Vacuum Breaker Induced Overvoltages in Induction Motor Circuits

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Abstract - **Current interruption by vacuum circuit breakers in 3-phase induction motor circuits can result in very high switching overvoltages owing to the virtual current chopping inherent in these devices. Power factor correction capacitors may mitigate the problem if they are switched with the induction motor, but the supply circuit would still be vulnerable. Such a circumstance arose in an electrical supply to a large induction motor in a factory in Hong Kong, which led to the failure of the resin-cast supply transformer. In this paper, the results of a study of vacuum breaker induced overvoltages are presented. The study was performed using a stochastic breaker model which was developed using MODELS and incorporates the random nature of current chopping, arcing time, virtual current chopping and withstand characteristics of the gap. The results show the circumstances that lead to excessive overvoltages, and the effects of various mitigation measures.**

Keywords: Transient Analysis, Modelling, Circuit Breaker Overvoltages, EMPT

I. INTRODUCTION

When a circuit breaker is opened, the two electrical networks at either side of the breaker are disconnected and each of the networks proceeds to redistribute its trapped energy. As a result of this energy redistribution, each network will develop a voltage that appears simultaneously at the respective terminals of the breaker. The algebraic sum of these two voltages then represents the Transient Recovery Voltage (TRV). The recovery voltage phenomenon depends on the conditions that prevail at the moment of the interruption of a current. TRV rises almost instantaneously once the contacts of the breaker start parting and its magnitude can normally get higher than 2 p.u. if no protection method is applied. This surge travels down to the load side and source side and can cause damage to the equipment. Therefore it is necessary to apply appropriate protective measures.

A few different mathematical circuit breaker models exist and they all take into account arc thermal instabilities. At the moment there is no existing universal precise arc model because of the complexity of the arc physics. Many of these models are characterised by experimentally measured parameters to describe the statistical properties of different phenomena taking place in the breaker opening process. In this paper a generic model which does not require any measured parameters is presented. It incorporates the random nature of arc angle, current chopping and virtual current chopping by choosing random values from a range of typical values for each related variable during simulation.

II. THE CIRCUIT BREAKER MODEL

The generic model incorporates different stochastic properties inherent to vacuum circuit breaker operation by the use of the random number generator in MODELS in EMTP. The description of the different properties is as follows:

1. *Current Chopping*

Analytical determination of chopping current values for a specific breaker is complex. Experience has shown that chopping currents range from 3A to 12A for modern vacuum breakers. Therefore, a uniform distribution truncated at 3A minimum and 12A maximum was used to represent the statistical nature of current chopping. The switch opens once the absolute value of the current exceeds the statistically determined value.

2. *Dielectric Strength*

Literature shows that a linear dependency dielectric strength and contact distance can be assumed [1]. A typical relation is as follows:

$$U_A = U_0 + a \times s$$

where $U_0 = 1$kV

a = 20 kV/mm

s = actual contact distance

A statistical variation of 15% standard deviation of the withstand voltage is incorporated. This linear withstand relation was used to for the real case study in which the actual withstand characteristics are not known. For the evaluation of different protective measures applied to induction motor circuit, the withstand characteristics of the gaps of two different circuit breakers were used. The characteristics are shown in Figures 1 and 2.

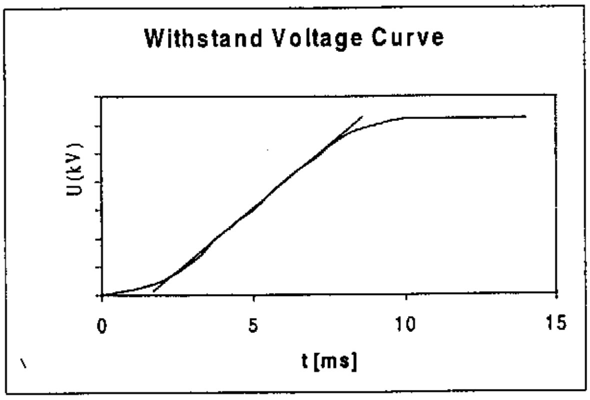

Fig. 1. Withstand voltage curve of breaker 1

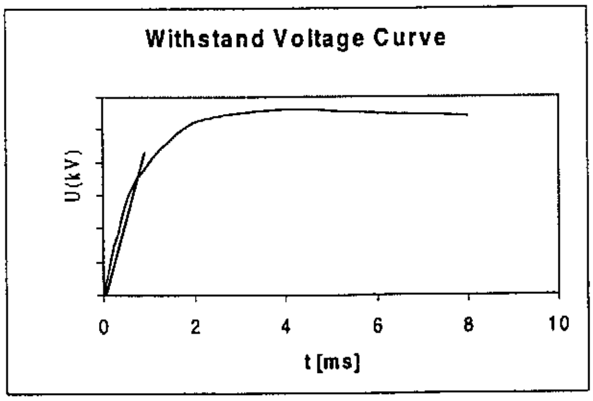

Fig. 2. Withstand voltage curve of breaker 2

As shown in Figures 1 and 2, realistic data suggest that the recovery characteristics can be approximated with a linear relation in the first few microseconds as shown by the straight lines and afterwards the curves reach a 'saturation' value.

3. *Virtual Current Chopping*

A reignition occurs when the TRV exceeds the withstand voltage of the breaker contacts. The high frequency component typical of TRV's will superimpose on the power frequency current. The high frequency currents are caused by the line to ground capacitances. When the high frequency current gets larger in magnitude than the power frequency current it can force current zeros at times other than those expected to occur normally with a 50 or 60 Hz current. Most vacuum circuit breakers have the ability to interrupt these high frequency currents and therefore it is possible that the breaker clears the circuit at a zero crossing which happens at a time prior to the natural one. As far as the load is concerned, it looks the same as if the power frequency current has been chopped and this phenomenon is called virtual current chopping.

The rate of change of current at zero-crossing determines whether a successful interruption will take place. The high frequency quenching capability of typical vacuum breaker is found in the range of 150 - 1000A/µs [2]. The *di/dt* limit was set to 500 A/µs in this study, above this limit no interruption of currents would be brought about.

III. PROTECTIVE MEASURES

An induction motor running at low load produces the worst switching overvoltages since it virtually behaves like pure reactor [3]. Owing to increase of stored energy in the inductance and capacitance in the circuit upon multiple restrikes, voltage escalation can lead to severe overvoltages. It is therefore important to apply appropriate protective measures to prevent equipment failure. The performance of different protective measures applied to a simple motor circuit (Figure 3) was evaluated and these measures include:

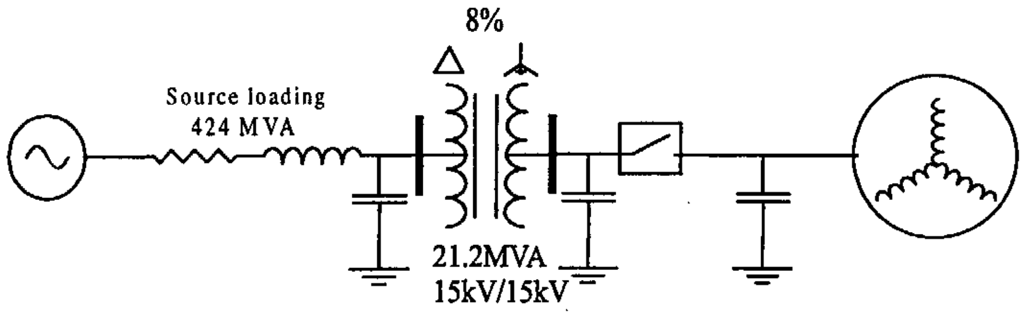

Fig. 3: One-line diagram for induction motor circuit

⇒ arrester (MOV) to ground at motor terminals
⇒ RC damper to ground at motor terminals
⇒ arrester across the breaker
⇒ arrester capacitor (MOV-C) damper

Overvoltages are statistical in nature. To cater for the random nature of different parameters of the breaker model including the arcing angle, chopping current and the withstand characteristics of the breaker contacts, Monte Carlo methods were used and 100 shots were run for each of the different cases with different protective measures. The magnitudes of the maximum reignition voltage in each case were recorded and are plotted as shown in Figures 4, 5, 6, 7 and 8. The different cases using circuit breaker 1 are shown in Table 1.

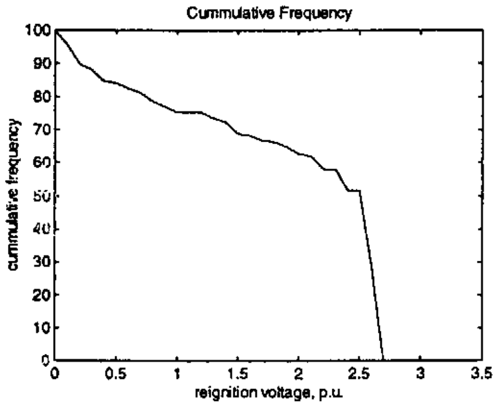

Figure 4 Case A

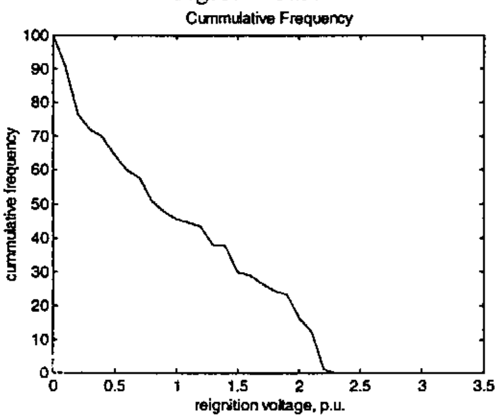

Figure 5 Case B

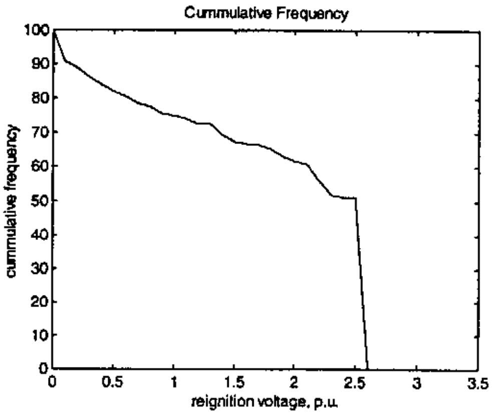

Figure 6 Case C

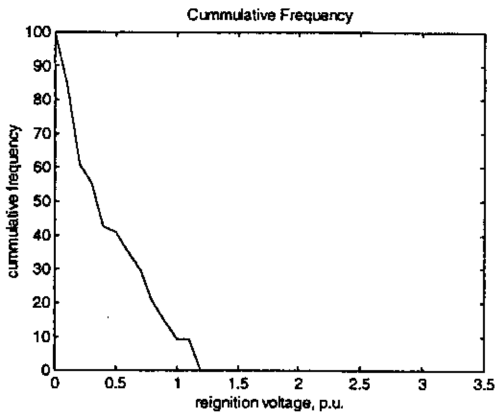

Figure 7 Case D

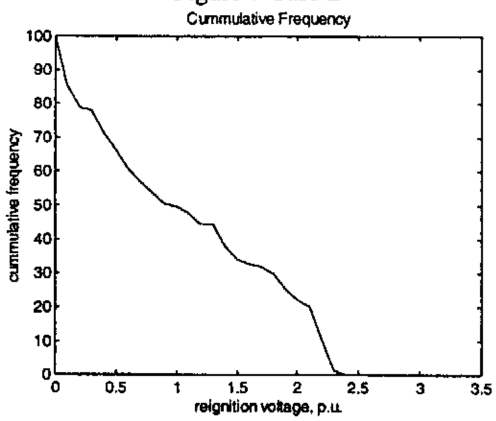

Figure 8 Case E

Case	Protection Applied
A	Nil
B	12kV MOV at motor terminals
C	RC damper: R = 50Ω C = 0.2μF
D	12kV MOV across C/B
E	MOV-C damper at motor terminals

Table 1

The figures show that the overvoltages do not reach higher than 3 p.u. in all cases. It is because the magnitude of overvoltages is restricted by the withstand voltage curve which is shown in Figure 1. Comparison of Figures 4 and 6 shows that the RC damper has almost no effects on the reduction of overvoltages, while measures involving the use of arrester seem to be more effective, as shown in Figures 5, 7 and 8. Connecting an arrester across the circuit breaker (Case D Figure 7) bring about the greatest reduction of overvoltages. Cases using breaker 2 show similar results.

IV. CASE STUDY

There was a recent failure of a dry-type transformer in a factory in Hong Kong. The failure involved a flashover of the gap between the low voltage lead and neutral, and was caused by an impulse. This event was studied using the generic circuit breaker model. The simulation circuit used is shown in Figure 9.

A lightly loaded induction motor was connected to the supply transformer by 60m of cable. The motor was switched off by a vacuum circuit breaker on the low voltage side of the transformer and an explosion was heard after the operator tried to switch it back on. These are "ideal" conditions for the generation steep-front voltage transients in electrical systems owing to the ability of vacuum interrupters to interrupt fast changing current and recover the dielectric strength between the contacts promptly. It was therefore speculated that the flashover/explosion was caused by the overvoltage generated during the operation of the breaker.

It is known that the value of chopping current has a direct impact on the overvoltage produced on the transformer low voltage side. This is because the abrupt change of current results in energy exchange of the transformer winding leakage inductance and the stray capacitance to ground and hence high frequency oscillation is resulted. In order to obtain the most severe overvoltages, a range of chopping current values was used and was represented by a Gaussian distribution with a mean of 10A and standard deviation of 15%. Some of the waveforms are shown as in Figures 10, 11, 12 and 13 and 14.

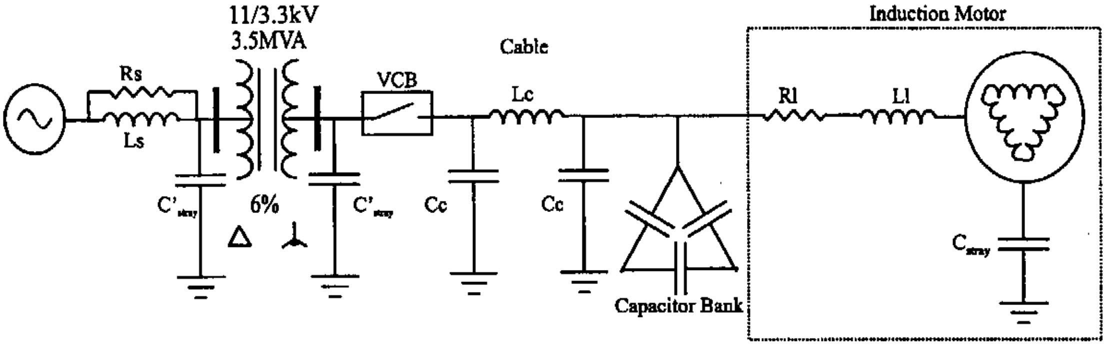

Fig. 9. Case study circuit

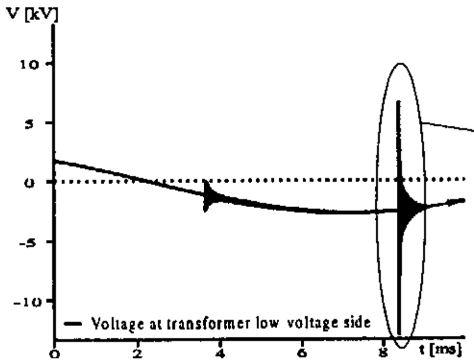

Fig. 10. Low-voltage side switching

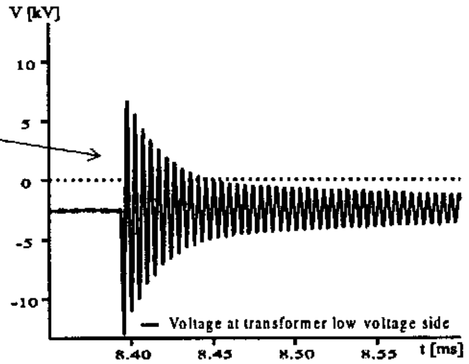

Fig. 11. Low-voltage side switching - magnified

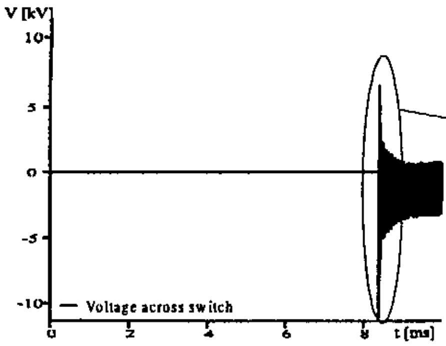

Fig. 12. Voltage across the breaker

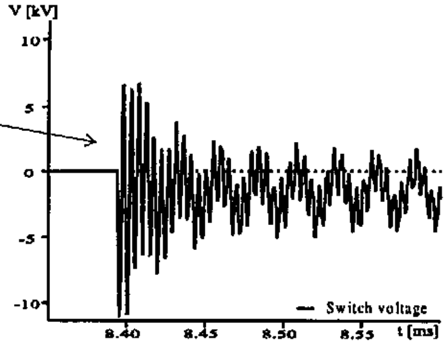

Fig. 13. Voltage across the breaker (magnified)

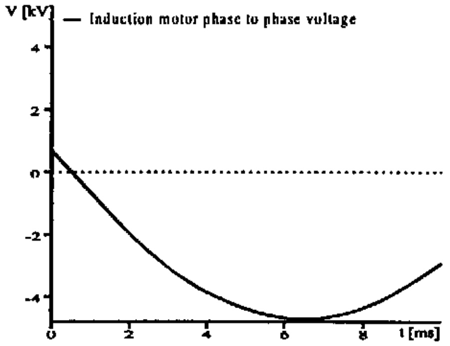

Fig. 14. Induction motor phase-to-phase voltage

The overvoltages generated are stochastic, and a typical case (not the "worst") is shown in Figures 10 and 11. The transformer low-voltage side voltage reaches as high as some 14kV (5.2p.u.) due to current chopping (12A in this case). As shown in Figure 10, the oscillation is damped in about 1ms by the resistor in the circuit. Figures 12 and 13 show the TRV across the breaker and the maximum magnitude is about 12kV (4.5p.u.). Figure 13 shows that the waveform comprises different frequency components. These frequency components are a result of superposition of the interaction of the capacitance and inductance in the circuit. Figure 14 shows the induction motor phase to phase voltage and its maximum magnitude is lower than 5kV (1.9p.u.). Also, when compared with Figures 10 and 12, the induction motor phase to phase voltage does not exhibit any high frequency oscillations. The explanation is as follows: the interaction of the capacitor bank with the magnetizing inductance of the motor dominates because of the large value of capacitance of the capacitor bank. In fact, consequently, the induction motor is protected against overvoltages.

To study the effect of the capacitor bank on the overvoltages generated on the source side and load side of the breaker, the same study was conducted on the circuit without the capacitor bank. Some of the waveforms are shown in Figures 15, 16, which show that the transformer low-voltage side can reach magnitudes of some

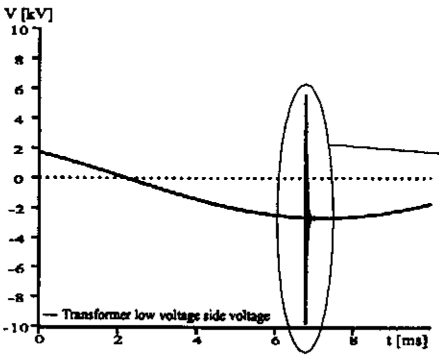

Fig. 15. Transformer low side voltage

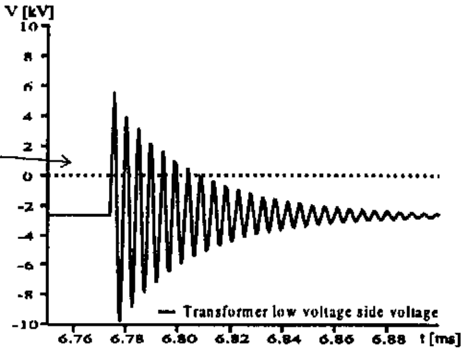

Fig. 16. Transformer low side voltage (magnified)

10kV. Compared with Figures 10 and 11, the waveform is similar to the case with the capacitor bank. v. statistical studies. The motor phase-to-phase voltage and the breaker TRV approached 20 p.u.

Monte Carlo methods were used to study the stochastic properties of overvoltages. The distribution curves of statistical overvoltages of different voltage quantities for the case with the capacitor bank are shown in Figs. 17, 18 and 19.

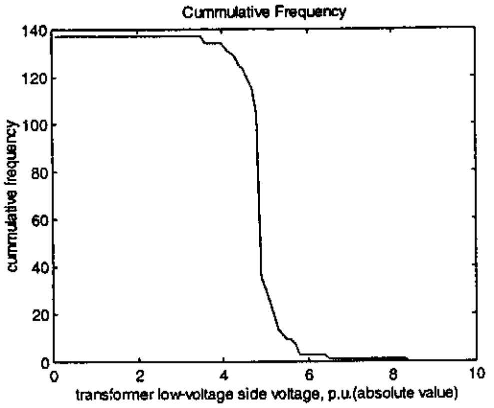

Figure 17 Cumulative frequency of low-voltage side voltage

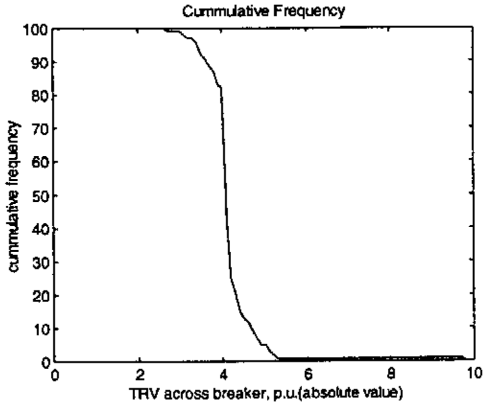

Figure 18 Cumulative frequency of TRV across breaker

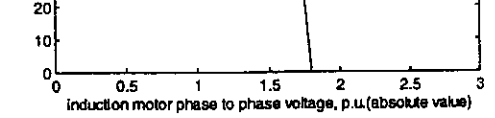

Figure 19 Cumulative frequency of induction motor phase to phase voltage

Figure 17 shows that there is 50% probability of getting overvoltages of higher than 5p.u.. The nature of the flashover which took place at the transformer low voltage side winding indicates that an overvoltage of more than 20kV or 7p.u. or rated voltage was generated. It is significant to note that this transformer was in operation for some 3 years, and there were 2 such flashover during this time. In fact, as shown in Figure 17, though the chance of getting 7p.u. overvoltages is low (less than 1%), it is not zero.

The cumulative frequency curve of the motor phase to phase voltage does not exhibit great variation and it has a mean value of about 1.6p.u. (Figure 19) while that of the TRV across the breaker has a similar shape as that of the low voltage side voltage and has a mean value of about 4p.u. (Figure 18).

V. CONCLUSIONS

A generic circuit breaker model is presented. It takes into account the stochastic nature of the different properties of vacuum circuit breaker. The model was used to evaluate the performance of different protective measures against overvoltages resulting from switching of a lightly loaded induction motor.

Statistical studies of the incident that happened in Hong Kong show that the stochastic nature of current chopping, a phenomenon inherent to vacuum circuit breaker operation, is the probable cause of the flashover of the transformer low-voltage side winding. Though the chance of getting chopping current value large enough to cause the overvoltage is very small in reality, results show that chance does exist and, in fact, it did occur in service. Further investigations show that the induction motor is protected by the capacitor bank and the motor phase to phase voltage does not reach higher than 2p.u.. When the capacitor bank is removed, the same voltage quantity could reach as high as 20p.u.

VI. ACKNOWLEDGEMENT

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VII.REFERENCES

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