Parametric Sensitivity Studies and Protective Measures for Switching Overvoltages Arising from VCBs in Induction Motor Circuit

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Abstract--Switching overvoltages are stochastic in nature and the conditions which may result in serious overvoltages are numerous. It has been found that switching operation of vacuum circuit breakers in motor circuits can cause large transient overvoltages at the motor terminals or the transformer terminals and there are many factors governing the transient overvoltages. In this paper, parametric sensitivity studies and protective measure are performed to evaluate the severity of these transients and apply suitable overvoltage protection, in order to reduce the risk of failure of the equipment. Finally, a real case study on the prospective voltage levels during the switching of the vacuum circuit breakers in an industrial installation in Hong Kong is presented.

Keywords: EMTP, Transient analysis, Vacuum circuit breaker, Switching overvoltage, Sensitivity studies

I. INTRODUCTION

Over the past several years, electrical equipment and installations have become increasingly vulnerable to transient overvoltages arising from lightning and switching transients. Interrupting current in an inductive load is well known to generate overvoltages that can cause dielectric breakdown of insulation.

Transient overvoltages studies and overvoltage protection in industrial power systems are recognized as crucial for the reliability of the electrical supply and equipment, especially in critical electrical services, such as in airports and hospitals. The overvoltage protection problem is exacerbated by the difficulty of accurately predicting overvoltages, since they are stochastic in nature, and in order to accurately predict system overvoltages, suitable simulation models are required which reflect the behavior of key components at power frequency as well as at frequencies corresponding to fast transients. A stochastic vacuum circuit breaker model [1] and a universal hybrid high-bandwidth (from power frequency to MHz) induction motor [2] have been developed in EMTP. Detailed studies have indicated that some combinations of the breaker characteristics as well as the rating of the motor and its running condition, may increase the risk of getting severe reignition or voltage escalation problems.

Other than the characteristics of the breakers and the motors, the severity of switching overvoltage transients also depends on several factors, including system fault level, cable lengths, grounding practice and presence of power factor correction capacitors. Consequently, it is necessary to determine, in general terms, which parameters, combinations of parameters and system configurations may lead to particularly severe transient conditions and to evaluate the performance of different protection measures. Rather than studying a large number of typical installations, parametric sensitivity studies are performed, aimed at identifying the essential parameters that could lead to potential equipment damages.

In this paper the results of overvoltage parametric sensitivity studies, incorporating the stochastic breaker model developed in [1] and the universal hybrid high-bandwidth induction motor model developed in [2] are presented. Different protection measures will be applied to the evaluation circuit and the performances will be compared. Finally, a real case study of the prospective voltage levels during the switching of the vacuum circuit breakers with motors in an industrial installation is presented.

II. STOCHASTIC VACUUM CIRCUIT BREAKER MODELS

The vacuum circuit breaker is represented by an ideal switch in EMTP, [1] as shown in Figure 1, where its states are characterized only as “open” or “closed”.

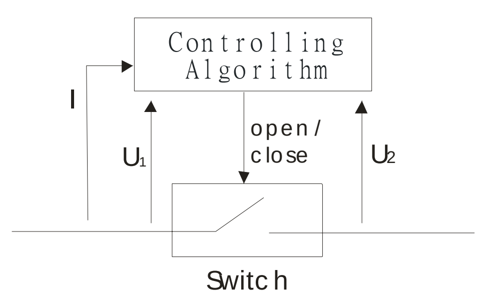

Fig. 1. Model of Vacuum circuit breakers

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The generic model incorporates different stochastic properties inherent to the breaker operation to control the actual state of the breaker during the computer simulation by considering different properties of the breakers: the arcing time, the dielectric strength characteristic, the magnitude of the chopping current, and the quenching capability of high frequency current at a zero crossing. These stochastic variables were randomly chosen as described in [1].

III. UNIVERSAL HIGH-BANDWIDTH HYBRID MODEL

The universal high-bandwidth hybrid induction motor model [2] comprises two components: (i) the ATP/EMTP d-q dynamic model representing the appropriate back EMF and (ii) a passive network representing the high-frequency transient behavior. The parameters of the d-q dynamic model were found from the data provided by manufacturers, while the parameters of the passive network were determined from measurements on small machines and an extrapolation method was applied to estimate the values for larger machines.

The hybrid model, aimed at obtaining a global solution taking into account the high and low frequency phenomena, is shown in Figure 2.

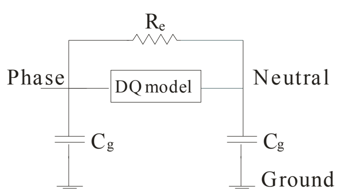

Fig. 2. Universal high-bandwidth hybrid model

IV. PARAMETRIC SENSITIVITY STUDIES

Switching overvoltages are stochastic in nature and the conditions which may result in serious overvoltages are numerous. Rather than studying a large number of typical installations, parametric sensitivity studies were performed, aimed at identifying the essential parameters that could lead to potential damage to equipment.

The following parameters governing the severity of switching overvoltages were evaluated in a parametric sensitivity study, using the network shown in Figure 3. After some preliminary studies, the following parameters were selected as having the most effect on the magnitude of the switching overvoltages:

- Short circuit ratio
- Source types
- Characteristics of cables
- Rating and location of power factor correction capacitors
- Motors running conditions

The network comprises an 11kV source with a fault level of 50MVA, a 5 MVA, 11 kV/3.3 kV delta star-grounded transformer with leakage impedance of 8%, a vacuum circuit breaker, a 20m cable connecting the motor to the breaker, and a 420kW induction motor.

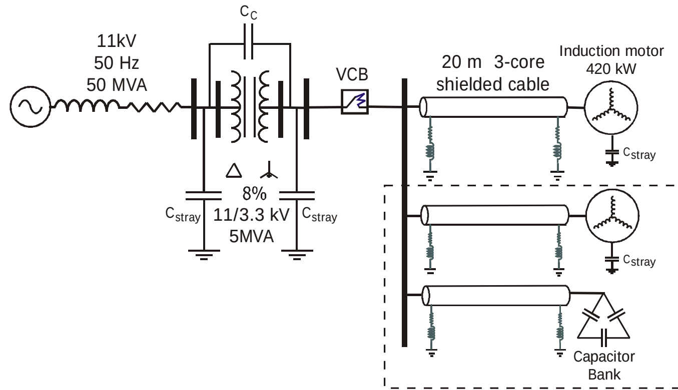

Fig. 3. Evaluation circuit to perform parametric sensitivity studies

Monte Carlo methods were used to study the stochastic properties of overvoltages. The mean values and the 2% overvoltages in each case are listed in the following table:

TABLE I
MEAN AND 2% OVERVOLTAGES FOR DIFFERENT CASES

	Variation parameters	Voltage at motor terminal (p.u.)	
		Mean	2 %
1	None: Base Case	2.96	3.68
2	Short Circuit Ratio: 20	2.98	3.65
3	Short Circuit Ratio: 5	2.97	3.70
4	Complex source type	1.77	2.04
5	Motor cable type: pi section model	3.02	3.63
6	Motor cable type: Constant parameters model	2.48	3.07
7	Grounding of motor cable sheath: grounded at receiving end	2.96	3.46
8	Grounding of motor cable sheath: grounded at sending end	2.98	3.46
9	Grounding of motor cable sheath: ungrounded at both ends	2.99	3.58
10	Motor cable length: 50m	2.56	3.10
11	Motor cable length: 100m	2.16	2.63
12	Capacitor bank rating and location: 86kVAr, at motor terminals	1.05	1.26
13	Capacitor bank rating and location: 86kVAr, 20m from motor terminals	1.05	1.26
14	Capacitor bank rating and location: 86kVAr, 20m from load side of VCB	1.05	1.27
15	Capacitor bank rating and location: 86kVAr, 50m from load side of VCB	1.05	1.25
16	Capacitor bank rating and location: 86kVAr, 100m from load side of VCB	1.05	1.18
17	Capacitor bank rating and location: 35kVAr, 20m from load side of VCB	1.05	1.27
18	Motor starting	2.61	10.08

As can be seen in Table 1, the mean and 2% overvoltages at the motor terminal are not much influenced by the short circuit ratio and the grounding practices of the cable sheath.

The overvoltage for a complex source is less severe than that for an inductive source, as expected. This is because the surge impedance presented by other cables connected at the switching bus acts to reduce the level of the incident wave.

The simulation models of the cable were compared by studying Cases 1, 5 and 6. It was found that the frequency dependent model can well represent the damping. Cases 1, 10, and 11 compare the effect of the cable length on the overvoltage at the motor terminals. It is clear that longer cables lead to a reduction of the overvoltages. This is because surge impedance of the network formed by the motor inductance and the cable capacitance is higher for shorter cables, and higher surge impedance leads to higher suppression peaks for a given chopping current.

When power factor correction capacitors were connected, the overvoltages generated at the motor terminals were found to be precluded. However it was found that while the location and the rating of the power factor correction capacitors do not have an obvious effect on the overvoltage generated, they affect the low frequency harmonic distortion at the motor terminals. When the power factor correction capacitors are physically close to the motor terminals and/or for smaller ratings of the power factor correction capacitors the harmonic distortion components are less damped and at a higher frequency.

The operating mode of the motor at the time of switching was found to be the most significant factor governing the severity of overvoltages generated. It was found that the overvoltages generated from switching a starting motor are more severe than those from switching a running motor, with the 2 % overvoltage more than 10 p.u. This is because a running motor continues to generate back EMF after it is switched off, and the voltage across the vacuum circuit breaker builds up very slowly as the applied voltage of the system and the back EMF of the motor drift apart. On the other hand, aborting a motor start may generate severe overvoltage since the motor has no back EMF.

V. Protective Measures

The control of overvoltages is defined as “the condition within a system wherein the expected transient overvoltages are limited to a defined level”. In this paper the effectiveness of protective control has been evaluated.

Different protection measures were applied to the network shown in Figure 3. The protective measures evaluated are listed in Table II:

TABLE II
DIFFERENT CASES FOR OVERVOLTAGE STUDY

Case No.	Protection applied
1	Nil
2	3kV arrester at motor terminal
3	3kV arrester at motor terminal with 6m separation distance
4	3kV arrester at transformer low voltage side
5	3kV arrester at transformer low voltage side with 6m separation distance
6	3kV arresters across the vacuum circuit breaker
7	RC damper at motor terminal: R = 30Ω C = 0.2μF
8	RC damper at transformer terminal: R = 30Ω C = 0.2μF

Monte Carlo methods were used to determine the statistical overvoltages. One hundred shots were run for each case. The mean and the 2% overvoltages in each case are presented in the following table:

TABLE III
MEAN AND 2% OVERVOLTAGES FOR DIFFERENT CASE

Case No.	Voltage at motor terminal (p.u.)		Voltage across breaker (p.u.)		Voltage at transformer low voltage side (p.u.)	
	Mean	2%	Mean	2%	Mean	2%
1	5.043	6.294	6.753	8.647	3.371	6.394
2	2.557	2.691	5.400	6.196	3.393	4.045
3	2.644	2.700	5.376	6.285	3.376	4.057
4	5.054	6.549	6.533	7.798	2.558	3.080
5	5.054	6.400	6.445	7.600	2.589	5.250
6	3.874	4.283	2.588	2.695	2.077	2.650
7	1.560	1.850	3.076	3.650	3.362	3.900
8	4.971	6.550	4.664	6.250	1.233	3.050

As can be seen in Table III, when no protection devices are applied, the mean and 2% TRVs are more than 6.5 p.u. and 8.5 p.u. respectively. Cases 2 and 3 have arresters connected to ground at the motor terminals and there is a significant reduction in the statistical overvoltages. Note that the lead length has a relatively small effect on the overvoltage magnitudes. The arresters have little effect on the TRV and the voltage at transformer low voltage terminals.

Cases 4 and 5 have arresters connected to ground at the transformer low voltage side. There is a significant reduction in the statistical overvoltage. The effect of the lead length is more pronounced than with the previous case, since absent the cable between the transformer and the breaker, the rise times of the overvoltages are much higher. The TRV and the statistical overvoltages at the motor terminal are not significantly reduced.

An effective protection method corresponds to Case 6 which has arresters connected across the breaker. With the installation of arresters at only one location, the 2% overvoltages at both the motor and transformer terminals are limited to 4.5 p.u. and the TRV is reduced by more than 50% when compared with the statistical overvoltages of Cases 2 and 3 (arresters connected to ground at motor terminal). Note the dependency of the cable length, for the overvoltages at the motor terminals.

RC damper to ground at motor terminal and transformer low voltage side are applied in Cases 7 and 8 respectively and it was found that the overvoltage at the motor terminal is reduced significantly. Moreover, the 2% overvoltages at other locations are also reduced. When the RC damper is connected to the transformer low voltage side, the reduction on the TRV is not as much as in the previous case.

VI. Real Case Study

In this installation, the existing oil circuit breakers were replaced with VCBs and a study was commissioned to determine (i) if onerous overvoltages would result from VCB switching operations, and (ii) the effectiveness of the surge protection devices proposed. The stochastic VCB model developed in this research was used in the study, as well as the models of the cables, motors, transformers and surge arresters.

The simplified schematic diagram of the supply circuit is shown in Figure 4. There are totally 4 motors which can be run at the same time and only one induction motor is connected to the system in the simulation which demonstrates the overvoltage on the load side, for comparison with site measurements.

A typical result from field measurements is shown in Figure 5. This shows some high frequency ringing of very small magnitude at the point of switching off, and again some low frequency (several hundred Hz) voltage distortion around the switching off point. The waveform of simulation result is shown in Figure 6. For both cases, current chopping was shown to result in high frequency, low magnitude voltage ringing at the point of current chopping, followed by some low frequency (of the order of several hundreds of Hz) voltage distortion of moderate magnitude.

The simulation results for the switching of the induction motors compare well with the field measurements. For the low frequency voltage distortions, the waveforms produced by both simulation and field measurements are very close in both magnitude and frequency.

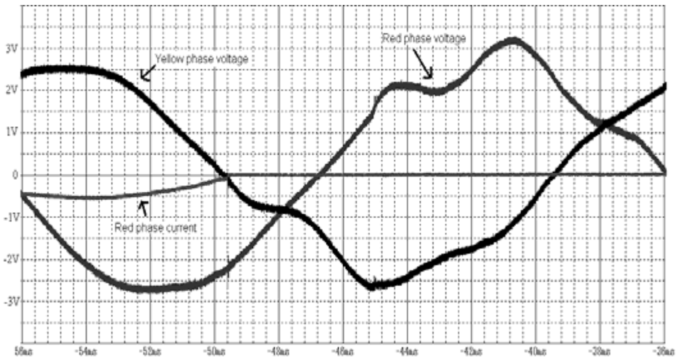

Fig. 5. Field test results – voltage at load side of the breaker

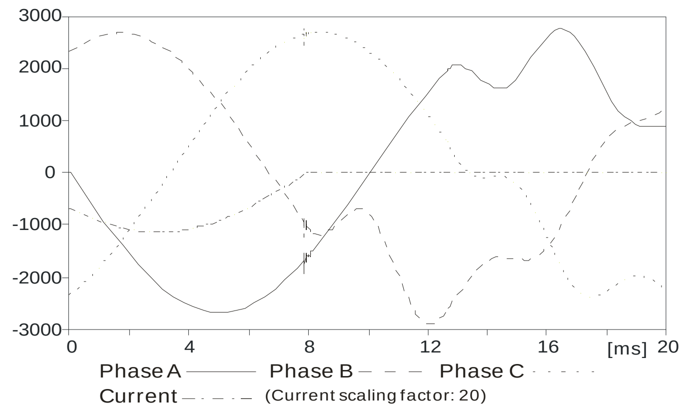

Fig. 6. Simulation results – voltage at load side of the breaker

Statistical overvoltages were also determined for cases without power factor correction capacitors and the result is shown in Figure 7. As mentioned in section IV, when power factor correction capacitors were connected, the overvoltages generated were precluded. Hence severe overvoltages were expected and, as shown in Figure 7, the 2% overvoltages exceed 5 p.u.

The case study with no power factor correction capacitors connected was repeated with arresters connected at the terminals of the motor, and the statistical overvoltage was limited to some 2.5 p.u. With the arrester connected longitudinally across the breaker the overvoltages were similarly limited at the terminals of the transformer and across the terminals of the breaker (TRV), and were limited to less than 4 p.u. at the terminals of the motor.

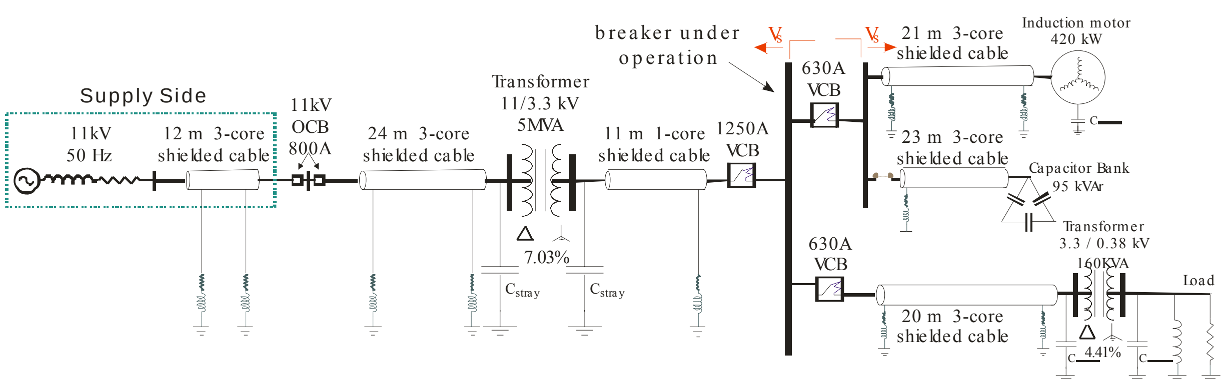

Fig. 4. General schematic diagram of the pump motor installation

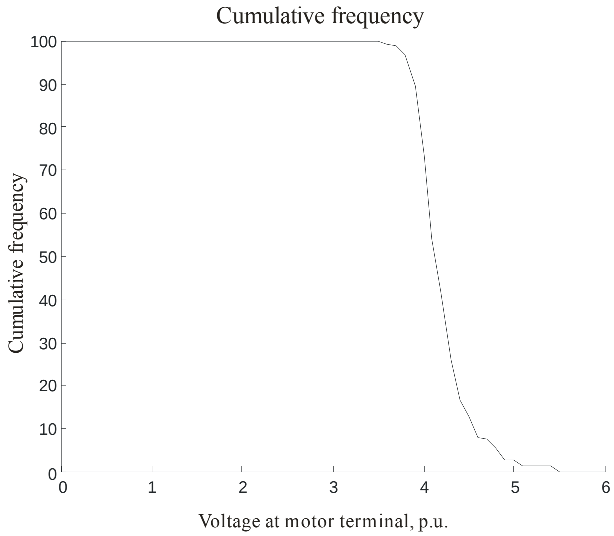

Fig. 7. Cumulative frequency of voltage at motor terminal without power factor correction capacitors

VII. Conclusions

A stochastic model of vacuum circuit breakers developed in EMTP to study system overvoltages resulting from current chopping together with a universal induction motor which allows the analysis of low- and high-frequency phenomena were presented.

Parametric sensitivity studies were performed in order to determine parameters and combinations of parameters most likely to lead to onerous overvoltages. It was found that the rate-of-change of the dielectric strength and the arcing time of the breaker are the most sensitive factors in the estimation of the TRV, while the influence of the quenching capability on the escalation voltage is less pronounced.

On the other hand, the operating mode of the motor at the time of switching was found to be the most significant factor governing the severity of overvoltages generated. When switching off a starting induction motor, onerous overvoltages can occur. Also, the shorter the cable connecting to the motor to the breaker, the more severe the overvoltages generated. On the other hand, the presence of the power factor correction capacitors precludes the production of serious overvoltages. The effects of the short circuit ratio, grounding practices of the cable sheath, length of the cable connecting the motor to the power factor correction capacitors and the rating of the power factor correction capacitors on the overvoltages severity were found to have less impact.

The performance of different protection measures was evaluated. It was found that connection of an arrester across the breaker can be effective in reducing the overvoltages at the terminals of connected equipment providing the cable lengths are not excessive. The results also demonstrate the importance of the location and installation method of the protective devices. Even with short lead lengths, the fast-front overvoltages generated by the breaker can result in a protective level higher than the clamping voltage of the arrester at the terminals of the equipment.

A study dealing with VCB switching of pump motors indicated that statistical phase-to-ground overvoltages can be as high as 6 p.u. when the power factor capacitors are not connected. Field measurements of the switching overvoltages were made in this study and the measured waveforms compared well with the corresponding waveforms obtained from the simulation results, and this serves to verify the model. The simulation gives somewhat more pessimistic results, however even the pessimistic results indicate that the vacuum circuit breakers do not produce onerous overvoltages in this installation, largely because of the presence of the power factor correction capacitors.

VIII. Acknowledgment

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IX. References

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X. Biographies

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