Info Letter No. 7

Load-dependent voltage change

For the regulation of the voltage U_{Load} at a predetermined value at the specified load point (e.g. the end of a branch conductor), the load-dependent difference between the voltage at the step transformer and the voltage at the load point can be compensated by a corresponding automatic adjustment of the setpoint of the voltage regulator in order to keep the voltage at the load point constant regardless of load fluctuations.

$$U_{sett2} = U_{sett1} + U_{comp}$$

U_{comp} : Difference between the effective values of U_T and U_{Load}

Voltage drop on a three-phase conductor

For high-voltage power lines, in the energy technology for determining the voltage difference between the beginning and end of a line, instead of the general line equations simple approximate formulas are used, where the equivalent circuit on which it is based is shown in Figure 1. The results meet the accuracy requirements of the voltage regulation, which can only be carried out in stages.

The simplification of the general conduction equation is possible with power lines because their lengths always "short compared to the wavelength λ" of the fundamental of the operating voltage (λ approximately 6,000 km at 50 Hz). As limits for the following approximate formulas, line lengths of about 150 km for overhead lines and 50 km for cables apply.

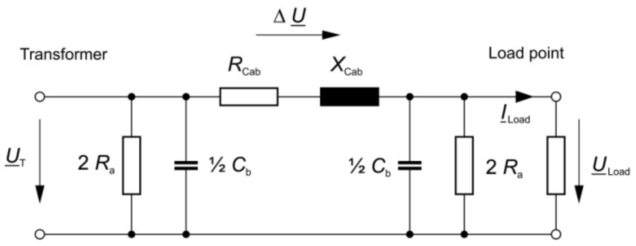

Figure 1 *Equivalent circuit of the short electricity lines (π-schematic, single-phase AC overhead power line).*

For the load-dependent voltage difference (phase-neutral voltage) on the three-phase line between the tapped transformer and the load point the following applies:

$$\Delta\underline{U} = \underline{U}_T - \underline{U}_{Load} = \underline{Z}_{Cab}\ \underline{I}_{Load} = \Delta\underline{U}\ e^{j(\varphi Z_{Cab} + \varphi I_{Load})}$$

$\underline{I}_{Load}$ of the current consumed in the consumer circuit at the load point

φZ_{Cab} angle of the conductor impedance $\underline{Z}_{Cab}$

I_{Load} angle of the current $\underline{I}_{Load}$ at the load point ($\varphi_{ILoad} = \varphi_{ULoad} - \varphi_{ZLoad}$)

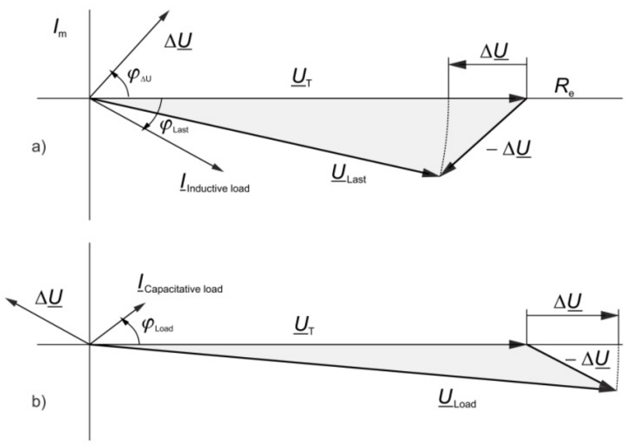

Figure 2 *Voltage vector of the single-phase equivalent circuit in a short electricity line*

a) With an inductive load the voltage drop in the line is positive and thus the voltage $\underline{U}_{Load}$ at the load point is less than the voltage $\underline{U}_T$ at the transformer.

b) With a capacitive load the reverse applies, i.e. the voltage at the load point is higher than at the transformer. Such loads mainly occur at night.

Line simulation

Because the actual value of the voltage on the load on the voltage regulator normally is not available, the voltage drop on the line is approximated in a line simulation of R_{Cab} and X_{Cab}, through which the current $I = I_{Load}$ (w_2 / w_1) flows. The discharge resistance and the operating capacitance of the equivalent circuit is not taken into account and the small difference between the angles at the beginning and end of the line (transformer and load point) is also neglected.

Load-dependent voltage drop

In the series control, for the change in the set point, only the difference of the effective values of transformer voltage and load voltage is a determinant, so that the angles of the two voltages are meaningless in this context. The complex voltage difference $\Delta\underline{U}$ determined from the line simulation (the impedance of the line) is not different from the difference of the two effective values, so that the complex voltage difference cannot be used directly to change the setpoint.

To determine the value of $U_{comp} = |U_T| - |U_{Load}|$ required for the voltage compensation the indirectly measurable voltage at the load must therefore be calculated from $\underline{U}_{Load} = \underline{U}_T - \Delta\underline{U}$. - The basic relationships are illustrated in Figure 3.

The value known as the "series voltage" (phase-neutral voltage) has almost the same value as the voltage U_{comp}.

$$U_{comp} \approx U_{lengCab} = I_{Last} \left(R_{Cab} \cos\varphi_{Load} \pm X_{Cab} \sin\varphi_{Load} \right)$$

The sign of $X_{Cab} \sin\varphi_{Load}$ is negative when the current is leading and positive when the current is lagging.

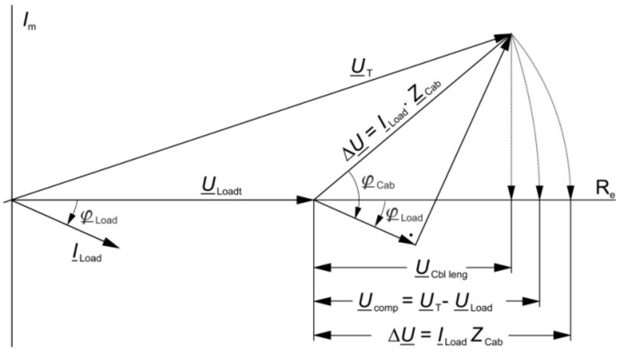

Figure 3 *Comparison of the values ΔU, U_{comp} and $U_{lengCab}$ (with an inductive load)*

Example 1

Line 10 km; $\underline{Z}_{Cab} = 4\ e^{j60°}\ \Omega$ ($R_{Cab} = 2.0\ \Omega$; $X_{Cab} = 3.5\ \Omega$);
$\underline{U}_T = 20\ e^{j0°}$ kV; $\Delta I_{Load} = I_{Loadmax} - I_{Loadmin} = 200$ A;

What is the voltage U_{Load} at the load point at various angles of load current (against the real axis Re)?

What are the values of U_{comp} with a change in $\cos\varphi_{Load}$ and the type of load?

Result (calculation with program E-2.5.1)

$\cos\varphi_{Load}$	0.80 ind.	0.90 ind.	0.90 cap.	0.80 cap.
Angle $\varphi\ I_{Load}$	– 37°	– 26°	+ 26°	+37°
φ_{ZCab}	+ 60°	+ 60°	+ 60°	+60°
$\varphi\Delta_U = \varphi_{ZCab} + \varphi\ I_{Load}$	+ 23°	+ 34°	+ 86°	+97°
$U_{Load} = I_{Load}\ Z_{Load}$	18726 V	18864 V	19954 V	20221 V
$\Delta U = Z_{Cab}\ I_{Load}$	806 V	806 V	806 V	806 V
$U_{comp} = U_T - U_{Load}$	+ 744 V	+ 674 V	+ 83 V	-72 V
$U_{lengCab}$	+ 740 V	+ 665 V	+ 55 V	-100 V

In order to compensate for the voltage difference between the tapped transformer and the load point, i.e. to keep the voltage at the load point at 20 kV, the nominal value in the voltage regulator must be changed to the respective value of U_{comp} (not to $|\Delta U\ |$ = 806 V!). The value of U_{comp} is chosen for the voltage compensation according to $\cos\varphi_{Load}$ e.g. the corresponding value for $\cos\varphi_{Load} = 0{,}90_{ind}$ is $\Delta U^* = 674$ V, then this value is wrong for other values of the $\cos\varphi$ of the load (see table)!

Current-dependent change in the setpoint

With an almost uniform displacement factor and only an inductive load, instead of the voltage U_{comp} the value ΔU^* which is exclusively dependent on the load current can be used.

The difference between $\Delta U = \Delta I_{Load}\ R_{Cab}$ and U_{comp} must then be compensated for with an adjustment factor c.

$$\Delta U^* = \frac{U_{comp}}{\Delta U}\ I_{Load}\ R_{Cab} = c\left|\Delta\underline{U}\right|$$

Selection criteria

For the selection of the appropriate approximation formula or correction factor the shifting factor of the load, the type of load, and the line data of therefore important.

The mandatory conditions are given in the table.

	Correction of the setpoint	
Characteristics	**voltage dependent** (Line simulation)	**current dependent** (equivalent resistance)
Line data	exact value of R and X must be available	not available
$\cos\varphi$ of the load (at the load point)	randomly variable	almost constant constant
Type of load	inductive or capacitive	Only inductive

Voltage drop at the transformer

For determining the total voltage variation required for the voltage control on a supply line, a transformer can be regarded as a line element with an inductance and resistance. With a constant primary voltage, the secondary voltage decreases as a result of the load. The difference between the effective values at idle and under load depends on the secondary current and the corresponding phase angle φ_{se} and produces a voltage drop. At constant input voltage, the relative change of the output voltage between idle and the nominal load of the transformer is directly proportional to its relative short-circuit impedance.

In principle the same load-dependent voltage drop applies as for lines.

Example 2

Tapped transformer

Rated voltage U_r	110 kV/21 kV
Rated load S_r	40 MVA
Short-circuit impedance z	10 % of Z_{ref}
Short-circuit losses P_V	150 kW
Load current I_{Load}	1003 A
Shift factor cos	0.80

Calculated data (calculation with program E-2.6.1)
Rated current I_r
I_r = 1443 A

Sort-circuit impedance Z_k
Z_k = 0.8 Ω

Active component z_R
R = 0.024 Ω
z_R = 0.3 % of Z_k

Short-circuit phase angle φ_k
$\cos\varphi_k = R / Z_k = 0.03$; $\varphi_k = 88.3°$

Short-circuit voltage U_k
0.8 Ω • 1443 • √3 = 2.0 kV

u_k = (2.0 kV / 20 kV) 100 % = 10 % of U_r

and thus $z = u_k$

Terminal voltage U_{Term} 19483 V

Voltage drop ΔU
20000 V – 19483 V = 517 V; 4,5 % of 20 kV

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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!