Simulation of switching overvoltages in the mine electric power supply system

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Abstract. Overvoltages occur in mine power supply systems during switching off consumers with high inductive load, such as transformers, reactors and electrical machines. Overvoltages lead to an increase of insulation degradation rate and may cause electric faults, power outage, fire and explosion of methane and coal dust. This paper is dedicated to simulation of vacuum circuit breaker switching overvoltages in a mine power supply system by means of Simulink MATLAB. The model of the vacuum circuit breaker implements simulation of transient recovery voltage, current chopping and an electric arc. Obtained results were compared to available experimental data.

1. Introduction
Switching off the overvoltage is one of the most common types of electric power supply system problems. These overvoltages are mainly caused by switching off the high inductive and capacitive or heavy resistive load, such as power transformers, reactors, capacitor banks and electrical machines. Those overvoltages are especially relevant to ungrounded neutral mine power supply systems.

The problem for the underground coal mine electric power supply system comes from availability of long 6 kV cable lines with significant capacitance supplying heavy inductive load which consist of clustered powerful electric drives. Overvoltage causes the degradation of insulation, and those are the major causes of outages in 6-10 kV cable lines. For instance, almost 50% of ground faults in 6-10 kV cable lines are caused by switching overvoltage. It is also possible that these electric faults would cause both power supply outages and accidents with ignition and explosion of methane and coal dust [1, 2].

A simplified structure of the mine section electric power supply is represented in Figure 1. Main consumers are electric drives of conveyor lines, coal plough-machines, ventilators and pumps. Mine is supplied by the 100 kV aerial line. Electric energy is distributed from the main transformer station of 110/6 kV to surfaced and underground facilities. Underground consumers are supplied by two cable lines through mine section transformers rated as 6/0.6 kV. The mine section transformer station supplies three asynchronous drives of the conveyer rated as 500 kW each, the cutting-loading machine rated as 536 kW and the pumping station rated as 1000 kW. There are two vacuum circuit breakers QF at the beginning and the end of the line. Vacuum circuit breakers are used because of their reliability and fire-explosions safety replacing oil circuit breakers, despite having a higher overvoltage ratio [3].
In order to address possible power supply problems caused by breaker switching, it is required to estimate possible overvoltages. As it is hard to analyze these processes experimentally, the mathematical and computer simulation of the circuit breaker operation could be suggested. The model of the circuit breaker must adequately represent the switching process by means of modeling the arc ignition, the existence of the chopping current electric arc and arc re-ignition in case recovery voltage is higher than momentary dielectric strength.

There are models of vacuum breakers [4, 5] in the EMPT/ATP environment, but there are no similar solutions for Simulink MATLAB. The authors of papers [6, 7] provided the simulation of transient recovery voltage of vacuum breakers, but did not simulate the electric arc. Also, available simulations of the electric arc in Simulink MATLAB [8, 9, 10] are based on the controlled current source model and are not applicable for breaker simulation. This paper represents an attempt to simulate all mentioned processes in the vacuum circuit breaker for switching overvoltage simulation.

2. Vacuum breaker modeling

Modeling of the vacuum breaker switching is complicated by the difficulty of physical processes and their mathematical description. In order to represent them in SimPowerSystem Simulink MATLAB, two models were made: the model of an arc interrupter of the vacuum circuit breaker simulates a dynamic arc current-voltage characteristic; the breaker control model simulates transient voltage recovery and chopping current.

2.1. Transient voltage recovery simulation

After physical separation of breaker’s contacts, the electric arc is ignited. Arc exists until current drops to the chopping current value of $I_c$. It varies from 3A to 15A depending on a contact surface material and is approximately 2÷5 A for Cu-Cr contacts [6]. After arc extinguishing, recovery voltage $U_r$ is formed between the contacts of the breaker:

$$U_r = U_g - U_l,$$

where $U_g$ – electric grid voltage, $U_l$ – load voltage.

Load voltage $U_l$ depends on magnetic energy which is stored in inductive elements in the switched off part of the circuit and can be calculated according to formula

$$W = \frac{L_0 I_c^2}{2},$$

where $L_0$ – inductance of the switched off part of the circuit, $I_c$ – chopping current.
Stored energy is transferred from inductance $L_0$ to capacitance $C_0$ and back causing oscillations with frequency $f_0$:

$$f_0 = \frac{1}{2\pi\sqrt{L_0C_0}}.$$  \hspace{1cm} (3)

Maximum overvoltage corresponds to peak value $U_p$ of oscillating load voltage $U_L$. It can be calculated as:

$$U_p = \sqrt{\frac{L_0I_c^2}{C_0}}.$$  \hspace{1cm} (4)

If recovery voltage exceeds discharge voltage between contacts of the breaker, the electric arc will re-ignite and the process will be repeated multiple times. The recovery voltage increases in accordance with the contacts movement speed and depends on availability of electrical charges in the arc extinguishing chamber [11, 12].

This process was modeled in Simulink Matlab as a breaker state control subsystem represented in Figure 2. It is activated for the closing operation when a Breaker control singular signal is received and formulates an Arc control signal in accordance with measured recovery voltage, breaker current and the previous state of the breaker. The breaker state control subsystem generates a singular Arc control signal in two cases: recovery voltage is higher than the discharge voltage; recovery voltage is lower than the discharge voltage, but arc current is higher than chopping current. In any other cases this signal is equal to 0.

In order to simulate this process, several assumptions were made. It was considered that the contacts movement and dielectric strength of the gap are constant so discharge voltage increases linearly. Initial dielectric withstand was modeled by variable initial gap $L_0$ between contacts. Electric strength of the gap between contacts was considered to be $50kV/mm$, chopping current was considered to be equal to $5A$.

### 2.2. Electric arc simulation

There are different approaches to electric arc modeling. Thermodynamic based models of the arc were proposed by various authors such as Mayer, Cassie, Schwarz, Schavemaker, Habedank and many others [8, 9, 10].

All models implement the arc with non-linear electric conductance, where momentary arc conductance is a function of power, supplied through the arc plasma channel, but are based on different concepts of the arc column. As the Mayr model represents a low current arc and conductivity reduction better, it was considered to be more suitable for the vacuum circuit breaker simulation case.

Simulation is based on the generalized model of the process in the electrical arc, described at statics by equation (9):

$$u_{\text{arc}} = R_{\text{arc}}(i_{\text{arc}})i + U_c = \frac{U_{\text{arc init}}(i_{\text{arc}})}{i_{\text{arc}}}i + U_c,$$  \hspace{1cm} (5)
where \( u_{arc} \) – arc column voltage, \( i \) - arc column current, \( i_\theta \) – arc state current, \( R_{st} \) – static arc column resistance, \( U_{arc, a} (i_\theta) \) – the static arc current-voltage characteristic, \( U_c \) – the voltage drop at contactors.

The low current arc voltage loss at contacts can be neglected and the current-voltage characteristic can be generally approximated to the static process as follows:

\[
U_{arc} (i_\theta) = U_0 \left( \frac{i_\theta}{I_0} \right)^n,
\]

where \( U_0, I_0 \) are reference points of the static arc current-voltage characteristic, \( n \) – the parameter based on the type of the arc characteristic.

For the case of the static arc with characteristic equation (6) for the Mayer arc model, the arc conductance is assumed to vary with time at low currents, in accordance with

\[
\frac{1}{g} \frac{dg}{dt} = \left( \frac{u_{arc}}{P} - 1 \right) \frac{1}{\tau},
\]

where \( \tau \) – the Mayer arc time constant, \( P \) – arc power losses, \( g \) – momentary conductivity of the arc.

In order to simulate the breaker with arc ignition in Simulink SimPowerSystem, the model represented in figure 3a was developed in accordance with equation (7).

The model is based on the controlled voltage source and represents a voltage drop under closed, open and arc conditions of the vacuum breaker. The breaker switch is triggered by the Breaker control signal and turns the breaker from the closed state to the open state if the control signal is 0. The arc switch is triggered by the signal from the Arc control subsystem and turns the breaker from the closed state to the arc state if the control signal is 1. Arc inertia is modelled by means of the Transfer Fcn block. In order to avoid singularity at current zero crossing, the viscous friction function was used.

Developed models were integrated into the singular three-phase vacuum circuit breaker model, represented in figure 3b.

Figure 3. The circuit breaker model with electric arc implementation – a); the model of a three-phase vacuum circuit breaker – b)

The model consists of three one-phase breakers and breaker control subsystems, one per phase. It is activated by the Breaker control signal and provides measurement of recovery voltage \( U_r \) and breaker current \( I \).
3. Breaker Simulation Results
The developed model of the vacuum circuit breaker was tested in the electric circuit of the underground mine section (figure 4) simulated by means of SimPowerSystems Simulink MATLAB.

![Image](image_url)

**Figure 4.** The model of the mine power supply system.

The purpose of the experiment was to investigate processes in the circuit breaker switching off. Disconnection of the mine section with the belt conveyor shown in figure 1 was taken as an example. The deenergized part of the circuit consists of underground transformer station Tr-r2 with three transformers 6/0.66 kV rated as 630 kW each, cable line 0.66 kV L-3, and motors (IM) of the conveyor electric drive. All other consumers were represented by equivalent RLC load (Load). The line section is switched off by the vacuum circuit breaker (VB) at the command of the breaker control block (BC). Phase currents and circuit breaker voltage measurements are presented on the oscilloscope (Osc.). Model parameters are represented in table 1.

The model also includes a three-phase power source, the aerial line of 110 kV (L-1), the main power transformer of 110/6 kV (Tr-r1) and the cable line of 6 kV(L-2). Capacitance of the cable and aerial lines was modeled by conductance C1, C2, C3.

| 3-ph VS | L-1 | Tr-r 1 | L-2 | Tr-r 2 | L-3 | IM | Load |
|---------|-----|-------|-----|-------|-----|----|------|
| $U_{L-1}$ | 110 | $R_i = 0.414$ | 110/6kV | $R_i = 0.0845$ | 6/0.66 kV | $R_i = 0.0405$ | 6000 |
| kV; $f = 50$ | Ohm/km; | $(Y - D)_{11}$ | Ohm/km; | $(Y - D)_{11}$ | Ohm/km; | kW; | kW; |
| Hz. | $L_i = 9 \cdot 10^{-4}$ | $l_1 = 19745$ | $l_0 = 22 \cdot 10^{-3}$ | $l_0 = 113 \cdot 10^{-12}$ | $V_n = 0.6$ | $Q_n = 2764$ |
| $C_1 = 10^{-8}$ | F/km; | H | $C_0 = 8.7 \cdot 10^{-9}$ | F/km; | H | kW; | kVAR. |
| $l = 20$ | Ohm; | $l_2 = 0.00111$ | km. | km. | km. |

At 0.4 s, the breaker control block sends a switching off signal. Figure 5 represents oscillograms of the breaker voltage and current in relation to nominal line voltage and current. Figure 5c and figure 5b provide oscillograms of transient voltage in the vacuum breaker with simultaneous phase switching and without it.
As figure 5 shows, in case of nonsimultaneous switching, overvoltage on the circuit breaker exceeds the nominal line voltage 2 times. For the case of non phase-controlled switching, the overvoltage is 6 times higher than the nominal voltage. A high level of overvoltage is caused by switching of high power motors with low nominal voltage and requires the usage of surge arresters and other means of limitation. Multiple arc reignitions did not occur. The results of the simulation correspond to experimental data provided in [10, 13-15].

4. Conclusion
This paper presented modeling of switching overvoltages in the mine power supply system caused by the vacuum circuit breaker. The model allows the simulation of switching overvoltages, caused by the existence of chopping current in vacuum breakers; the ignition of the electric arc with a nonlinear current-voltage characteristic; the electric arc re-ignition in case the transient recovery voltage is higher than the discharge voltage between contacts of the breaker.

The vacuum circuit breaker model was tested for the case of switching off the mine section circuit, including high powered conveyor electric drives. Simulation results indicate a possibility of high ratio overvoltages in mine power supply and correspond to available experimental data.

The developed model could be applied for vacuum circuit breaker switching simulations in order to estimate a possible effect on the power quality in mine power supply systems.

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