Modeling Fault Conditions for Parallel Series-Compensated Lines

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Abstract — **This paper presents ATP-EMTP modeling of fault conditions for parallel of series compensated lines. The developed model of the lines including Metal Oxide Varistors (MOVs), voltage and current instrument transformers and antialiasing analog filters has been used for generating the fault data for investigation of digital relaying algorithms. Alternative algorithms for the fault loop impedance measurement have been compared in terms of speed and quality of estimation. Based on the results of the performed analysis, certain recommendations have been given regarding the protection techniques for parallel series compensated lines.**

Keywords: Parallel Transmission Lines, Series Capacitor Compensation, EMTP, Transient Study, Protective Relaying, Fault Loop Impedance Measurement.

I. INTRODUCTION

Parallel series-compensated lines are very important links between power generation and energy consumption regions. Such the links exhibit the advantages resulting from both parallel lines arrangement and series capacitor compensation [1]. Series capacitors (SCs) can be installed at different locations. This paper, however, focuses on the parallel lines compensated with three phase banks of SCs installed in the middle of both the lines (Fig.1).

Distance protection for series compensated lines faces certain problems caused first of all by the fact that the impedance seen by a relay is not a strict geometrical measure of the distance to a fault. The apparent impedance is affected by the series capacitors and their non-linear overvoltage protecting arresters (MOVs) in both steady state and dynamic aspects. Also subsynchronous oscillations may occur under high resistance faults as well as the voltage and/or current inversion, what causes the traditional protection methods to fail.

Improvement of series compensated line protection calls for detailed study of transient phenomena. For this purpose ATP-EMTP model of the mutually coupled parallel lines compensated in the middle together with the relay measurement chains (Fig.1) has been developed. The computations using ATP-EMTP and Matlab have been conducted according to Fig.2.

In order to provide for the apparent fault loop impedance a strict geometrical measure of the distance to a fault, fundamental frequency equivalenting of SC&MOV branch is applied [7]. Besides this, good dynamic performance of impedance algorithms under the conditions specific to a series compensated line has to be provided. The later is the main aim of this study. Variety of impedance measuring algorithms have been extensively tested with respect to this.

II. ATP-EMTP MODEL

The parallel lines from Fig.1 (300 km, 400 kV, 50 Hz, compensated in the middle at 70 % in each line) were modeled as a cascade of four-ports, each representing a 50 km long parallel lines' segments (mutually coupled transposed Clarke model used).

The MOVs were modeled as non-linear resistors approximated by the standard voltage-current characteristic:

$$i = P\left(\frac{v}{V_{REF}}\right)^{q} \qquad (1)$$

The parameters of (1) assumed in this study were: $q = 23$, $P = 1\text{kA}$, $V_{REF} = 150$ kV.

Each MOV is protected from overheating by firing the complementary air-gap by the thermal (overload) protection (Fig.3a). The MOV protection was modeled as energy-based using ATP-EMTP MODELS (Fig.3b): the energy absorbed by the MOV is integrated (P) and the MOV becomes by-passed by firing the air-gap when this energy reaches its pre-defined limit (E_{LIM}).

The relay measuring chain was modeled as well. CVTs were represented by their 4th order linear models while CTs were simulated taking into account their saturation branches.

The analog anti-aliasing filters were represented by the 2nd order approximation with the cut-off frequency set at $1/3$ of the assumed sampling rate $f_s = 1$ kH.

III. TRANSIENT STUDY

Transient phenomena are of primary importance in evaluation of protective relay operation. Therefore, the developed ATP-EMTP model has been used in the transient studies carried out for a variety of fault conditions.

In this paper the two representative cases are included and discussed. Fig.4 presents transients for an a-g fault applied just in front of SCs&MOVs (fault F1 in Fig.1) while Fig.5 - for the same fault type but occurring just behind SCs&MOVs (fault F2 in Fig.1). Fault resistance for both the considered faults assumed 0.1 Ω.

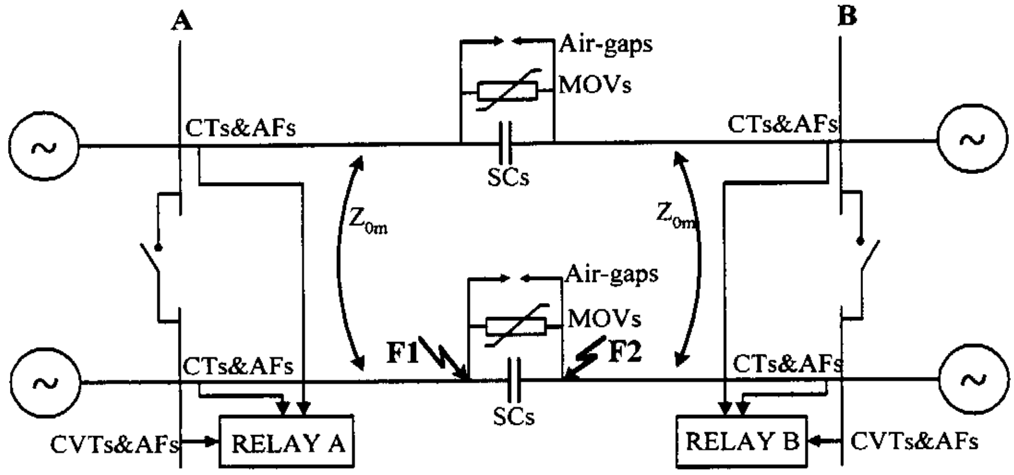

Fig.1. Arrangement of the studied series compensated parallel lines.

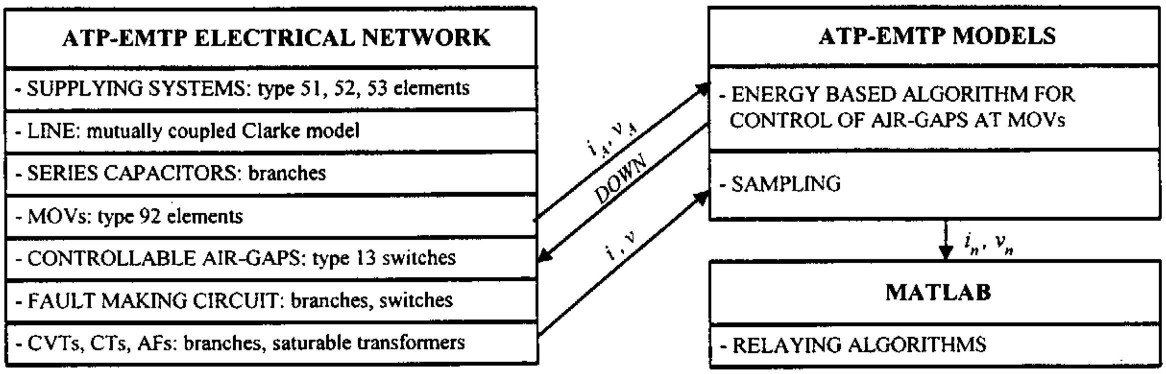

Fig.2. Structure of the computations.

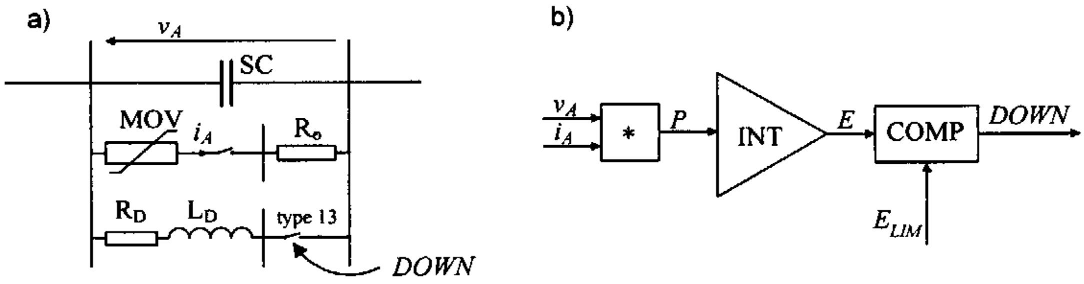

Fig.3. Modeling of SC&MOV branches: a) circuit diagram, b) block diagram for air-gap control algorithm.

Figs.4a and b present phase voltages and currents for the faulty line in case of the fault F1 (just in front of the SCs&MOVs). The waveforms are little distorted as the SCs&MOVs are not contained in the fault loop. The phase currents from the healthy parallel line (Fig.4c) contain transients resulting from linear operation of this line MOVs. Transients in the healthy line currents are also important for relay operation as the zero sequence component of these currents together with the zero sequence component of the faulty line currents have to be taken when composing the relay effective current in the case of the considered phase-to-ground faults. The simulations confirmed that transients in the relay input current (not in the voltages) determine primarily the relay dynamic performance. In respect to this, Fig.4d presents the relay input current filtered with the use of the half cycle Fourier algorithm. Both, the cosine and sine orthogonal components of the relay input current do not contain visible distortions after the data window is filled with the fault data exclusively. Thus, one can expect good conditions for the impedance measurement.

Figs.5a and b present the phase voltages and currents for the faulty line in case of the fault F2 (just behind the SCs&MOVs). Distortion in these waveforms results from the nonlinear operation of the SC&MOV present in the fault loop. Fig.5c shows the voltage drops across the SCs&MOVs in the faulty line. In the faulty phase one observes the voltage limited at around 150 kV and the air-gap firing 55 ms after the fault. In contrary, the SCs&MOVs in the other phases of the faulty line (Fig.5c) and in all the phases of the healthy line (Fig.5d) operate linearly. Thus, again, the phase currents in the healthy parallel line (Fig.5e) contain transients resulting from the linear operation of the MOVs.

Fig.5f presents the relay input current for the considered phase-to-ground fault filtered with the use of the half cycle Fourier algorithm. It is worth to notice that both, the cosine and sine orthogonal components of the relay input current contain some distortions even though the data window gets filled with the fault data. This indicates that in this case (the fault behind SCs&MOVs) the conditions for the impedance measurement are worse than in the previous case of the fault in front of the SCs&MOVs. Changes in the relay input signals due to air-gap firing undergo much later than the required time span for the relay operation, and thus, are of no further interest from relay measurement standpoint.

IV. FAULT LOOP IMPEDANCE MEASUREMENT

Variety of algorithms for the fault loop impedance measurement have been studied in this paper. The full and half cycle Fourier algorithms have been taken into consideration and the differential equation technique has been also tested. The application of all these algorithms for single series-compensated lines has been studied in [9]. Such the analysis but for parallel series-compensated lines follow with presenting representative results in Fig.6.

For deriving the differential equation based algorithm it was assumed that the fault loop circuit is described analogously as for an uncompensated line by the following differential equation:

$$Ri(t) + L\frac{di(t)}{dt} = u(t) \qquad (2)$$

Writing (2) in digital form [9] yields:

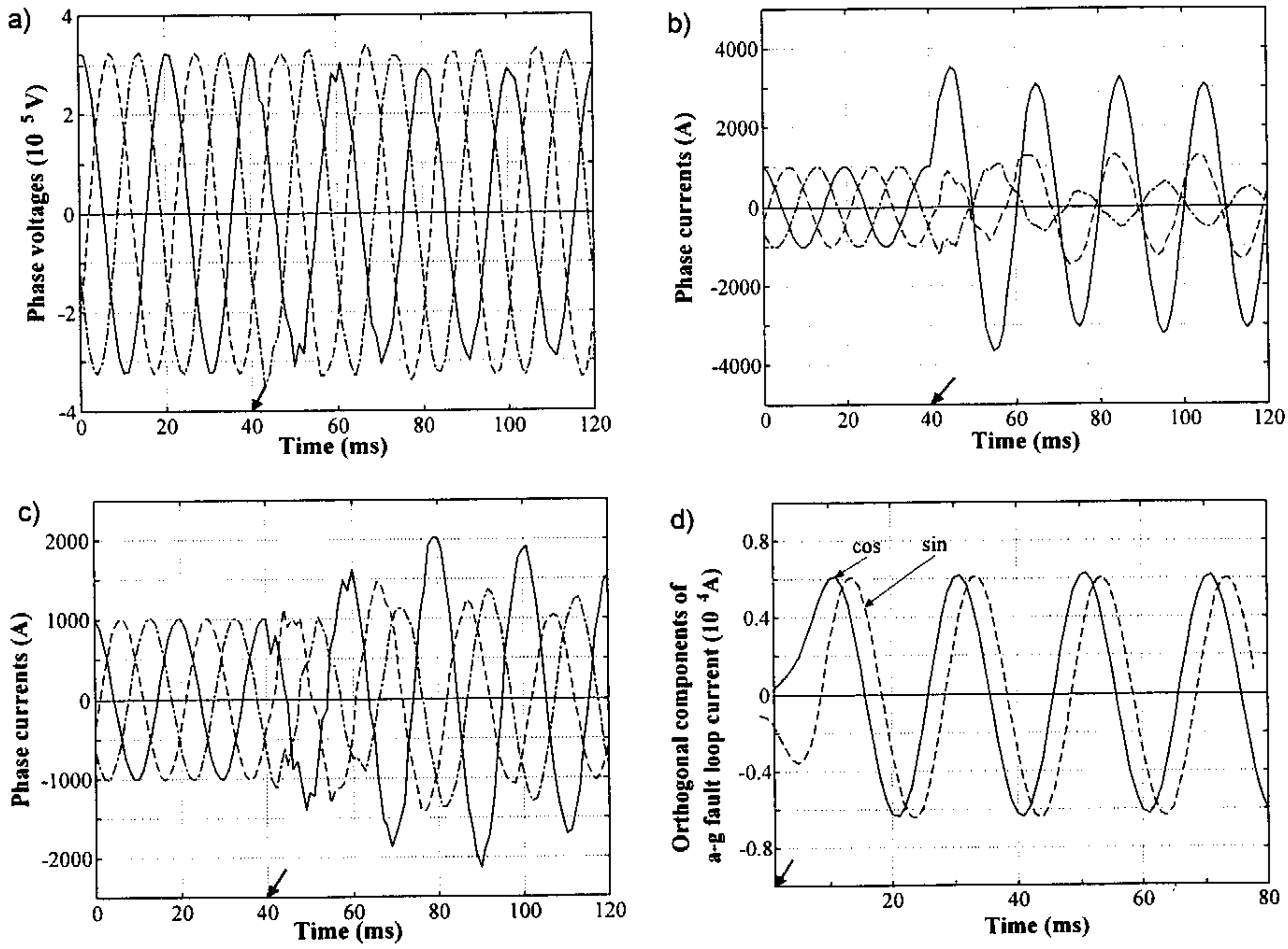

Fig.4. Sample a-g fault in front of the SCs&MOVs (F1): a) phase voltages, b) phase currents of the faulty line, c) phase currents of the healthy line, d) half cycle Fourier orthogonal components of the a-g fault loop current.

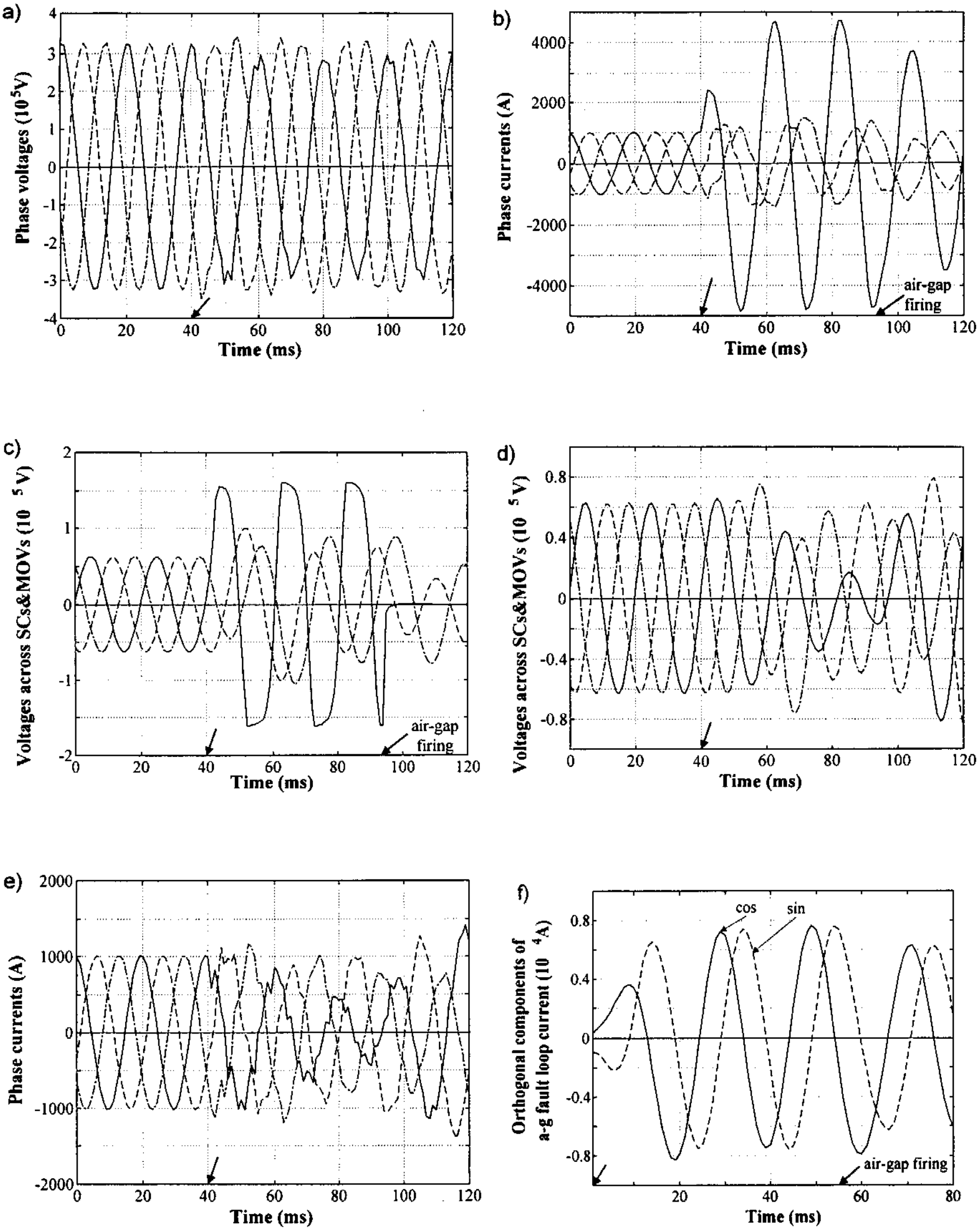

Fig.5. Sample a-g fault behind the SCs&MOVs: a) phase voltages, b) phase currents of the faulty line, c) voltage drops across the SCs&MOVs in the faulty line, d) voltage drops across the SCs&MOVs in the healthy line, e) phase currents of the healthy line, f) half cycle Fourier orthogonal components of the a-g fault loop current.

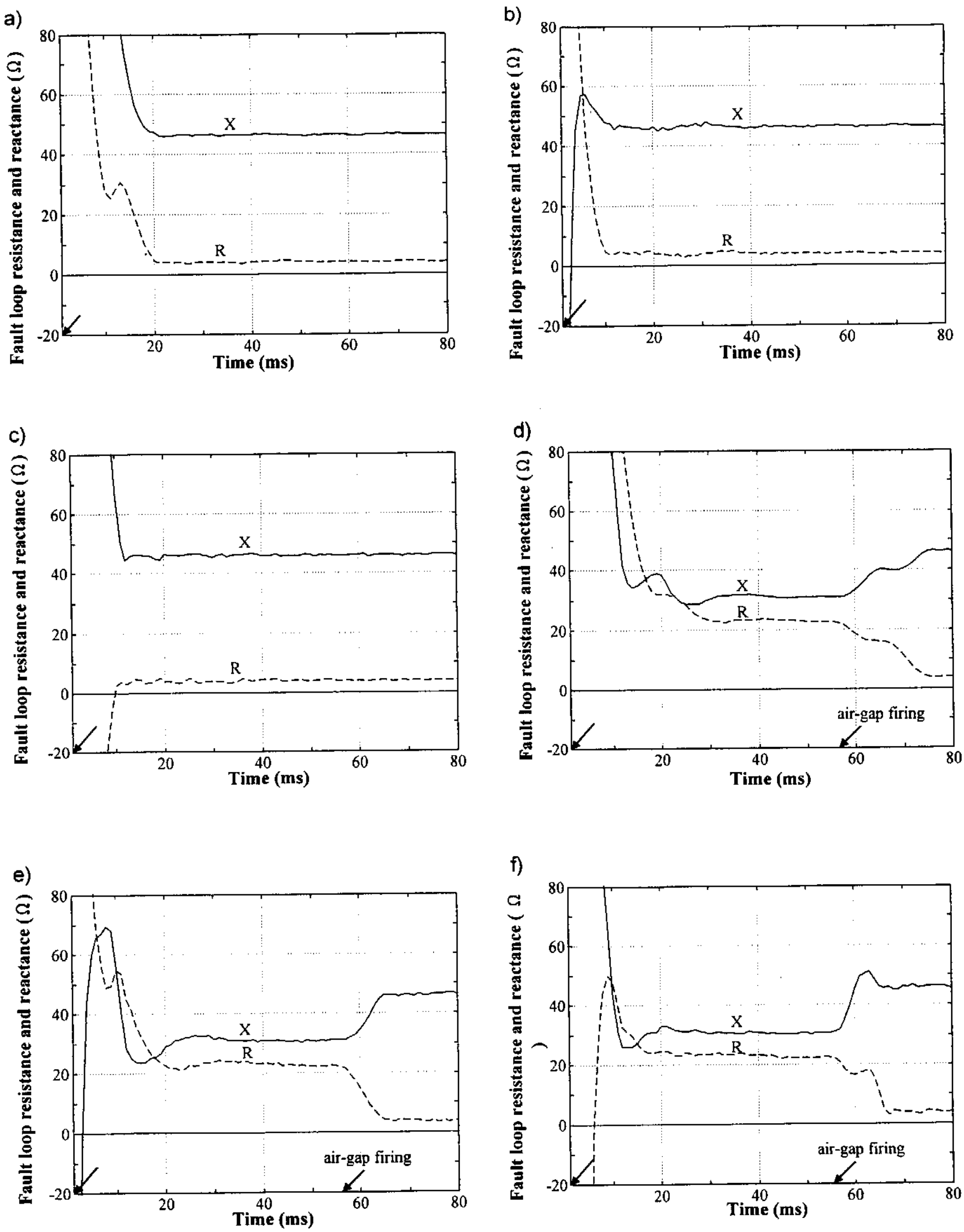

Fig.6. Fault loop impedance measurement for the sample a-g faults occurring just in front of the SCs&MOVs (fault F1) and just behind the SCs&MOVs (fault F2): a) fault F1 - full cycle Fourier algorithm, b) fault F1 - half cycle Fourier algorithm, c) fault F1 - differential equation based algorithm, d) fault F1 - full cycle Fourier algorithm, e) fault F1 - half cycle Fourier algorithm, f) fault F1 - differential equation based algorithm.

$$Ra_1 + Ld_1 = b_1$$
$$Ra_2 + Ld_2 = b_2 \qquad (3)$$

from which the sought values R and L are derived constituting the impedance algorithm:

$$R = \frac{d_1 b_2 - d_2 b_1}{a_2 d_1 - a_1 d_2}$$
$$X = \frac{a_2 b_1 - a_1 b_2}{a_2 d_1 - a_1 d_2}\omega_1 \qquad (4)$$

ω_1 radian fundamental frequency,
$a_1, a_2, b_1, b_2, d_1, d_2$ coefficients dependent on the way of digital representing of (2).

In [9] it was proposed to decouple the current and voltage signals into their orthogonal components first, and then to apply rectangular differentiation. This gives:

$$a_1 = \frac{1}{2}[i_s(k) + i_s(k-1)] \qquad a_2 = \frac{1}{2}[i_c(k) + i_c(k-1)]$$
$$b_1 = \frac{1}{2}[u_s(k) + u_s(k-1)] \qquad b_2 = \frac{1}{2}[u_c(k) + u_c(k-1)] \quad (5)$$
$$d_1 = \frac{1}{T}[i_s(k) - i_s(k-1)] \qquad d_2 = \frac{1}{T}[i_c(k) - i_c(k-1)]$$

where: subscripts s, c denote quadratic (sine) and direct (cosine) orthogonal components.

The half-cycle sine/cosine filters have been used for orthogonalization of both current and voltage signals.

Fig.6a, b, c illustrates impedance measurement for the case of the considered fault in front of the SCs&MOVs. In this case all the algorithms show good performance with the settling time equal to 20ms (full cycle Fourier) or to 10ms (half cycle Fourier or differential equation algorithm with half cycle filters for orthogonalization).

In the case of the considered fault behind the SCs&MOVs (Fig.6d, e, f) much worse performance of the algorithms is observed. The full cycle (Fig.6d) and the half cycle (Fig.6e) Fourier algorithms exhibit the settling time larger than their data windows. The differential equation algorithm shows performance similar to the half cycle Fourier algorithm. Thus, this algorithm is not much superior than the half cycle Fourier algorithm as it was the case for a single series-compensated line [9]. The reason which stands for that relies in specific nature of transients for the parallel lines. Composing the relay input current for a phase-to-ground fault in parallel lines one has to take zero sequence component of the healthy line where transients result from linear operation of the MOVs.

V. CONCLUSIONS

ATP-EMTP modeling of fault conditions for parallel series-compensated lines has been presented. The developed model has been used for studying the fault phenomena relevant to protective relaying. Sample simulation results illustrating the nature of the fault transients have been included and discussed.

Alternative algorithms for a fault loop impedance measurement have been studied and compared in terms of speed and quality of estimated impedance components.

For faults occurring in front of the SCs&MOVs all the considered algorithms show good performance with the settling time fundamentally equal to the used data window. In contrary, much worse conditions for a fault loop impedance measurement appear for faults behind SCs&MOVs. The Fourier algorithms exhibit the settling time larger than their data windows. The differential equation algorithm shows performance similar to the half cycle Fourier algorithm and thus these algorithms are recommended for relay application. Further improvement of impedance measurement can be obtained with on-line estimation of the voltage drop across SCs&MOVs and using the developed differential equation impedance algorithm.

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