THE INFLUENCE OF LARGE-SCALE DISPERSED CO-GENERATION ON SHORT CIRCUITS IN RURAL NETWORKS

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SUMMARY

Increasingly application of co-generation in industrial and rural areas forces distribution companies to search the limits of their networks. In this paper the maximum amount of co-generation in relation with the maximum admissable short-circuit currents at the connection to the main feeder is investigated in an existing 10kV network. From the results of simulations in the time domain simple calculation methods are derived to determine the maximum admissible number of co-generation units in this network.

INTRODUCTION

In the north of Holland large areas of glass houses are increasingly energized by dispersed co-generation units to satisfy the demand of electricity and heat. The separate 0.4 kV co-generation units are in the range of 0.4 - 1.2 MVA and are connected to a 10kV cable grid, being a part of the grid which also energizes parts of villages and townships. The bulk of energy is provided through a 50kV meshed grid with 50/10kV substations. The 10kV distribution network is radially under normal operation conditions .
In this paper is investigated how much additional co-generation power can be installed in the existing 10kV grid without exceeding the short-circuit limits in the existing grid and 50/10kV substations.
In the short-circuit calculations the instantaneous values of all line currents and the node voltages in the 10kV grid are given. From simulations of several short circuits in the 10kV grid a method is derived, which enables to calculate the maximum amount of co-generation in an existing infrastructure with the help of simple formulas, practical assumptions and data of protection devices.

ORIGINAL 10 kV NETWORK

Figure 1 depicts the original network used for this study. The radial 10kV-cable network is energized by the 50/10 kV transformer at node 1, being a part of a 50/10 kV substation. The cable and transformer data are given in table 1.
The total co-generation power installed in the 10 kV network is nearly 8 MVA, distributed as follows:

node 5:	3 units of 510 kVA	gen.1
node 16:	1 unit of 630 kVA	gen.2
node 17:	2 units of 630 kVA	gen.3
node 13:	3 units of 630 kVA	gen.4
node 12:	1 unit of 1125 kVA	gen.5
node 13:	1 unit of 1125 kVA	gen.6

10KV Distribution Network

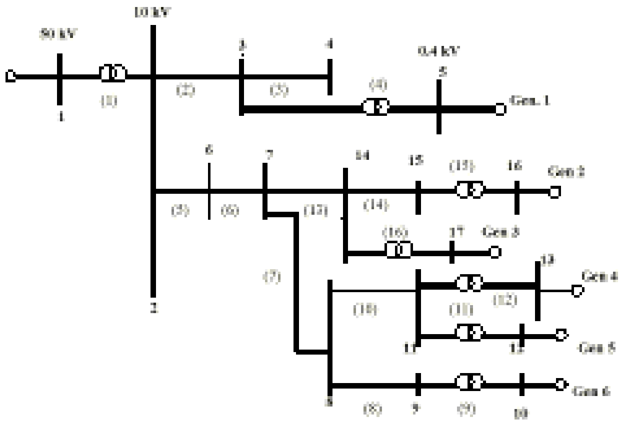


Figure 1

Cable / Trans-former	RK	XK	ZK
1	0.74	15.80	15.82
2	0.39	0.17	0.42
3	0.39	0.13	0.41
4	1.14	6.84	6.93
5	0.01	0.01	0.01
6	0.56	0.28	0.63
7	0.06	0.02	0.07
8	0.06	0.01	0.06
9	1.14	6.84	6.93
10	0.05	0.01	0.05
11	1.14	6.84	6.93
12	1.14	6.84	6.93
13	0.03	0.02	0.04
14	0.02	0.01	0.02
15	1.57	7.17	7.34
16	1.57	7.17	7.34

Table 1: Cable and transformer data in Ω

All generators have a rated voltage of 400V and are connected to the 10kV-grid through 10/0.4 kV transformers. The data of generators and transformers are given in table 2.

Unit	X"	ng	transf	Xk	nt	Xres	Rres	Zres	Fdamp
1	34.30	3	4	6.84	1	18.27	1.14	18.31	1.82
2	23.10	1	15	7.17	1	30.27	1.57	30.31	1.85
3	23.10	2	16	7.17	2	15.14	0.79	15.16	1.85
4	23.10	3	12	6.84	1	14.54	1.14	14.58	1.78
5	16.00	1	11	6.84	1	22.84	1.14	22.87	1.85
6	16.00	1	9	6.84	1	22.84	1.14	22.87	1.85

Table 2: generator-transformer impedances

The resulting reactance Xres is calculated from

$$X_{res} = \frac{X''}{ng} + \frac{X_k}{nt}$$

where X" is the sub-transient reactance and ng is the number of coherent generators connected to one node. Xk is the transformer leakage reactance and nt the number of transformers in parallel. Zres is the resulting impedance, including the transformer resistance.
The secondary 10kV-busbar, node 2, is dimensioned for 37 kA peak value. During a short circuit at node 2 the peak value of the current from the 50kV side is about 25 kA.
The protection and isolation of the feeder cables from the 50/10 kV substation, node 2, to the 10kV-grid is performed by Magnefix type MD4 load break switches. The rated current is 400 A, the maximum peak value is 31.25 kA.

SHORT-CIRCUIT CALCULATIONS

Knowledge about the short-circuit current values in distribution networks is important for the protection of installed equipment and components. For the possible damage to equipment and components, we consider different aspects of the short-circuit current. The sub-transient current is responsible for the maximum electromagnetic forces, but the time duration of the current and the shape of its curve determines the thermal stress of equipment and components. Both aspects have to be treated.

For the calculation of the time duration of the short-circuit currents SIMNET [1] is used. This simulation program enables the calculation of grid currents, node voltages and machine-state variables in the time domain. The result is the instantaneous values of currents and voltages including their DC components. The generator-models consist of the well-known 7^{th}-order Park equations.
The graphical output of each three-phase current and voltage can be depicted in three “sinusoidal” curves. During the transient state, a significant difference in the instantaneous values of the three phases can occur. SIMNET offers the possibility to display the maximum instantaneous value of the current and/or voltage appearing in the three phases. This quantity is the magnitude of the time-dependent positive-sequence phasor [2], which includes all information about the three phase currents and is independent of the instant of closing into a fault. The maximum value of the short-circuit current is calculated.

To develop a fast but accurate calculation of the first maximum in the time-dependent short-circuit current in a radial network, the following approaches are used.

- When the resulting impedances Zres of the supply units, consisting of one or more transformers and generators , are considerable greater than the impedances of the network cables, as a first approximation, the influence of the cable impedances can be neglected in the calculation. As a consequence ,the short-circuit current is the total of the short-circuit current in line 1 and the short-circuit currents in the supply units. The separate contributions to the short-circuit current are calculated by dividing the generator voltage by the resulting impedance Zres, see table 2. This gives the RMS value of the steady-state short-circuit current Iac. To obtain the peak value at t=0, including the maximum DC-term, the result must be multiplied by $2\sqrt{2}$:

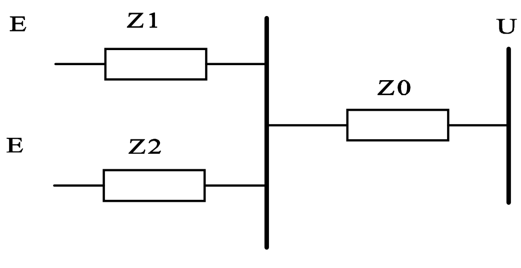
$$I_{sc}(PEAK) = 2\sqrt{2}\, I_{ac}(RMS)$$

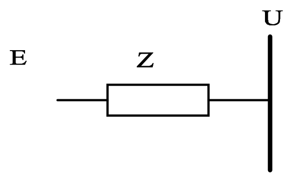
- The method can be extended by including a damping factor. After applying a short circuit, the first peak of the short-circuit current appears after 1/4 period of the rated network frequency i.e. after 10 ms when f=50Hz. In that time the DC-component has diminished with a factor

$$e^{-\alpha}\text{, where } \alpha = \omega \frac{R_{res}}{X_{res}} t = \pi \frac{R_{res}}{X_{res}}$$

The peak value of the short-circuit current Isc(PEAK) can be calculated as follows:

$$I_{sc}(RMS) = F_{damp}\, I_{ac}(RMS) \text{ where } F_{damp} = 1 + e^{-\alpha}$$
$$I_{sc}(PEAK) = I_{sc}(RMS)\sqrt{(2)}$$





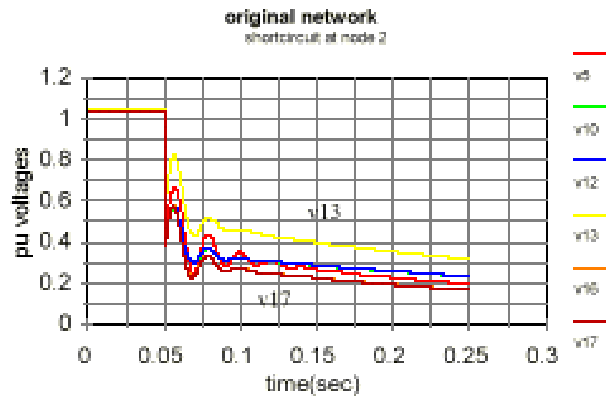


Figure 3 : generator-node voltages

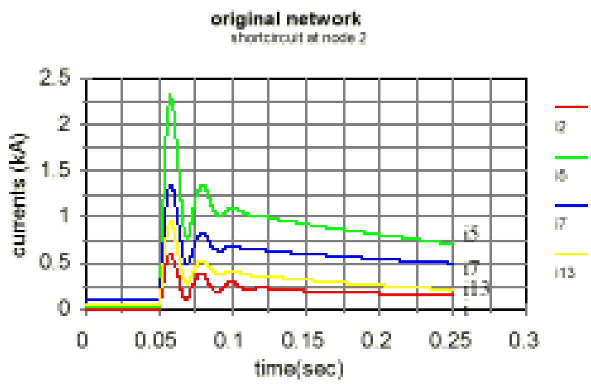


Figure 5: line currents

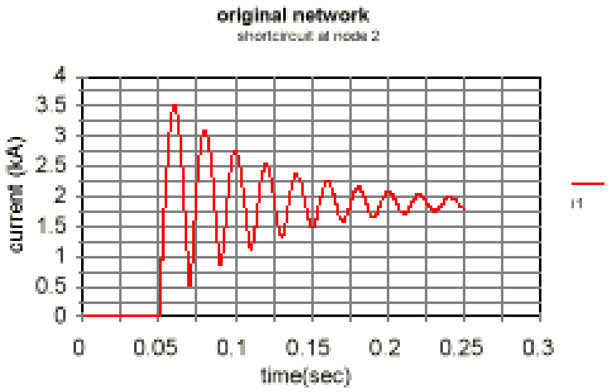


Figure 4 : line current 1

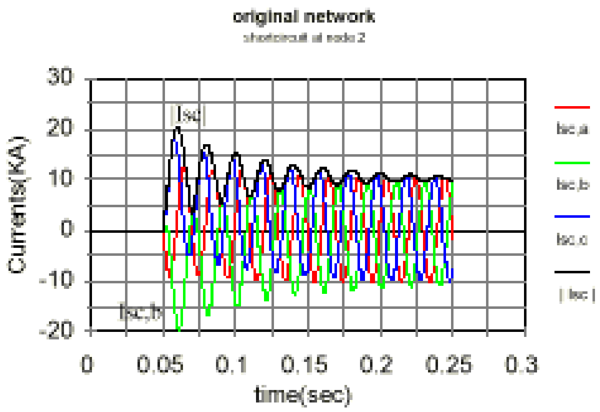


Figure 6: Short-circuit current at node 2

- When one or more cable impedances have a significant influence on the short-circuit current they can be included into the calculation through the following reduction technique. In figure 2 two different supply units with the complex impedances Z1 and Z2 are connected to the grid through a cable with complex impedance Z0. This network can be replaced by one impedance Z', when we assume that the generator voltages are equal.

The impedance Z' is calculated as:

$$\frac{1}{Z'} = \frac{1}{Z_{1'}} + \frac{1}{Z_{2'}}$$

where

$$Z_{1'} = Z_1 + Z_0\left(1 + \frac{Z_1}{Z_2}\right)$$

$$Z_{2'} = Z_2 + Z_0\left(1 + \frac{Z_2}{Z_1}\right)$$

With this reduction technique all generating units in one branch, including the cables connected, can be reduced to one impedance connected to the node where the short circuit is applied. From the resulting impedance of the reduced branch the damping factor Fdamp is calculated. Finally, the short-circuit current is the sum of the branch currents at the short-circuited node.

Short circuit at node 2 in the original network

In the network, depicted in figure 1, the generators are loaded at 80% of their rated values, which represents a generating power of 6.4 MVA. The total load in the network is approximately 6 MVA. At t=0.05 sec a symmetrical short circuit is applied to the main busbar at node 2. The simulation results are shown in figs 3-6.

In figure 3 the voltages at the generator nodes 5, 10, 12, 13, 16 and 17 are depicted, while figures 4 and 5 show the maximum RMS line currents in the lines 1 and 2, 5, 7 and 13 respectively. Figure 6 shows the three phase currents and the maximum current |Isc| at node 2.

***Note that |Isc| is approximately the envelope curve and that the result has to be multiplied by √2 to obtain the actual peak value*.**

In figure 2 it can be seen that the generator-node voltages become lower than 80%, which will cause the generators to be disconnected from the grid in today's practice.

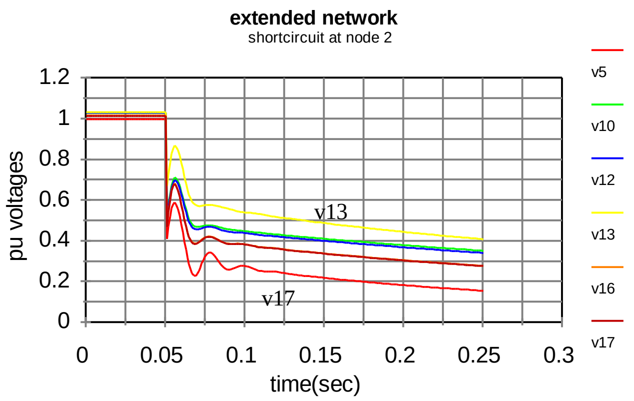


Figure 7: node voltages

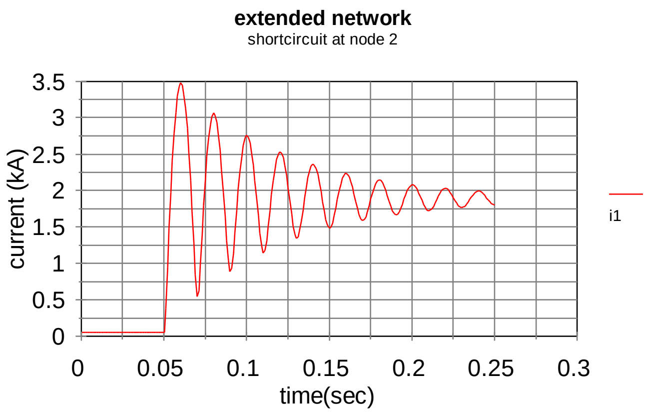


Figure 8: max. Line current 1

The first peak in the short-circuit current curves, calculated by approximations and from the simulation are given in table 3.

Approx	1	2	3	simulation
line 1	18.25	17.51	17.51	17.50
gen 1	0.65	0.59		
line 2	0.65	0.59	0.57	0.60
gen 2	0.39	0.36		
gen 3	0.78	0.73		
line 13	1.18	1.09		0.95
gen 4	0.82	0.73		
gen 5	0.52	0.48		
gen 6	0.52	0.48		
line 7	1.86	1.69		1.30
line 5	3.03	2.78	2.12	2.30
Isc(RMS)	21.93	20.89	20.20	21

Table 3: Maximum short-circuit currents in kA related to 10kV
1: Only Zres, 2: including Fdamp, 3: including cables

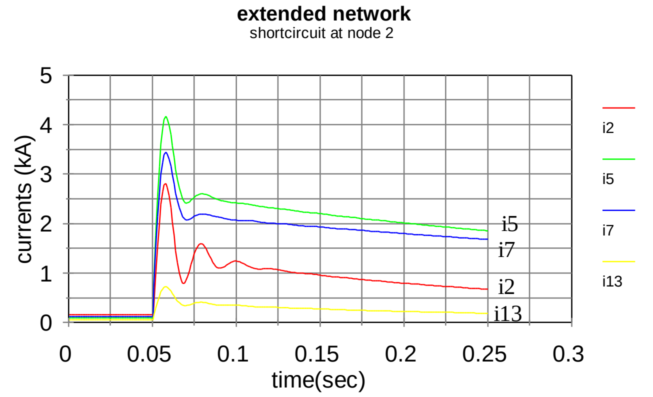


Figure 9: Max. Line currents

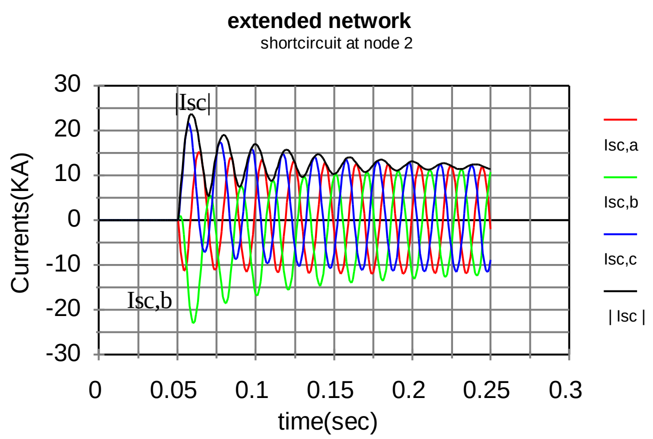


Figure 10: Short-circuit current at node 2

From the original network it is clear that all calculation methods provide satisfactory results. The peak value of the short-circuit current is 30 kA and does not exceed the maximum current of 37 kA for the substation. Also the currents in the lines connected to node 2 stay below their limits.

Short circuit at node 2 in an extended network

The amount of co-generation is increased with 17.9 MVA by extending the number of units in node 9 to 11 coherent units of 1125 kVA and in node 5 to 14 units of 510 kVA. The total generating power is 0.8 x 25.9 = 21 MVA.
The number of parallel transformers of the supply units involved and the local loads in the network are adjusted to match the increased rated power.
The resulting impedances of the supply units are given in table 4.

Unit	X"	ng	transf	Xk	nt	Xres	Rres	Zres	Fdamp
1	34.30	14	4	6.84	7	3.43	0.16	3.43	1.86
2	23.10	1	15	7.17	1	30.27	1.57	30.31	1.85
3	23.10	2	16	7.17	2	15.14	0.79	15.16	1.85
4	23.10	3	12	6.84	1	14.54	1.14	14.58	1.78
5	16.00	1	11	6.84	1	22.84	1.14	22.87	1.85
6	16.00	11	9	6.84	11	2.08	0.10	2.08	1.85

Table 4: generator-transformer impedances

The simulation results of this case are depicted in the figures 7 - 10 similarly as in the previous example.
The first peak of the short-circuit currents and the result obtained from the simulation are given in table 5.
When the amount of co-generation power is increased with a factor three , it is observed that no longer the simple calculation methods are in agreement with the simulation results. They give too high values for the maximum short-circuit currents. This means that the influence of the cable impedances can not be neglected any more.

Approx	1	2	3	simulation
line 1	18.25	17.51	17.51	17.50
gen 1	3.47	3.23		
line 2	3.47	3.23	2.65	2.80
gen 2	0.39	0.36		
gen 3	0.78	0.73		
line 13	1.18	1.09		0.70
gen 4	0.82	0.73		
gen 5	0.52	0.48		
gen 6	5.72	5.31		
line 7	7.06	6.51		3.40
line 5	8.23	7.60	3.98	4.20
Isc(RMS)	29.95	28.34	24.14	23.8

Table 5: Maximum short-circuit currents in kA, related to 10 kV
1: Only Zres, 2: including Fdamp, 3: including cables

The currents, due to co-generation in lines 2 and 5 are considerably under their limits. The peak value of the short-circuit current at node 2 has increased to 34 kA, which is still below the maximum value of 37 kA. In comparison with the previous case it learns that the increase of the peak value of the short-circuit current is only 4 kA. A further increase in generating power up to 44 MVA shows a short-circuit current of 37 kA. Meanwhile we have about 5.5 times the original amount of co-generation installed. This result leads to the conclusion that the impedance in the grid is a major limiting factor for the short-circuit current in rural cable networks. This is in particular true when the power generation is situated at some distance of the substation. Large amounts of co-generation, situated closer to the substation, have a greater influence on short-circuits in the substation, what can be verified with the calculation approach in this paper.

Another important issue is the stability of the system. The influence of the presence of large amounts of co-generation in rural radial networks on the stable operation in normal state and during disturbances has to be investigated separately. This holds both for rotor-angle and voltage stability including the tap-changer control of the 50/10kV substation transformer.

CONCLUSIONS

For the determination of the short-circuit power at the busbar of a substation, due to dispersed co-generation in the distribution network connected, no general rule can be given. The short-circuit power depends strongly on the underlying network and where the co-generation units are situated.
Three approximations for the calculation of the peak-value of the short-circuit current in radial networks with significant dispersed co-generation have been given.
The first two approaches can be applied when the resulting impedances of generating units including their transformers are much greater than the cable impedance between the units and the place of disturbance.
The third calculation method, which can be programmed into a spread-sheet easily, also provides proper results when, due to large increase in co-generation and therefore more parallel co-generator units, the resultant impedances are in the order of the cable impedances. The results of these methods are compared with the results of numerical simulations and show good agreement.

REFERENCES

[1] G.C.Paap, “SIMNET, network simulation program”, Department of Electrical Engineering, Delft University of Technology, The Netherlands.

[2] G.C.Paap, “Symmetrical Components in the Time Domain and their Application to Power Network Calculations”, *submitted for publication in IEEE Trans. on Power Systems.*