A VOLTAGE SAG STUDY IN A LARGE INDUSTRIAL DISTRIBUTION SYSTEM

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Abstract - **The method of fault positions has been used to study the post-fault voltage sags in the supply to a large chemical industry. The main concern are faults in the on-site distribution systems. The during-fault and post-fault voltages have been simulated by using the PSCAD/EMTDC package. A comparison with a measured sag has been made, showing good agreement. The simulation results taught us that post-fault voltage sags mainly occur during faults in the MV networks. Strengthening the supply, or reducing the (post-fault) motor load are needed to solve this.**

I. INTRODUCTION

Most industrial and commercial customers experience spurious equipment trips mainly due to faults in the public utitily system. But very large customers, with large on-site distribution networks, could end up in a position where they "cause their own equipment trips". Such a situation is described in this paper.

II. DESCRIPTION OF THE CASE

A large chemical industry in The Netherlands is connected to the public supply at 150kV. The power is distributed to about 25 plants through a small 150kV grid and 5 distribution networks with voltage levels of 30kV, 10kV, 6kV and 2kV. The individual plants are supplied at 10kV, 6kV and 2kV. The (low voltage) distribution systems inside the plants have not been taken into account here.

Almost all plants operate round-the-clock, and have very high costs in case of an interruption of plant operation. The supply therefore has double redundancy at 150kV and single redundancy in the MV distribution networks. Part of the 150kV and all the MV connections are underground cables.

Despite this redundancy, a number of faults in the mid 80's led to interruption of plant operation for several plants and very large interruption costs. A study quickly showed that the equipment in the plants had become more sensitive to short-duration voltage sags over the years. To prevent further problems it was decided to improve the equipment ride-through. A compatibility criterion was proposed by the unit responsible for HV and MV distribution. The equipment in the plant should be able to ride through the voltage sag shown in Figure 1; 95% of the sags due to faults in the distribution system were assumed to be less severe than this criterion [1,2].

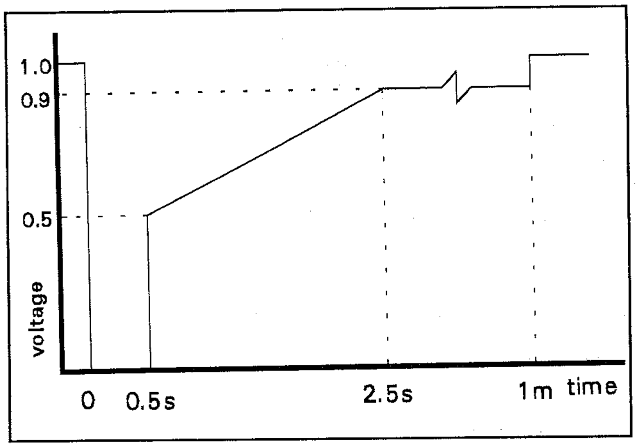

Figure 1. Compatibility criterion proposed.

Note that Figure 1 is not the shape of a voltage sag as it could appear in this system, but a voltage tolerance curve which serves as a guideline for the ride-through requirements of installed equipment. The (500ms,0%) point is determined by the fault-clearing time for a bus-bar fault (cleared by over-current relays); the (1min,90%) point is determined by the run-up time of large induction motors. The slope from (0.5sec,50%) to (2.5sec,90%) was thought to account for the post-fault voltage sag due to re-acelleration of the induction motors [3]. The actual shape of the post-fault voltage sag was the main uncertainty in the compatibility criterion. As recent

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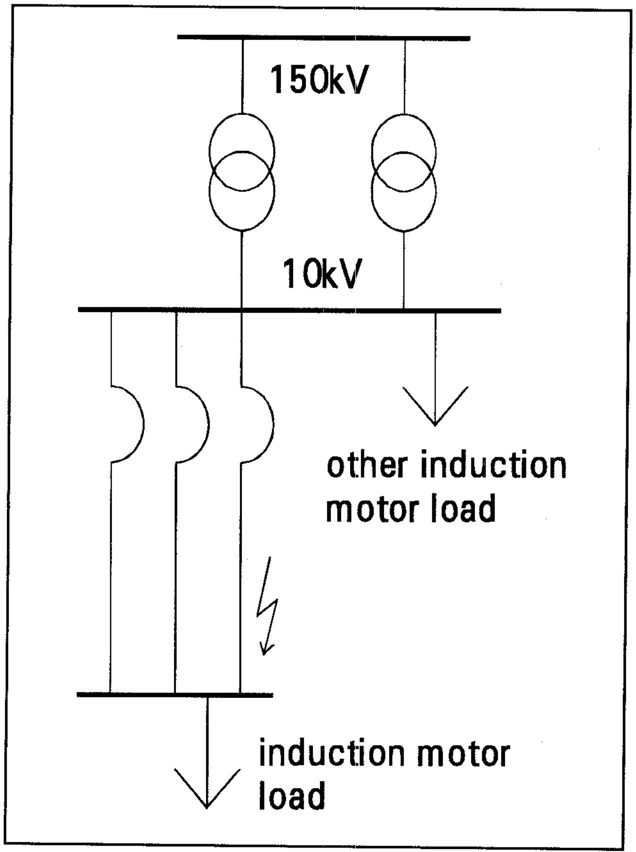

Figure 2. Fault position leading to severe post-fault sag.

faults still led to interruption of plant operation for some plants, it was decided to do a detailed study after the post-fault voltage sag.

III. POST-FAULT VOLTAGE SAGS

When a fault occurs near an induction motor, the voltage at the motor terminals will drop. This will lead to a reduction of the mechanical torque produced by the motor. As the load torque will remain the same, the motor will slow down. When the voltage returns after fault clearing, the motor draws a high current of low power factor to re-accelerate and to rebuild the magnetic flux in the air gap. In a system with a large induction motor load, these inrush currents can keep the voltage low for up to several seconds. This extended reduction of the voltage after fault-clearing is referred to as the post-fault voltage sag [3].

The post-fault voltage sag can be especially severe in systems with redundancy through parallel operation. The protection removes the faulted feeder, thus making the supply weaker. The inrush current to the most affected motors has to be supplied through this weakened supply.

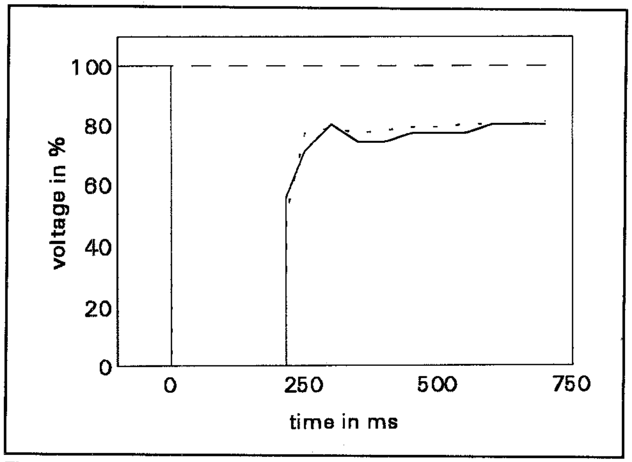

Figure 3. Comparison between measurements (solid line) and EMTDC simulations (dots).

Figure 2 shows part of one of the distribution networks. The main 10kV substation is fed through two 150/10kV transformers. A total of about 12MW of induction motor load is fed through three cable connections. Each cable connection contains a fault-current limiting reactor. A short circuit in one of the three cables caused a severe post-fault sag, and led to the tripping of a number of plants. A fault recorder captured the during-fault and post-fault voltages. This enabled a comparison with simulation results.

Figure 3 gives the measured post-fault voltage magnitudes together with the results of the EMTDC simulation. EMTDC is a time-domain that uses Park's equations for induction motor modelling [4]. EMTDC gives acceptable results, especially when keeping in mind that the motor data available was very limited. We used a number of 10kV and 6kV motors for which data was available and spread those over the plants such that the active power consumption for each of the busses corresponded to the actual value.

From the measured voltages it also becomes clear that the voltage dips again after the initial recovery. The post-fault motor current contains two components: a large short-duration current immediately after fault-clearing which rebuilds the airgap magnetic field (we tend to refer to this as the "electrical inrush") and a smaller but long-duration current during the actual acelleration of the motor (the "mechanical inrush").

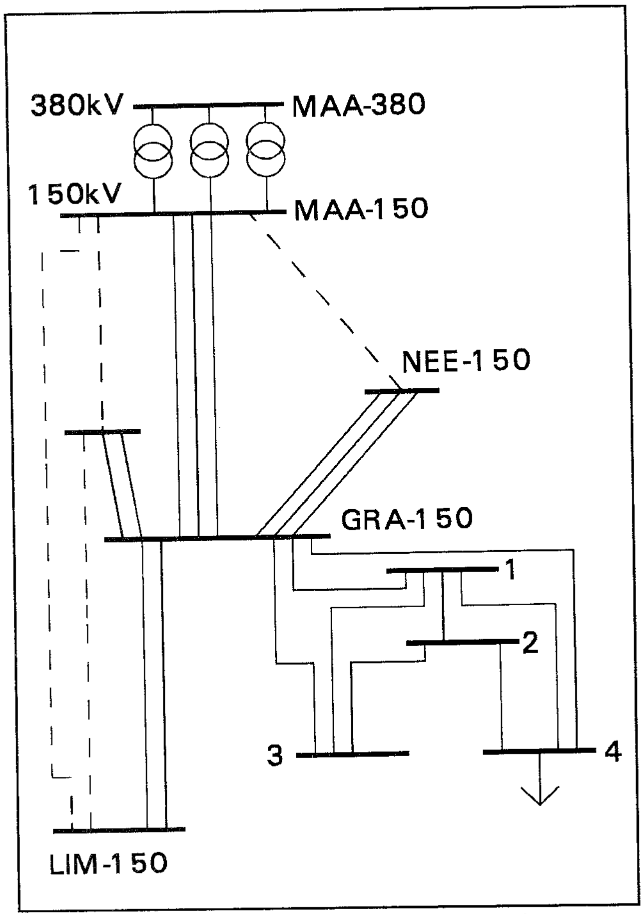

Figure 4. 150kV subtransmission network.

IV. SIMULATION DETAILS AND RESULTS

The study concentrated on the distribution network in which the above-mentioned fault took place. The supply that has been studied is shown in Figure 4 and 5. Figure 4 shows the 150 kV subtransmission network. This network is connected at the substation MAA to the Netherlands (and European) 380kV grid. From here the power is distributed over the area through a number of loops. The dotted lines indicate some of these loops. The power to the chemical industry is transported mainly via two parallel overhead lines between MAA-150 and GRA-150. The industrial sub-transmission network is connected by three overhead lines or cables to GRA-150. From each of the four industrial 150kV substations (indicated 1 through 4) an industrial distribution system is fed. The system studied here is connected to substation 4, indicated by an arrow. Figure 5 shows this distribution system. The fault position discussed before (Figure 2) is indicated by the letter F.

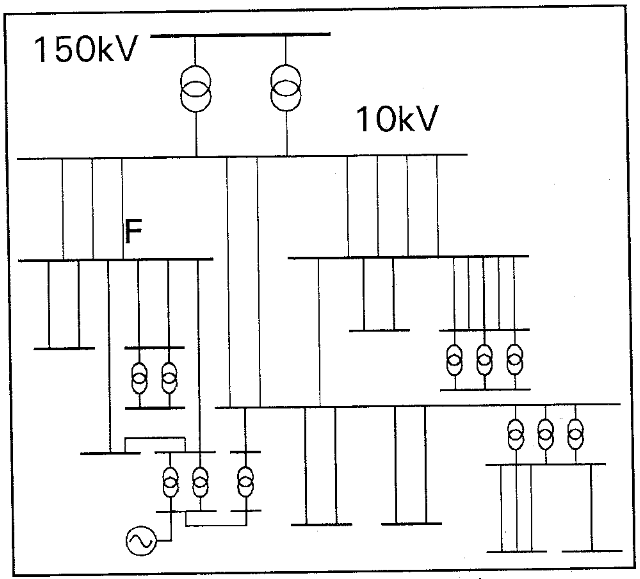

Figure 5. MV distribution network.

The method of fault positions [5] has been used to calculate voltage sag tables for some of the plants in the distribution system shown in Figure 5. For a large number of fault positions in the distribution and subtransmission networks, the voltage sag has been determined by using EMTDC. From the component failure rates the expected number of fault occurrences has been determined for each fault position. The results are presented in a voltage sag table. Each entry in the table gives the expected number of spurious trips for a piece of equipment with the corresponding voltage tolerance. The voltage tolerance is assumed to be rectangular, no conclusions can be drawn from this table for non-rectangular equipment voltage tolerances. Thus, the entry in the table for the 500ms column and the 70% row, indicates how often a piece of equipment is expected to trip in case it can withstand a voltage less than 70% for up to 500 milliseconds [3].

In the forthcoming sections some of these voltage sag tables are presented. As a large fraction of the faults are three-phase faults and they are considered the most severe for the post-fault sag, only three-phase faults have been studied.

A. Faults in the distribution system

Table I gives the expected number of sags per year exceeding a given duration and magnitude, due to faults in the industrial distribution system. It can be seen that the post-fault voltage sags are quite severe. An indication of the cause for this is already given before. A further explanation will follow.

TABLE I
EXPECTED NUMBER OF VOLTAGE SAGS PER YEAR, DUE TO FAULTS IN THE INDUSTRIAL DISTRIBUTION SYSTEM.

	100ms	250ms	500ms	750ms	1.0s	1.25s
90%	1.02	0.77	0.73	0.68	0.61	0.57
85%	1.02	0.75	0.67	0.55	0.43	0.39
80%	1.02	0.48	0.34	0.15	0.14	0.12
75%	0.83	0.12	0.11	0.09	0.05	0.09
70%	0.83	0.09	0.09	0.07	0.03	0.03
65%	0.79	0.08	0.08	0.06	0.03	0.03

A few remarks are needed here. The resulting number of sags is of course strongly dependent on the component failure rates used. These are in many cases company dependent: maintenance and operation can have a large influence.

Sags due to faults in other distribution systems have not been considered in this study. A rough calculation shows that the voltage drops to 65% for a fault on the main MV bus in a neighbouring distribution network. This will not lead to much post-fault sag. For faults near other busses the voltage remains above 65%.

B. Faults in the industrial sub-transmission system

Table II gives the expected number of sags per year due to faults in the industrial subtransmission system. It is clear that the post-fault voltage sag is of much less concern now. There are three reasons for this:

* the fault-clearing time is less for faults at 150kV than for faults in the MV networks;

* the supply is less weakened due to the double redundancy in the industrial 150kV network;

* the faults are (electrically) further from the induction motors, the voltage at the motor terminals thus drops less and the motors slow down less;

* increase in source impedance at the motor terminals is less for the loss of an HV connection that for the loss of an MV connection or transformer.

TABLE II
EXPECTED NUMBER OF VOLTAGE SAGS PER YEAR, DUE TO FAULTS IN THE INDUSTRIAL SUB-TRANSMISSION SYSTEM

	100ms	250ms	500ms	750ms	1.0s	1.25s
90%	0.15	0.15	0.11	0.03	0.03	0.01
85%	0.15	0.09	0.05	0.03	0.01	
80%	0.15	0.01	0.01			
75%	0.15					
70%	0.15					
65%	0.15					

Against all this works the fact that for a fault in the sub-transmission system all induction motors in all the industrial distribution system will experience a considerable voltage sag. They will thus all demand an inrush current after the fault. The inrush current taken by motors in the other distribution networks is not taken into account here. The error made by this is however expected to be small, as less than 10% of the post-fault voltage drop is over the 150kV source impedance.

C. Faults in the public sub-transmission system

Table III gives the expected number of sags per year due to faults in the public sub-transmission system. The results are fairly similar to those for faults in the industrial sub-transmission system.

TABLE III
EXPECTED NUMBER OF VOLTAGE SAGS PER YEAR, DUE TO FAULTS IN THE PUBLIC SUB-TRANSMISSION SYSTEM.

	100ms	250ms	500ms	750ms	1.0s	1.25s
90%	0.51	0.32	0.12	0.11	0.09	0.01
85%	0.51	0.12	0.11	0.09	0.01	
80%	0.51	0.01	0.01			
75%	0.51					
70%	0.51					
65%	0.51					

One has to note here that only a simplified version of the public supply has been taken into account. Only faults on lines close to MAA-150 and GRA-150 have been studied. Other faults are not expected to cause much post-fault sags. But the number of during-fault sags has certainly been underestimated, and probably also the number of shallow post-fault sags.

An impedance model of the 150kV network has been used to calculate the expected number of during fault sags. This showed that one can expect about one sag a year below 90% magnitude. As the 150kV grid is high impedance grounded, single-phase faults do not have to be taken into account.

D. Faults in the public transmission system

Simulations showed that a fault in the 380kV grid, very close to the substation MAA-380, can lead to a post-fault voltage sag, comparable to the worst one for a fault at 150kV. The 380kV substation has a very high fault level. Therefore the influence of faults at 380kV deminished for increasing distance from the MAA-380 bus (although this can still lead to exposed lengths of hundreds of kilometers). A generator feeds in at the MAA-150 bus (not modelled in our simulations) which significantly decreases the influence of faults at 380kV. Simple calculations show that for a fault at the 380kV bus, the voltage in the 150kV system drops to about 25%.

V. CONCLUSIONS AND OVERVIEW

From the above it can be concluded that three-phase faults in the industrial distribution system cause severe post-fault sags. Faults in the transmission or sub-transmission system cause less severe post-fault sags. The industrial system is resistance grounded; the 150 kV sub-transmission system is high-impedance grounded. So single-phase faults in these systems are not of much concern. The 380kV transmission system is solidly grounded, so single-phase faults at 380kV can cause a considerable voltage sag at the motor terminals; but still less than in case of a three-phase fault. Simulations show that single-phase faults seldom cause any significant post-fault sag.

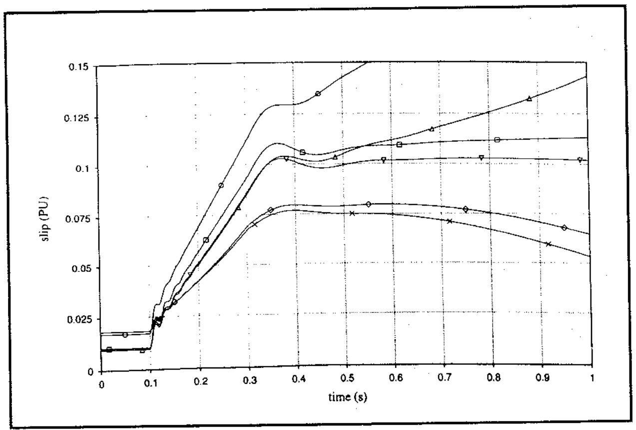

Figure 6. Motor slip during and after a short circuit.

Figure 6 gives the slip for some large induction motors at various positions in the system, during and after a 200 milliseconds fault at position F in Figure 5. One can see that at least two motors do not accelerate at all, where two others are only marginally stable. These motors will draw a large current for a long time, and thus cause a very severe post-fault voltage sag. The simulations have been stopped around 1 second after the fault as this is when the under-voltage protection of the large (medium-voltage) motors starts to trip. Some motors will be tripped by these relays, causing the voltage to come back and the remaining motors to re-accelerate.

Taking this into account in a new compatibility criterion is not of much use. The existing setting of the under-voltage relays would determine the compatibility criterion. And the compatibility criterion dictates the new settings, which immediately makes the criterion no longer valid. Other mitigation methods are required here.

A simple rule-of-thumb in the design of industrial distribution systems is that the available short-circuit power should be at least 12 times the total induction motor load. In that case the motors will be able to re-accelerate after a fault (assuming the inrush current is 5 times the nominal current, and that they can accelerate with 70% voltage). Applying this criterion to Figure 2 gives for the required fault level at the upper 10kV bus: 450MVA, and 180MVA for the lower 10kV bus. The actual fault levels are 513MVA and 183MVA. That would appear to be sufficient. But for a fault as indicated in Figure 2, the available fault level to re-accelerate the motors is only 138MVA, as the faulted connection has been removed by the protection. This is well below the amount required, and it can be expected that some motors will stall. For a fault in one of the transformer connections the available post-fault power is only 256MVA versus 450MVA required. The simulations show that this fault will lead to a very severe post-fault voltage sag.

To prevent severe post-fault voltage sags and stalling of induction motors, the system has to be strengthened or the amount of motors to be reaccelerated has to be reduced. The first solution requires expensive changes in the distribution system. A potentially much cheaper way of implementing the latter solution is by tripping the non-essential motors through their under-voltage relays before the essential motors stall. The tripped motors can be brought back to the supply later, either automatically or manually.

VI. ACKNOWLEDGEMENTS

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