CALCULATION OF SAG QUANTITIES INCLUDING PROTECTION SETTINGS AND BREAKERFAILURE IN VOLTAGE SAG PREDICTION.

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ABSTRACT

Of all power quality aspects voltage sags are the Dutch main Power Quality concern. At PNEM, a utility company in the southern part of the Netherlands, a computer program has been developed which can predict voltage sags at any substation in the medium voltage grid. With the use of this program we are able to present our customers a quantification of the kind, the severity and frequency of sags to be expected at a specific site. This paper presents the calculation method and how the results can be used to verify the need for and the effect of sag mitigation techniques.

INTRODUCTION

Although the average Dutch medium voltage customer only suffers five sags per year, the damage those (comparatively) few dips cause, still aggravates these customers. The satisfaction of the customers is depending on the ratio of the experienced sags to the expected sags.

Because of the deregulation of the regional electricity companies (REC's), this item plays more and more an important role. The customers want to know what kind of sags they can expect and they want an estimation of the frequency of their occurrence.

PNEM has developed a computer tool for system analysis. These analysis are based upon systematic calculation of short circuit currents and voltages on many points of the system. The behavior of the protection relays and the probability of breaker/protection failure are taken into account. A part of the results of these analysis predict the severity and frequency of voltage sags due to short circuits.

This paper will first introduce the concept of the MV grids at PNEM, then the different possibilities of characterizing sags are shown. After that the calculation method itself will be discussed. Then the results of a specific case study follows. At the end a conclusion will be given.

CHARACTERISTICS OF THE PNEM 10 kV SYSTEM

At PNEM large customers are connected to the MV-grid (10 kV). A part of the 10 kV grid is meshed built and operated: this is in fact a sub-transmission grid.

An other part is meshed built but radial operated: the distribution grid. The sub-transmission grids are fed from the 150 kV system through Yd-transformers of 35 to 77 MW.

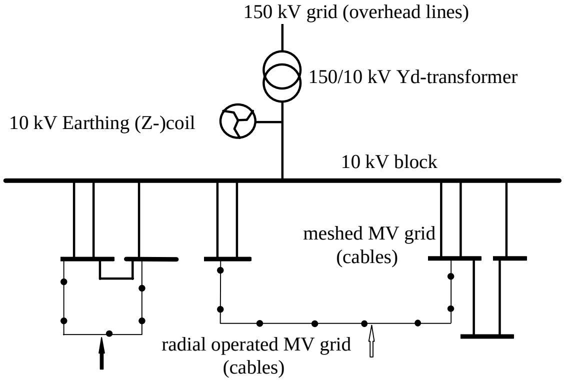

Figure 1: Typical PNEM MV grid

The protection system of the meshed operated part consists of single distance or differential relays. The protection system of the radial operated part consists of definite time overcurrent relays.

The 150 kV grid is built as overhead lines. There are Petersen coils installed for system earthing.

The 10 kV grid (sub-transmission and distribution parts) consist completely of cables. Thus we apply no autoreclosure in the 10 kV system. Earthing coils are installed to limit the phase to earth fault currents to a maximum of 2500 A.

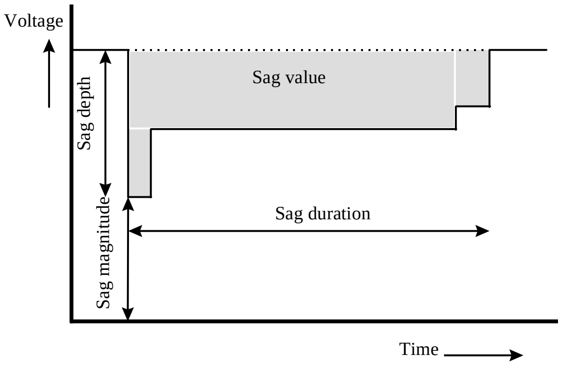

Figure 2: Characterization of sags

Due to the relative high short circuit power (between 25 and 300 MVA) and the relative low motor powers (< 1 MW), most sags are due to short circuits and not to heavy starting loads.

CHARACTERISTICS OF SAGS

Sags can be characterized in a number of ways. See figure 2. One way is the duration of the sag. Another possible and often used variable is the magnitude of the remaining voltage (sag magnitude).

For voltage sag mitigation devices (UPS/DVR), the complement of the sag magnitude, the sag depth is more meaningful. However the relation between these two values should be seen vectorial. See figure 3. This is particular so when we talk about equipment that is sensitive to jumping of phase angles [1,2].

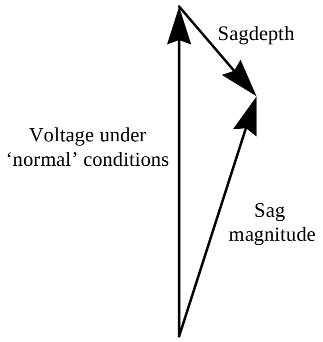

Figure 3: Relation between depth and magnitude of a sag

Another important characteristic can be given by the 'sag value'. This is the drop in rms voltage integrated over the sag duration. This must be calculated for every portion of the time that the sag depth changes due to switching actions. In combination with the ratings of the equipment to be protected, this value gives an indication of the energy that is needed by the sag mitigation devices to restore the voltage.

The above mentioned characteristics: duration, magnitude, depth and value are all characterizations of the sags themselves. However to determine whether a specific node in the system is sensitive for the occurrence of sags there are two more figures to be determined.

First there are the so called 'critical distances' or fault positions [3,4]. For every node in the system it is possible to calculate tables in which we can see what the severity of a short circuit (depth and/or value of the sag) would be, should it occur on a particular spot in the system. In this manner a sort of map of the grid where short circuits cause problematic sags can be created.

Second the so called 'sensitive length' can be calculated. The length of all the (parts of the) cables where a short-circuit could cause a problem is added. Problems can be caused by sag depth or sag value.

CALCULATION METHOD

Originally the software was developed for the analysis of the configuration of our MV grids and its protection schemes. Different schemes and configurations can easily be compared. The used short circuit calculation algorithm is very simple. Therefore it is possible to obtain relative short calculation times. The loads in the system are assumed to have a constant impedance. This is not correct but the deviations are small enough to be neglected for our purpose. Because of the relative short distances in our grids, the transport of reactive power also produces only small problems in the calculations. Later on we also applied the program for our 150 kV system. This was possible because of the relative short distances in this grid.

The complete analysis software is based on the systematic calculation of short circuits in every part of the grid.

In every situation we first perform a short-circuit calculation to determine the currents in every cable or line and the remaining voltage on every node.

The characteristics of the distance and differential relays are known and the settings are given in the input of the program.

We also take into account the reactions of the relays on phase to earth faults, the over-current, the under-impedance and the under-voltage behavior and the possibility for trip commands between one relay and another.

With the voltages and currents from the short circuit calculations we can determine the reaction of every differential, distance or overcurrent relay in the system.

For distance relays the (electrical) distance to the fault is calculated.

Calculation of sag duration, depth and value:

When all the reaction times of the relays are known, the relays which will give the first trip command can be determined. This is the duration of the first part of the sag. The depth of the sag on every node in the system until this time is also known. Multiplication of all these depths with the duration gives the sag values for all the nodes.

Next the cables that have received a trip command are taken out of service. Now a new short circuit calculation is performed. Then the reaction of all the relays in the system giving us the values for the following part of the sag are determined. We keep recalculating until there are no more relays that produce trip commands. The deepest sag depth during these calculations will be registered in the tables for the 'critical distances'. When there are no more currents flowing other than the currents due to the loads in the system and the node or cable in which the short circuit was simulated is isolated, all the quantities for this particular sag are determined. When the short circuited cable or node is not isolated from the system, a (severe) situation occurs in which the protection scheme has failed to isolate the fault. In this case it is assumed that the final result of this short circuit will eventually cause the whole MV-system (the 150/10 kV transformer) to go down. This means that in this case there is no sag for all of the nodes in this part of the system!

Determination of the chance of occurrence:

Short circuits are simulated on every node and many times in every cable, e.g. every 3 % of the length of the cables. It is assumed that the probability of a short circuit in a cable is directly coupled with the length of the cables. The value

of this probability is known from the fault registration system of PNEM [5].
The breakers in the medium voltage grids have the bad habit of failing sometimes. Sometimes due to failures in the breakers, sometimes due to failures in the protection system. This figure also follows from the same registration system. With the following procedure the effect of failure of breaker/protection is taken into account:
After the calculations of the sag properties due to all the simulations of short circuits in a specific cable (or on a specific node) the software determines which breakers have received a trip command during any of these simulations. For these breakers, one by one, a failure of the breaker/protection system is simulated by setting the reaction time of the relay to infinity. Then all the short circuit simulations for that particular cable (or node) are repeated. Now the back-up system will react (or fail) as in reality. We only assume one breaker to fail at the same time. The 'critical distance' for these situations are not (re)determined. First because in most cases this value will not be affected, secondly because in this value it is not possible to account for the probability of protection/breaker failure.

In the MV system the probability of a short circuit on a substation is neglected with respect to the probability of a short circuit in a cable. This is not the case in the HV system.
When all the simulations are completed and the reaction to short circuits anywhere in the system is known, the 'sensitive length' for each node can be determined by simply adding all the lengths of the cables where the sag depth or sag value due to a short circuit in that part of the cable is higher than a certain value. These values were registered in the tables for the 'critical distances'. This is done for every node in the system.

RESULTS

Let us now take a closer look at the results of calculations that have been made on the grid of figure 4. It is to be noted that in figure 4 not all the cables that are present in the system are drawn.
In the input for the calculations (as in reality) there were 26 cables with an average length of 3.7 km in the meshed part, protected by differential and distance relays and 153 cables with an average length of 1.5 km in the radial operated part, protected by 98 overcurrent relays.

First the contribution of the sags in the 150 kV grid are calculated for the node to which the transformer is connected. In substations 10 % of the short circuits are assumed to be multi phase faults. For the overhead lines this is 15 %. Single phase faults in the HV system have no effect because of the Peterson coil. These figures are added to the figures of all the nodes in the MV grid. In the MV grid a combination of 35% single phase faults and 65% multi phase faults is used, numbers that originate from the earlier mentioned fault registration system of PNEM.

From this same registration system we also know the probability of a short circuit in a cable. In the calculations a probability of 0.021 occurrences/km/year is used. For the probability of breaker/protection failures a value of 5 % is taken. Unfortunately this also is a realistic number for the MV system.

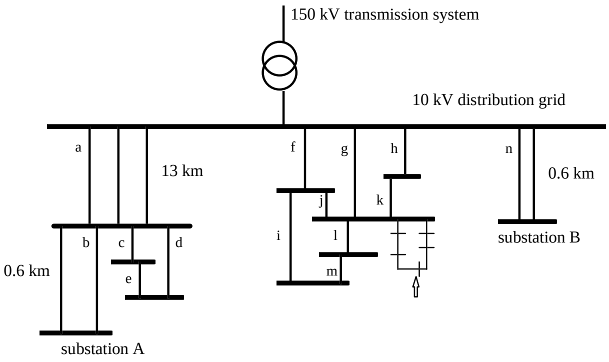

Figure 4: Simplified MV grid

Basically the program gives three important results: sag profiles, critical distances and sensitive length.

Sag profiles

The software produces sag frequency profiles or voltage sag coordination charts [10]. For the substations A in our case study the table 1 was calculated. We can also present these figures in the form of a 3D-plot (figure 5):

Table 1: Sag frequency in #/year for substation A

Sag depth	Sag duration in seconds							
	> 3 s	>2½-3 s	>2-2½ s	>1½-2 s	>1-1½ s	>½-1 s	>0.1-½ s	<=0.1 s
10 - 20 %	0.0662	0	0.0015	0.0064	0.2852	0.3321	0.2769	0.2479
20 - 30 %	0.0099	0	0.001	0.0037	0.06	0.1743	0.1717	0.0624
30 - 40 %	0	0	0.0016	0.0045	0.0719	0.2665	0.2708	0.042
40 - 50 %	0	0	0.0014	0.0037	0.0049	0.1057	0.3839	0.0646
50 - 60 %	0.0001	0	0.0018	0.0056	0.0364	0.1108	0.2043	0.2453
60 - 70 %	0.0068	0	0.0017	0.0008	0.0543	0.0849	0.1494	0.0946
70 - 80 %	0.0322	0	0.0369	0.0083	0.0538	0.097	0.1691	0.367
80 - 90 %	0	0	0.0014	0.0007	0.0745	0.0709	0.0751	0.1795
>= 90 %	0.0001	0	0.0011	0.0148	0.0719	0.0341	0.1211	0.0851

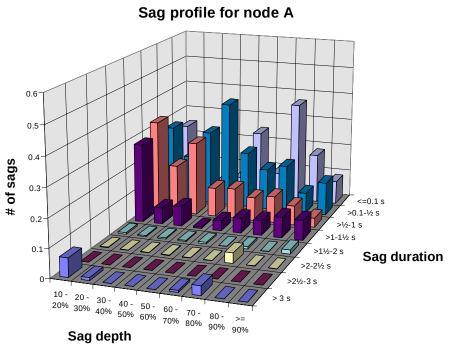

Figure 5: Sag profile substation A

For a even better insight in the figures it is better to present a graph of the cumulated frequencies [6]. See figure 6 for substation A.

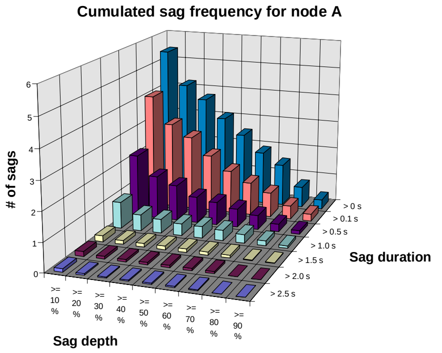

Figure 6: Cumulated sag frequency substation A

In this plot we can see what the minimal specifications of a sag mitigation technique must be in order to mitigate a certain number of sags [5].

As previously mentioned there is also the possibility to present the sag values instead of sag depth. Now we have one table (table 2) or 2 2D-plots (figures 7 and 8) for the figures of two substations A and B.

Table 2: Sag value frequencies

Sag value frequencies		
Sag value in procent*sec	# of sag/year	
	Node A	Node B
> 250 %s	0	0
>240 - 250 %s	0	0
>230 - 240 %s	0.0003	0
>220 - 230 %s	0.0006	0
>210 - 220 %s	0.0006	0
>200 - 210 %s	0.0004	0
>190 - 200 %s	0.0003	0
>180 - 190 %s	0.0108	0.0001
>170 - 180 %s	0.0085	0.0047
>160 - 170 %s	0.0026	0.0025
>150 - 160 %s	0.0008	0.0007
>140 - 150 %s	0.0285	0.0256
>130 - 140 %s	0.0542	0.0264
>120 - 130 %s	0.0649	0.0312
>110 - 120 %s	0.0543	0.0245
>100 - 110 %s	0.0435	0.0161
> 90 - 100 %s	0.0678	0.0525
> 80 - 90 %s	0.0991	0.0647
> 70 - 80 %s	0.0768	0.0593
> 60 - 70 %s	0.1406	0.1623
> 50 - 60 %s	0.1223	0.1725
> 40 - 50 %s	0.24	0.1867
> 30 - 40 %s	0.5848	0.2405
> 20 - 30 %s	0.8719	0.4032
> 10 - 20 %s	1.1384	1.5118
<= 10 %s	1.8006	1.6574

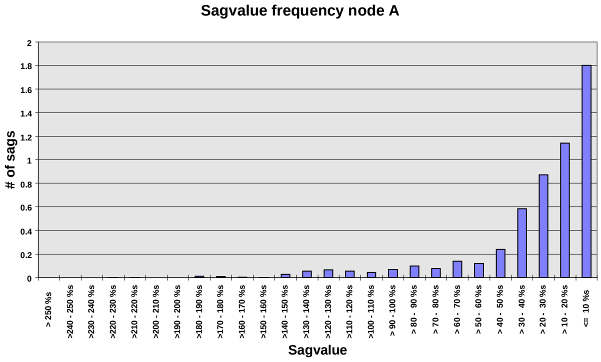

Figure 7: Sag value frequency for substation A

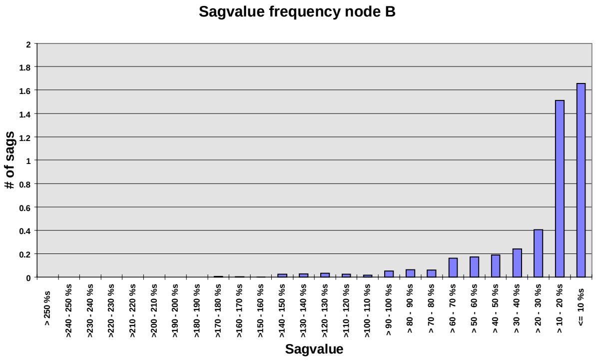

Figure 8: Sag value frequency for substation B

These figures are very useful to determine the effect of sag mitigation techniques [5] in order to make a cost benefit analysis.

Critical distances

Let us now look at the tables for the critical distances. Only the columns of the cables that are numbered in figure 4 are shown (table 3).
The way to read this table is as follows: When a three phase fault occurs on a distance of 10.5% from the beginning of cable ‘a’, there will be a sag depth of 85% on substation A.

Table 3: Critical distances (sag depth) substation A

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Critical distances (sag depth in % for multiphase fault) for node A:

Distance¦ Cable
   [%]  ¦   a    b    c    d    e    f    g    h    i    j    k    l    m    n ¦
--------¦-------------------------------------------------------------------------
     1.5¦  97  100  100   99   81   99   99   99   69   74   74   73   49  100 ¦
     4.5¦  92  100   99   97   80   97   96   98   68   73   73   73   49   99 ¦
     7.5¦  88  100   98   95   80   95   94   97   67   73   73   72   49   99 ¦
    10.5¦  85  100   97   94   79   93   92   96   65   73   73   71   49   99 ¦
    13.5¦  82  100   97   92   79   91   90   95   64   73   73   70   49   99 ¦
    16.5¦  80   99   96   91   79   90   88   94   63   73   73   69   49   98 ¦
    19.5¦  78   99   95   89   78   88   86   93   62   72   73   69   49   98 ¦
    22.5¦  76   99   94   88   78   86   84   92   61   72   72   68   49   98 ¦
    25.5¦  75   99   94   87   77   85   82   91   60   72   72   67   50   98 ¦
    28.5¦  74   99   93   86   77   84   81   90   59   72   72   66   50   97 ¦
    31.5¦  73   99   92   84   77   82   80   89   58   72   72   66   50   97 ¦
    34.5¦  73   99   92   83   76   81   78   88   58   71   72   65   50   97 ¦
    37.5¦  72   99   91   82   76   80   77   87   57   71   72   64   50   97 ¦
    40.5¦  72   99   91   82   76   79   76   86   56   71   72   64   50   96 ¦
    43.5¦  72   99   90   81   76   78   75   85   55   71   72   63   50   96 ¦
    46.5¦  72   99   89   80   75   77   74   84   55   71   72   63   50   96 ¦
    49.5¦  72   99   89   79   75   76   74   84   54   71   72   62   50   96 ¦
    52.5¦  73   99   88   78   75   75   73   83   54   71   72   62   51   96 ¦
    55.5¦  73   99   88   78   75   75   72   82   53   71   72   61   51   96 ¦
    58.5¦  74   99   87   77   74   74   72   81   53   70   72   60   51   95 ¦
    61.5¦  75   99   87   77   74   73   72   81   52   70   72   60   51   95 ¦
    64.5¦  76   99   86   76   74   73   71   80   52   70   72   59   51   95 ¦
    67.5¦  77   99   86   76   74   72   71   80   51   70   72   59   52   95 ¦
    70.5¦  78   99   85   75   74   72   71   79   51   70   72   59   52   95 ¦
    73.5¦  80   99   85   75   74   71   71   78   51   70   73   58   52   95 ¦
    76.5¦  81   99   84   74   74   71   71   78   51   70   73   58   52   95 ¦
    79.5¦  83   99   84   74   73   71   71   77   50   70   73   57   53   95 ¦
    82.5¦  85   99   83   74   73   71   71   77   50   70   73   57   53   95 ¦
    85.5¦  87  100   83   74   73   70   71   77   50   70   73   57   53   95 ¦
    88.5¦  89  100   83   74   73   70   72   76   50   70   74   56   53   95 ¦
    91.5¦  92  100   82   73   73   70   72   76   50   70   74   56   54   95 ¦
    94.5¦  94  100   82   73   73   70   73   75   50   70   74   55   54   95 ¦
    97.5¦  97  100   81   73   73   70   73   75   49   70   74   55   55   95 ¦
--------¦-------------------------------------------------------------------------
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Let us assume that we have equipment installed on substation A which could withstand a sag depth of 75% or less. In this table we see that the equipment is vulnerable for multi phase short circuits anywhere in cables ‘b’, ‘c’ and ‘n’ and for almost the whole length of cable ‘h’. Remarkable is the lower sag depth in the middle part of cable 'a', due to the meshed operation. With the help of this table we can mark the vulnerable locations in figure 4 to obtain figure 9.

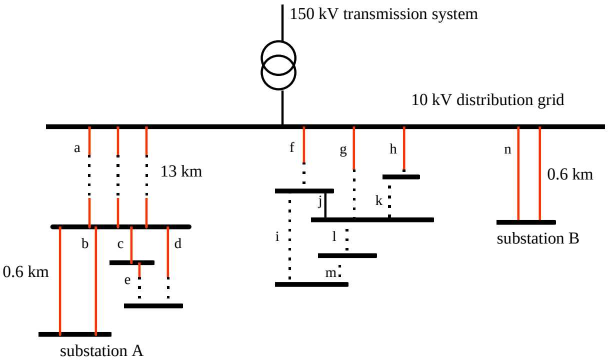

Figure 9: Marked cable parts for sag depth on substation A > 75 %

Multi phase faults in the dotted parts of the cables result in a sag depth on substation A of less than 75 %, while faults in the solid drawn cables result in a sag depth of 75 % or more.

We can go through the same procedure for substation B. The result is shown in figure 10.

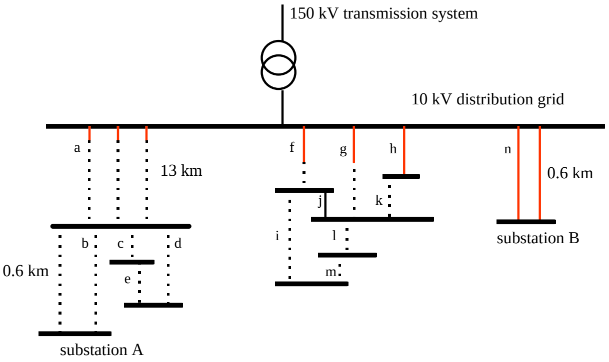

Figure 10: Marked cable parts for sag depth on substation B > 75%

In these pictures we get a very good overview of the critical locations in the grid.

In stead of the sag depth we can also use the sag value. Then we get a complete different picture. We present here table 4 for substation A. The way to read this table is as follows: When a three phase fault occurs on a distance of 10.5% from the beginning of cable 'a', there will be a sag value of 8 %s on substation A.

Table 4: Critical distances (sag value) substation A

Critical distances (sag value in %s for multiphase fault) for substation A:

Distance [%]	Cable a	b	c	d	e	f	g	h	i	j	k	l	m	n
1.5	14	0	103	110	48	20	20	20	7	7	114	7	5	18
4.5	14	0	103	109	48	19	16	20	7	7	115	7	5	10
7.5	9	0	102	107	48	16	16	20	7	7	115	7	5	10
10.5	8	0	101	94	48	16	16	16	7	7	116	7	5	10
13.5	8	0	100	92	49	16	16	16	6	7	117	7	5	10
16.5	8	188	100	90	49	16	16	16	6	7	118	7	5	10
19.5	8	187	95	89	49	16	16	16	6	7	119	7	5	10
22.5	8	187	94	87	49	16	16	16	6	7	120	7	5	10
25.5	7	186	94	86	50	16	16	16	6	7	121	7	5	10
28.5	7	186	93	84	50	16	16	16	6	7	122	7	5	10
31.5	7	186	92	83	50	16	16	16	6	7	123	7	5	10
34.5	7	185	92	81	50	15	16	16	6	7	124	7	5	10
37.5	7	185	91	80	51	15	16	16	6	7	22	6	5	10
40.5	7	185	91	79	51	15	16	16	6	7	22	6	5	10
43.5	7	184	89	78	17	15	16	16	6	7	22	6	5	10
46.5	7	184	88	76	17	15	16	16	5	7	22	6	5	10
49.5	7	183	88	75	17	16	16	16	5	7	22	6	5	10
52.5	7	183	87	74	17	16	16	16	5	7	22	6	5	10
55.5	7	183	86	73	17	16	16	16	5	7	22	6	5	10
58.5	7	182	86	72	18	16	16	16	5	7	22	6	5	10
61.5	7	182	85	71	18	16	17	16	5	7	22	6	5	10
64.5	8	182	85	70	66	16	17	16	5	7	22	6	5	10
67.5	8	181	84	69	65	16	17	16	5	7	86	6	5	10
70.5	8	181	83	69	65	16	17	16	5	7	85	6	5	10
73.5	8	181	83	68	64	16	17	16	5	7	84	6	5	9
76.5	8	180	82	67	64	16	18	16	5	7	84	6	5	9
79.5	8	180	81	66	64	16	18	179	5	7	83	6	5	9
82.5	8	180	81	65	63	16	130	177	5	7	83	6	5	9
85.5	9	179	80	65	63	141	127	175	5	7	82	6	5	9
88.5	9	179	80	64	62	139	125	173	5	7	82	6	5	9
91.5	9	179	79	63	62	137	123	171	5	7	81	6	5	9
94.5	9	178	79	63	62	135	121	169	5	7	81	6	5	9
97.5	10	178	78	62	61	133	120	167	5	7	80	6	5	9

The zero values in cable 'b' indicate that, when a three phase fault occurs in the first 13.5 % of cable 'b', substation A will be isolated from the grid, thus there will be no sag. This is caused by the settings of the protection relays. When we mark the cables for sag values > 100 %s we obtain the drawings in figure 11 and 12.

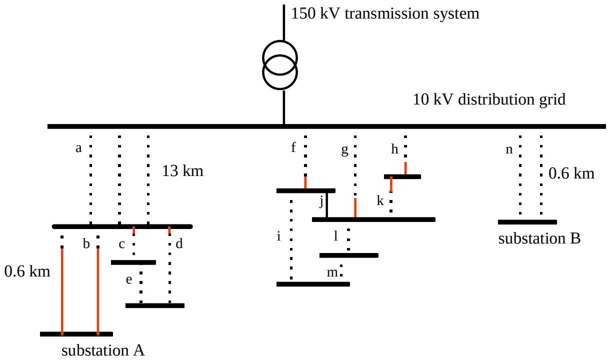

Figure 11: Marked cable parts for sag value on substation A > 100 %s

These results are very different from the previously obtained drawings. This is caused by the high effect of the sag length. Because of the settings of the distance relays to 85 % of the length of the cables, short circuits in the last (or first) part of the cables have a longer duration then in the middle part where the relays at the begin and end of the cables both react rapidly.

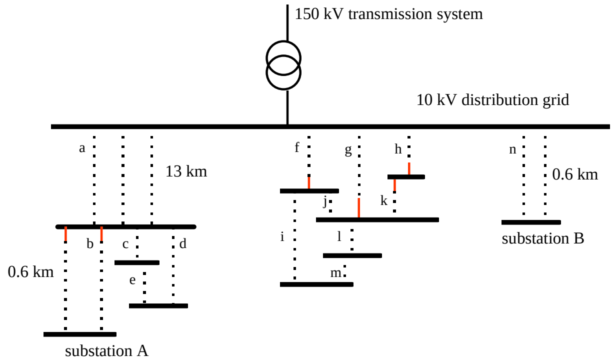

Figure 12: Marked cable parts for sag value on substation B > 100 %s

Sensitive length

For easy comparison of the vulnerability of different nodes to sag depth or sag value the program produces a simple table where the length of the cableparts in which we have a problem is added. This is the sensitive length. In the table below we have the sensitivity values for three phase and one phase faults for sag depths of 70, 50 and 30 % and for sag values of 10, 100 and 200 %s.

Table 5: Sensitive length for substations A and B

	Node A	Node B
70% - 3f	105.9	41.2
70% - a	0.8	0.0
50% - 3f	172.6	82.1
50% - a	0.8	0.0
30% - 3f	260.7	186.7
30% - a	0.8	0.0
10% - 3f	239.3	209.4
10% - a	52.2	12.7
100% - 3f	19.4	19.2
100% - a	0.0	0.0
200% - 3f	0.0	0.0
200% - a	0.0	0.0

Total grid length: 323 km.

E.g.: The voltage on node A will, for 3 phase short circuits on 105.9 km of the grid of 323 km show a sag depth of more than 70%.

CONCLUSIONS

With the help of the discussed computer program we are able to give a quick and clear overview on the vulnerability of certain nodes in respect to voltage sags due to short-circuits in a MV system. We can see that it makes a great difference whether we look at the sag depth or at the sag value.

The effect of different protection schemes as well as the effect of breaker failures can be accounted for in the sag profiles.

We can draw 'maps' of the meshed and radial power networks to visualize the spots where short circuits have a significant influence on the sag quantities. The vulnerability of one node is comparable to that of another one.

We are able to quantify the effect of different sag mitigation techniques.

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