MODELLING FAULT CONDITIONS FOR PROTECTION OF SERIES COMPENSATED LINES

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Abstract-**This paper presents modelling of fault conditions and analysis of the relevant, both steady state and transient, phenomena for protection of series compensated transmission lines. Based on the results of analysis, certain recommendations have been given regarding the protection techniques for series compensated lines.**

Keywords: power system protection, series compensated line, distance relay.

I. INTRODUCTION

When a series compensated line suffers a fault behind its series capacitors (SCs) a fault loop considered by a distance relay contains one or even two complexes of SCs and their overvoltage protecting arresters (usually Metal-Oxide Varistors (MOVs)). The SCs with their MOVs cause certain shift of the measured impedance vector: down (due to the negative equivalent reactance of SC and MOV), and right (due to the equivalent resistance). As a result, a far end fault may be seen by the relay much closer than actually located. Therefore, to avoid overreaching, the first zone of a relay is usually set to cover less than 30% of the total line length providing very poor protection for a line [1,2].

The investigation towards better protection for series compensated lines calls for detailed modelling of fault conditions and careful analysis of the phenomena, what is the primary motivation for this paper.

II. THE MODEL

This paper is focused on single line arrangement with the SCs installed in the middle of the line (Fig.1a). ATP-EMTP is used as a simulation tool [3,4].

The line (300km, 400kV, 50Hz, compensated at 70%) is modeled as a cascade of four-ports, each representing a 50km long line segment (transposed Clarke model used [3]).

The MOVs are modeled as non-linear resistors approximated by the standard v-i characteristic [3,5] (Fig.1b):

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

where: i, v — MOV current and voltage, respectively,
V_{REF} — the reference voltage,
P — the reference current,
q — the exponent of approximation.

Each MOV is protected from overheating by firing the complementary air-gap by the thermal (overload) protection. The MOV protection is modeled as energy-based: the energy absorbed by the MOV is integrated and the MOV becomes shunted by firing the air-gap when this energy reaches its pre-defined limit (Fig.2).

The relay measuring chain is modeled as well. CVTs are represented by their 4th order linear models while CTs are simulated taking into account their saturation branches [6]. The analog anti-aliasing filters are represented by the 2nd order approximation with the cut-off frequency set at 1/3 of the sampling rate [7].

Numerous simulations have been performed using the developed model. The studied factors include: pre-fault power flow; fault type, location, resistance and inception angle; source impedances; energy limit for MOVs; and others.

Such statistical picture taken for the considered line enables to draw a number of conclusions regarding the operating conditions for a distance relay for series compensated transmission lines.

III. THE RESULTS

Both faulty semi-steady-state and transient bahaviour of the studied system have been considered in the paper.

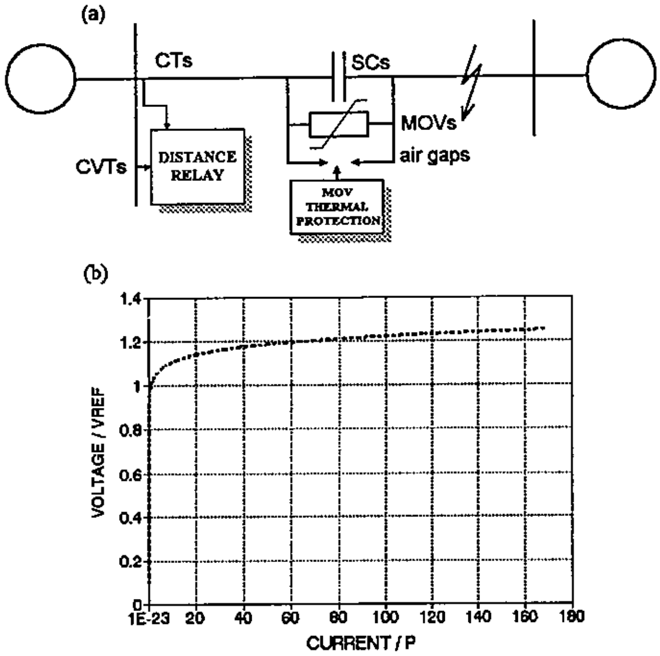

Fig.1. One-line diagram of the studied 300km, 400kV series compensated line (a); and the v-i characteristic of the installed MOVs (b). The MOV data used are P=1kA, V_{REF}=150kV, q=23.

A. The equivalent series RC circuit for the SC and MOV

For analysis of relay operation, the parallel connection of fixed capacitor and its non-linear protecting resistor (MOV) was represented by the first harmonic equivalent series reactance X_A and resistance R_A as shown in Fig.3a [8]. X_A and R_A occur in any fault loop considered by a relay during a fault behind SCs and make such a loop non-linear with respect to the current amplitude.

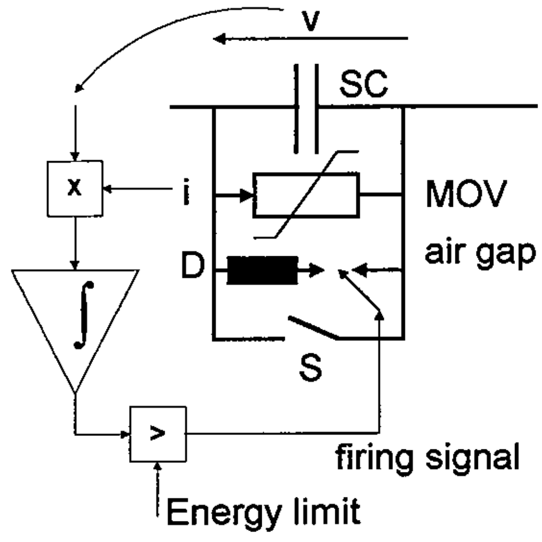

Fig.2. The basic arrangement of the SC, MOV and the thermal protection (D - damping reactor, S - switch for permanent by-passing of the SC).

For comparison the equivalence has been done in two ways:

1. analytically, assuming the sinusoidal wave of the current,
2. by means of digital simulation assuming sinusoidal wave of the electromotive forces of the supplying systems and allowing the current to assume its natural waveform during the faulty steady state.

Figs.3b and c present the results. In general one concludes:

(i) the parallel connection of SC and MOV acts as a pure capacitive reactance up to certain level of the current (here 2.1kA); this is so due to the MOV operating only above the certain level of the voltage drop across the SC and MOV,

(ii) the equivalent series resistance displays its local maximum,

(iii) the equivalent reactance decreases with the increase of the current, and consequently:

(iv) for low currents, the SC and MOV system acts as a pure capacitive reactance, while for high currents - as pure resistance,

(v) as a result of a kind of feedback, this equivalent R-X circuit controlled by the current controls back the fault current itself.

Comparing Figs.3b and c one observes considerable differences between the equivalent circuits. Since the actual fault currents are not pure sinusiodal waves, the method denoted as (2) assuming the electromotive forces to be sinusoidal is more accurate and is recommenced in this paper.

The equivalent R-X circuits are the solid base for correction of the impedance measured by conventional distance relays and fault locators.

B. The relay overreaching

The equivalent negative reactance X_A appearing in a fault loop may cause the relay to overreach as shown in Fig.4 where from the actual fault position, given by certain fraction of the line impedance vector, one moves by the twisted (the infeed effect) fault resistance, R_F, and next moves down due to X_A, and next - right due to R_A making the seen fault position much closer than the actual one. In addition, the final placement of the seen impedance depends on the current amplitude which controls X_A and R_A.

The fault current depends on fault location, fault resistance and system impedances. The current controls the operating points of MOVs and thus the equivalent resistance and reactance of the systems of SCs and MOVs. These parameters in turn control the current to certain extend.

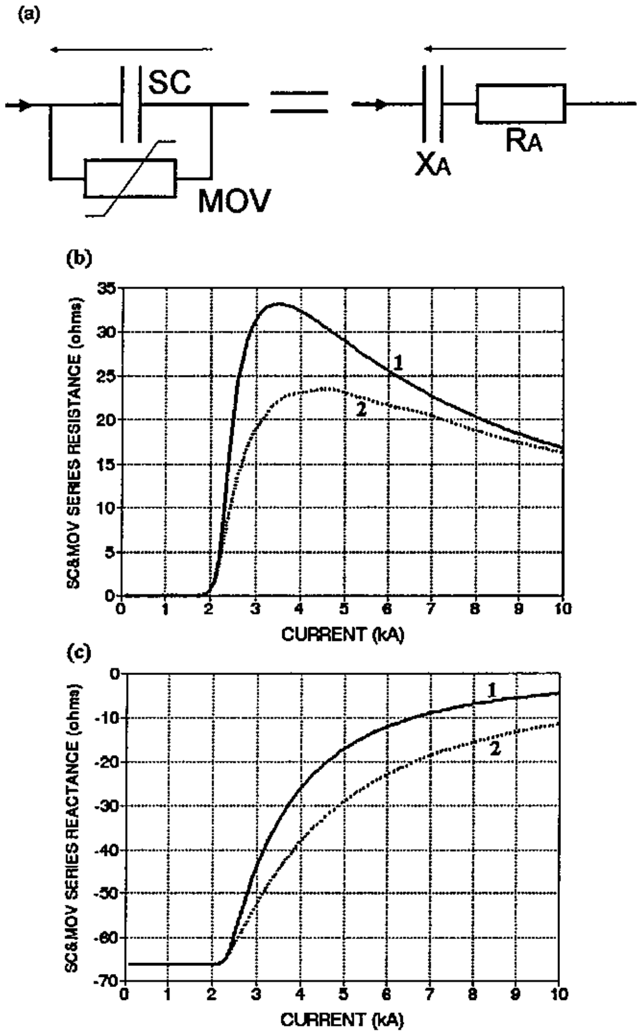

Fig.3. The equivalenting principle for the SC and MOV (a), the equivalent series resistance (b) and reactance (c).
1 - the phase current assumed sinusoidal,
2 - the electromotive forces assumed sinusoidal.

Therefore for the same fault location and resistance, the impedance seen by a distance relay depend on the system (source) impedances. In particular, under very weak systems, the line acts as fully compensated (liner range of MOV operation), but under strong sources the line is no longer compensated (few percent of capacitance seen - compare Fig.3c for high fault currents). This effect is not observed in traditional non-compensated lines.

However, by measuring the amplitude of the current, distance relays and fault locators may compensate for the R-X circuit representing the parallel arrangement of SC and MOV. The current flowing through the SC and MOV is available to the relay, however, only when a fault occurs behind the SC and MOV as seen from the relaying point. For faults in front of SCs some extra techniques are needed.

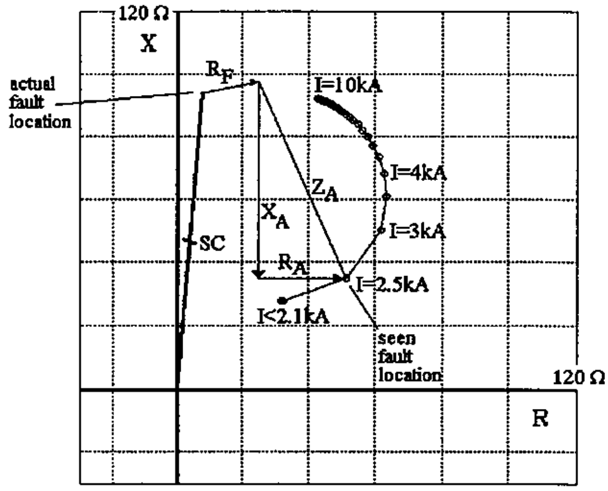

Fig.4. Illustration of the effect of relay overreaching in series compensated lines (R_F - fault resistance twisted due to the infeed effect).

C. The subsynchronous oscillations

The subsynchronous oscillations in both currents and voltages at the relaying point appear during faults behind SCs with low fault currents when the MOVs almost do not operate and do not damp these natural oscillations. Such oscillations are a source of considerable measuring errors.

During low current faults the MOV operates in its linear range - with very high parallel resistance. Thus, for such fault currents negletion of the MOV is justified, and the compensating capacitor is considered as fully included in the fault circuit. This simplification leads to the R-L-C circuit model of a fault loop. In consequence, both the relaying signals are distorted by slowly decaying oscillatory components of the subsynchronous nature. An analysis of relaying signals spectra showed [9] that oscillatory subsynchronous components are of the frequency very close to the fundamental one (Figs.5a and b).

In general, this frequency depends on:

- source impedances,
- line length,
- compensation rate,
- fault resistance, and
- distance to a fault.

As the line is longer (300 km) and the compensation rate is higher (70%), the frequency of such subsynchronous oscillation disturbance is closer to the fundamental one. At the same time, the frequency decreases as the distance to a fault increases.

The presence of such components in the processed signals creates certain difficulties for measurement. This is clearly illustrated by the simulation results from Fig.6. Three-phase

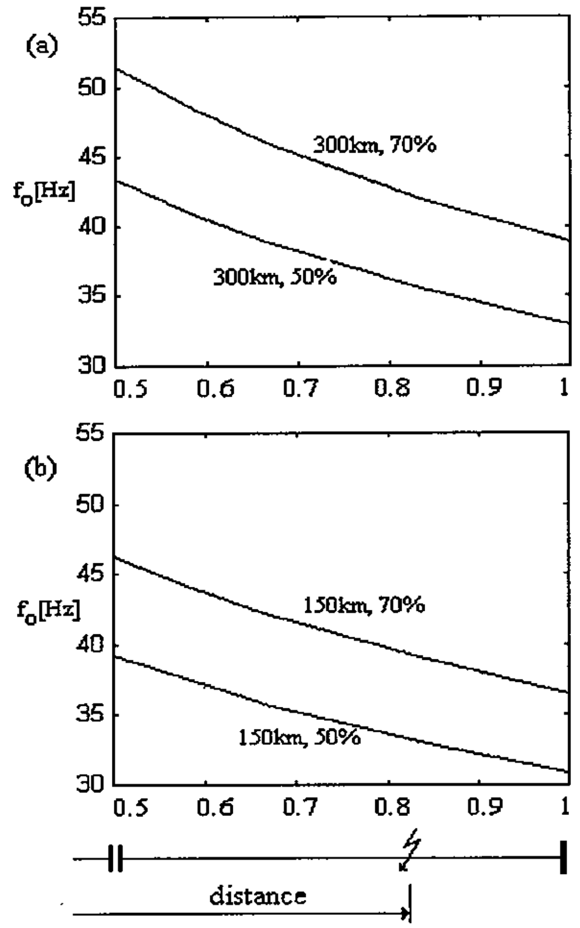

Fig.5. Variation of the subsynchronous oscillatory components frequency (f_0) with the distance to a fault for different line length and compensation rates.

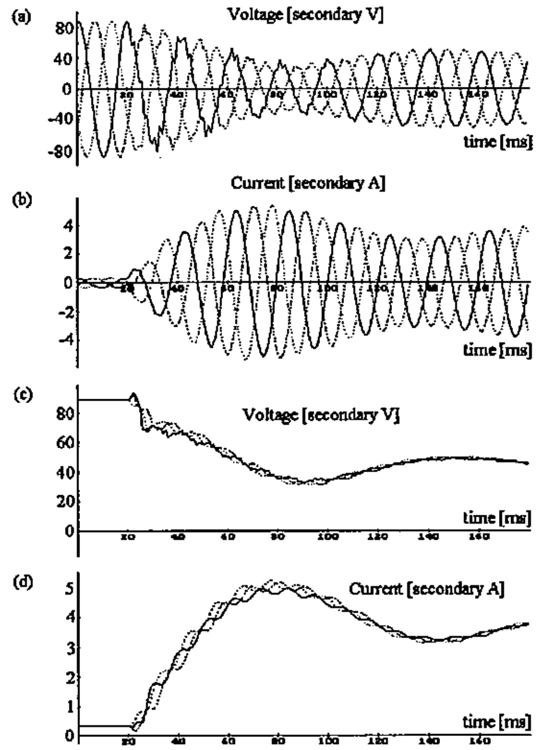

Fig.6. Fault behind a capacitor with linear operation of MOVs: (a) secondary voltage waveforms, (c) voltage amplitudes estimated by half-cycle Fourier algorithm, (b) secondary current waveforms, (d) current amplitudes estimated by half-cycle Fourier algorithm.

fault on the transmission line of 300km length, compensated at 70% with fully linear operation of MOVs, was studied there. A fault was applied at a location 50km away from the remote line end (Fig.1a). Secondary voltage and current signals contain oscillatory components of the frequency equal to around 42Hz. Quite small difference between this frequency and the fundamental one results in characteristic envelope of the signals (Figs.6a and b). Very slow increase of fault currents is observed and voltage transients are also long lasting. Figs.6c and d present voltage and current amplitudes estimated by the half-cycle Fourier algorithm. In the figures considerable measuring errors are observed. The same effect is observed as far as the fault loop impedance is considered [9].

Effective rejection of subsynchronous oscillations from the relaying signals by any kind of filtration is troublesome. It is so, because the data window of such the filter ought to be adequately short (for fast operation of a relay) and at the same time, the components to be filtered out have the frequency comparatively close to the fundamental one. In addition, this frequency is not constant - it depends on such random factors as a fault type, distance to a fault, and value of fault resistance. The subsynchronous oscillations decay usually with a comparatively long time constant. For the simulated system and considered solid faults this time constant is of the order of 70ms. However, if a fault occurs through the resistance, this time constant becomes adequately smaller.

The measurement algorithm [9] overcoming these difficulties assumes the R-L-C character of the fault loop. In such a model C is known, while R and L are estimated with the use of least-squares method. The method provides good results and in addition it is immune to frequency deviations.

D. The DC components of the relaying signals

The DC components in both voltage and current signals have been analyzed in the paper under variety of operating conditions. The following conclusions are drawn:

- the DC components in phase voltages are caused rather by CVT induced transients than by the phenomena specific for series compensated lines,

- if the line suffers a fault behind its series capacitors as seen from the relaying point, the DC components in the phase currents are not observed: either the envelope is observed (a liner operation of MOVs) or almost pure sine waveform (non-linear range of MOV operation),
- if the line suffers a fault in front of its series capacitors, the DC components are always present in the phase currents except the case of a single-phase fault with certain inception angle.

This observation can be a base for recognizing the fault position with respect to the series capacitors.

E. Impedance trajectories

Fig.7, as an example, shows the fault trajectory for the R-to-S-to-ground fault located at 2/3 of the line length with 60Ω fault resistance. One may see the large displacement of the seen impedance due to X_A and R_A in the first stage of the faulty steady state (position (a) in Fig.7). Next, 46ms after the fault, the phase R MOV is shunted by its thermal protection (movement from (a) to (b)), so is the phase S unit few ms later (movement from (b) to (c)). Those switchings move up the measured impedance to its natural position (c) since the fault loop (R-to-S) is no longer compensated (both the SCs are by-passed).

In general, protective relays and fault locators operate under a sequence of events, such as: fault, asynchronous by-passing of MOVs in some of the phases, and finally clearance of a fault. In order to compensate for the equivalent impedance of SCs and MOVs one needs to identify whether or not the system of SC and MOV in a particular phase operates or just got by-passed (shunted).

IV. Impedance Measuring Algorithms

In this paper two impedance algorithms from the frequency domain family are considered [10]:

(a) a full-cycle Fourier method,

(b) a half-cycle Fourier method;

and four algorithms from the differential equation domain:

(c) a rectangular differentiation based method,

(d) a rectangular differentiation based method with additional pre-filtration,

(e) a Gear three-point differentiation based method with additional pre-filtration, and

(f) a rectangular differentiation based method combined with orthogonal components.

Based on a number of simulations the following conclusions have been drawn [10].

When a fault loop does not contain SCs&MOVs, the operating conditions for any impedance algorithm are better and:

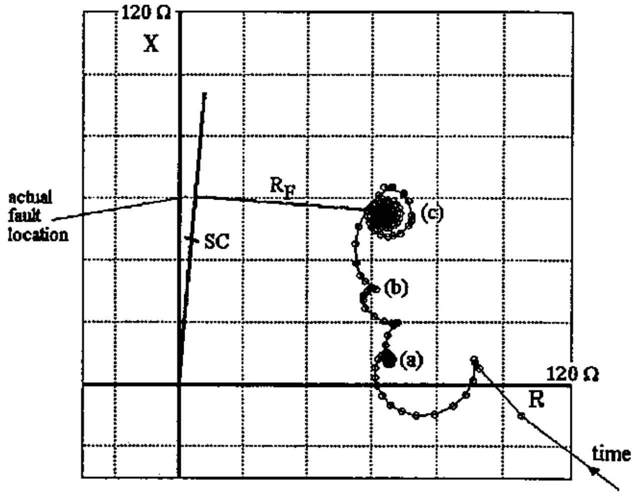

Fig.7. Impedance trajectory for a phase-to-phase fault located behind the SCs as seen from the relaying point.

- fundamental frequency based methods give accurate impedance estimates when the pre-fault samples leave the data window,
- the differential equation based methods return the accurate impedance estimates after time delay caused by the additional pre-filtration; it is justified to apply pre-filtration with very short data window;
- none of the considered methods shows oscillations and/or danger of transient overreaching - the estimated impedance settles surely at its faulty semi-steady-state position.

In contrary, when a line suffers a fault behind its SCs, and consequently, a fault loop contains the system of SCs and MOVs:

- the fundamental frequency based methods give the accurate impedance estimates with the delay of the data window plus additional three quarters of a cycle up to one cycle;
- the differential equation based methods must be equipped with additional pre-filtration otherwise they give very poor time response both during transients and in faulty semi-steady-state;
- the method combining differential equation technique with orthogonal components and the method based on differential equation with Gear three-point differentiation and additional pre-filtration provide the settling time around half a cycle regardless the fault location.

V. Conclusions

The developed EMTP model for generating the input data for study of the distance relay principle applied to series-compensated line allows to investigate the influence of MOVs nonlinear operation on voltage and current relaying signals and impedance measurement.

Faults behind a series capacitor, i.e. with involvement of a capacitor in the fault loop, have been studied from the point of view of the distance relaying principle.

For low current faults, with linear operation of MOVs, the linear model of a fault loop was considered to determine the frequency range of subsynchronous oscillations in the relaying signals. The analysis has shown that such distortion of the relaying signals is a source of considerable measurement errors.

For high current faults nonlinear operation of MOVs has been studied. The presented sample simulation results explain the nature of MOVs behaviour. An influence of MOVs nonlinear operation on the fault loop impedance measurement is shown. In order to study quantitatively the distance principle, the series R-C nonlinear equivalent of the parallel arrangement of a compensating capacitor and its MOV protection has been introduced. The derived equivalent has been used for determining the shift of the impedance, seen by a distance relay, due to operation of MOVs.

Six methods for impedance measuring in series compensated lines have been studied [10].

The method combining the differential equation technique with orthogonal components is recommended since it provides half a cycle settling time for both short circuits in front of and behind SCs. In addition the method is immune to frequency deviations.

The simulative analysis has also shown that to speed-up further the impedance measurement it is justified to switch adaptively between different algorithms depending on the anticipated fault location.

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