Modelling of variable shunt reactor in transmission power system for simulation of switching transients

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Abstract - This paper describes a model of three-phase variable shunt reactor (VSR) for simulation of switching transients in EMTP-RV software. Inrush currents caused by VSR energization and overvoltages caused by de-energization are analysed. For this purpose, a model of VSR, substation equipment and electric arc in SF_6 circuit breaker was developed in EMTP-RV software.

Key words: variable shunt reactor, inrush currents, switching overvoltages, electric arc, EMTP-RV

I. Introduction

Shunt reactors are used in power transmission system for consuming an excessive reactive power generated by overhead lines under low-load conditions. These conditions can increase system voltages above the maximum operating voltage due to the Ferranti effect. By connecting shunt reactors to transmission system, voltages can be maintained within the prescribed limits, which is important for normal operation of high voltage equipment. Fixed shunt reactors are quite often switched on and off, 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.

Energization and de-energization of VSR on frequent basis cases high mechanical and electrical strains for VSR and substation equipment [1]. Occasionally at maximum consumption in electric power system, it is necessary to do the VSR de-energization which causes overvoltage due the small inductive current chopping. Small inductive current chopping is a complex appearance which requires detail modelling of circuit breaker and electric arc.

Overvoltage caused by de-energization may cause an insulation breakdown of VSR. To be protected from this risk, surge arresters are used in VSR bay [2]. Unlike de-energization, VSR energization may cause inrush current with high magnitudes and long-time constants. If VSR has a solidly grounded neutral, this switching operation causes zero-sequence current flow which can activate zero-sequence current relays [2].

To avoid the appearance of high inrush current and overvoltage during VSR de-energization, it is required to perform controlled switching, a method which eliminates harmful transients via time controlled switching operation. Controlled switching reduces mechanical and dielectric stress of circuit breaker and VSR, and reduces the probability of restrike phenomena in circuit breaker [2], [3].

This paper describes model of a three-phase 400 kV VSR in 400/110 kV substation for simulation of switching transients in EMTP-RV software. Except VSR model, this paper contains model of circuit breaker with electric arc and other high voltage equipment in VSR bay. Also, in this paper inrush currents and overvoltages are calculated caused by VSR switching.

II. Model for simulation of VSR switching transients

VSR bay inside 400 kV substation was modelled in detail including model of VSR, circuit breaker and other high voltage equipment. Five limb core VSR was considered in this paper, with delta connected windings and solidly grounded neutral point. Technical data of VSR are given in Table 1 [4].

TABLE I. Technical Data of VSR

Rated voltage	400 kV	
Rated frequency	50 Hz	
Core type	Five limb	
Reactive power	150 MVAr	75 MVAr
Rated current	216.95 A	108.25 A
Total losses (at 400 kV)	240 kW	150 kW
Zero sequence impedance	1200 Ω per phase	2400 Ω per phase
Capacitance of winding to ground	3.8 nF per phase	

Each phase of VSR was represented by winding inductance L connected in series with resistance representing copper losses R_{Cu}. Resistance R_{Fe} representing iron losses was added in parallel with the winding branch as shown in Figure 1.

Copper and iron losses are calculated from total losses P_{Tot} using the following expressions [5]:

$$P_{Cu} \approx 0.75 \cdot P_{Tot}\,, \tag{1}$$

$$P_{Fe} \approx 0.25 \cdot P_{Tot}\,. \tag{2}$$

Resistances representing copper and iron losses in the model are determined from the following expressions:

$$R_{Cu} = \frac{P_{Cu}}{3 \cdot I_n^2}\,, \tag{3}$$

$$R_{Fe} = \frac{U_n^2}{P_{Fe}}\,. \tag{4}$$

Zero sequence inductance L_0 of VSR is determined by using the following equation:

$$L_0 = \frac{Z_0}{\omega} \tag{5}$$

The magnetic coupling between the star connected phases was represented by a zero-sequence inductance which provides a path for the zero-sequence current [6].

The calculation of inrush currents requires an adequate modelling of the nonlinear flux–current curve which describes the magnetizing characteristics of the VSR iron core. Recorded RMS voltage–current curves obtained from manufacturer were converted into instantaneous flux–current saturation curves (Figure 2 and Figure 3) which were used in the nonlinear inductance model in EMTP-RV [6] and approximated with two segments.

400 kV SF_6 circuit breaker in VSR bay with two breaking chambers was modelled in EMTP-RV considering nonlinear behaviour of electric arc (Figure 4).

Grading capacitors (500 pF) are connected in parallel with breaking chambers.

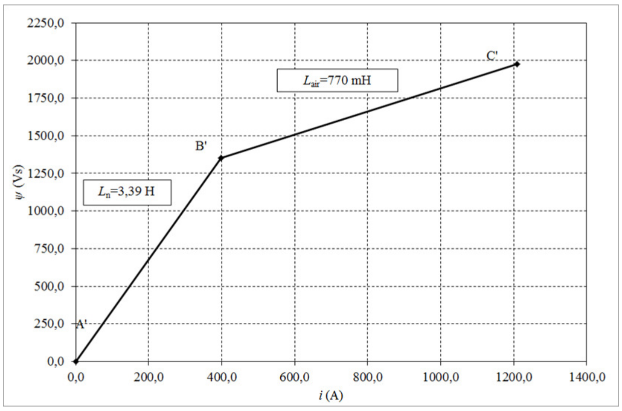

Figure 2. Instantaneous flux-current saturation curve (150 MVAr)

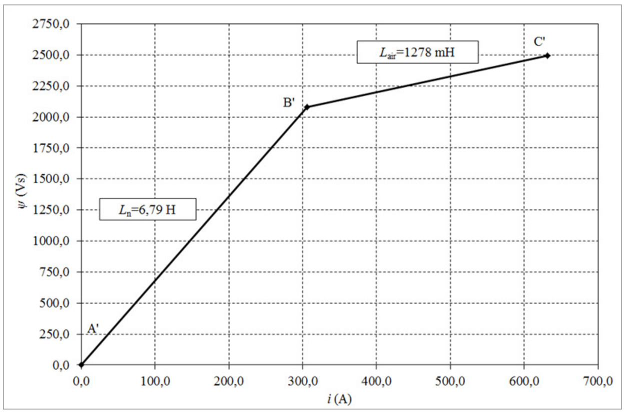

Figure 3. Instantaneous flux-current saturation curve (75 MVAr)

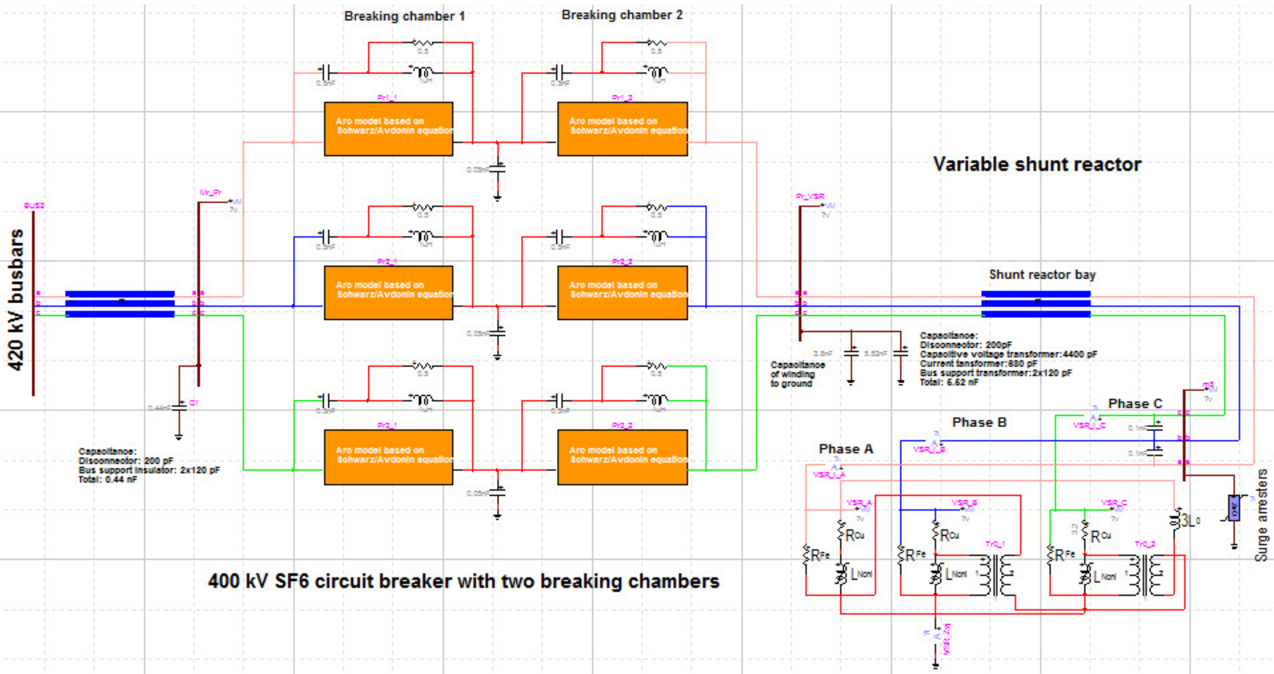

Figure 1. Model of VSR in EMTP-RV

Electric arc was mathematically described with Schwarz/Avdonin differential equation [8], [9], which was solved by using numerical integration in EMTP-RV [7].

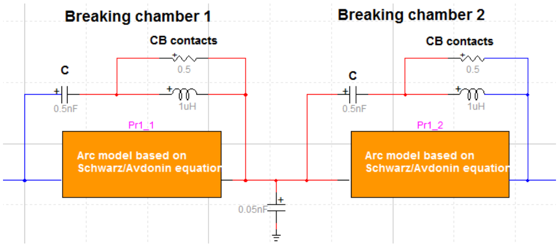

Figure 4. Model of electric arc in EMTP-RV: 400 kV SF_6 circuit breaker with two breaking chambers

Since switching of VSR produces high frequency transients, other substation equipment in VSR bay were represented by capacitance to ground (Table II) [10], [11]. Surge arresters were modelled by nonlinear U-I characteristic obtained from manufacturer data.

TABLE II. CAPACITANCE TO GROUND OF HIGH VOLTAGE EQUIPMENT

High voltage equipment	Capacitance (pF)
Disconnector	200
Circuit breaker	60
Current transformer	680
Capacitive voltage transformer	4400
Bus support insulator	120

III. SIMULATION OF SWITCHING TRANSIENTS

Switching transients were simulated in case of 150 MVAr and 75 MVAr reactive power.

A. Uncontrolled energization of VSR

Current waveforms in case of uncontrolled energization of 150 MVAr reactive power at time instants t_A=15 ms, t_B=14 ms, t_C=16 ms are shown in Figure 5 and Figure 6 [4].

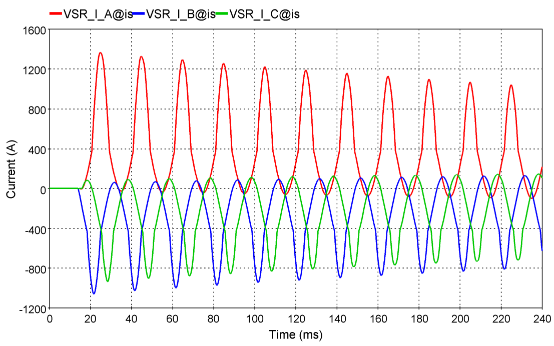

Figure 5. VSR currents: I_{Amax}= 1362.0 A, I_{Bmax}= -1059.0 A, I_{Cmax}= -936.0 A

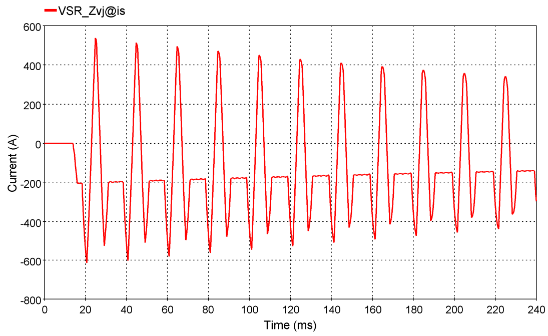

Figure 6. VSR zero-sequence current, I_{Zmax}= -614.0 A

Uncontrolled energization produces inrush currents and zero sequence currents of high amplitudes with relatively long duration. This event may trigger unwanted operation of overcurrent protection relays. Figure 7 and Figure 8 show current waveforms in case of uncontrolled energization of 75 MVAr reactive power.

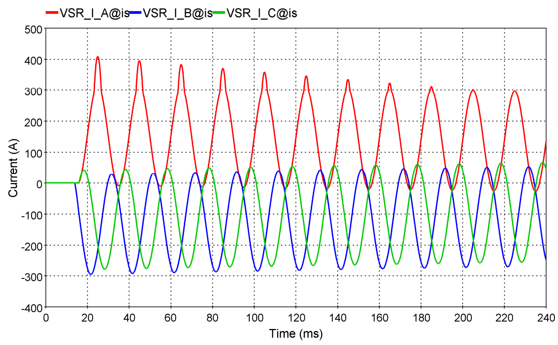

Figure 7. VSR currents: I_{Amax}=408.4 A, I_{Bmax}=-295.1 A, I_{Cmax}=-279.1 A

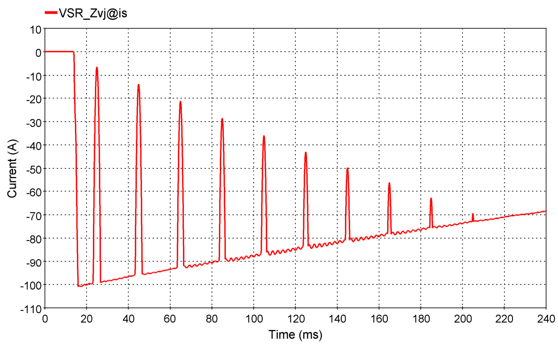

Figure 8. VSR zero-sequence current, I_{Zmax} =-100.9 A

Inrush current amplitudes are lower in case with 75 MVAr reactive power.

B. Controlled energization of VSR

Controlled switching at optimum time instant corresponding to voltage peak value in each phase reduces inrush currents significantly. Current waveforms during controlled switching for 150 MVAr reactive power are shown in Figure 9 and Figure 10, while for 75 MVAr reactive power are shown in Figure 11 and Figure 12.

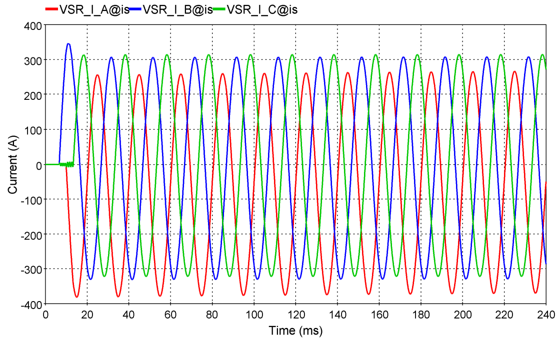

Figure 9. VSR currents: I_{Amax}= -381.0 A, I_{Bmax}=344.4 A, I_{Cmax}= -322.6 A

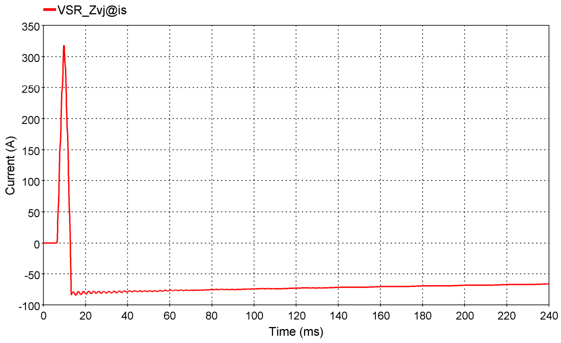

Figure 10. VSR zero-sequence current, I_{Zmax}= 315.5 A

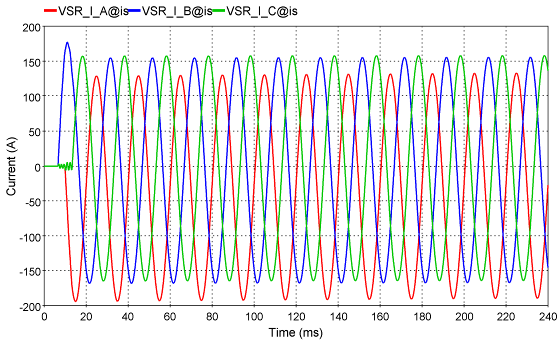

Figure 11. VSR currents: I_{Amax}=-193.2 A, I_{Bmax}=176.9 A, I_{Cmax}=-165.3 A

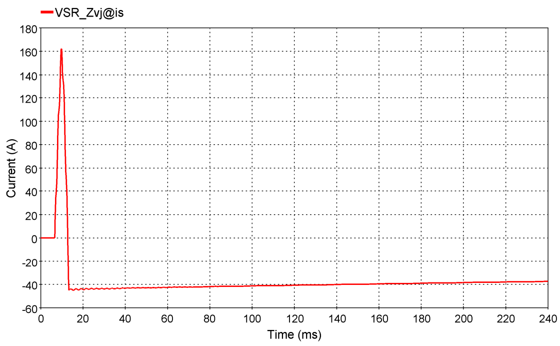

Figure 12. VSR zero-sequence current, I_{Zmax}=162.3 A

C. Deenergization of VSR

Overvoltages across VSR were determined in case of maximum/minimum reactive power. Previously described circuit breaker model was used in simulations. Effect of surge arresters on overvoltage reduction is shown in Table III. Higher overvoltages appear in case when reactive power of VSR is at minimum value (75 MVAr).

TABLE III OVERVOLTAGES ON VSR

Reactive power (MVAr)	Surge arresters in VSR bay	VSR overvoltages (kV)		
		Phase A	Phase B	Phase C
150	No	550.6	667.0	642.1
150	Yes	-501.1	471.3	516.8
75	No	834.8	880.2	978.9
75	Yes	-540.3	535.2	-542.4

Overvoltage amplitudes across the breaking chambers of circuit breaker during VSR deenergization are shown in Table IV. Surge arrester are not considered in this case.

TABLE IV OVERVOLTAGES ACROSS THE BREAKING CHAMBERS OF CIRCUIT BREAKER

REACTIVE POWER (MVAR)	Voltages across breaking chambers (kV)					
	Phase A		Phase B		Phase C	
	U_{1max}	U_{2max}	U_{1max}	U_{2max}	U_{1max}	U_{2max}
75*	568.9	583.8	561.7	551.0	580.3	576.9
75**	620.1	927.1	632.7	866.1	654.5	1103.3

*with grading capacitors, ** without grading capacitors

Figure 13 and Figure 14 show voltage waveforms across breaking chambers in case with and without grading capacitors.

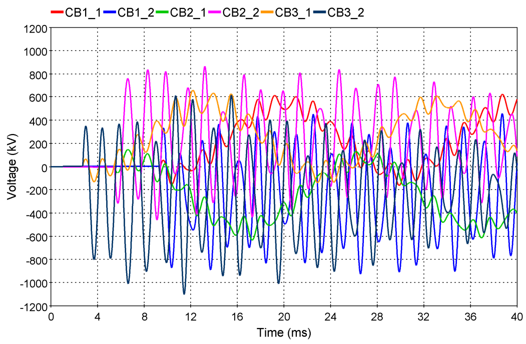

Figure 13. Voltages across breaking chambers (without grading capacitors)

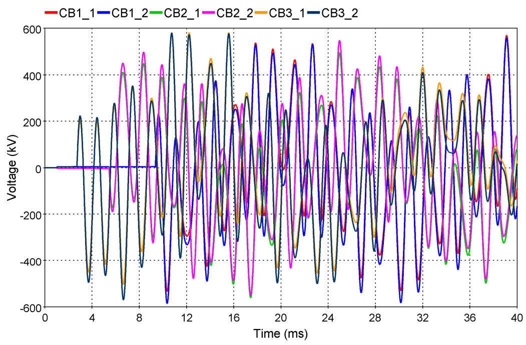

Figure 14. Voltages across breaking chambers (with grading capacitors)

Simulation results show that grading capacitors equalize potential distribution across breaking chambers of circuit breaker. Overvoltage amplitudes across the breaking chambers are higher in case of 75 MVAr reactive power. In case without grading capacitors [12], nonlinear voltage distribution across breaking chambers increases the probability of restrike occurrence inside the circuit breaker which produces steep overvoltages.

Surge arresters reduce both overvoltages on VSR and overvoltages across breaking chambers. Overvoltages on VSR in case of 75 MVAr without surge arresters are shown in Figure 15 [4].

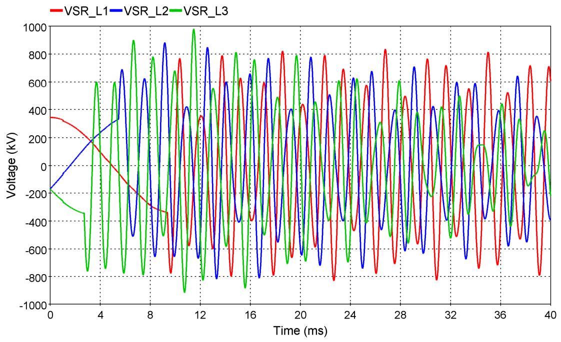

Figure 15. VSR overvoltages: U_{Amax}=834.8 kV, U_{Bmax}=880.2 kV, U_{Cmax}=978.9 kV

Harmonic analysis of VSR overvoltages show that 12th and 17th harmonic have highest amplitudes corresponding to dominant frequencies of voltage oscillations (Figure 16).

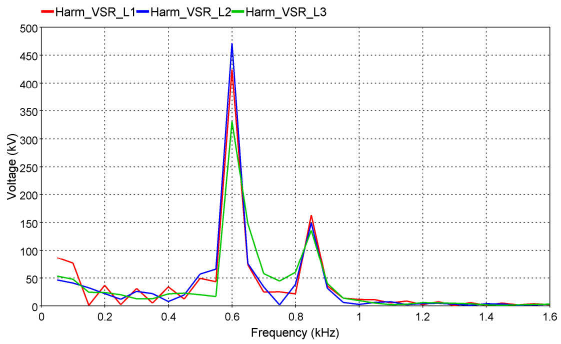

Figure 16. Harmonic analysis of VSR overvoltages

IV. CONLUSION

This paper describes the model of 400 kV variable shunt reactor with reactive power 75-150 MVAr for analysis of switching transients. Apart from variable shunt reactor, SF_6 circuit breaker with an electric arc was modelled in detail in EMTP-RV software.

Transients calculation was performed for controlled and uncontrolled VSR energization at its lowest and highest reactive power. Controlled energization significantly reduces both inrush currents and zero-sequence currents. Simulation shows that inrush currents in case of 75 MVAr are significantly lower compared to 150 MVAr.

Overvoltages on VSR and on circuit breaker were calculated during VSR de-energization. Overvoltages on VSR are significantly higher during de-energization in case of 75 MVAr. In all cases surge arresters reduce overvoltages on VSR and on breaking chambers.

Calculation shows that grading capacitors equalize potential distribution across the breaking chambers, which reduces the probability of restrike occurrence inside the circuit breaker.

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