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Vacuum circuit breaker modelling for the assessment of transient recovery voltages: Application to various network configurations

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ABSTRACT

Vacuum circuit breakers (VCBs) are widely used for medium voltage applications when low maintenance, long operating life, and large number of allowable switching cycles are required. The accurate estimation of the transient recovery voltages (TRVs) associated with their switching operation is indispensable for both VCB sizing and insulation coordination studies of the components nearby the switching device. In this respect, their accurate modelling, which is the object of the paper, becomes crucial. In particular, the paper illustrates two applications of a VCB model, which show the model capabilities of simulating TRVs due to opening/closing operation, namely the switching of large electrical motors and the switching of cables collecting offshore wind farms (OWFs). Data from digital fault recorder (DFR) in a water-pumping plant and from a measurement campaign in an OWF using a high-bandwidth GPS-synchronised measurement system, respectively, are used for model validation. It is shown that the inclusion of detailed VCB models significantly improves the agreement between the measurements related to both pre- and restrikes and the corresponding simulation results obtained by using two well-known electromagnetic transient simulation environments, namely, EMTP-RV and PSCAD/EMTDC. The procedure adopted for the identification of the VCB model parameters is described.

1. Introduction

Several international standards provide indications on the sizing of vacuum circuit breakers (VCBs) taking into account the effect of transient recovery voltages (TRVs) occurring during closing and opening switching operations (e.g., [1–3]). The sizing methods described in the standards cover most of the possible operating conditions of the VCBs, which are characterised by an improved reliability with respect other types of circuit breakers [4]. However, some peculiar scenarios exist that may require more detailed studies and the use of electromagnetic transient simulations. This paper deals with two of such typical scenarios: (a) the case in which the VCB is demanded to interrupt the inrush current of a large motor shortly after the closing sequence due to the intervention of a motor relay; (b) the switching of cables collecting offshore wind farms (OWFs).

In the former scenario, the VCB is requested to interrupt a large inductive current with a superposed a-periodic component. The combination of peculiar systems configurations, together with the VCB's fast recovery of its dielectric strength and ability to interrupt high-frequency currents, might result in large TRVs and VCB current re-ignition [5].

The latter scenario is particularly interesting since the possible consequences of components failures associated to OWFs are more severe compared to land based ones due to higher repair costs and loss of revenue [6]. Since switching overvoltages are the possible cause of component failures observed in some existing OWFs [7], simulations are widely used for the identification of the overvoltages experienced by the electrical equipment in the OWF, as well as for assessment of the adequacy of the adopted design decisions [8]. In Refs. [8,9] it has been shown that insufficient representation of the VCB is the main cause of discrepancies between measurement and simulation results of inrushes occurring in OWFs.

The post-current zero period of VCBs is well described in the literature (e.g., [10,11] and references therein). In particular, the re-ignition behaviour when the VCB is called upon interrupting a low

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amplitude inductive current has been investigated in several studies (e.g., [12–19]). Similarly, the occurrence of multiple prestrikes during the VCB closing sequence in OWFs have been investigated in, e.g., Refs. [8,9,20–23].

The purpose of this paper is to present the application of a VCB electromagnetic transient (EMT) model for the accurate assessment of the TRVs generated both during opening and closing switching operations and its implementation in two well-known simulation environments, namely, EMTP-RV and PSCAD/EMTDC. The VCB model is capable to represent the main phenomena taking place in the VCB, namely: (i) the current chopping; (ii) the cold withstand voltage characteristic (or cold gap breakdown voltage) and (iii) the high frequency current quenching. The corresponding parameters are tuned and the accuracy of the model is assessed by comparing the computer results with field measurements for the two above mentioned scenarios. In particular, the opening operation of large inductive currents is analysed with reference to actual manoeuvres in a water-pumping plant, whilst the analysis of the closing sequence in OWFs will be based on experimental data obtained during the energisation of a radial feeder in the Nysted OWF, also known as Rødsand (Denmark).

The paper is organised as follows. Section 2 briefly illustrates the two scenarios of interest and describes, in detail, both the implementations of the VCB model and of the complete models of the two plants where it is included, namely the water-pumping plant and the OWF. Section 3 describes the identification of the parameters and presents the comparison between the simulation results and the available field measurements. Section 4 concludes the paper.

2. Simulation models

2.1. VCB characteristics

During the closing of the VCB contacts, as a consequence of the decreasing contact gap distance, a number of so-called prestrikes are almost inevitable. Depending on the voltage impressed across the contacts, multiple prestrikes might occur generating high frequency currents.

Similarly, during a VCB opening, contacts usually start to separate at random with respect to the current waveform. If the contact separation starts just after current zero crossing, the gap has a long time (little less than half of the fundamental period) in order to recover its dielectric strength before the following current zero crossing. Since typical delay for the contacts to be mechanically fully separated is lower than 10 ms, no re-ignition would be expected. On the other hand, if the contact separation starts just before the natural current zero, the dielectric strength of the gap is low at the current zero crossing. The developed TRV will much likely exceed the dielectric strength of the gap and a process similar to the VCB closing sequence will occur. The difference is that as the length of the contact gap increases so does its dielectric strength, resulting in increased voltage level at which re-ignition occurs. This is generally referred to as voltage escalation [24,25].

The most known characteristic of the VCB is its capability of prematurely quenching a low amplitude AC current during the opening sequence. This peculiar characteristic is of particular concern when the VCB is requested to disconnect a large inductive load (e.g., an unloaded transformer), resulting in high overvoltages on the disconnected load and TRVs on the VCB [24].

The occurrence of multiple prestrikes and re-ignitions and their associated TRVs is difficult to predict, as it depends on many factors such as dielectric and current quenching properties of the VCB, surge impedances of the network, mechanical tolerances causing a spread in the contact velocity, point on wave of closing/opening switching operation, and so on.

These peculiar characteristics justifies the effort for the specific modelling of VBCs in electromagnetic simulations of TRVs.

2.2. VCB model

The specific characteristics of the VCB model are described in the following for the opening and closing sequences. As this paper deals with two scenarios, one relevant to the opening switching of the large inductive currents of motor start-ups, and the other relevant to the closing operation in an OWF, the VCB model is denoted as VCB1 for the first and VCB2 for the second one, respectively. VCB1 has been implemented in the model of a water-pumping plant developed in the EMTP-RV simulation environment. VCB2 has been implemented in the model of the Nysted OWF developed in the PSCAD/EMTDC simulation environment.

For both cases, due to the availability of actual measurements, the arcing time is assumed to be known.

The representation of the following properties, usually included in the model (e.g., [26,27]): (i) current chopping capability; (ii) contact dielectric strength; (iii) high frequency current quenching capability is described in the following.

2.2.1. VCB1 model

(*i*) *Chopping current*: a constant and known value of the chopping current has been assumed, although it depends on different parameters, such as the contact material or the load surge impedance, and may be considered statistically distributed [28].

(*ii*) *Dielectric strength*: a linear relationship with the time can be assumed for the withstand voltage during the contact separation $U_{b,op}$:

$$U_{b,op}(t) = A_1 \left(t - t_{op}\right) + B_1 \tag{1}$$

where t_{op} (in μs) is the time for contact separation. A_1 is the rate of change of the dielectric strength of the contact gap (in V μs^{-1}) as the contact gap d increases. B_1 is the TRV withstand just before contact separation. $U_{b,op}$ is bounded by the maximum value of the TRV capability voltage ($U_{b,max,op}$). The parameters are typically provided by manufacturers or by means of fitting between available measurements and simulation results. The linear relationship (also assumed in Refs. [1,2]) is justified by the limited preceding arc current and the resulting breakdown voltage equal to the cold withstand voltage characteristic that depends on the contact gap length and therefore on the velocity of the contacts ([12,16]). The statistical distribution of the withstand voltage characteristic has been analysed in Ref. [29].

(*iii*) *Quenching capability*: the capability to quench the high frequency currents due to re-ignitions is represented by the slope QC of the re-ignited current at its zero crossing. QC is typically found in the range of several hundred amperes per microseconds and it is calculated according the following equation [12,16,17]:

$$QC_{op}(t) = D + C\left(t - t_{op}\right) \tag{2}$$

where C (in A μs^{-2}) is the rate of rise of the quenching capability, D is the quenching capability prior to contact separation. The maximum current quenching capability $QC_{max,op}$ is generally unknown and it requires a specific tuning to meet the simulations with the measurements.

Fig. 1 shows the implemented single-phase model of the VCB1 in the EMTP-RV environment. The VCB characteristics described above for the opening sequence are implemented using a flip-flop logic block, which produces an open or close signal to the VCB switch, depending on the output of the two blocks *VCB_closing* and *VCB_opening*.

An RLC branch is put in parallel to account for the open contact gap stray capacitance, resistance and inductance. The values of