Dynamical simulation of a Vacuum Switch with PSCAD

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Abstract - The switching behavior of vacuum switches (VS) is different to that of other circuit breakers. There are several effects which have to be taken into account, for example the current chopping, the dielectric strength of vacuum gap, the arc voltage, the quenching capability of high frequency currents, virtual current chopping and prestrikes. In some earlier investigations the characteristics of vacuum circuit breakers had been simulated in different ways by taking into account some of the effects mentioned above. There are mainly two different approaches for modeling vacuum circuit breaker: The first is to use an ideal circuit breaker which is switched on/off after different criteria have been checked. The second is to use a variable resistor whose value is changed continuously. The VS model discussed in this paper is modeled with PSCAD and takes into account chopping current, dielectric strength of vacuum gap, arc voltage and quenching capability. It is represented by a variable resistance and is used to simulate frequently switching of inductances and capacitances. The stress of VS is investigated and the energy conversion in the vacuum tube: As the current through a VS is flowing from moment of contact separation until next zero crossing, together with arc voltage, the energy conversion is very high, dependent on the moment of contact separation.

Keywords - Vacuum Switch, Model, Simulation, PSCAD

1 Introduction

Generally vacuum switches are limited in their ratings, for example the maximum rated voltage is about $24\,\mathrm{kV}$ and the maximum current is approximately $800\,\mathrm{A}$ [1]. These values differ slightly comparing different manufacturers, but are in the same range. VS offer the possibility to switch very often and much faster compared to vacuum circuit breakers: As they are opened and closed by a contactor, they only need about three seconds to be switched again. A possible application could be a frequently switched inductance or capacitance. But in this case a problem occurs - dependent on losses in VS, it can warm up very fast and external cooling is possibly needed. In this paper, the first step is done to simulate the expected values of power dissipation in VS while switching an inductive load.

In the following section, the special characteristics of VS during a switching process are presented. The model of VS, which was created, is described afterwards. Then the corresponding electric circuit is introduced. Finally energy conversion in VS is assessed and the next steps are discussed.

2 Switching characteristics of VS

There are mainly four different effects, which are important to consider, if a model of VS should be created. These are

- Dielectric recovery of gap
- Chopping current
- High frequency quenching capability
- Prestrikes

2.1 Chopping current and arc voltage

If VS is switched off, the contacts start to separate. In the last point of contact, a very high current density exists, which heats up contact material. Metal vapour emerges and current is going on to flow through the metal vapour arc. If it falls below an assigned value, the metal vapour arc collapses [2]. This value is called chopping current and strongly depends on contact material. It can be calculated by [3]:

$$i_{chopping} = (2\pi f \cdot \hat{\imath} \cdot \alpha \cdot \beta)^{q} \tag{1}$$

f	=	frequency in Hz
$\hat{\imath}$	=	current amplitude in A
α	=	$6.2 \cdot 10^{-16}\,\mathrm{s}$
β	=	14.3
q	=	$(1-\beta)^{-1}$

In the considered case, the used material is a chrome copper alloy, and according to [4] or [5] the chopping current is then lower than $5\,\mathrm{A}$. This corresponds very well to the calculated value by eq. (1). While the contacts are open and current is flowing, there is a small voltage across the arc, which is about $10-30\,\mathrm{V}$. This is because the arc is diffuse at smaller currents [2][6]. In this investigation the current is approximately $800\,\mathrm{A}$, so the arc voltage can be assumed to be constant. It is not neglected, as voltage and current form an electrical power dissipation, which heats up the VS. If switching events occur frequently, temperature can rise. Switching capability is degrading with rising temperature.

2.2 Dielectric recovery mechanisms

It is important to distinguish between cold gap dielectric strength and dielectric strength of vacuum gap directly after current is interrupted. The first one is due to the fact, that opening of contacts of VS needs some milliseconds. If contact distance of an open gap is about $2-4\,\mathrm{mm}$, a linear coherence between contact distance and time can be assumed, which isn't possible for greater contact distances ($6-8\,\mathrm{mm}$), that appear in vacuum circuit breakers. As contact distance increases nearly linear with time at small gaps, electric strength does so too. It can be calculated by

$$U = a \cdot x \tag{2}$$

a = Slope of dielectric strength in kV/mm
x = contact distance in mm

Typical rates of voltage rise are $40-60\,\mathrm{kV}/\mathrm{ms}$. If the voltage across VS exceeds dielectric strength, a restrike will occur and the current continues to flow through the opened VS. Worst case is switching off VS shortly before a current zero. Then the current is interrupted immediately and a transient recovery voltage of the electric circuit can exceed electric strength of not completely opened contacts.
The second recovery mechanism is the dielectric strength of gap immediately after current is interrupted. In this case, the atoms of metal vapour have to condense on the condensation shield [7]. During this process, the dielectric strength of the gap increases very fast. A typical value is $50\,\mathrm{kV}/\mu\mathrm{s}$ [2]. After one microsecond dielectric strength rises with smaller slope. If the transient recovery voltage across VS is higher than this value, current interruption will be permanently impossible, because this process reoccurs in every attempt to interrupt the current.

2.3 High frequency quenching capability

A VS is able to quench high frequency currents. They can arise if a restrike of VS occurred. After the restrike, line current is superimposed by high frequency currents, dependent on the connected electric circuit. The resulting current can have many zero crossings with different slopes. If a slope is smaller than a particular value, current can again be interrupted by VS shortly after restrike [3].

2.4 Prestrikes

When VS is switched on, contacts are moving together, which needs some milliseconds. As the dielectric strength of gap decreases with smaller contact distance, a breakdown can occur before contact is completely closed. This effect is called prestrike and causes high rates of voltage rise.

It should be mentioned, that there exists another effect, which isn't part of this investigation, called virtual current chopping. If the current in one line is chopped after VS has been switched off, currents can be induced into the other lines dependent on the electric circuit and coupling of the three phases. The superimposition of line current and induced current can result in a zero crossing in the respective phase if they have opposite sign and are in the same range. VS can interrupt this current according to its quenching capability of high frequency currents described above.

3 Simulation

3.1 PSCAD

The software used to create a model of VS is PSCAD, which is an graphical user interface for EMTDC (electro-magnetic transients simulation and control simulation engine). The differential equations of electric circuit and control circuit are solved by a solver with fixed stepsize. Size of computer memory is limiting this value, because with decreasing stepsize, memory needed is increasing. An error message will occur, if stepsize is chosen too small for a particular memory size. This causes a problem: as periodically switched events should be analyzed, a compromise between accuracy and required memory has to be found. The VS-Model, described in this paper, is written in FORTRAN77 code. It is possible to create own models and integrate them into component library of PSCAD if they are not available. Parametrization of VS is done by filling the input mask. Usually the program runs without problems, and if there is one, the error-description is adequate to get an idea of what is wrong with the simulation case. This is only mentioned, because some of the other simulation software differs considerably.

3.2 VS-Model

The VS-Model described in this paper is modeled by a variable resistance. This is important for considering the arc voltage. Input parameters are VS-voltage, VS-current and a switching command. The output parameter is the value of resistance. Furthermore there are several parameters, which can be admitted by the input mask.

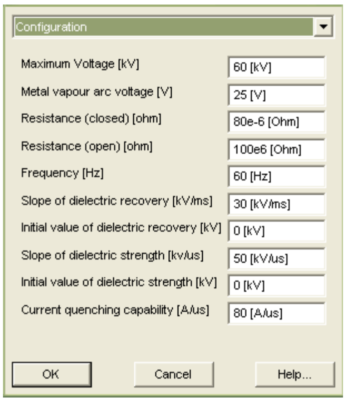

Figure 1: Input mask of VS

Here electrical parameters are defined, such as resistance in closed or opened position and maximum voltage. Additionally, values of arc voltage, rise of dielectric strength and rise of dielectric recovery can be chosen. The value of resistance is changed dependent on the different criteria discussed in section 2. The arc voltage is modeled as a constant value (25 V) in order to simplify the model. The corresponding value of resistance is calculated by $r = V_{arc}/i_{VS}$. Both dielectric recovery mechanisms are modeled by the equations

$$v_{contact}(t) = 30\,\mathrm{kV}/\mathrm{ms} \cdot t \tag{3}$$

effective only at moment of contact separation and

$$v_{dielectric}(t) = 50\,\mathrm{kV}/\mu\mathrm{s} \cdot t \tag{4}$$

effective at every current interruption. These values are limited by maximum voltage of VS (60 kV). Closing of contacts is modeled with $60\,\mathrm{kV} - v_{contact}$. A function checks di/dt of current at every zero crossing to consider the current quenching capability of VS. The value is set to a maximum of $80\,\mathrm{A}/\mu\mathrm{s}$. If this value is exceeded, current will go on flowing until next zero-crossing.

3.3 Electric Circuit

Figure 2 shows the electric circuit, in which VS is simulated. A voltage source provides a line to line voltage of $V = 18\,\mathrm{kV}$. Its resistivity is $1\,\mathrm{m}\Omega$. The load is an inductance in delta connection. Its value is $L = 105\,\mathrm{mH}$. The resulting current is $I_{rms} = 786\,\mathrm{A}$.

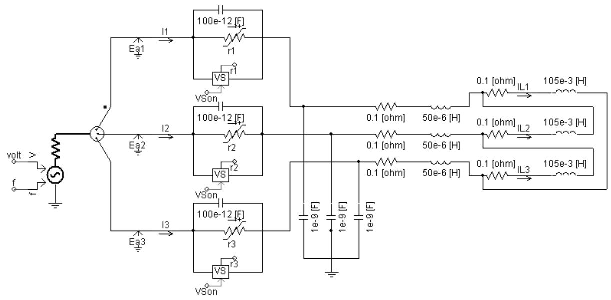

Figure 2: Electric circuit with inductive load

As can be seen in figure 2, VS-Model returns a value, which is directly assigned to the variable resistance component. There are stray capacitances across VS (12 pF) and from line to ground (9 nF). The resistance ($0.1\,\Omega$) and inductance ($50\,\mu$H) represent properties of the supply line to the load. The resistors ($0.1\,\Omega$) in delta connection represent ohmic losses of the inductances.
As mentioned in section 2.2, worst case for VS is being switched off directly before a zero crossing of the current. This is shown in figure 3:

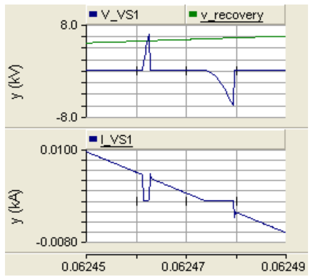

Figure 3: Restrikes in VS

In the upper graph, the dielectric strength (upper curve with slope), and the transient recovery voltage (TRV) is plotted. The lower graph presents the current. As current reaches the chopping value (5 A in this case), it will be immediately interrupted. TRV now increases until the dielectric strength of gap is exceeded. Then value of resistance is set to $r = V_{arc}/i_{VS1}$, current starts to flow but is superimposed by a high frequency part. At the zero crossing of the high frequency current, VS quenches the current and TRV arises again with opposite sign. Dielectric recovery again is exceeded, current starts flowing but this time without zero crossing. In a $60\,\mathrm{Hz}$ grid, the current will continue to flow for approximately $8\,\mathrm{ms}$ until the next zero crossing occurs.

3.4 Power dissipation and energy conversion

As VS is modeled by a resistor with variable value, it will produce power loss which is converted into heat.

It can be calculated by

$$P_{loss}(t) = i^2(t) \cdot R_{VS} = |v_{VS}(t) \cdot i_{VS}(t)| \qquad (5)$$

If $P_{loss}(t)$ is integrated over time, energy, which is inserted into VS can be obtained:

$$E(t) = \int P_{loss}(t) \cdot dt \qquad (6)$$

The next figure shows the power dissipation and energy in a VS when a restrike occurs after the VS was switched off shortly before a zero crossing of current.

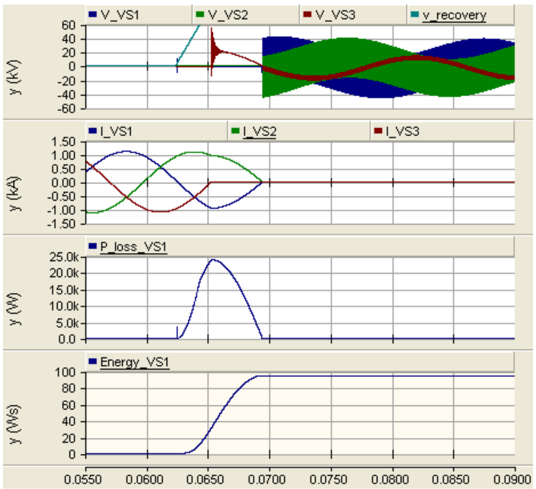

Figure 4: Voltage and current of VS while being switched off

The highest frequency, which occurs in the considered circuit, is approximately $25.6\,\mathrm{kHz}$ and a result of the interaction of load inductance and stray capacitance to ground. The stepsize of the solver is set to $1\,\mu\mathrm{s}$. The moment of contact separation can be identified in the top graph, when dielectric strength ($v_{recovery}$) starts to increase. The small negative peak in the same moment shows the unsuccessful current interruption in line 1. Meanwhile, current of line 3 (I_{VS3}) reaches zero and is successfully interrupted. This is because the contacts are opened completely and the rise of TRV (V_{VS3}) doesn't exceed the dielectric recovery of the gap. Simultaneously, currents of line 1 and 2 are influenced due to the missing possibility of current flow in line 3. As their values fall under the chopping current, they are successfully interrupted, too.
Power dissipation can be seen in the third graph. The peak in the beginning is a miscalculation, but has no big effect on energy in VS, which can be seen in the last graph as a function of time. Power dissipation reaches a peak value of $\hat{P}_{loss} = V_{arc} \cdot \hat{i}_{VS1} \approx 24\,\mathrm{kW}$. The value of the curve in the last graph at $t = 0.07\,\mathrm{s}$ is the energy which is converted in VS after one unsuccessful current interruption. It is $E \approx 98\,\mathrm{Ws}$.
Figure 5 shows repeated switching operations every three seconds. This is what special vacuum switches are able to handle. The simulation stepsize in this case was set to $10\,\mu\mathrm{s}$. The worst case is regarded here, too. Every switching-off operation is taking place shortly before current zero in the respective phase. It can be seen, that prestrikes do not have a big impact on the energy increase when the load is inductive. The current is increasing slowly by reason of inductance, and, together with the arc voltage, power loss is comparatively small. Like before, the increase of energy is approximately $98\,\mathrm{Ws}$ for every switching-off process.

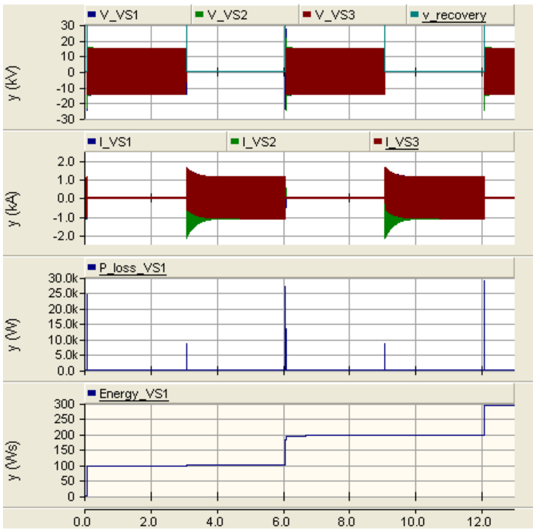

Figure 5: Periodically switching of VS

3.5 *First considerations about heat balance*

The power loss, which occurs during the switching operations heats up the contacts of VS so that switching capability is reduced. P_{loss} is an equivalent to the heat flux $\dot{Q}$. The value of E, calculated above, is an equivalent to heat Q. In the example mentioned above, an inductive load is periodically switched and in worst case, $E \approx 98\,\mathrm{Ws}$ has to be transferred out of VS at every switching-off operation. There are different heat transport mechanisms, for example thermal conduction, heat emission and convection. Referring to [10], heat transport consists mainly of thermal transfer into contact material. As vacuum is the surrounding medium, there will be no heat transfer by convection. The Temperature of copper contact material in the root point of an arc is approximately $1353\,\mathrm{K}$ [2], which is slightly higher than the melting temperature. Now it has to be investigated, if therefore heat dissipation occurs by heat emission. If yes, the only face which could absorb emission is the condensation shield. It surrounds the complete contact gap and is connected to one of the two contacts. So even if some heat was absorbed by this shield, it would have to be transferred towards the respective contact by thermal transfer. The major part of heat dissipation will be thermal conduction through both contacts of the VS. Therefore a high thermal conductivity is necessary, which is the case when copper or a chrome copper alloy is used [2]. In order to estimate, how fast heat can be transferred out of the VS, the next step will be a finite element calculation of this problem. It can be reduced to a two-dimensional problem, because the VS-tube is rotationally symmetric. The calculated values of P_{loss} can be taken as the input parameters for the heat source.

4 Conclusion

A model of VS was created which takes into account special characteristics of vacuum switches like chopping current, high frequency quenching capability, dielectric recovery mechanisms and prestrikes. Arc voltage is considered, too, in order to estimate the value of power loss in VS connected to a electric circuit, where an inductive load is switched on and off periodically. This VS-Model can now be used, to simulate overvoltages at VS connected to different electric circuits as well as power dissipation. By calculating this value, which is proportional to the heat flux, it is possible to get input parameters for a finite element calculation of the geometry of VS. This assessment is necessary in order to estimate the influence of the thermal transport mechanisms, thermal flux and heat emission. The results of the simulation will then be used to analyze, if VS can be switched more often than every three seconds, and if additional cooling devices are necessary and generally able to assure a sufficient heat discharge.

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