. Because of the predominantly *inductive* short-circuit impedances of the transformers, this is often called the *circulating current*, instead of the term "circulating reactive current" being used. (see Table 2, Part 3/Info Letter 12)

The reasons for different values and angles of the off-load voltages can be

- with identical transformers: different position of the tap changer (different transmission ratios)
- with transformers that are not identical: different voltage jumps of the voltage steps and different short-circuit impedances

For the magnitude and the angle of the circulating current only the series of short-circuit impedances  $Z_k$  of the parallel operating transformers, including the impedance  $Z_{Ltg}$  of the connecting line between the two transformers are

relevant, but not the impedance of the load. This circulating current flows even when there is no load ( $Z_L = \infty$ ). In this section, first all the impedances between the two transformers (connecting lines/bus bar, switches, terminals) are ignored.

Circulating current strength

$$I_{cir} = \frac{E_{A0} - E_{B0}}{Z_{kA} + Z_{kB}}$$

Because the circulating current strength can assume considerable values because of the small short-circuit impedances of transformers even with small differences in the off-load voltages (the tap positions), the circulating current must be monitored and minimized in voltage regulation transformers operated in parallel. Even when similar transformers are always operated with the same tap positions, the circulating current must be monitored for a period of time not congruent with the switching phase.

### Example 4

Given values:

$$u_{krA} = u_{krB} = 10 \%$$

$$\varphi_{kA} = \varphi_{kB};$$

$$I_{rA} = 288.7 \text{ A};$$

$$I_{rB} = 721.7 \text{ A};$$

$$\Delta u_0 = 4 \%, \text{ nominal voltage } U_r = 20 \text{ kV}$$

Because  $u_{kA} = u_{kB}$  and  $\varphi_{kA} = \varphi_{kB}$  when calculating the values the same result is obtained as when calculating with complex values.

$$u_{kA} = u_{kB} = 1156 \text{ V};$$

$$\Delta u_0 = 800 \text{ V}$$

$$Z_{kA} = 1156 \text{ V} / (288.7 \text{ A}) = 4.00 \ \Omega;$$

$$Z_{kB} = 1156 \text{ V} / (721.7 \text{ A}) = 1.60 \ \Omega$$

$$Z_{kA} + Z_{kB} = 5.60 \ \Omega$$

$$I_{cir} = 800 \text{ V} / (5.6 \ \Omega \sqrt{3}) = 82.5 \text{ A}$$

Because the circulating current is not directly measurable with the usual measurement equipment, indirectly determined proxies for the circulating current can be used.

The topic is continued in Part 3 / Info Letter No. 11

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The Excel programs used for the examples can be obtained from: [www.a-eberle.de](http://www.a-eberle.de) (Download Center)

The series will be continued.

We will gladly supply missing Info Letters at any time!

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