ATP-EMTP Investigation of a New Distance Protection Principle for Series Compensated Lines

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Abstract **– A new algorithm for the first zone of protective distance relays for transmission lines compensated by series capacitors, installed in the middle and at both ends, is presented. The concept relies on determining two conditional impedances and comparing them with three characteristics specially shaped on the impedance plan. The conditional impedances are calculated from the fault loop quantities composed as for the classic distance relays, but in case of voltages additionally the compensation for the voltage drop across the bank (or banks) of series capacitors is performed. The sample fault cases and the evaluation results for the developed algorithm are presented. ATP-EMTP package has been used for simulation versatile faults and generating reliable fault data used in the evaluation of the algorithm.**

Keywords – series-compensated line, capacitor bank, non-linear circuit, distance algorithm, ATP-EMTP, simulation

I. INTRODUCTION

Both, the technical and economical benefits resulting from using series capacitor compensation in power transmission lines are well-recognized and known [1]. At the same time such lines are considered as the power system items, which are extremely difficult for protecting them [2]-[7] as well as for locating faults [8].

In this paper a new distance protection principle for a transmission line compensated with a three phase capacitor bank installed in the middle (Fig. 1a), or with capacitor banks at both ends (Fig. 1b), is investigated. Series Capacitors (SCs) equipped with Metal-Oxide Varistors (MOVs) (Fig. 2a, b), when set on a transmission line, create certain problems for its protective devices. Under faults behind SCs&MOVs a fault loop becomes strongly nonlinear, and in consequence the nature of transients, as well as the steady state situation, is entirely different, when comparing with traditional lines. Operation of the thermal protection (TP) at the MOV sparks the associated air-gap and thus shunts the MOV. However, high speed tripping of the first zone algorithm is basically prior to operation of the TP and thus there is no need to reflect the TP within the considered here distance algorithm.

Direct application of the classic distance protection (designed for traditional lines) to the series-compensated lines results in considerable shortening of the first zone reach and also in poor transient behavior [1]. In order to overcome these difficulties the new distance protection principle for the first zone has been developed.

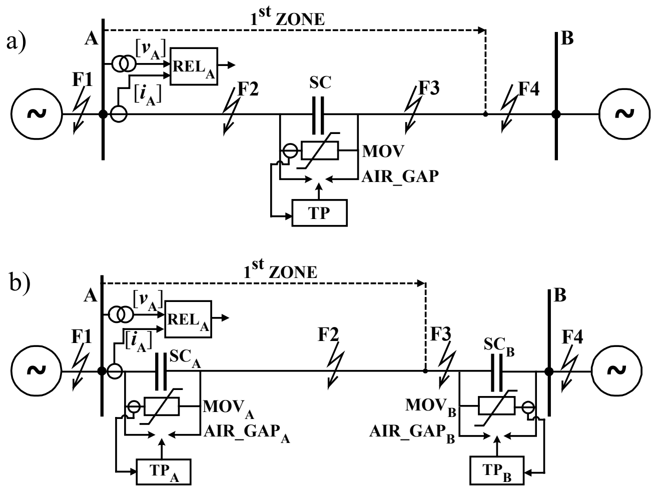

Fig. 1 Transmission line compensated with: a) capacitor bank in the middle, b) capacitor banks at both ends

The new protection principle for a line compensated with a capacitor bank installed in the middle (Fig. 1a) has been introduced in [2] and in this paper further evaluation of this idea is presented. Moreover, the principle from [2] is adapted here to application to lines compensated with capacitor banks installed at both ends (Fig. 1b).

In Fig.1 the characteristic locations of faults are depicted. Faults: F2, F3 (Fig. 1a), F2 (Fig. 1b) belong to the first zone and have to be reliably tripped. As a result of applying the new principle one assures that the first zone covers the same portion of a line as in case of classic distance relays applied for protecting traditional uncompensated lines, i.e. around 80% of the line length. The other forward faults: F4 (Fig. 1a), F3, F4 (Fig. 1b), which overreach such first zone have to cause blocking. On the other hand, the backward faults F1 (Fig. 1a, b) can be discriminated with use of the directional element from [9].

II. NEW DISTANCE PROTECTION PRINCIPLE

The new concept relies on determining the conditional impedances (Fig. 3a) and comparing them with the three characteristics specially shaped on the impedance plan (Fig. 3b). The characteristic A1 plays a role of the fundamental first zone area covering some 80% of the line length. The region A2 is provided for recognition of close faults, while the characteristic A3 is shaped for detecting whether a fault involving not too high fault resistance occurs behind the SCs&MOVs (F3, F4 – Fig. 1a) or not.

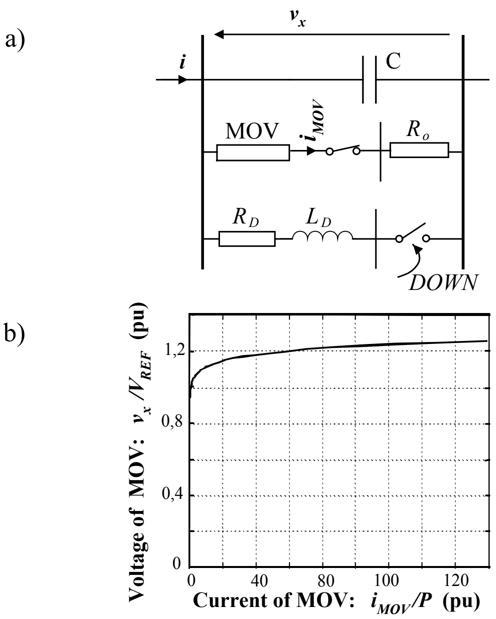

Fig.2 Compensation bank: a) model of SC&MOV circuit, b) voltage-current characteristic of MOV

For the considered lines (Fig. 1a, b) one can distinguish the three conditional impedances: – impedance without compensation ($\underline{Z}$), – impedance with single compensation ($\underline{Z}_{c1}$), – impedance with double compensation ($\underline{Z}_{c2}$).

The respective "compensated" impedance ($\underline{Z}_{c1}$ or $\underline{Z}_{c2}$) is calculated from the fault loop quantities composed as for the classic distance relays, but with the compensation in case of the fault loop voltage. The compensation is performed for the voltage drop across the single capacitor bank (in both cases of Fig. 1) or for the voltage drops across two banks (in case of the line from Fig. 1b). For this purpose the voltage drops across SCs&MOVs have to be estimated on the base of the parameters of SCs&MOVs and locally measured phase currents. Such efficient algorithm is presented further and investigated.

Voltages from phases *a, b, c* after the single ($[v_{c1}]_{abc}$) and the double compensation ($[v_{c2}]_{abc}$) are defined as:

$$[v_{c1}]_{abc} = [v]_{abc} - [v_{x1}]_{abc} \tag{1}$$

$$[v_{c2}]_{abc} = [v]_{abc} - [v_{x1}]_{abc} - [v_{x2}]_{abc} \tag{2}$$

In each phase the respective voltage drop across the local SC&MOV ($[v_{x1}]_{abc}$) or the voltage drops across both the local ($[v_{x1}]_{abc}$) and the remote SC&MOV ($[v_{x2}]_{abc}$) are subtracted from the original phase voltages ($[v]_{abc}$).

The single (1) or double (2) compensation requires estimation of the voltage drops across the respective SCs&MOVs. For this purpose let us consider a parallel connection of the SC and the MOV as shown in Fig. 2a. Voltage-current characteristic (Fig. 2b) [3, 6] is described by the following analytical approximation:

$$i_{MOV} = P\left(\frac{v_x}{V_{REF}}\right)^q \tag{3}$$

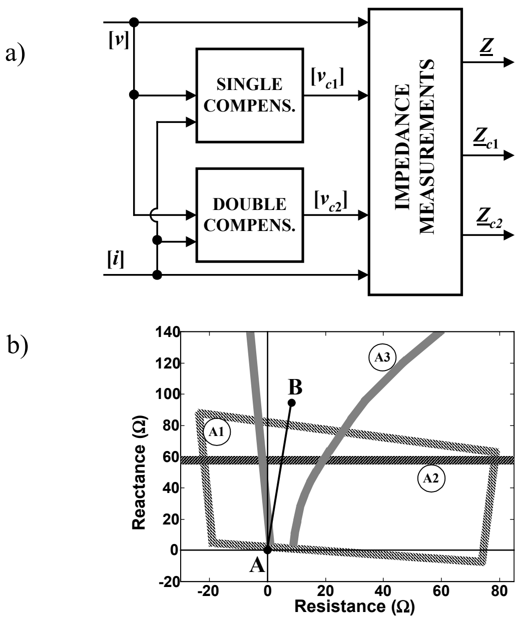

Fig. 3 New distance protection principle: a) determination of conditional impedances, b) three impedance characteristics

Thus, the non-linear circuit of Fig. 2a can be described by the following non-linear differential equation:

$$C\frac{dv_x(t)}{dt} + P\left(\frac{v_x(t)}{V_{REF}}\right)^q - i(t) = 0 \tag{4}$$

In order to solve (4) for the unknown voltage drop ($v_x(t)$) one needs to transform this continuous-time differential equation into its algebraic discrete-time form. The 2nd order Gear differentiation rule [10] has been taken for this purpose, i.e. the following substitutions apply:

$$i(t) \to i(n)\,,\ v_x(t) \to v_x(n) \tag{5a}$$

$$\frac{dv_x}{dt}(t) \to D[3v_x(n) - 4v_x(n-1) + v_x(n-2)] \tag{5b}$$

$$D = \frac{2\pi f}{2\sqrt{(1-\cos(a))^4 + (2\sin(a) - 0.5\sin(2a))^2}} \tag{5c}$$

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

Inserting (5) into (4) yields the algebraic equation:

$$A_q x(n)^q + A_1 x(n) - A_0(n) = 0 \tag{6}$$

in which:

$$x(n) = v_x(n)/V_{REF} \tag{7a}$$

$$A_q = P\,,\quad A_1 = 3DCV_{REF} \tag{7b}$$

$$A_0(n) = i(n) + \frac{A_1}{3V_{REF}}\left(4v_x(n-1) - v_x(n-2)\right) \tag{7c}$$

Equation (6) is to be solved for $x(n)$ (the pu value of the sought voltage drop $v_x(n)$ at the present sampling instant (n). The parameters of this equation: A_q and A_1 are constant, while $A_0(n)$ depends on the present sample of the current entering the bank and the two previous samples of the voltage drop. In order to ensure good convergence of the algorithm, appropriately modified Newton-Raphson method has been used [2]. The form (6) of the equation is numerically efficient for *"small"* values of $A_0(n)$ while for *"large"* values of $A_0(n)$, it should be re-written to:

$$A_q y(n) + A_1 y(n)^{(1/q)} - A_0(n) = 0 \tag{8}$$

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

The border value of A_0 alternating the optimal forms: (6) and (8) is:

$$A_0^{\ *} = A_q\left(\left(A_1/(qA_q)\right)^{(1/(q-1))}\right)^q + A_1\left(\left(A_1/(qA_q)\right)^{(1/(q-1))}\right) \tag{9}$$

Using the Newton-Raphson method the form (6) is solved iteratively by applying the following algorithm:

$$x_{new}(n) = x_{old}(n) - \frac{A_q x_{old}(n)^q + A_1 x_{old}(n) - A_0(n)}{qA_q x_{old}(n)^{(q-1)} + A_1} \tag{10}$$

while the form (8) with the algorithm:

$$y_{new}(n) = y_{old}(n) - \frac{A_q y_{old}(n) + A_1 y_{old}(n)^{(1/q)} - A_0(n)}{A_q + (A_1/q)y_{old}(n)^{((1-q)/q)}} \tag{11}$$

The flow-chart of the algorithm for estimation of a voltage drop is shown in Fig. 4. At the outputs of the procedures for "*SMALL*" and "*LARGE*" values of $A_0(n)$, the convergency of iterative calculations according (10) and (11) is checked. For this purpose the difference between two consecutive values of $x(n)$ (or $y(n)$) is checked – if is lower than the prescribed value the iterative calculations are stopped. Otherwise, the calculations are continued.

It has been found that the algorithm ensures satisfactory accuracy for time steps as large as 1/20th of a cycle (it needs 2-3 iterations to find a solution). For shorter time steps (higher sampling frequencies) the algorithm performs even better. Instead of checking the convergency of the calculations, the pre-scribed number of iterations (for example performing only 3 iterations) can be used.

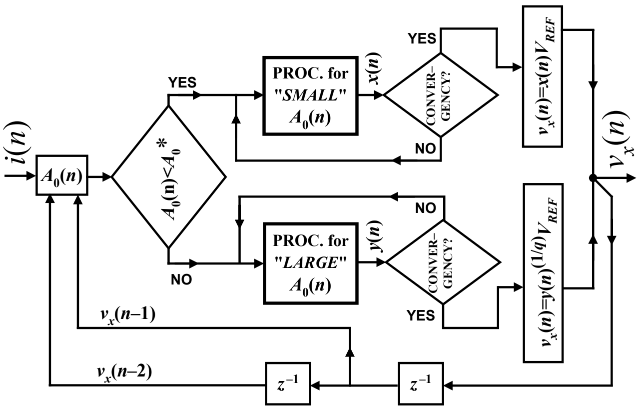

Fig. 4 Flow-chart of the algorithm for estimation of a voltage drop across SC&MOV

Fig. 5 shows the example of the estimation of the voltage drop across SC&MOV circuit under single phase-to-ground fault applied behind the SCs&MOVs in the line with the single compensation (Fig. 1a). The specifications of the fault were as follows – distance to fault: 0.667 pu, fault inception: 40 ms, fault resistance: 10 Ω.

In Fig. 5a the typical distortion of phase currents, relevant for series-compensated lines, is shown. In healthy phases the linear operation of MOVs results in distorting of currents with slowly decaying sub-harmonic oscillations. Air-gap firing, short-circuiting the SC&MOV, takes place at around 120 ms, thus after around 80 ms from the fault inception.

In Fig. 5b the actual and estimated voltage drop across the SC&MOV from the faulted phase are shown. The estimation algorithm is of the recursive form (see: $A_0(n)$ – (7c)) and thus at the beginning of estimation the constant offset is visible, which after applying the special starting procedure [2] is then removed. After removal of this offset the estimated voltage drop is very close to the actual drop registered from the simulation. It is worth to notice that the estimated voltage drop reproduces the actual drop more accurately during the fault. This is so since shunt capacitances of the line, which are neglected within the estimation algorithm, introduce then lower errors. Slightly higher errors of the estimation are observed during the pre-fault period.

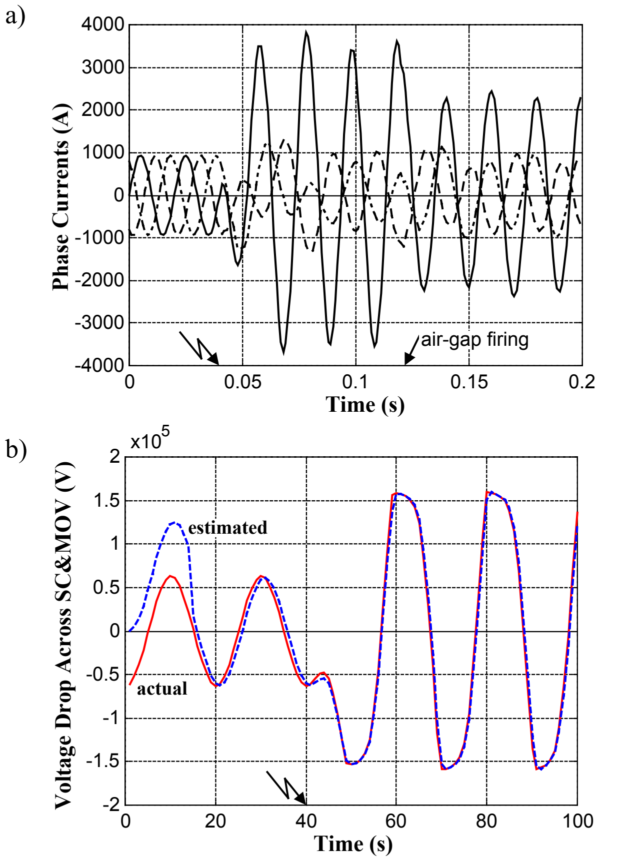

Fig. 5 Example of estimation of a voltage drop across SC&MOV: a) phase currents, b) actual and estimated voltage drop from the faulted phase

III. ATP-EMTP Testing of the New Distance Protection Algorithm

A. Line compensated with capacitor bank in the middle

The 300 km, 400 kV transmission line, compensated in the middle at the rate of 70% (Fig. 1a) was modeled using ATP-EMTP [11]. The line was represented by the Clarke model. The measurement channels, containing Capacitive Voltage Transformers, Current Transformers and analog filters, have been implemented in the model as well [2].

The following parameters for the MOV characteristic (3) have been set:

- V_{REF} = 150 kV
- $P = 1$ kA
- $q = 23$
- maximum MOV energy: 15MJ.

Fig. 6 shows the results for the example 1 with the following specifications:

- *a-g* fault
- distance to fault: 0.667 pu
- fault resistance: 10 Ω.

The conditional impedance $\underline{Z}$ without the compensation (Fig. 6c) settles inside the regions: A1, A2 and outside: A3. The conditional impedance $\underline{Z}_{c1}$ with the single compensation (Fig. 6d) settles inside all the regions: A1, A2, A3. This assures reliable and fast (around 10 ms) tripping.

Selected results of evaluation of the presented algorithm were reported in [2]. Here the further evaluation has been performed. The robustness of the algorithm against the change of the infeed impedances has been taken for interest (Table I). It was assumed that the "average" infeed impedance (of equivalent sources at both ends Z_A, Z_B) is equal to around 16% of the line impedance. The infeed impedances were – increased by 10, – decreased by 10 (in comparison to the "average" value).

From Table I results that under the considered conditions certain worsening of the presented algorithm is observed, especially for the week sources at both sides (Test Group 8). In order not to allow for that, the new settings for the regions (A1, A2, A3) and introducing some internal delays has been considered. As a result of that the quality of protection has been obtained comparable with that for the "average" infeed impedances [2].

Table I Results of testing the algorithm with respect to the change of infeed impedances

Test Group	Z_A/Z_{A_aver}	Z_B/Z_{B_aver}	False Trip. [%]	Missing operations [%]	Average tripping time [ms]
1	1	0.1	0	4.17	12.64
2	1	10	0	0	12.62
3	0.1	0.1	0	2.38	12.21
4	0.1	1	12.5	1.79	11.98
5	0.1	10	4.17	0	11.64
6	10	0.1	4.17	17.26	18.19
7	10	1	16.67	11.90	17.60
8	10	10	45.83	12.50	17.64

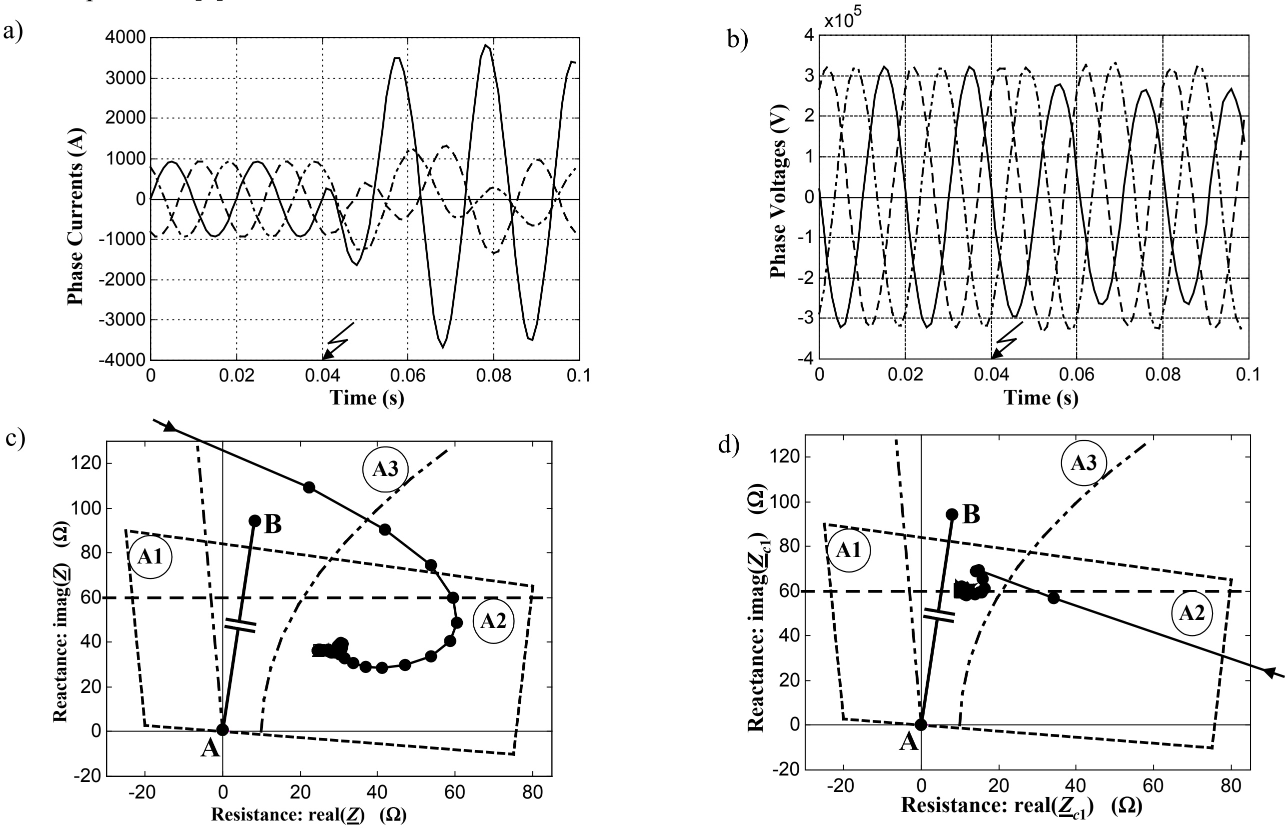

Fig. 6 Example 1 – line compensated in the middle: a) phase currents, b) phase voltages, c) trajectory of the conditional fault loop impedance determined without the compensation, d) trajectory of the conditional fault loop impedance determined with the single compensation

B. Line compensated with capacitor bank at both ends

The simulation studies have been performed with use of the ATP-EMTP model of the 400kV, 300km line with series capacitors at both ends – SC_A and SC_B are identical and provide the compensation of 35% each (together 70% compensation).

The following parameters for the MOV characteristic (3) have been set:

- V_{REF} = 75kV
- $P = 1$ kA
- $q = 23$
- maximum MOV energy: 15MJ.

The system impedances at both ends A and B were assumed as identical and equal to 16% of the total line impedance, what corresponds to the "average" infeed impedances. Power exchange from the systems A, B was taken as follows:

- the side A pumps 917MW and –251.9MVA to the line
- the side B pumps –891.8MW and 76.5MVA to the line.

Operation of the presented distance algorithm under the representative fault case is shown in Fig. 7. The specifications of this fault are as follows:

- fault type: *a-g*
- fault distance: 0.667 pu
- fault resistance: 10 Ω.

Fig. 7 presents the results for the example 2: the measured phase currents (Fig. 7a) and voltages (Fig. 7b), the conditional impedance $\underline{Z}_{c1}$ – determined with the single compensation (Fig. 7c) and the conditional impedance $\underline{Z}_{c2}$ – determined with the double compensation (Fig. 7d). The conditional impedance $\underline{Z}_{c1}$ settles inside the regions: A1, A3 and outside: A2. Similarly, the conditional impedance $\underline{Z}_{c2}$ settles inside the regions: A1, A3 and outside: A2. This assures reliable and fast (after around 10 ms) tripping.

Using the developed ATP-EMTP model, a number of fault cases have been studied. The diversity of the cases has been achieved by changing:

- type of fault (single phase, phase-to-phase, phase-to-phase-to-ground, three-phase),
- fault location (backward, forward – within the line at every 50km),
- fault resistance (0, 5, 25 ohms).

The influence of the direction of the pre-fault power flow on the operation of the algorithm was studied by analyzing operation of relays A and B. In total 528 fault cases have been studied.

The presented new distance protection algorithm has been tested on the simulated testing cases and the following results have been obtained for the relays from both the ends:

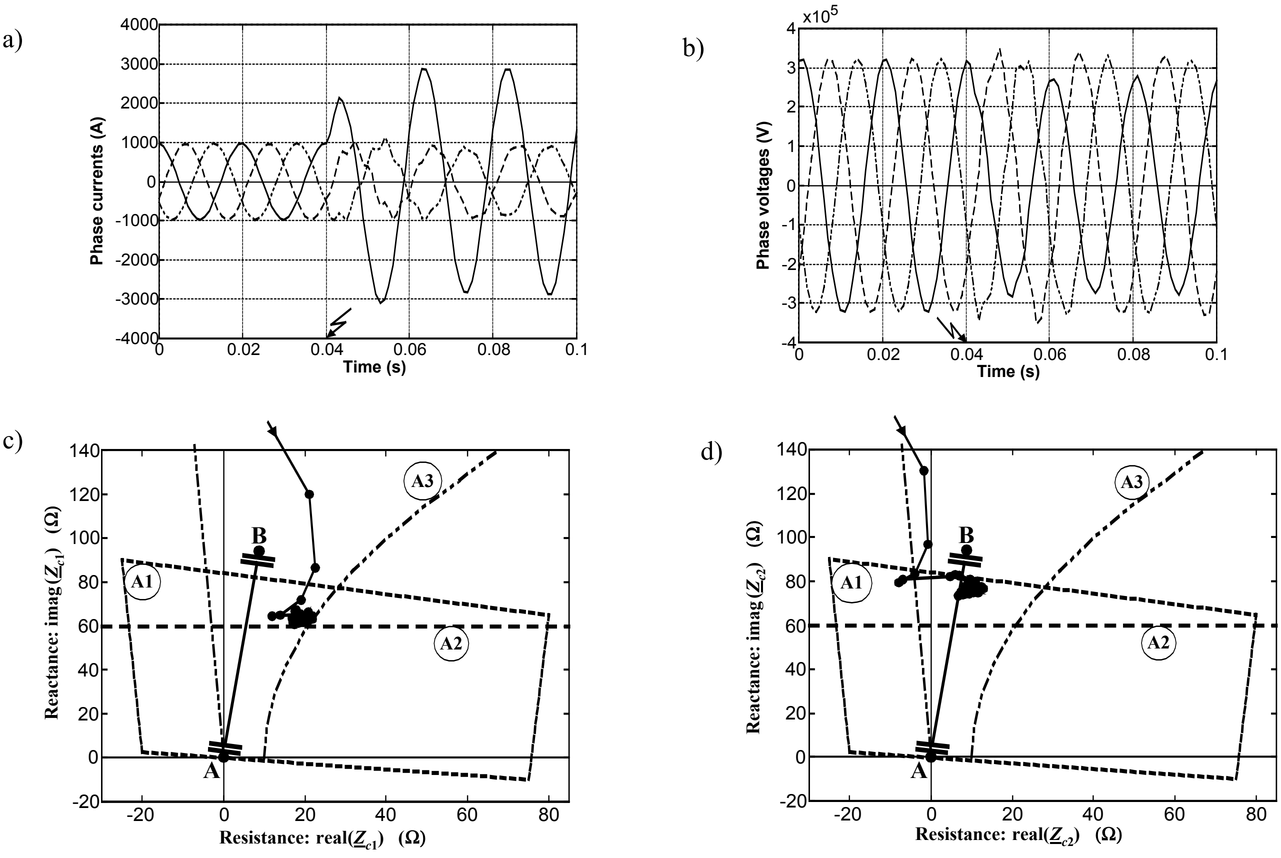

Fig. 7 Example 2 – line compensated at both ends: a) phase currents, b) phase voltages, c) trajectory of the conditional fault loop impedance determined with the single compensation, d) trajectory of the conditional fault loop impedance determined with the double compensation

REL_A:

10% missing operations out of 120 internal faults, average tripping time: 13.2ms, 0% false trippings out of 96 cases.

REL_B:

12.5% missing operations out of 120 internal faults, average tripping time 10.9ms, 0% false trippings out of 96 cases.

The above results have been obtained for the settings identical to those applied for the line compensated by SCs installed in the middle [2].

In the next step the algorithm has been optimized in terms of its settings. In the way of digital ATP-EMTP simulation the new set of settings has been found. As a result certain further improvement of the algorithm performance has been achieved. Finally, pretty satisfactory performance has been provided since the algorithm operates for some 94-95% of all the faults located on the line with the reach of 70% of the actual (geometrical) line length. The average time of the first zone unit only slightly exceeds half a cycle.

IV. CONCLUSIONS

This paper presents the new distance protection algorithm for transmission lines compensated with capacitor bank installed in the middle or with the banks at both ends. In the algorithm the specific conditions for impedance measurement, which are relevant for such lines, are fully taken into account.

Good dynamic performance of impedance measurement is achieved by including SCs&MOVs into the fault loop model. For this purpose effective digital algorithm for estimation of the voltage drop across SCs&MOVs has been developed. The algorithm relies on on-line solving the strongly nonlinear differential equation describing the SC&MOV circuit. Fast convergence of iterative calculations has been achieved due to moderating the strong nonlinearity of the considered equation by altering between two optimal forms, depending on the operating point of the MOV. As a result, only two or three iterations are required, allowing for on-line application even under not too high sampling frequency of 1000 Hz.

The presented distance protection is based on determining the two conditional impedances and comparing them with three specially shaped impedance characteristics. In case of the line compensated with a capacitor bank installed in the middle the conditional impedances, accordingly without the compensation and with the single compensation, are determined. The single and the double compensations are used for the line compensated at both ends. The proposed three impedance characteristics suit for both modes of capacitor compensation considered in this paper. However, for improving the distance algorithm for the line compensated at both ends slight changes of the impedance characteristics were considered.

ATP-EMTP study of diverse fault cases proved satisfactory performance of the presented protection algorithm. Different specifications of the faults and for the infeed impedances were considered in the study. Correct operation of the presented distance algorithm has been obtained for some 94-95% of all the faults located on the line with the reach of 70-80% of the actual, i.e. geometrical line length. The average time of the first zone unit is around half a cycle. Thus, the quality of protection of the considered series-compensated lines with use of the presented distance algorithm is comparable with that, which is for the classic distance protection applied for traditional uncompensated lines.

REFERENCES

[1] CIGRE SC-34 WG-04, „Application guide on protection of complex transmission network configurations", CIGRE materials, 1990.

[2] M.M. Saha, B. Kasztenny, E. Rosolowski, J. Izykowski, „First zone algorithm for protection of series compensated lines", IEEE Trans. on Power Delivery, Vol.16, NO.2, pp. 200–207, 2001.

[3] D.L. Goldsworthy, "A linearized model for MOV-protected series capacitors", IEEE Trans. on Power Systems, Vol.2, No.4, pp.953-958, 1987.

[4] C. Gagnon, P. Gravel, „Extensive evaluation of high performance protection relays for the Hydro-Quebec series compensated network", IEEE Trans. on Power Delivery, Vol.9, No.4, pp.1799-1811, 1994.

[5] E. Rosolowski, B. Kasztenny, J. Izykowski, M.M. Saha, „Comparative analysis of impedance algorithms for series compensated lines", Proceedings of the Power System Protection Conference, Bled, Slovenia, pp.21-26, 1996.

[6] F. Ghassemi, J. Goodarzi, A.T. Johns, „Method for eliminating the effect of MOV operation on digital distance relays when used in series compensated lines", Proceedings of the Universities Power Engineering Conference, Manchester, UK, pp.113-116, 1997.

[7] J.A.S.B. Jayasinghe, R.K. Aggarwal, A.T. Johns, Z.Q. Bo, „A novel non-unit protection for series compensated ehv transmission lines based on fault generated high frequency voltage signals", IEEE Trans. on Power Delivery, Vol.13, No.2, pp.405-413, 1998.

[8] M.M. Saha, K. Wikstrom, E. Rosolowski, J. Izykowski, R. Dutra, "Analysis of fault location algorithms for parallel transmission lines with series compensation", Proceedings of International Conference on Power System Transients – IPST'2001, Rio de Janeiro, Brazil, pp. 429-434, 2001.

[9] P.G. McLaren, G.W. Swift, Z. Zhang, E. Dirks, R.P. Jayasinghle, I. Fernando, „A new positive sequence directional element for numerical distance relays", Proceedings of Power Tech Conference, Stockholm, Sweden, pp. 540–545, 1995.

[10] J. Stoer, R., Bulirsch, "Introduction to numerical analysis" Springer-Verlag, New York, 1980.

[11] H. Dommel, „Electro-Magnetic Transient Program", BPA, Portland, Oregon, 1986.