Electric Power Systems Research 138 (2016) 50–57

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Transients caused by switching of 420 kV three-phase variable shunt reactor

Alan Župan[a], Božidar Filipović-Grčić[b,*], Dalibor Filipović-Grčić[c]

[a] Croatian Transmission System Operator Ltd., Kupska 4, Zagreb 10000, Croatia
[b] Faculty of Electrical Engineering and Computing, University of Zagreb, Zagreb 10000, Croatia
[c] Končar Electrical Engineering Institute, Zagreb 10000, Croatia

ARTICLE INFO

Article history:
Available online 5 January 2016

Keywords:
Variable shunt reactor
SF_6 circuit breaker
Controlled switching
Inrush current
Electric arc model
EMTP-RV simulations

ABSTRACT

This paper describes transients caused by uncontrolled and controlled switching of three-phase 420 kV variable shunt reactor (VSR). The model for the analysis of the transients caused by switching of VSR was developed in the EMTP-RV software. It includes a dynamic electric arc in SF_6 circuit breaker and the model of substation equipment. Inrush currents due to VSR energization and overvoltages due to de-energization were determined at tap positions corresponding to lowest 80 MVAr and highest 150 MVAr reactive power. Based on the calculation results, mitigation measures and operating switching strategy of VSR were proposed.

1. Introduction

The function of shunt reactors in transmission networks is to consume the excessive reactive power generated by overhead lines under low-load conditions, and thereby stabilize the system voltage. They are quite often switched on and off on a daily basis, following the load situation in the system. Instead of having two or more shunt reactors with fixed power ratings, a single variable shunt reactor (VSR) could be used for compensation of reactive power.

The actual magnitude of the inrush current due to VSR energization is quite dependent on the range of linearity of the VSR core and on the time instant of circuit breaker pole operation. Switching operations at unfavorable instants can cause inrush currents that may reach high magnitudes and have long time constants. In case when VSRs have a solidly grounded neutral, unsymmetrical currents cause zero-sequence current flow, which can activate zero-sequence current relays. This may cause difficulties such as unwanted operation of the overcurrent relay protection [1].

De-energization of the VSR can impose a severe duty on both the shunt reactor and its circuit breaker due to current chopping that occurs when interrupting small inductive currents. The switching overvoltages can be dangerous for the equipment if the peak value exceeds the rated switching impulse withstand voltage of the VSR. However, the overvoltages resulting from the de-energization are unlikely to cause an insulation breakdown of VSRs as they are protected by surge arresters connected to their terminals. The severity of the switching duty increases when single or multiple reignitions occur. Such voltage breakdowns create steep transient overvoltages on VSR with the front time ranging from less than one microsecond to several microseconds and may be unevenly distributed across the VSR winding. So these steep fronted transient voltages are stressing the entrance turns in particular with high inter-turn overvoltages. Therefore some mitigation measures should be considered to reduce the chopping overvoltages and the risk of reignition of the circuit breakers.

Uncontrolled switching of shunt reactors, shunt capacitors and transmission lines may cause severe transients such as high overvoltages or high inrush currents [2]. Conventional countermeasures such as pre-insertion resistors, damping reactors or surge arresters can be used to limit the switching transients. In addition, system and equipment insulation can be upgraded to withstand the dielectric stresses. These methods, however, may be inefficient, unreliable or expensive, and do not treat the root of the problem [3].

Controlled switching is a method for eliminating harmful transients via time controlled switching operations. Closing or opening commands to the circuit breaker are delayed in such a way that switching occurs at the optimum time instant related to the voltage phase angle. Controlled switching has become an economical substitute for a closing resistor and is commonly used to reduce switching surges. The number of installations using controlled switching has increased rapidly due to satisfactory

---

* Corresponding author. Tel.: +385 1 6129 714; fax: +385 1 6129 890.
E-mail addresses: alan.zupan@hops.hr (A. Župan), bozidar.filipovic-grcic@fer.hr (B. Filipović-Grčić), dfilipovic@koncar-institut.hr (D. Filipović-Grčić).

http://dx.doi.org/10.1016/j.epsr.2015.12.010
0378-7796/© 2015 Elsevier B.V. All rights reserved.

Table 1
VSR data.

Rated voltage	420 kV	
Rated frequency	50 Hz	
Reactive power	150 MVAr (tap position 1)	80 MVAr (tap position 29)
Rated current	206 A	110 A
Core type	Five limb	
Total losses (at 420 kV)	232 kW	145 kW
Zero sequence impedance	1.2 kΩ per phase	2.2 kΩ per phase
Capacitance of winding to ground	3.8 nF per phase	

service performance since the late 1990s [4,5]. Currently, it is often recommended for shunt capacitor and shunt reactor banks because it can provide several economic benefits such as the elimination of closing resistors and the extension of a circuit breaker nozzle and contact maintenance interval. It also provides various technical benefits such as improved power quality and the suppression of transients in transmission and distribution systems [6].

This paper describes the transients caused by the switching of a three-phase 420 kV VSR. The inrush currents due to VSR energization and the overvoltages due to de-energization were analyzed. For this purpose, a model of VSR, substation equipment and electric arc in SF_6 circuit breaker was developed in the EMTP-RV software.

2. Model in EMTP-RV

The VSR considered in this paper has 29 tap positions, and the tap-changing order is in opposite direction, i.e. it starts from tap position 29 (lowest amount of 80 MVAr consumption) and the final position is 1 (highest amount of 150 MVAr consumption). The VSR lowers the voltage by tapping from tap position 29 to tap position 1. VSR manufacturer data are shown in Table 1.

Fig. 1 shows the change of VSR reactive power, current and impedance with respect to tap position.

VSR switching transients were calculated only in case of lowest (80 MVAr) and highest (150 MVAr) reactive power. The calculation of inrush currents requires an adequate modeling of the reactor nonlinear flux–current curve. The nonlinearity is caused by the magnetizing characteristics of the VSR iron core. Recorded RMS voltage–current curves obtained from manufacturer were converted into instantaneous flux–current saturation curves (Fig. 2) which were used in the nonlinear inductance model in EMTP-RV [7] and approximated with two segments (linear area A–B, below knee of the saturation curve and saturation area B–C).

Each phase of a three phase VSR was modeled as a nonlinear inductance with a serially connected resistance $R_{Cu} = 1.36\ \Omega$, representing the copper losses, and a parallel connected $R_{Fe} = 3.04\ k\Omega$, representing the iron losses. The magnetic coupling between the three star connected phases was represented with a zero-sequence inductance $L_0 = 3.7$ H which provides a path for the zero sequence current [8].

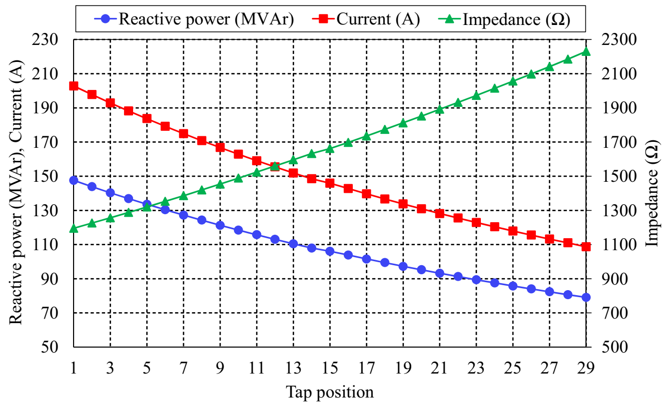

Fig. 1. VSR power, current and impedance versus tap position.

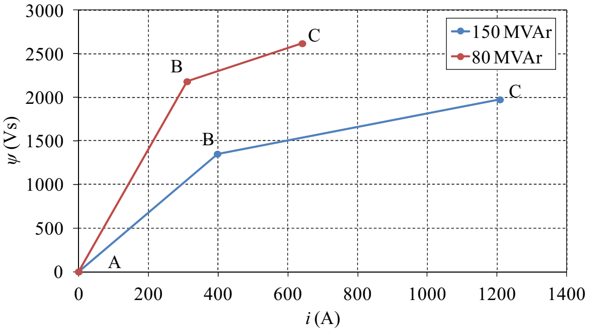

Fig. 2. Instantaneous flux–current saturation curve of VSR.

The VSR model in EMTP-RV is shown in Fig. 3

The equivalent 420 kV network was represented with positive ($R_1 = 1.1\ \Omega$, $L_1 = 47.13$ mH) and zero ($R_0 = 3.14\ \Omega$, $L_0 = 64.87$ mH) sequence impedances, determined from single-phase and three-phase short circuit currents.

The equipment in the high voltage substation was represented by surge capacitances [9], whereas busbars and connecting leads by a frequency dependent line model. MO surge arresters in the VSR bay of rated voltage $U_r = 330$ kV were modeled with a nonlinear U–I characteristic with respect to switching overvoltages.

SF_6 circuit breaker with two breaking chambers was represented by the Schwarz-Avdonin electric arc model [10,11] and grading capacitors of 500 pF connected in parallel to the breaking chambers. The EMTP-RV model shown in Fig. 4 consists of the equivalent 420 kV network, the main busbars, the SF_6 circuit breaker and equipment in VSR bay.

3. Uncontrolled energization of VSR

The following instants of circuit breaker pole closing were considered: $t_A = 15$ ms, $t_B = 13$ ms and $t_C = 17$ ms (Fig. 5). Simulations were carried out in case of the VSR lowest (80 MVAr) and highest (150 MVAr) reactive power.

3.1. Tap position 1: Reactive power 150 MVAr

Figs. 5 and 6 show calculated VSR voltages and currents, respectively. The highest inrush current occurs at an instant near the voltage zero-crossing in phase A, since it results with the maximum DC component of current.

The conducted simulation showed that a transient inrush current with an amplitude of 4.27 p.u. and a high DC component lasted for 3.2 s (Fig. 7). This could cause difficulties such as unwanted operation of the overcurrent relay protection.

A zero-sequence current occurred in case of uncontrolled reactor energization (Fig. 8) as a consequence of asymmetry. This may cause a false operation of the relay protection used for detecting single phase-to-ground faults.

3.2. Tap position 29: Reactive power 80 MVAr

Figs. 9–12 show calculation results. The conducted simulation showed that a transient inrush current with an amplitude of 2.16 p.u. and a high DC component lasted for 4 s (Fig. 11). The inrush and zero-sequence currents were significantly lower in this case compared to the case corresponding to 150 MVAr (Fig. 12).