Overvoltage protection study on Vacuum breaker switched MV motors

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OVERVOLTAGE PROTECTION STUDY ON VACUUM BREAKER SWITCHED MV MOTORS

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Abstract - This article presents the main results of a large overvoltage protection simulation study, carried out on vacuum breaker switched motors. Different protection solutions, as well as a great number of electrical network parameters, motor starting current and connecting cable characteristics were varied. The study showed that overvoltage protection installation is highly recommended for frequently started MV motors, switched by vacuum breakers regardless of the cable length, or even motor starting current. The main conclusions and results of this study are presented and commented on. The well known ATP-EMTP and MATLAB software were used for these analyses.

Index Terms — Vacuum circuit breaker, overvoltage protection, surge-arrester, R-C filter, motor switching, ATP, EMTP, MATLAB, Alternative Transients Program, Electromagnetic Transients Program. Line and Cable Constants

I. INTRODUCTION

This article deals with overvoltage protection of motors switched by vacuum circuit breaker (VCB). In some specific applications, such as frequent opening on motor start, there may be reignition on opening. It is principally due to short arc time before current chopping in the first phase to cut, combined with some characteristics of the surrounding power network and some breaker characteristics such as its dielectric strength recovery and ability to cut the high frequency arc current. Vacuum as isolating medium has high arc quenching capability and the arc current is cut very quickly after reignition. This results in transient recovery voltage that, if higher than the momentary dielectric strength of the breaker, may be followed by another arc reignition at higher voltage level. This process is called voltage escalation. It continues until the moment where the transient recovery voltage of the breaker after arc quenching remains lower than the momentary dielectric strength. The issue is detailed in [1]-[4]. Depending on the installation conditions, i.e. voltage level, motor power, cable length, cable type, cable screens earthing, and the application, i.e. frequent motor opening on start, there may be a risk of high overvoltages.

Many articles, [5]-[9] have already dealt with the overvoltage protection related to the risk of overvoltages, and the principal solutions are well known. However, they are often targeting a particular vacuum breaker-motor application. The principal contribution of this study is the large field of practical applications it covers by considering a great part of the installation conditions mentioned earlier. It was motivated by a will to have a more complete view of the problem as well as an idea of the convenience of the generally recommended overvoltage protection solutions. During the simulations, the maximum arc time before current chopping on the first phase to cut was 0.3ms, in order that potentially high overvoltages are generated.

The first step was a detailed modelling of the vacuum breaker, based on comparisons with test results. Then, a specific software application, for automatic simulation tests execution and results recordings was developed.

This application permitted to consider many network parameters, in order to cover the majority of practical situations that may occur.

The acceptable overvoltage level is defined in the IEC 71-2:1996 as 3.0pu in case of switching with reignitions. This maximum level was accounted for in the study. However, motors are able to withstand higher overvoltages, and this should be taken into account, when choosing an appropriate protection. Some withstand values of the overvoltage levels, as a function of the impulse rise-time are depicted on Fig. 1:

![Fig. 1 Maximum motor withstand overvoltage level, [7], 1992](image)

According to the above, the maximum withstand level for motor protection can be increased as a function of the rise-time, and, in some cases, can be greater than 6.0pu. For our study, a second maximum is fixed at 5.0pu. This overvoltage level is valid for well isolated motors, and/or relatively new ones, again related to the surge rise-time.

With the considered installation parameters, more than 12 000 case studies were generated and simulated. As a result, very detailed overvoltage protection recommendations were made. They are analyzed for the elaboration of a protection recommendations guide for motors switched by vacuum breaker. Some of the guide lines are described in this article. Principle confirmation of the main conclusions can be found in [8], [16], [17].
The next section presents briefly the vacuum breaker model development. Section III describes the complete test-circuit, including the VCB model and starting motor model. Section IV gives an idea of the used program supply. Sections V and VI analyze the results of the overvoltage study. Sections VII and VIII close this article with acknowledgements and final conclusions.

II. VACUUM BREAKER MODEL DEVELOPMENT

The first step in the study was the establishment of the breaker model. A preliminary bibliographic research, [11], [12], [13], gave the main ideas in vacuum breaker modeling for overvoltage analysis. A primary version of the model was developed in ATP-EMTP software, by using the MODELS Section. The model fitting was performed by superposing the simulation results with those recorded in laboratory tests. For this purpose it was necessary to model also the laboratory test circuit. The last is defined by the IEC 62271-110:2005, circuit A.

The dielectric strength recovery, chopping current level and high-frequency arc quenching were analyzed from the recordings and introduced in a convenient way in the model. In a nutshell the vacuum breaker was modeled as three ideal switches, controlled by a MODELS block as on the next figure:

![MODELS](image)

Fig. 2 ATP-EMTP VCB model

The above model also takes into account a measured delay between openings of the three phases of about 0.3ms.

The breaker model fitting has followed two main steps:

1. Test circuit model validation, and chopped current value determination, by comparing with the recordings without reignition
2. Vacuum breaker model validation, by comparing with the recordings with reignition

Fig. 3 and Fig. 4 show the close matching of the test results and vacuum breaker model.

![Fig. 3 Laboratory test circuit validation, comparison without reignitions](image)

![Fig. 4 Vacuum breaker model validation, real test comparison in case of multiple reignitions](image)

As it can be seen, in Fig. 4, the vacuum breaker model gives satisfactory results, regarding the overall behaviour, as well as a good matching of the peak values and often the instants of reignition. The HF arc quenching results from comparison of the current rate of rise with a given arc quenching capability (in kA/ms), linearly increasing in time, after contact separation. This approach is similar to the one described in [13]. Thus the VCB model was validated in opening.

A common practice for overvoltage protection studies [11] is a statistical approach, meaning that each test case is simulated a given number of times in order to ensure trapping of the worst-to-happen situation. The statistically varied breaker parameters were the moment of the contact separation on the three phases after the opening order, in the range 0 - 0.3ms, which in turn was the maximum arc time before current chopping in the first phase to cut. This was detected as critical arc time to...
produce potentially high overvoltages. The chopped current level and the dielectric strength were varied randomly during each step of the simulation by ±15%.

III. OVERVOLTAGE TEST CIRCUIT DESCRIPTION

A. Electrical schema

The basic electrical scheme was drawn from the IEC 62271-110:2005, circuit A, and is shown on the Fig. 5.

![Fig. 5 Electrical diagram of the tested circuit](image)

The presented circuit is particularly convenient to experience high overvoltages, due, partially, to the low capacitance at the source side (33nF). The latter depends on the upstream circuit. In our case it represents a short upstream circuit i.e. the vacuum breaker is connected close to the main busbar. In a future study we are going to investigate the impact of this capacitance on the overvoltage levels and the protection recommendations.

For the generation of the different test cases the following circuit parameters were systematically varied:
- The source voltage: 3.3-11kV
- The source earthing impedance: Isolated, 40 Ohm, direct
- The cable type: multicore, single core, grounded on one side or both sides
- The cable length: 10-1250m
- The motor starting current: 25-3000A
- The applied protection: without, surge arrester, wave-sloping capacitor and R-C branch
- The protection emplacement: motor side or breaker side
- The protection connecting cable length: 3m for all, and also 1m for surge arrester on each side (motor to protection and protection to ground).

B. Cable modeling

The motor connecting cable was modeled by the LCC (Line Cable Constants) routine, available in ATP-EMTP. The frequency dependent SEMLYEN model was chosen as most appropriate for modeling the single core cables, and the distributed parameter Bergeron model was used for the multicore cables. The corresponding frequency, at which the cable parameters are calculated is a function of their length and isolation, the last in terms of its dielectric constant, as recommended in the ATP-EMTP Rule Book.

C. Starting motor model

As it could be seen on Fig. 5, the motor model is an electric circuit equivalent, characterized by an R-L three phase ungrounded load and parallel capacitors to ground, calculated according to the indications in the above mentioned IEC standard (Lmot-Cmot circuit tuned at 15 kHz). The R-L values are calculated in order to obtain a starting current 6 times greater than the nominal one.

D. Surge arrester modeling

The surge arrester was modeled using ZnO Fitter routine, available in ATP-EMTP. A connecting cable, between the motor and the hot spot of the arrester, and between the cold spot and the ground was modeled. The length of this cable is very important, since for fast surges the voltage drop on it may substantially decrease the voltage seen by the arrester and thus reduce its efficiency. For that reason, special attention was paid and two different connecting cable lengths were considered: 1m and 3m on each side.

IV. PROGRAM FOR AUTOMATIC TESTS RUN

As it was said, the study has covered a great majority of realistic situations, concerning the voltage level, cable type and length, motor power (starting current). Thus, it was necessary to develop an adapted program able to generate, execute and analyze each different case, as well as to record the results of interest. This task was performed by coupling three different software packages:

1. MATLAB was used for the overall control of the process, the case generation, execution and post treatment.
2. ATP-EMTP was used to perform the electrical network simulations
3. MS Excel served for recording the final results.

Having a total number of more than 12 000 test cases, 5 statistical simulations per case were performed, matching an acceptable overall simulation time and statistical parameters variation.

V. SIMULATION RESULTS

A. Case without any protection

The first test case was without overvoltage protection devices. In such a way, preliminary information about the expected surge-voltage levels as well as the situations where protection may not be needed is gathered. All of the studied network configurations showed high overvoltage levels that have reached values far above the recommended dielectric strength for lightning strike. More detailed analysis showed it was due to the phenomenon of Virtual Current Chopping (VCC), [14], [15]. This phenomenon is to cut the load current in an adjacent phase by capacitive and inductive surge transmission between phases, originating from the first cutting phase. In such a case, due to the high chopped current value, the produced overvoltage is very important. In return, the created surge is transmitted back and forward to the adjacent phases.

This phenomenon took place with all the motors, including those having a starting current of 3000 A. Normally it is believed that the value of this current is great enough to avoid that a fast transient forces it to zero and it gets cut. However, simulations, confirmed by laboratory recordings, showed that high frequency currents, passing through the breaker, can reach more than 5000 A. An example of cutting with VCC is shown on the Fig. 6. The simulated cable length is 500m, for a 1000A starting current machine at 11kV. The cable capacitance is of around 221nF, and the total capacitance...
to ground with machine's capacitance included is 226.6nF. The corresponding natural oscillating frequency is 2.39 kHz.

Fig. 6 VCC phenomenon on adjacent phase B, 11kV, 1000A starting current machine, 500m SC cable

As it can be seen the VCC takes place around 1ms after the cutting in the first phase at around 0.5ms.

A similar situation, with lower maximum overvoltage levels is observed for larger motors, starting current up to 3000A, even if the cable length is 1250m. The results are also confirmed in [8] and [16].

The cable type is also an important factor, influencing in a great manner the overvoltages. With multicore cable, the probability of high overvoltages is greater than that with single core cables, and it is less reduced with the cable length, compared with single core cable. This is due to the higher capacitive coupling between phases, because of the proximity of the cables as well as the lack of screens on them.

The neutral earthing of the power system wasn't found to have a clear influence on the overvoltage level; similar levels were observed with the three different earthing.

B. Protection by Surge Arrestors

A common means of overvoltage protection is the use of surge arrester. In fact this is the most widely used protection and the least expensive. The same test cases as previously were loaded for simulation. Now two connection points are considered:

1. At motor terminals
2. At the breaker

In this example the VCC phenomenon has been avoided, but the current in the adjacent phase is experiencing fast transients. Again the efficiency of the arrester will be a function of its connecting cable length.

In a second step the connection cable length was reduced to 1m on each side. The results obtained were more optimistic. They showed that:

1. Surge-arrestors were able to reduce substantially the overvoltages and can be recommended for overvoltage protection.
2. Connecting them to the motor terminals is more efficient, but the connection cable length should be very short (<1m), the obtained overvoltage level could be sometimes even lower than 3pu, but is more often greater. Thus the average value has not been over 5.0pu for all the motors, voltage levels and different cable lengths. Some limitations were observed when cable screens were grounded on breaker side only.
3. It is possible to connect them on the breaker side and still to get an overvoltage level of about 4pu; that is acceptable for some motors, in such case the connection cable length is respected easily.
4. For protection on motor side, the overvoltage levels were slightly dependent on cable type. However, for three-core cables, with motors of starting currents in the range 100-600A @11kV, the observed average overvoltages were somewhat higher (3.75pu, 1m arrester cable) than for 25-50- >600 A (3.3pu, 1m arrester cable).
5. For protection mounted on motor side, with single core cables, screens grounded on both sides, the average overvoltage levels were under 3.0pu for cable length greater than 200m and system voltage under 5.5kV.
6. The voltage rise time is not modified by surge arrestors, i.e. it is possible to get an acceptable overvoltage maximum value but not being able to stand the overvoltage rise time, also confirmed in [18].

Surge arrestors did not avoid completely the risk for VCC, although they have reduced it by limiting the overvoltages up to a given level.
overvoltage protection is needed i.e. when the overvoltage level should strictly remain lower than 3pu. Inserting surge capacitor helps increasing the voltage rise time by reducing the natural oscillation frequency of the circuit on the motor side. The same test cases were loaded for simulation. The tested capacitor value is 500nF, available for this voltage level range. The obtained results showed that:
1. The wave-sloping capacitor is quite independent of motor cable type (single core or multicore)
2. The overvoltage levels are limited far below 3.0pu (less than 2.0 pu was typical), but its application is limited only to motors with starting current of less than 300A@3.3kV, and less than 200A@11kV.
3. With more powerful motors the natural circuit frequency becomes too high and the voltage variation is faster. This leads to multiple reignitions on the first phase to cut and a consequent transient transmission, followed by the VCC phenomenon. The overvoltage levels are much higher than 5.0pu. The situation is close to the case without any protection. Increasing the capacitor value will certainly decrease the rise-time, however fast transients would be also quickly transferred between phases.

Fig. 8 shows a typical simulation result, the same case as previously, the surge arrester is replaced by wave-sloping capacitor:

![Figure 8](image)

Compared to the situation without any protection, the capacitor has decreased the frequency of the oscillations, but the VCC can be clearly observed.

D. Protection by R-C filter

The R-C filter is the last overvoltage protection equipment, considered in this study. The resistance and capacitor values were chosen in the generally recommended and available range of 30-50 Ohm, 200 – 500nF, [6]. Two sets of values were considered, in order to determine the effect the capacitor has on suppressing overvoltages. The two sets were:
1. R=30 Ohm, C=250nF;
2. R=30 Ohm, C=500nF.

The obtained results showed that the higher capacitor value had stronger effect and wider application possibilities. From an economical point of view this would be more expensive solution, but in practice the capacitor prices in this range are close to each other. The issue is more related to the resistance which will see much more current in a normal steady state. We are going to discuss here the results obtained with the second R-C combination.

In general, the results showed that the R-C filter is the best solution for overvoltage protection:
1. Some limits appear with multicore cables; this issue has been observed also with wave-sloping capacitors. But for single core cables, grounded on both sides the R-C filter gave very satisfactory results, limiting the over voltages far below the 3.0pu level when connected on the motor side for all the motors, voltage levels and different cable lengths.
2. On the breaker side R-C filter have a limited application, in terms of starting current (<600A@3.3kV; <200A@11kV), for an overvoltage limitation under 3.0pu.
3. Connecting them on the breaker side will generally limit the overvoltages under 5.0pu with some exceptions on 11kV.

A typical situation is shown in Fig. 9; the example is the same as that in A. the arrester being replaced by the R-C filter:

![Figure 9](image)

It can be observed that the current in phase A is chopped, and is later followed by reignition. At that time the current value has already grown sufficiently to avoid zero crossing. This delay of the reignitions is due to the presence of the resistor. The corresponding overvoltage was lower than 2.0pu.
The current on phase B is modified with the reignition in the first phase but the transient is very small. The VCC is avoided.

A similar situation was observed with all the motors. In fact the series resistor attenuates the voltage across the breaker, thus delaying the reignitions. Within some cycles, the current is cut successfully. One disadvantage of R-C filter is the need for supervising the resistance. In this study we considered a value of 30 Ohm, selected in the range 30-50 Ohm. In fact, for economical purposes, it may be more convenient to realize a specific cost/efficiency analysis in order to size the resistance in a larger range. It will obviously require a good knowledge of the network surrounding the breaker and modeling in the high frequency domain.

VI. RECAPITULATIVE OF RESULTS AND CONCLUSIONS

The performed simulations helped the understanding of the overvoltage problems related to vacuum breaker opening during motor start. We recall that the analysis concerned the potentially risky situation when there is very short arc time (<0.3ms) between the breaker poles separation and the current chopping in the first phase to cut. Based on the simulation results, for overvoltage protection with different protection equipment, the following conclusions for limitation of overvoltages can be clearly defined:

1. Motors that are frequently started and aborted on start may, depending on network parameters and arc time, experience high overvoltages. In such application conditions a protection is to be provided.
2. The VCC phenomenon occurs more frequently than it is generally believed. We found it responsible for all of the high overvoltages in simulations. This is confirmed also by laboratory tests.
3. The neutral earthing on the source side has not got a limiting impact on overvoltages.
4. Multicore cables are more likely to contribute to high overvoltages than single core cables.
5. The two tested sets of single core screen earthing did not show a clear influence on overvoltage levels. However, in [17] it is suggested that screen earthing on motor side could limit the overvoltages up to 1.6-1.8pu. This issue is analyzed in an ongoing research.
6. Vacuum breaker opening on motor start requires a study for overvoltage protection. In the vast majority of analyzed cases, the lack of protection lead to high overvoltages.
7. Surge arrestors can provide an acceptable overvoltage protection; however they should be connected with very short cables (less than 1m on each side). Connecting them on the motor side is preferable and more efficient for overvoltage levels around 3.0pu, on the breaker side they can successfully limit up to 4.0pu. The arrestors efficiency is also connected to the ratio of their residual crest voltage, compared to the system voltage. Surge arrestors do not modify the voltage rise time. They are applicable generally when the motor connecting cable is relatively long.
8. Wave-sloping capacitors were found very effective in suppressing overvoltages. Their application is however limited to motors with maximum 300A starting current, decreasing with the system voltage.
9. R-C filter (30 Ohm+500nF) was found to be the most effective overvoltage protection (far below 3.0pu, with some exceptions for multicore cables). It is necessary to connect the filter on the motor side. However, this solution is the most expensive too. In practical situations, there would be a need to study the sizing of the resistance in order to meet some cost/efficiency requirements.

VII. CONCLUSIONS

In this paper we have discussed an overvoltage protection simulation study when motors are switched by vacuum circuit breaker. It has covered a great part of the practical situations, related to installation conditions, as well as system and motor characteristics. For the purposes of this study an adapted automated program supply has been developed, providing a powerful tool for further analysis. Finally, detailed application recommendations are given. Our work on this subject is still continuing with analysis of the source capacitance impact on the overvoltage levels as well as some other network parameters. Results will appear in a further contribution.

VIII. ACKNOWLEDGMENT

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