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REFLECTING OF SERIES CAPACITORS EQUIPPED WITH MOVs IN PROTECTION AND FAULT LOCATION ALGORITHMS FOR SERIES-COMPENSATED TRANSMISSION LINES

This paper deals with reflecting of parallel branches of a compensating series capacitor (SC) and its over-voltage protection – Metal Oxide Varistor (MOV) in a transmission line for both protective relaying and fault location purposes. The presented methods of reflecting SCs&MOVs have been deeply investigated with using fault data generated with the ATP-EMTP software.

Introduction. Increased transmittable power, improved power system stability, reduced transmission losses, improved voltage control, flexible power flow control and the environmental reasons stand for installing compensating Series Capacitors (SCs) [1, 3–12] on long transmission lines. Series Capacitors (SCs) equipped with MOVs [1], when set on a transmission line (Fig. 1), create certain problems for its protective relays [10, 12] and fault locators [9, 11]. In order to overcome these difficulties one requires applying the adequate representations of SCs&MOVs. For a distance protection the instantaneous voltage drops across SCs&MOVs have to be estimated on the base of locally measured phase currents and the parameters of SC&MOV banks [9, 11]. Such the algorithm, based on *on-line* solving the non-linear differential equation is presented further. In turn, providing high accuracy for fault location in series-compensated lines requires determining the representations of SCs&MOVs in the form of the fundamental frequency equivalents. Use of ATP-EMTP software [2] for this purpose has been proposed.

Model of series-compensated line. Fig. 1 presents the scheme of the studied series-compensated line. The compensation capacitors are equipped with MOVs, which were modelled as non-linear resistors approximated by the standard voltage-current characteristic [11]:

$$i_{MOV} = P\left(\frac{v_x}{V_{REF}}\right)^q \tag{1}$$

The following parameters of the approximation (1) have been taken in the further quantitative analysis: q=23, P=1kA, V_{REF}=150kV.

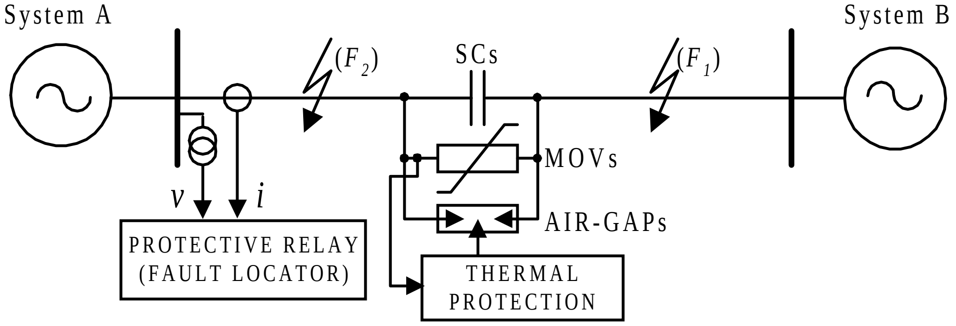

Fig. 1. Scheme of a single series-compensated line

Reflecting of SC&MOV banks for distance protection. Let us consider a parallel connection of the series capacitor SC, and the MOV. Assuming the analytical approximation of the MOV (1), this non-linear circuit can be described by the following non-linear differential equation:

$$C\frac{dv_x}{dt}+P\left(\frac{v_x}{V_{REF}}\right)^q-i=0 \tag{2}$$

In this equation, all the parameters are known and constant; the current *i* entering the bank is measured (neglecting the shunt parameters of the line this is the current in the substation); while the voltage drop v_x is to be calculated. To solve for v_x one needs to transform the continuous-time differential equation (2) into its algebraic discrete-time form. The 2nd order Gear differentiation rule has been taken for this purpose, i.e. the following substitutions apply:

$$i(t)\to i_{(n)},\quad v_x(t)\to v_{x(n)} \tag{3a}$$

$$\frac{dv_x}{dt}(t)\to D\left(3v_{x(n)}-4v_{x(n-1)}+v_{x(n-2)}\right) \tag{3b}$$

where: $a=2\pi fT_s$, f – frequency, T_s – sampling period, n – discrete time index,

$$D=2\pi f\Big/2\sqrt{(1-\cos(a))^4+(2\sin(a)-0.5\sin(2a))^2}\ .$$

Inserting (3) into (2) yields the algebraic equation:

$$F(x)=A_qx^q+A_1x-A_0=0 \tag{4}$$

in which: $x=\dfrac{v_{x(n)}}{V_{REF}}$, $A_q=P$, $A_1=3DCV_{REF}$, $A_0=i_{(n)}+\dfrac{A_1}{3V_{REF}}\left(4v_{x(n-1)}-v_{x(n-2)}\right)$.

Equation (4) is to be solved for x (pu value of the sought voltage drop v_x at the present sampling instant n). The two parameters of this equation: A_q and A_1 are constant, while A_0 depends on the present sample of the current entering the bank and the two historical samples of the voltage drop. In order to ensure good convergence of the algorithm, appropriately modified Newton-Raphson method has been used. The form (4) of the equation is numerically efficient for *"small"* values of A_0 while for *"large"* values of A_0, it should be re-written to:

$$F(y)=A_qy+A_1y^{\frac{1}{q}}-A_0=0 \tag{5}$$

(where: $y=x^q$) and solved for y.

The border value of A_0 alternating the optimal forms: (4) and (5) is:

$$A_0{}^*=A_q\left(\left(A_1/qA_q\right)^{(1/q-1)}\right)^q+A_1\left(\left(A_1/qA_q\right)^{(1/q-1)}\right) \tag{6}$$

The form (4) is solved iteratively using the Newton-Raphson method by applying the following algorithm:

$$x_{new}=x_{old}-\frac{A_qx_{old}{}^q+A_1x_{old}-A_0}{qA_qx_{old}{}^{q-1}+A_1} \tag{7}$$

The form (5) is solved iteratively using the Newton-Raphson procedure:

$$y_{new} = y_{old} - \frac{A_q y_{old} + A_1 y_{old}^{\frac{1}{q}} - A_0}{A_q + \frac{A_1}{q} y_{old}^{\frac{1-q}{q}}} \tag{8}$$

Flow-chart of the complete algorithm is depicted in Fig. 2 (*note:* z^{-1} – represents a time delay corresponding to a single sampling period).

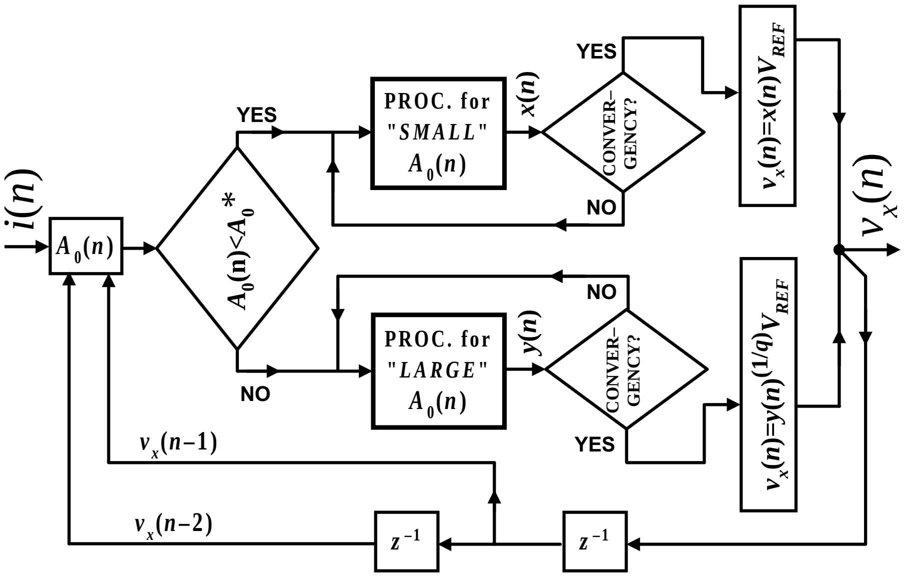

Fig. 2. Flow-chart of the digital algorithm for estimation of a voltage drop across SC&MOV

For faults occurring in front of SCs&MOVs (F_2 in Fig. 1) the classic distance relay principle can applied. However, some modifications are required for faults behind SCs&MOVs. In this case the fault loop impedance has to be calculated using the original measured currents, but the voltages compensated for voltage drops across SCs&MOVs. The estimated voltage drops across the SCs&MOVs are used to compensate the measured phase voltages (the voltage drop is subtracted in each phase (*a*, *b*, *c*) separately, regardless of the type of fault):

$$[v_{comp}]_{abc} = [v]_{abc} - [v_x]_{abc} \tag{9}$$

Fig. 3 illustrates operation of the algorithm for a sample 400kV line under the SLG fault just behind the compensating bank (as seen from the substation A) with 5Ω fault resistance. In the measured phase voltages (Fig. 3, *a*) and phase currents (Fig. 3, *b*) one observes the characteristic distortion of the waveforms. On the other hand, in the sound phases the MOVs operate linearly, what results in slowly decaying sub-harmonic oscillations (Fig. 3, *c*). Fig. 3, *d* shows the actual voltage drop across the SC&MOV from the faulted phase (EMTP simulation) and the signal estimated with the presented algorithm. The accuracy of voltage reconstruction is very good. Note that the signal is calculated at the sampling instants only (1000 Hz sampling frequency was assumed) and therefore the calculated voltage drop is presented as the stair waveform.

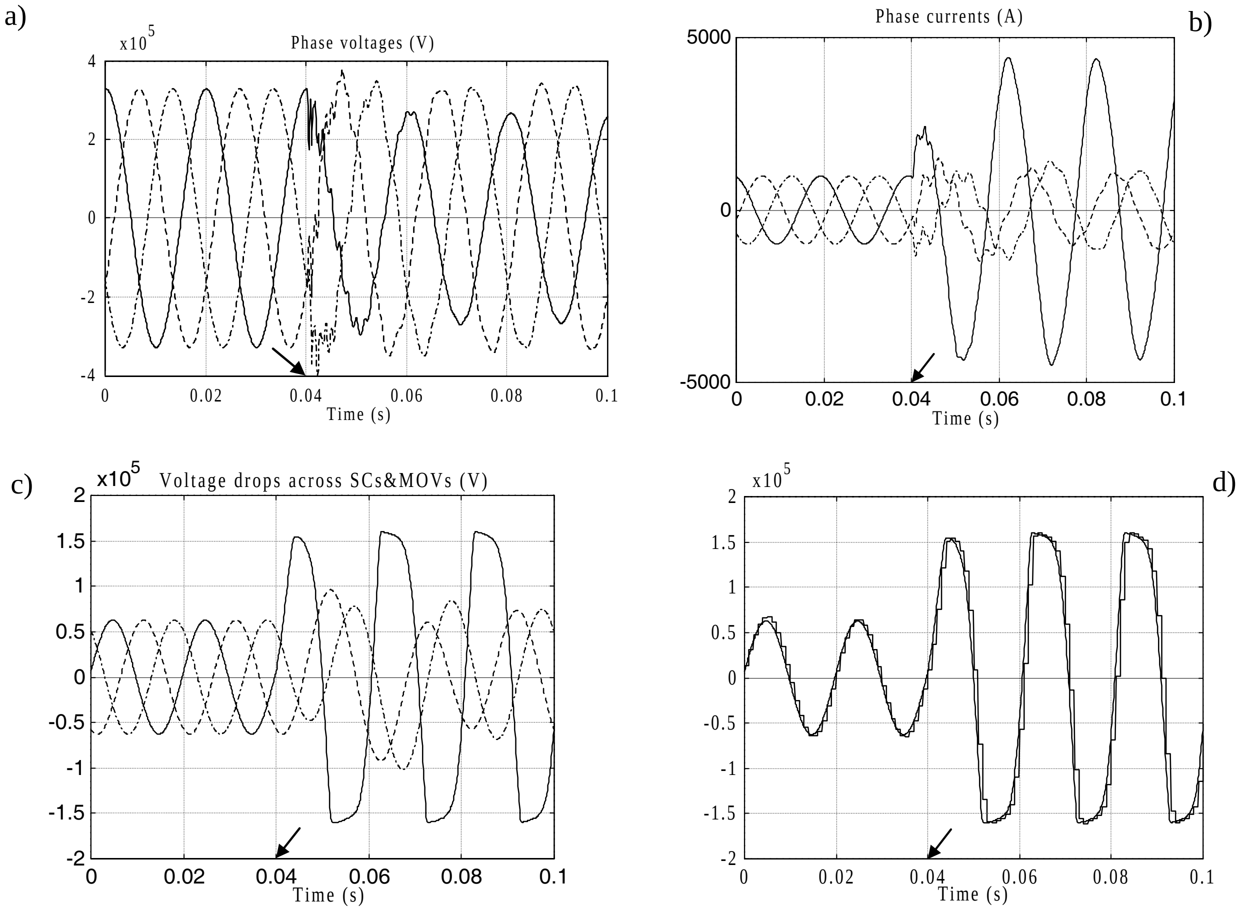

Fig. 3. The sample fault:
a – measured phase voltages; b – measured phase currents (input to the algorithm);
c – voltage drops across SCs&MOVs from simulation; d – voltage drop across SC&MOV
in the faulted phase – from simulation and estimated (output from the algorithm)

Results of fault loop impedance measurements for the considered sample fault are depicted in Fig. 4.

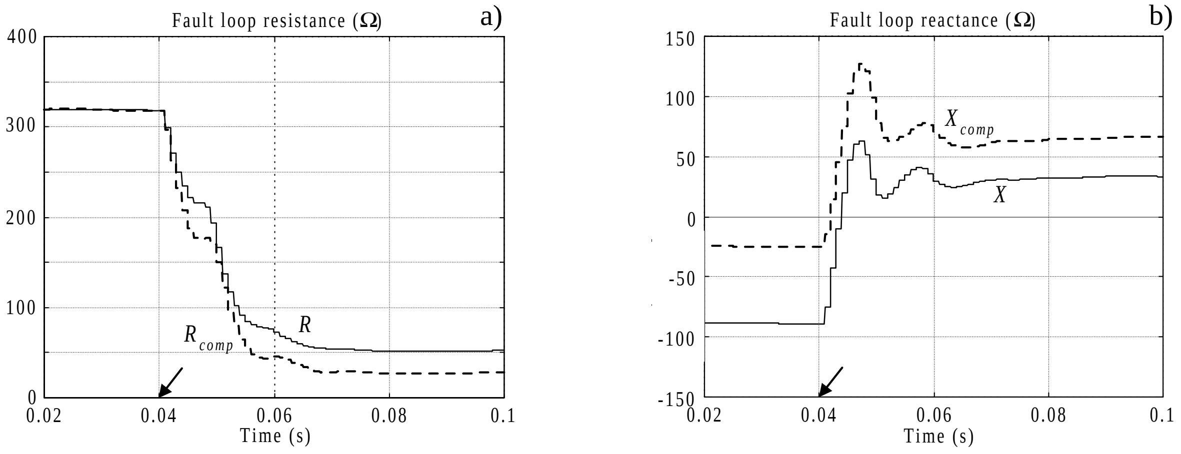

Fig. 4. Fault loop resistance/reactance measurements performed without (R, X)
and with compensating (R_{comp}, X_{comp}) for voltage drops across SCs&MOVs

Full-cycle Fourier filters were utilized in the measurement. For pre-fault state the compensation is only for the reactance. In contrast, in post-fault period the compensation is for both resistance and reactance.

Equivalenting of SC&MOV banks for fault location. Fig. 5 presents the principle of the fundamental frequency equivalenting. The parallel connection of a fixed series capacitor and its non-linear protecting resistor MOV (Fig. 5, *a*) was represented for the steady state by the fundamental frequency equivalent (Fig. 5, *b*). The equivalent is of the form of a series branch with the resistance R_v and the reactance X_v, both dependent on the amplitude of a fault current. Fundamental frequency currents and voltage drops denoted in the original scheme (Fig. 5, *a*) and in the equivalent (Fig. 5, *b*) must match.

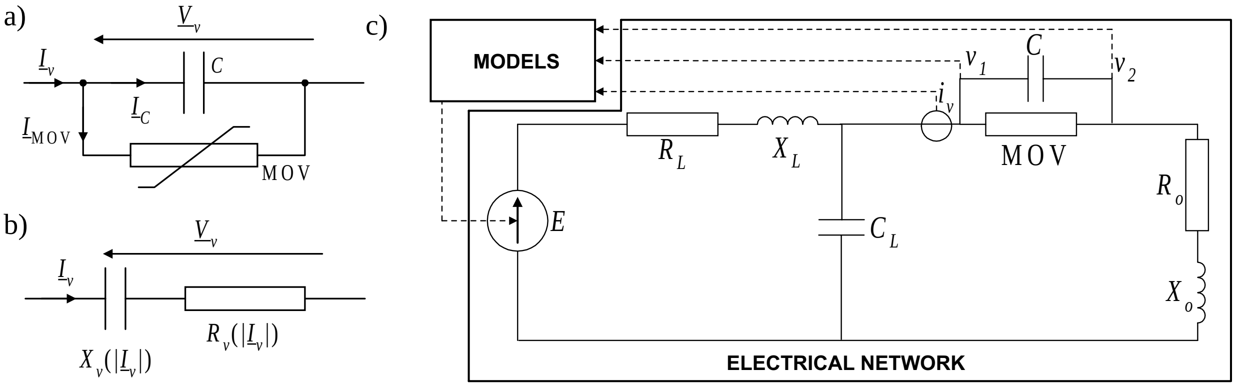

Fig. 5. Equivalenting of SC&MOV:
a – original circuit; b – scheme of the fundamental
frequency equivalent; c – principle of using ATP-EMTP for the equivalenting

The equivalenting has to be done by scanning through different points on the equivalent characteristic. Therefore the network to be equivalented has to be simulated with different amplitudes of the fault current entering the parallel connection of the SC and the MOV. This was achieved by changing amplitude of the voltage of the supplying source.

Fig. 5, *c* presents the idea of the equivalenting by using ATP-EMTP [2]. The considered circuit is supplied by the source for which the voltage amplitude is controlled in the MODELS units. The inductive impedance (R_L, X_L) represents the resultant impedance of the source and the line segment from the substation up to the SC&MOV installation point. The capacitance C_L corresponds to the shunt capacitance of this local segment of a line, while R_0 and X_0 – the equivalent impedance for the remote faulty line segment together with the remote supplying system. Exchange of the signals between the units of ATP-EMTP: the MODELS and the Electrical Network is shown in Fig. 5, *c*. Simulation time interval is subdivided into the subintervals with different amplitudes of the voltage source. This amplitude is determined in the MODELS and sent to the Electrical Network. Length of the simulation subintervals is set in such a way that steady state measurement is achieved in each the subinterval. This requires setting wider subintervals for smaller voltage amplitudes when long lasting transients are due to linear operation of MOVs. On the other hand, for higher supplying voltage amplitudes MOVs operate in non-linear range and shorter the subintervals are applied.

Voltages at both the SC terminals (v_1, v_2) and the current entering the SC&MOV complex (i_v) are picked from the Electrical Network and sent to the MODELS.

The results of the equivalenting for different rates of the capacitor compensation, i.e. at 60, 70 and 80 % rates, for 400 kV and 300 km transmission line are shown in Fig. 6.

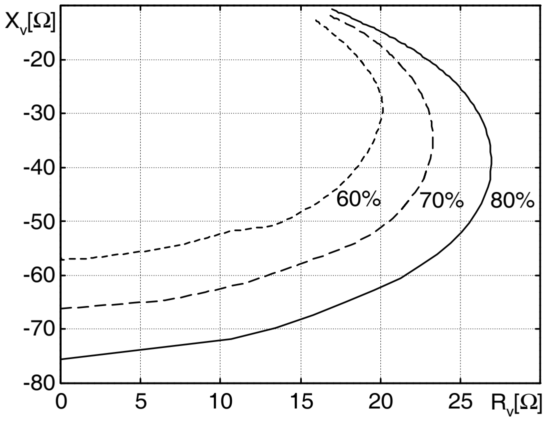

Fig. 6. Fundamental frequency equivalents for different compensation rates: loci of the equivalent impedance.

It was assumed when determining the equivalents shown in Fig.6 that the identical MOVs – as specified in (1) are used, while different SCs are installed – providing 60, 70 or 80 % compensation of the line, respectively. It is seen that the capacitance of the SC influences mainly the equivalent resistance (R_v). For the analysed compensation rates the equivalent reactance (X_v) differs only for low amplitudes of the fault current (when MOVs operate linearly or almost linearly).

Conclusions.

- Series capacitors equipped with MOVs create certain problems for transmission line protective devices and fault locators. In order to cope with these difficulties, adequate representations of SCs&MOVs have to be developed. Such the representations, for both distance protection and fault location purposes, have been delivered in the paper. Firstly, efficient digital algorithm for estimating a voltage drop across the complex of SC&MOV has been delivered. Its application to distance protection has been considered. The delivered estimation algorithm is based on *on-line* solving the strongly non-linear differential equation and is of recursive form. The other form of reflecting SCs&MOVs has been considered for using to fault location purposes. In this case the fundamental frequency concept has been employed.
- The time step of the algorithm for estimating SC&MOV voltage drop is directly determined by the applied sampling frequency. This substantially differs from the regular simulation, where much shorter time steps can be used. Moreover, the estimation algorithm is intended for *on-line* application to distance protection and thus fast convergence of the algorithm is required. To meet all these specific requirements for the estimation algorithm the appropriately modified Newton-Raphson method has been proposed. The strong non-linearity of the equation is moderated by switching between two forms of the equation depending on the operating point of the MOV.
- Fundamental frequency equivalent of SC&MOV circuit, designated for application to fault location purposes, is of the form of the series impedance. Both, resistance and capacitive

reactance of this impedance are current dependent components. Incorporation of the equivalent or the equivalents (in cases of inter-phase faults) into the fault loop model allows effective compensation for the presence of SCs&MOVs banks in the considered fault loop.

- ATP-EMTP based fundamental frequency equivalenting of SC&MOV circuit has been found as much more accurate than by using the fundamental harmonic analytical method, commonly used in the nonlinear circuit theory. In the developed ATP-EMTP program the SCs&MOVs circuits together with their vicinity are reflected. Thus, actual shapes of the signals in the circuit are taken into account. The equivalents have been determined for different compensation rates of the considered transmission line. It has been found that the compensation rate influences mainly the equivalent fault resistance while the equivalent capacitive reactance differs substantially only for low amplitudes of the fault current when MOVs operate linearly or almost linearly.

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