CALCULATION OF THE FAULT LEVEL CONTRIBUTION OF DISTRIBUTED GENERATION TO DISTRIBUTION NETWORK

Marián Mešter

ABSTRACT

Paper deals with the calculation of the fault level contribution of distributed generation according to IEC Standard 60909. To illustrate its application, the methodology is applied to a study medium voltage network with a variety of distributed generation resources.

1. INTRODUCTION

Distribution network are characterized by design maximum fault current, i.e. short-circuit capacity. Distributed generation resources are typically connected to the distribution network, at the low or medium voltage level. Therefore they contribute to the total fault level of the distribution grid. Hence, the basic requirement for permitting the interconnection of distributed generation resources is to ensure that the resulting fault level remains below the network design value.

2. THE METHODOLOGY OF IEC 60909 STANDARD

The IEC 60909 International Standard [1] is intended to give the methodology for the fault-currents calculation in three-phase a.c. systems at a nominal frequency of 50 or 60 Hz. The short-circuit currents is considered as the sum of an a.c. symmetrical component and of an aperiodic decaying component. The Standard distinguishes between near-to-generation and far-from-generation short circuits. The methodology includes of a.c. motors contribution, too.

In the present, two numerical methods for short-circuit calculations are used: superposition method and equivalent voltage source method. Superposition method gives the short-circuit current only in relation to one assumed amount of the load. Hence, it need not lead to maximum short-circuit current in the system. For removing this lack, it was developed the equivalent voltage source method [2].

The calculation method, used in the IEC Standard 60909 determines the short-circuit currents at the location *F* using equivalent voltage source: $cU_n / \sqrt{3}$. This source is defined as the voltage of an ideal source applied at the short-circuit location in the positive sequence system, whereas all other sources are ignored. All network components are replaced by their internal impedances (see Fig.1.).

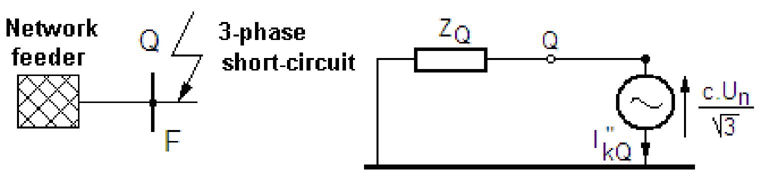

Fig.1. Equivalent voltage source method

In the calculation of the maximum short-circuit currents, the voltage factor *c* may be assumed equal to c_{max}, for any voltage levels (see Tab.1.). According to Fig.1., in the case of balanced short-circuits the initial symmetrical short-circuit current is calculated:

$$I_k^{"} = \frac{cU_n}{\sqrt{3}.Z_Q} \tag{1}$$

where: Z_Q - magnitude of an equivalent short-circuit impedance $\mathbf{Z_Q}$,

Tab.1 Voltage factor c

<table>
<tr><th rowspan="2">Nominal voltage U_{n}</th><th colspan="2">Voltage factor c for calculation of</th></tr>
<tr><th>maximum short-circuit currents c_{max}</th><th>minimum short-circuit currents c_{min}</th></tr>
<tr><td>Low voltage
100 V - 1000 V (IEC 60038, Tab.I.)</td><td>1,05
1,10</td><td>0,95</td></tr>
<tr><td>Medium voltage
> 1 kV - 35 kV (IEC 60038, Tab.III.)</td><td rowspan="2">1,10</td><td rowspan="2">1,00</td></tr>
<tr><td>High voltage
> 35 kV (IEC 60038, Tab.IV.)</td></tr>
</table>

3. FAULT LEVEL CALCULATION

In distribution network, the maximum fault level typically occurs at the busbars of the infeeding substation, due to large contribution of the upstream grid [3]. If any distributed generation unit (units) is in the grid included, the resulting fault level is the sum of the maximum fault currents due to:

- the upstream grid,
- the various types of generators,
- the large motors connected to the distribution network.

3.1 Contribution of the upstream grid

The contribution of the upstream grid is calculated according to IEC 60909:

$$\mathbf{I_k''} = \frac{c_{\max} U_n}{\sqrt{3}\left(\mathbf{Z_{Qt}} + \mathbf{Z_{KT}}\right)} = \frac{c_{\max} U_n}{\sqrt{3}\left(\mathbf{Z_Q} / t_r^2 + K_T \mathbf{Z_{TLV}}\right)} \tag{2}$$

where: $\mathbf{Z_Q}$ - is the impedance of the upstream grid at the connection point Q,

$\mathbf{Z_T}$ - is the impedance of the transformer,

K_T - is a correction factor used for the impedance of the transformer.

For the impedances of network feeder and transformer we can write:

$$Z_Q = \frac{cU_{nQ}}{\sqrt{3} I_{kQ}''} \tag{3}$$

where: I_{kQ}'' - is the initial symmetrical short-circuit current at the high voltage connection point Q,

$$Z_T = \frac{u_{kr}}{100}\frac{U_{rT}^2}{S_{rT}}, \qquad R_T = \frac{u_{Rr}}{100}\frac{U_{rT}^2}{S_{rT}} = \frac{P_{krT}}{3I_{rT}^2}, \qquad X_T = \sqrt{Z_T^2 - R_T^2} \tag{4}$$

where: u_{kr} - is the short-circuit voltage of the transformer [%],

u_{Rr} - is the rated resistive component of the short-circuit voltage [%],

P_{krT} - are the load losses at the rated current.

Typically value of ratio $R_Q / X_Q = 0{,}1$.

$$K_T = 0{,}95 . \frac{c_{\max}}{1 + 0{,}6 x_T} \tag{5}$$

where: K_T - correction factor for transformer

3.2 Contribution of the distribution generation units

Most frequently are connected to the MV (medium-voltage) distribution networks wind turbines and small hydroelectric plants. Other types of distribution generation units (like fuel-cells, photovoltaics, small cogeneration units, microturbines, etc.) are mostly connected in to LV (low-voltage) networks. The calculation of contribution of the distribution generation units is not included in the IEC 60909. Only induction motors are dealt with, whereas the parameter values of synchronous generators provided in [4] are applicable to units of very large size [3].

Short–circuit current for conventional synchronous generators is given:

$$\mathbf{I}_{\mathbf{k}}^{"} = \frac{c_{\max} U_n}{\sqrt{3}\left(\mathbf{Z_G} + \mathbf{Z_T} + \mathbf{Z_L} + \mathbf{Z_R}\right)} \qquad (6)$$

where: the impedances of generator (G), transformer (T), line (L), reactor (R) – if any are included

a.) Impedances for generators connected directly to the network (included correction factor K_G) are given:

$$\mathbf{Z_G} = R_G + jX_d^{"} \qquad K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{\max}}{1 + x_d^{"} \sin\varphi_{rG}} \qquad (7)$$

where: $R_G = 0{,}15.X_d^{"}$,

$X_d^{"}$ - subtransient reactance of synchronous machine,

K_G - correction factor for generators connected directly to the grid.

b.) Synchronous generator connected to the grid through a unit transformer:

$$\mathbf{Z_S} = t_r^2 \cdot \mathbf{Z_G} + \mathbf{Z_{THV}} \qquad (8)$$

$$K_{SO} = \frac{U_{nQ}}{U_{rG}\left(1 + p_G\right)} \cdot \frac{U_{rTLV}}{U_{rTHV}} \cdot \left(1 \pm p_T\right) \cdot \frac{c_{\max}}{1 + x_d^{"} \sin\varphi_{rG}} \qquad (9)$$

where: K_{SO} - correction factor for generators connected to the grid through a unit transformer.

c.) Impedance of asynchronous generators connected directly to the network is given:

$$Z_G = \frac{1}{I_{LR}/I_{rG}} \cdot \frac{U_{rG}}{\sqrt{3} I_{rG}} = \frac{1}{I_{LR}/I_{rG}} \cdot \frac{U_{rG}^2}{S_{rG}} \qquad (10)$$

where: $R_G = 0{,}1.X_G$,

$I_{LR}/I_{rG} = 8$ – typical ratio of locked-rotor current to rated current of the machine.

d.) For generators connected to the grid via power electronic converters [3]:

$$\mathbf{I}_{\mathbf{k}}^{"} = k.I_{rG} = c.t \ \text{(for time } \Delta t\text{)} \qquad (11)$$

where: Δt - is the maximum duration of the contribution, before the distributed generation unit is disconnected by its own protection. The value of Δt depended on the protection and fault. It is needed only for breaking and thermal current calculations.

A typical value of $k = 1{,}5$ - representing the short-time over-current capability of the grid-side converter. Special case of generator used for variable speed wind turbines is doubly-fed induction generator (DFIG). For this case we can use $I_{LR}/I_{rG} = 8$ and $R_G = 0{,}1.X_G$ for the generator impedance [3].

4. CASE STUDY

For the illustration of short-circuit current calculation including distributed generation units helps case study in Fig.2. Four distributed generation stations with total power cca 17 MW are connected to the medium voltage substation. They are three wind farms with six identical wind turbines and one small hydroelectric plant - SHP (with three identical turbines).

The data about case study network are given in Table 2.

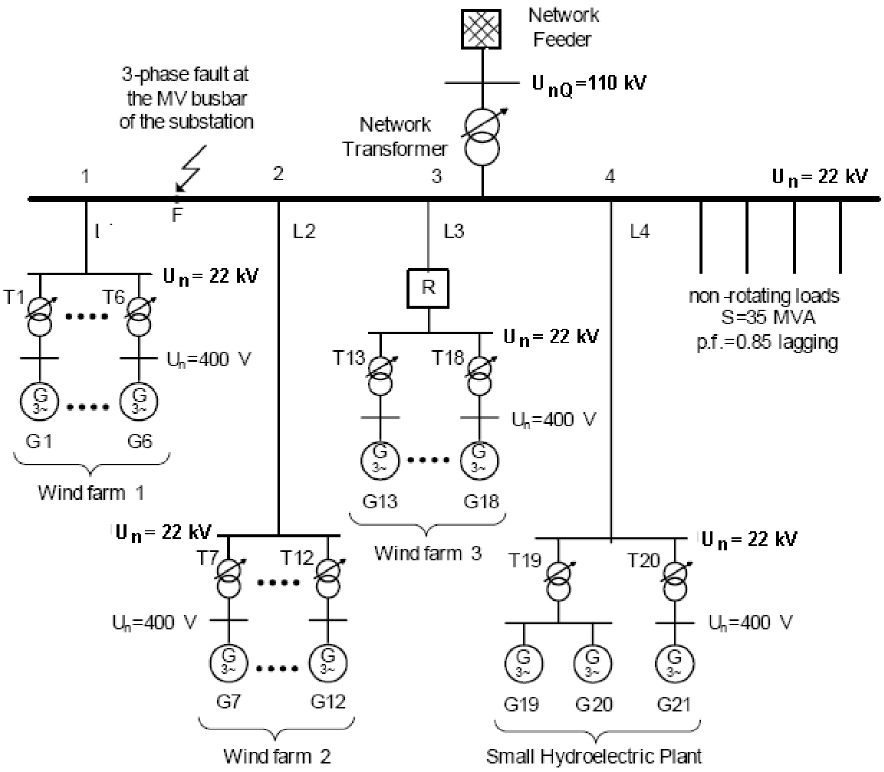

Fig.2. Case study

Tab.2 Data of the case study

Network feeder	$U_{nQ} = 110\ kV$, $S''_{kQ} = 2500\ MVA$, $R_Q / X_Q = 0{,}1$
Network transformer	$S_{rT} = 63\ MVA$, $u_{kr} = 17{,}5\ \%$, $\Delta P_{kT} = 360\ kW$, $t_r = 110/23\ kV$
Wind farm No.1	6 x 600 kW (G1-G6)
generator	synchronous with converter: $P_{rG} = 600\ kW$, $U_{rG} = 400\ V$, $I_{rG} = 866\ A$
transformer	T1-T6: $S_{rT} = 630\ kVA$, $u_{kr} = 6\ \%$, $u_{kRr} = 1{,}2\ \%$, $t_r = 22/0{,}4\ kV$
line L1	overhead line (22 kV): $R_L = 0{,}215\ \Omega/km$, $X_L = 0{,}334\ \Omega/km$, $l = 10\ km$ underground cable: $R_L = 0{,}162\ \Omega/km$, $X_L = 0{,}115\ \Omega/km$, $l = 0{,}5\ km$
Wind farm No.2	6 x 660 kW (G7-G12)
generator	DFIG: $P_{rG} = 660\ kW$, $U_{rG} = 400\ V$, $I_{rG} = 950\ A$
transformer	T7-T12: $S_{rT} = 700\ kVA$, $u_{kr} = 6\ \%$, $u_{kRr} = 1{,}2\ \%$, $t_r = 22/0{,}4\ kV$
line L2	overhead line (22 kV): $R_L = 0{,}215\ \Omega/km$, $X_L = 0{,}334\ \Omega/km$, $l = 10\ km$ underground cable: $R_L = 0{,}162\ \Omega/km$, $X_L = 0{,}115\ \Omega/km$, $l = 0{,}5\ km$
Wind farm No.3	6 x 850 kW (G13-G18)
generator	asynchronous: $P_{rG} = 850\ kW$, $U_{rG} = 400\ V$, $I_{rG} = 1225\ A$, $I_{LR} = 5{,}5\ kA$
transformer	T7-T12: $S_{rT} = 1000\ kVA$, $u_{kr} = 6\ \%$, $u_{kRr} = 1{,}1\ \%$, $t_r = 22/0{,}4\ kV$
reactor	$S_{rR} = 5\ MVA$, $U_{rR} = 22\ kV$, $u_{kr} = 14\ \%$
line L3	overhead line (22 kV): $R_L = 0{,}215\ \Omega/km$, $X_L = 0{,}334\ \Omega/km$, $l = 10\ km$ underground cable: $R_L = 0{,}162\ \Omega/km$, $X_L = 0{,}115\ \Omega/km$, $l = 1\ km$
Small hydro. plant	3 x 1500 kW (G19-G21)
generator	synchronous: $S_{rG} = 1650\ kW$, $U_{rG} = 400\ V$, $x''_d = 0{,}18\ p.u.$, $\cos\varphi = 0{,}9$
transformer	T19: $S_{rT} = 4\ MVA$, $u_{kr} = 6\ \%$, $u_{kRr} = 1\ \%$, $t_r = 22/0{,}4\ kV$ T20: $S_{rT} = 2{,}5\ MVA$, $u_{kr} = 6\ \%$, $u_{kRr} = 1\ \%$, $t_r = 22/0{,}4\ kV$
line L4	overhead line (22 kV): $R_L = 0{,}215\ \Omega/km$, $X_L = 0{,}334\ \Omega/km$, $l = 7{,}5\ km$

Table 3 shows fault level calculation results for a three-phase fault at the MV busbars of the substation.

Tab.3 Results of fault level calculations

Network feeder	$Z_Q = 5{,}3240\ \Omega \Rightarrow \mathbf{Z_{Qt}} = \mathbf{Z_Q} / t^2 = 0{,}0232 + j0{,}2316\ \Omega$
Network transformer	$\mathbf{Z_T} = 0{,}048 + j1{,}468\ \ \Omega,\ K_T = 0{,}9457 \Rightarrow \mathbf{Z_{Tt}} = 0{,}0454 + j1{,}3890\ \Omega$
Contribution of the upstream grid: $I''_{k3} = 8{,}6114\ kA \Rightarrow S''_{k3} = 328{,}1384\ MVA$	
Wind farm No.1	
generator	synchronous with converter: $I''_{ki} = 1{,}5.I_{rG} = 1{,}4250\ kA$
Contribution of the WF No.1: $I''_{k3} = 6.\left(I''_{ki} / t_r\right) = 0{,}1417\ kA \Rightarrow S''_{k3} = 5{,}3998\ MVA$	
Wind farm No.2	
generator	DFIG: $Z_Q = 0{,}0304\ \Omega \Rightarrow \mathbf{Z_{Qt}} = 9{,}1464 + j91{,}4641\ \Omega$
transformer	$\mathbf{Z_T} = 8{,}2971 + j40{,}6475\ \ \Omega,\ K_T = 1{,}0094 \Rightarrow \mathbf{Z_{Tt}} = 8{,}3751 + j41{,}0295\ \Omega$
line L2	$\mathbf{Z_L} = \sum_i R_i l_i + \sum_i X_i l_i = \mathbf{Z_{L2}} = 2{,}2310 + j3{,}3975\ \Omega$
Contribution of the WF No.2: $I''_{k3} = \dfrac{c_{\max} U_n}{\sqrt{3}\left(\mathbf{Z_{Gt}}/6 + \mathbf{Z_T}/6 + \mathbf{Z_{L2}}\right)} = 0{,}5300\ kA \Rightarrow S''_{k3} = 20{,}1943\ MVA$	
Wind farm No.3	
generator	asynchronous: $Z_G = 0{,}0420\ \Omega \Rightarrow \mathbf{Z_{Gt}} = \mathbf{Z_G}.t_r^2 = 1{,}2639 + j126{,}3900\ \Omega$
transformer	$\mathbf{Z_T} = 5{,}3240 + j28{,}5478\ \ \Omega,\ K_T = 1{,}0093 \Rightarrow \mathbf{Z_T} = 5{,}3734 + j28{,}8128\ \Omega$
reactor	$Z_R = X_R = 13{,}5520\ \Omega$
line L3	$Z_{L3} = 2{,}3120 + j3{,}4550\ \Omega$
Contribution of WF No.3: $I''_{k3} = \dfrac{c_{\max} U_n}{\sqrt{3}\left(\mathbf{Z_{Gt}}/6 + \mathbf{Z_T}/6 + \mathbf{Z_R} + \mathbf{Z_{L2}}\right)} = 0{,}3193\ kA \Rightarrow S''_{k3} = 12{,}1654\ MVA$	
Small hydroelectric plant	
generator	synchronous: $R_G = R_G / X''_d . x''_d . \left(U_{rG}^2 / S_{rG}\right) = 0{,}0026\ \Omega \Rightarrow \mathbf{Z_G} = 0{,}0026 + j0{,}0175\ \Omega$
transformer	$\mathbf{Z_{T19(HV)}} = 1{,}2100 + j7{,}1585\ \ \Omega,\ \mathbf{Z_{T20(HV)}} = 1{,}6000 + j9{,}4657\ \ \Omega$ $K_{T19} = 1{,}0092,\ K_G = 1{,}0415,\ K_{SO} = 1{,}0415$
$Z_1 = Z_{G19} // Z_{G20} + Z_{T19}$ $Z_2 = Z_{G21} + Z_{T20}$	$\mathbf{Z_1} = \dfrac{K_G \mathbf{Z_G}}{2} \cdot t_r^2 + K_{T19} \mathbf{Z_{T19}} = 5{,}3453 + j34{,}7188\ \Omega,\ \mathbf{Z_2} = K_{SO}\left(\mathbf{Z_G}.t_r^2 + \mathbf{Z_{T20}}\right) =$ $= 9{,}9147 + j64{,}8475\ \Omega$
line L4	$Z_{L4} = 1{,}6125 + j2{,}5050\ \Omega$
Contribution of SHP: $I''_{k3} = \dfrac{c_{\max} U_n}{\sqrt{3}\left(\mathbf{Z_1} // \mathbf{Z_2} + \mathbf{Z_4}\right)} = 0{,}5404\ kA \Rightarrow S''_{k3} = 20{,}5905\ MVA$	

3. CONCLUSIONS

We obtained following results:

- The fault level:
  - due to the upstream grid is 328,14 MVA,
  - due to the distributed generations is 52,95 MVA,
  - the total fault level: 381,09 MVA.
- Wind farm No.2 contributes about 4-times more short-circuit current than wind farm No.1, due to the different technology of generators.

- The reactor at the output of wind farm No.3 reduces its contribution of short-circuit current: without reactor, the current would increase by 45 % (0,4625 kA).
- Wind farm No.3 contributes less than wind farm No.2, although its power is higher (due to reactor).
- The most important is that the design fault level of such a distribution network would be around 350 MVA. Hence, the connection of amount of distributed generations (17 MW) drives the fault level to unacceptably high values.
- From a fault level perspective, distribution networks are not designed to accept large amounts of distributed generations [3]..

4. REFERENCES

[1] CEI IEC TR 60909: Short-circuit currents in the three-phase a.c. systems – Part 0: Calculation of currents. Slovenský ústav technickej normalizácie, April 2003.
[2] Mešter, M. Výpočet skratových prúdov v trojfázových striedavých sústavách. ABB Elektro, s.r.o., Bratislava, 2005, ISBN 80-89057-10-1.
[3] Boutsika, Th., Papathanassiou, S., Drossos, N.: Calculation of the fault level contribution of distributed generation according to IEC Standard 60909. http://users.ntua.gr/stpapath/index_en.htm
[4] CEI IEC TR 60909: Short-circuit currents in the three-phase a.c. systems – Part 4: Examples for the calculation of short-circuit currents. Slovenský ústav technickej normalizácie, April 2003.

This work was supported by Research and Development Support Agency under the contract No. APVT-20-026902 and by Scientific Grant Agency of the Ministry of Education of Slovak Republic and the Slovak Academy of Sciences under the projects VEGA No. 1/1061/04 and VEGA No. 1/3141/06.

Author address:
Ing. Marián Mešter, PhD.
Head of Data Grid Management
Východoslovenská energetika, a.s.
040 01 KOŠICE Slovak Republic
E-mail: mester_marian@vse.sk
Tel: +421 55 610 2396