THE INFLUENCE OF A VACUUM CIRCUIT BREAKER AND CIRCUIT PARAMETERS OF SWITCHING OVERVOLTAGES GENERATED DURING INTERRUPTION OF STARTING MOTORS

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ABSTRACT

A computer program has been developed for simulating voltage escalation (VE) when a vacuum circuit breaker (VCB) interrupts a starting motor. The influences of the vacuum circuit breaker's high frequency (HF) interrupting capability, dielectric strength rise, cable length and also, motor power, has been traced out to produce a sort of general view of the overvoltage phenomena in actual networks.

It has been discovered that HF interrupting capability is important for high power motors connected by short cables to the VCB when B-termination of VE predominates. In the majority of practical cases, overvoltage protection is recommended for both conventional and low surge contact materials.

1. INTRODUCTION

Interruption of a starting motor with a VCB, with respect to switching overvoltage creation, is known to be a potentially dangerous process. This process has been the main subject of investigation by many researchers over the past few years [1-6]. Several phenomena have been revealed to be responsible for overvoltage generation: natural current chopping, voltage escalation, and virtual current chopping.

Among these three, VE after clearing the first pole, is most important when analysing overvoltages created while interrupting starting motors of 6 kV rated voltage and below. This occurs because for relatively high values of starting currents, current chopping of the vacuum interrupter, and the corresponding overvoltage drops, when compared with other regimes [7]. Virtual current chopping has a very low probability for such voltage [8]. Anyhow, its appearance is induced by voltage escalation, after clearing the first pole. Both experimental and theoretical investigations of voltage escalation may become complicated because of the statistical nature involved. In the 1980's though, a very fruitful approach - the Monte-Carlo simulation technique, was applied to such an investigation [4-7]. This approach allows to calculate the statistical characteristics of the phenomena, aided by a special computer program that uses the experimental and statistical characteristics of a VCB in its calculations.

In several papers [4,5,7], some special electrical circuits were analysed. The results obtained for maximum overvoltages varied from very pessimistic [6] to very optimistic [7]. This is not surprising, considering the vast complexity of a phenomenon that depends upon interaction of a VCB and a circuit's parameters. Such an investigation may be useful for a particular investigation, but fails to provide a general view into how VCB and circuit parameters relate to overvoltage generation.

An attempt was undertaken in [6] at investigating maximum overvoltage influence by a VCB and circuit parameters. During this attempt, the real circuit was substituted by an equivalent circuit substituted the real with lumped elements representing the actual motor and cable. The values of these lumped elements changed independently, and their effect on overvoltage generation was then studied.

In actual networks this is not the case. Cable lengths may vary from dozens to hundreds of meters. However, the equivalent cable inductance and capacitance are changed simultaneously. Also, a motor's power is not independent of cable surge impedance: the higher the motor power, the lower the cable surge impedance. In our opinion, such interrelations of the circuit parameters should be considered when analysing peculiarities of VE, for the vide variety of parameters presented by actual networks.

The present investigation refers to 6 kV motors with power ranging from 200 to 3150 kW, connected by cables of up to 500m in length. This investigation also focuses on a comparison of the different criterion for HF current interruption, with respect to their influence on overvoltage generation. At the present moment, a physically and experimentally proven criterion for HF current interruption is absent. Therefore, the present work also aims to study sensitivity of a VE to HF current interruption ability.

2. VACUUM CIRCUIT BREAKER PARAMETERS

To develop a Monte Carlo simulation program, it is necessary to describe analytically the basic VCB parameters: current chopping, rise in dielectric strength, and ability of HF current interruption. This description is usually based on an experimental investigation of the VCB's statistical properties.

2.1 Current chopping

During our investigation, we ignored current chopping and assumed that the VCB interrupts power frequency current at natural zero. The reason for this assumption has already been discussed.

2.2 Dielectric strength rise

Dielectric strength rise (K-factor) was determined as a statistical value with a constant average of $\overline{EV}$ = const. This assumption is traditional, and seems to be proven in many experiments. The statistical properties of a dielectric strength rise are expressed by a Weibull distribution in the following form:

$$P(EV) = 1 - \exp\left(-\left(1.125\left(\frac{EV}{\overline{EV}} - 0.2\right)\right)^{m}\right) \quad (1)$$

where $\overline{EV}$ - EV average, m - parameter responsible for EV scattering.

2.3 High frequency current interruption capability

HF current interruption capability is subject to much investigation by many researchers over the last decade [8-11]. However even a qualitative criterion, which eludes the critics, has not been proposed until now. The most popularly accepted criterion is an interruptable current rate of current that decreased di/dt. Although criticized in some papers [9,10], it seems there is nothing better until now. To compensate for some uncertainty that this criterion presents, (interruptable di/dt possibly changes 2-3 times depending on circuit parameters), the present investigation uses a range of values for di/dt. The statistical properties of HF current interruption ability are expressed in the same way as in (1):

$$P\left(di/dt\right) = 1 - \exp\left(-\left(1.125\left(\frac{di/dt}{\overline{di/dt}} - 0.2\right)\right)^{n}\right) \quad (2)$$

where $\overline{di/dt}$ - average di/dt; n - parameter responsible for di/dt scattering.

To describe HF interrupting capability, we also used the «dielectric criteria of HF current interruption», proposed in [9].

$$U_r = 0.4 + 91d - 67.3d^2 \quad (3)$$

where d - interelectrode gap in mm; U_r - final recovery voltage after HF arcing in kV (average).

3. EQUIVALENT ELECTRIC CIRCUIT

Fig. 1 presents an equivalent three-phase electric circuit for a cable - motor network.

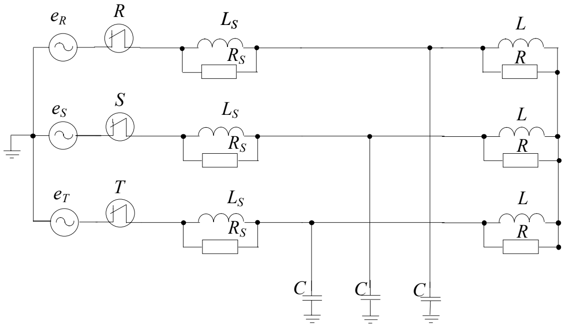

Fig. 1: Equivalent circuit.

Designation in Fig. 1 are as follows: e_R, e_S, e_T - symmetrical system voltages; *R,S,T* - VCB poles; *L* - motor equivalent inductance; *R* - a resistor taking into account resonant frequency damping in motor winding; *C* - equivalent system capacitance (cable + busbars + motor winding); L_S - equivalent high frequency circuit inductance (busbars + cable stray); R_S - resistor taking into account HF damping.

Equivalent circuit parameters are determined the same way as in [5].

5. RESULTS OF COMPUTER SIMULATION

With the aid of the program discussed earlier, the dependency of maximum overvoltage on cable length has been calculated for several different motors. Presented below is a coordination table for calculation.

Table 1

Motor power, kW	200 ÷3150
Motor net efficiency	0.92 ÷ 0.96
cos φ	0.74 ÷ 0.89
Starting current, A	168 ÷1834
Motor winding capacitance, μF	0.0094 ÷ 0.0229
Cable stray capacitance per meter, nF/m	0.25 ÷ 0.53
Cable stay inductance per meter, μF/m	0.2897 ÷ 0.2324

The input parameters of the program are as follows:

Circuit parameters
Rated voltage, kV
6;
Power frequency, Hz 50;
Motor winding damping factor 0.5;
HF current damping factor 0.8;
Ultra HF voltage overshoot factor 1.8.

VCB parameters based on CuCr contact material (if opposite not stated):

Average dielectric strength rise:

$$\overline{EV} = 20,\ 50\ \text{kV/ms}$$

Average interruptable di/dt :

$$\overline{di/dt} = 100,\ 200\ \text{A/}\mu\text{s}$$

Distribution parameters $m = n = 4$;
Busbars stray inductance, μH 15.

Figures 2-7 present maximum overvoltages (99%) vs cable length for 200, 1000 and 3150 W motors, with different k-factors and HF interrupting capabilities. Fig. 8 presents the same dependencies for low voltage contact materials (CuCr with Bi filling), with the following parameters: $\overline{EV}$ = 20 kV/ms; $\overline{di/dt}$ = 30 A/μs [6].

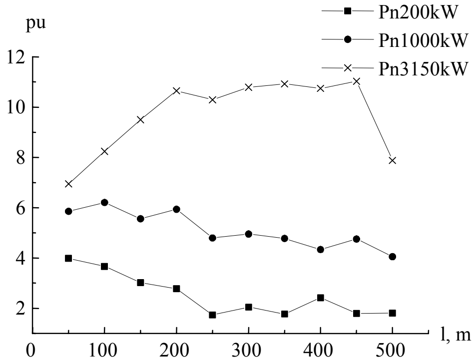

Fig. 2: Maximum overvoltages for $\overline{EV}$ =50kV/ms ms and $\overline{di/dt}$ = 100 A/μs.

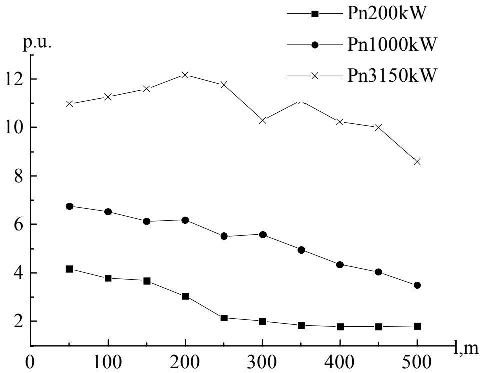

Fig. 3: Maximum overvoltages for $\overline{EV}$ =50 kV/ms and $\overline{{di}/{dt}}$ = 200 A/μs.

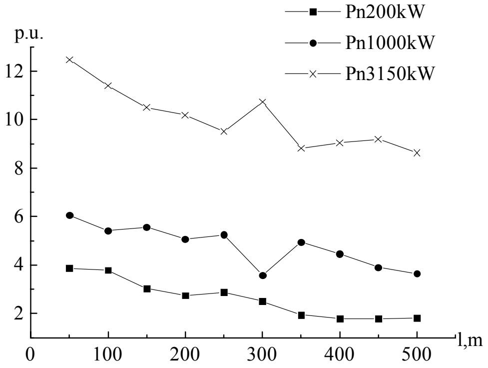

Fig. 4: Maximum overvoltages for $\overline{EV}$ =50 kV/ms and dielectric HF criteria.

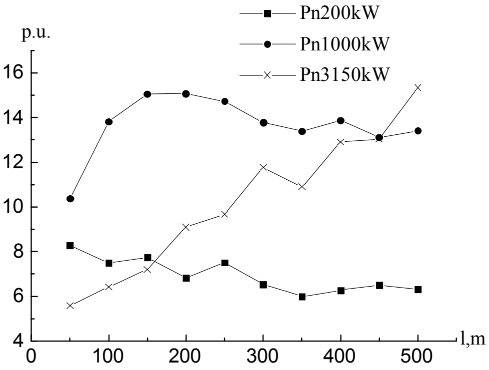

Fig. 5: Maximum overvoltages for $\overline{EV}$ =20 kV/ms and $\overline{{di}/{dt}}$ = 100 A/μ

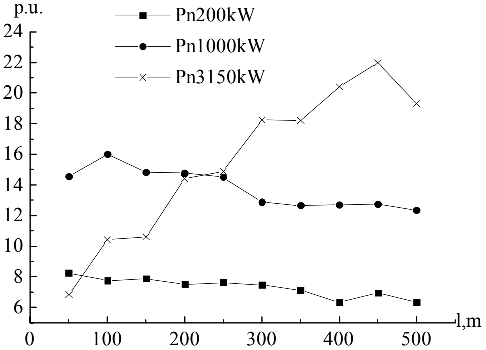

Fig. 6: Maximum overvoltages for $\overline{EV}$ =20 kV/ms and $\overline{{di}/{dt}}$ = 200 A/μ

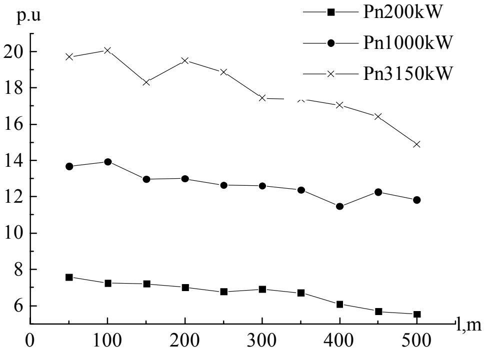

Fig. 7: Maximum overvoltages for $\overline{EV}$ =20 kV/ms and dielectric HF criteria.

6. DISCUSSION

6.1 The effect of cable length and high frequency interrupting capability

Looking at Fig. 2-4, it is possible to state that for 200 and 1000 kW motors, different HF interrupting capabilities produce almost the same results. $U_m(1)$ dependencies are slightly decreased, though. In contrast, for 3150 kW motors, $U_m(1)$ grows with cable length until 200m, for $\overline{{di}/{dt}}$=100, 200 A/μs. Observations of oscillograms show that this is due to B-termination of the VE. For dielectric criterion (even when P=3150kW), $U_m(1)$ dependency decreased and thus predicts higher overvoltage.

The same is also qualitatively true when $\overline{EV}$ =20 kV/ms (Fig. 5-7). This goes to show that a correct representation of HF interrupting ability is important for powerful motors and short cables, when B-termination of VE predominates. Experimental investigations have proven that the actual process is better described by the program, when the value of $\overline{di/dt}$ =100 A/μs is inserted.

6.2 The influence of motor power

Figures 2-4 clearly state that for the described parameters, the higher the motor power the higher the switching overvoltages. This assumption does not however, comply with the common belief that lower power motors produce higher overvoltages [12].

Such a contradiction we think, could be produced by a difference in VCB and circuit parameters, which were used in the present work and in [12]. The latter can be confirmed by Fig. 5, where the influence of motor power is not already synonymous. As was previously stated, this occurs because another process of VE termination (B-termination) is involved.

6.3 The effect of K-factor

Dielectric strength and the velocity of the VCB's movable contact determine the K-factor. From our observations for a VCB with CuCr contacts, the K-factor generally scatters in practice from 20 to 50 kV/ms. The results presented in Fig. 2-7 state that a higher K-factor usually produces lower overvoltages. An exception occurs however, for high power motors with short cables.

6.4 The effect of «low surge» contact materials

As is clear from Fig. 8, application of «low surge» contact materials, such as CuCr + Bi, generally decrease maximum overvoltages. However for many combinations of motor power and cable length, overvoltages still exceed the safety margin of 4.5 p.u.. Please note that for this contact material, the dependencies $U_m(1)$ increase for both 1000 kW and 3150 kW motors.

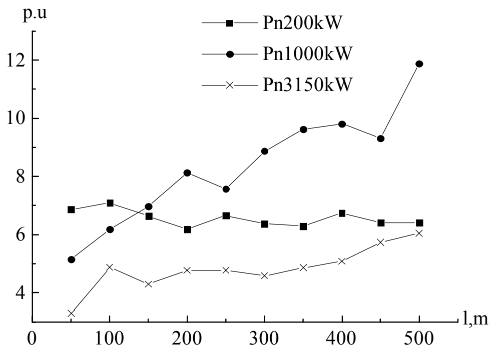

Fig. 8: Maximum overvoltages for low surge contact material.

7. CONCLUSIONS

The HF interrupting capability of a VCB should be especially accurate in description when considering high power motors connected to a VCB by short cables. In other such cases, the sensitivity of maximum overvoltages to interrupting ability is rather low. The criteria based on an interruptable di/dt better describes the actual switching behaviour of a VCB, for the presented range of motor power and cable length. The dependencies of maximum overvoltages on cable length and motor power are not synonymous. For more powerful motors, $U_m(1)$ increases up to 200m, depending on the K-factor generally lowers maximum overvoltages. An exception to this observation is when high power motors connect by short cables to circuit breakers.

In a majority of electrical circuits with starting motors, application of a VCB using conventional CuCr or low-surge contact materials, can possibly lead to dangerous overvoltage generation. For this reason, the practice of supplying a VCB together with the proper protection against such overvoltages seems absolutely necessary.

8. ACKNOWLEDGEMENT

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9. REFERENCES

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