Info Letter No. 11

Voltage regulation with step transformers in parallel to busbars (Part 3)

Measurement of the circulating current

Direct measurement of the circulating current is not possible with the usual measurement equipment. The calculation of the circulating current from the difference between the off-load voltages and the short-circuit impedance of the windings involves a relatively high cost, because the exact actual values of the complex quantities are required for this. For a voltage control based on the principle of circulating current minimization, proxy values for the circulating current can therefore be used. These proxy values are not universal, but nearly proportional for the circumscribed practical realities of the circulating current and sufficiently accurate for the stepped voltage regulation.

Calculation of the circulating current

The magnitude and the angle of the circulating current can be calculated using the generally available complex measurement values, the transformer currents I_{TA} and I_{TB}.

$$\underline{I}_{\mathrm{cir}} = \underline{I}_{\mathrm{TA}} - \left(\underline{I}_{\mathrm{TA}} + \underline{I}_{\mathrm{TB}}\right)\left(\frac{\underline{Z}_{\mathrm{kB}}}{\underline{Z}_{\mathrm{kA}} + \underline{Z}_{\mathrm{kB}}}\right)$$

With this equation the circulating current can also be correctly determined with $S_{rA} \neq S_{rB}$; $u_{krA} \neq u_{krB}$; $\varphi_{krA} \neq \varphi_{krB}$. The load data (load factor, load type, power factor) have no effect on the result.

Determination of the circulating current using the $\Delta I\sin\varphi$ procedure

In parallel operation on a busbar for $S_{rA} = S_{rB}$ and $u_{krA} = u_{krB}$ and $\varphi_{krA} = \varphi_{krB} = 90°$, the circular current is given by the measured reactive currents $I_{qA} = I_{TA} \sin\varphi_{TA}$ and $I_{qB} = I_{TB} \sin\varphi_{TB}$ of transformers A and B. If these conditions are met, then it is permissible to calculate the values with only the complex values.

$$I^*_{\mathrm{cir}} = \frac{1}{2}\left(I_{\mathrm{TA}} \sin\varphi_{\mathrm{TA}} - I_{\mathrm{TB}} \sin\varphi_{\mathrm{TB}}\right)$$

But if φ_{krA} and/or φ_{krB} < 90° (u_r / u_{kr} > 0), the resulting error in the measured circulating current I^*_{cir} becomes greater the smaller the cosφ of the load is. Likewise, with $S_{rA} \neq S_{rB}$ and/or $u_{krA} \neq u_{krB}$ the inaccuracy of the measurement values of I^*_{cir}increase with an increasing difference between the values. Even with $U_{A0} - U_{B0} = 0$, $I^*_{cir} \neq 0$.

Note:

The short-circuit phase angle is a function of the rated output class of the transformer. The deviation from 90° may be significant in transformers with a relatively small rated output.

Table 2

S_r [kVA]	100	500	1000
u_{kr} [%]	4	6	6
u_R [%]	2.14	1.56	1.35
φ_{kr} [°]	58	75	77
$\sin\varphi_{kr}$	0.845	0.966	0.974

S_r [kVA]	5000	10000	40000
u_{kr} [%]	8	10	11
u_R [%]	0.82	0.72	0.53
φ_{kr} [°]	84	86	87
$\sin\varphi_{kr}$	0.995	0.997	0.999

Determination of the circulating current using the $\Delta I\sin\varphi$ (S) procedure

For parallel operation of transformers with unequal power ratings, for $u_{krA} = u_{krB}$ und $\varphi_{krA} = \varphi_{krB} = 90°$ the circulating current I^*_{cir} is obtained from the measured reactive currents $I_{qA} = I_{TA} \sin\varphi_{TA}$ and $I_{qB} = I_{TB} \sin\varphi_{TB}$ and the output rating of the transformers A and B.

If the conditions $u_{krA} = u_{krB}$ und $\varphi_{krA} = \varphi_{krB} = 90°$ are met, it is permissible to calculate the values using only the complex values.

$$I^*_{\mathrm{cir}} = I_{\mathrm{qA}} - \left(I_{\mathrm{qA}} + I_{\mathrm{qB}}\right)\left(\frac{S_{\mathrm{rA}}}{S_{\mathrm{rA}} + S_{\mathrm{rB}}}\right)$$

Deviations of the transformer data from the conditions stated have the previously described effect on this measurement procedure.

Example 5

Transformers A and B are operated in parallel on a busbar.

Transformer	**A**	**B**
I_r	11 kV	11 kV
S_r	11.5 MVA	11.5 MVA
Load	5.7 MW	5.0 MW
U_{kr}	7.98 %	9.64 %
u_R	2.00 %	2.41 %

The following table shows the correct values of the circulating current and the values determined by the ΔIsinφ procedure, depending on the cosφ of the load.

$\cos\varphi$	U_{A0} - U_{B0}	I_{cir}	I^*_{cir} ($\Delta I \sin\varphi$)
0.90	0.22 kV	69 A	85 A
0.90	0.0 kV	0 A	18 A
0.70	0.22 kV	59 A	94 A
0.70	0.0 kV	0 A	28 A

Measurement technologies for indirect circulating current measurement

The mapping of the measured values (only the values) of I_{qA} and I_{qB} by an analog or digital value allows the computational processing of the measured values without special equipment expense. The derivation of the measured values from transformer A to transformer B and vice versa is easy. Calculation with complex values is not required.

Allowable measurement error

The inaccuracies in the measured values of I^*_{cir} with deviations from the requirements (q.v.) can be accepted for voltage regulation based on the principle of minimizing the circulating current if for each control there is a sufficiently large difference between the maximum value of I^*_{cir} with step position n, and the minimum value of I^*_{cir} at step position *n+1* is available.

Superposition of load current and circulating current

The circulating current is superimposed on the transformer currents that are supplied in the network and added to the current of the transformer with the larger secondary off-load voltage.

Example 6

Transformers A and B are operated in parallel on a busbar.

Transformer	A	B
U_r	10.5 kV	10.5 kV
S_r	10 MVA	6.3 MVA
U_{kr}	8.00 %	7.73 %
u_R	0.7 %	0.7 %

With U_{A0} - U_{B0} = 0.187 kV the following values are obtained:

Transformer A	I [A]	*I, Re* [°]
Load current I_{LA}	320	-34
Circuit current I_{cir}	48	-85
Total I_{TA}	352	-40

Transformer B	I [A]	*I, Re* [°]
Load current I_{LB}	209	-34
Circuit current I_{cir}	48	+95
Total I_{TB}	182	-22

The load on transformer A is increased by the circulating current because $U_{A0} > U_{B0}$ and that of transformer B is reduced. With high load levels there is thus a danger of overloading for one of the two transformers.

Example 7

Data from example 6

Transformer	A	B
I_r	550 A	346 A
I_{Tx} (U_{A0} - U_{B0} = 0)	316 A	206 A
I_{Tx}/I_{rx}	0.58	0.60
I_{Tx} (U_{A0} - U_{B0} = 315 V)	433 A	166 A
I_{Tx}/I_{rx}	0.79	0.48

The practical example shows that the relative load of transformer A, while increasing from 58 % to 79 %, is still below the rated value. Conversely, this means that the nominal output of transformer of A can only be used to about 80 %.

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The Excel programs used for the examples can be obtained from: ***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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