A NEW LOSSLESS CIRCUIT BALANCING THE MV DISTRIBUTION SYSTEMS FROM INSULATED SHIELD WIRES OF HV LINES

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ABSTRACT

Three-Phase Scheme Shield Wire Lines (MV lines obtained by isolating 2 shield wires of an HV transmission line) are intrinsically unbalanced. Even though the load supplied is balanced, negative sequence components of the voltage are originated by this unsymmetry. Balancing means are necessary in order to contain these components to tolerable values. The paper presents a new balancing circuit, made of static, lossless, low cost components. The circuit has important advantages with respect to the compensating means proposed and applied in the past. In particular its application, in addition to the balancing effect, enables reduction of the voltage drop and does not cause any increase of the active power losses. The paper presents the circuit in two different forms together with the principles that justify its genesis.

KEYWORDS: *Shield Wire Lines. Negative sequence components. Balancing circuits.*

1. INTRODUCTION

A *Shield Wire Line* (SWL) is a Medium Voltage (MV) line obtained by isolating the shield(s) wire(s) from the towers of an High Voltage line and energizing it (them) at MV with respect to ground in an ending station.

The original idea, proposed by Iliceto in 1982-83 in [1], consisted of [2]:

- Isolating one shield wire of an HV line and energizing it with respect to ground from the closest transformer station;
- Supply of single-phase loads along the line by means of single-phase distribution transformers branched between the shield wire and ground.

Successively, in 1985, for the lines equipped with two shield wires, it was proposed to isolate both shield wires and energize them in three-phase with respect to ground in order to supply also three–phase loads.

On the basis of the ideas above the unconventional schemes in [3] and [4] were presented. Details on engineering, application, operation experience and developments may also be found in [6].

Fig. 1 shows a *Three-Phase-Scheme* SWL [3],[4].

The simplified equivalent circuit of a stretch of unit length of such line, obtained by assuming as uniformly transposed the phase conductors of the main line and representing only the conductors of the SWL, is represented in Fig. 2.

In such line the three conductors, i.e. the two shield wires and the ground, behave as phase conductors; the main cause of the imbalances of the voltages at receiving end at full load is due to the different impedances of the ground return circuit and of the shield wires. Balancing of such asymmetries has been obtained, so far, by inserting in series, in the ground return circuit, a resistor reactor, such as to approximately balance the circuit. In such a way balancing is obtained by addition of a lossy element in series, in one of the line conductors. As an alternative it was also proposed to balance the voltages at the three-phase load pick-up by inserting, in the ground connection of the distribution transformers, a proper e. m. f., obtained from transformers equipped with on load tap changers and proper control of tap changing [6].

In this paper a new circuit is proposed, able to perform balancing of the voltages supplying the three-phase loads. The circuit is made of lossless, static, low cost elements: i.e. simple inductive and capacitive reactances. The circuit was conceived in July 1996 [7]. After some checks on viability [8], it is presented here in the following, together with the principles that justify its genesis.

2. BALANCING OF THE SWL RESISTANCES

Let us consider a SWL of a given length, a, supplying a balanced three phase load at receiving end. The equivalent circuit of such SWL may be obtained by the one in Fig. 2 by simply multiplying by the factor a the series impedances and the transversal capacitances. Let us now perform the following operations on such circuit:

a) let us disregard, at this stage, the presence of the series inductances; they will be taken into account in a second step;
b) let us disregard the e.m.f.s due to the electromagnetic coupling with the phase conductors of the main line (such e.m.f.s compensate each other in the hypothesis of phase conductors uniformly transposed);

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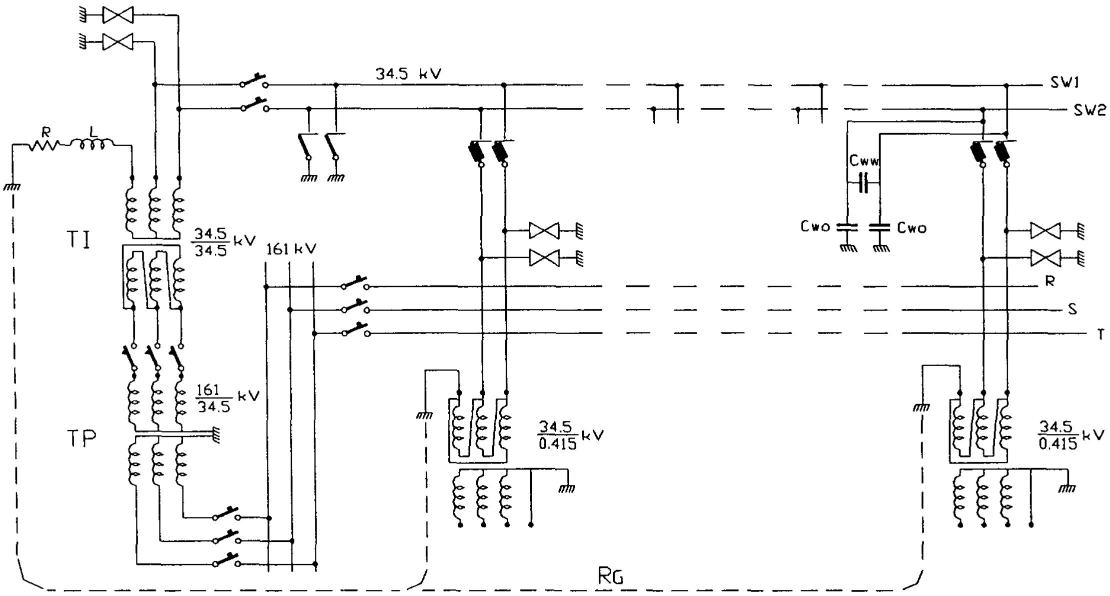
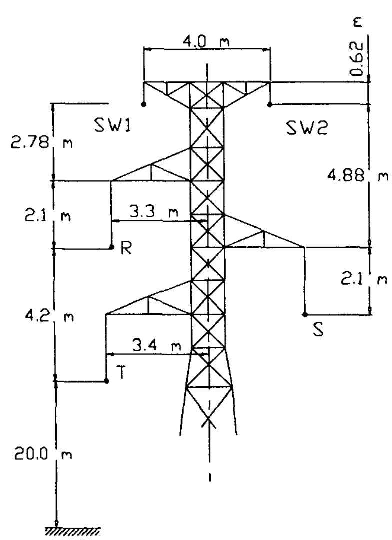


Fig. 1 – Schematic of a Three–Phase–Scheme, Shield Wire Line [3],[4].TP = Main 161/34.5 kV transformer. TI = Interposing transformer. Cww, Cwo = Antiferroresonance, p.f. correction and balancing capacitors (AFC capacitors).S_{w1}, S_{w2} = Shield wire conductors; R-L = resistor reactor compensating circuit (applied so far).



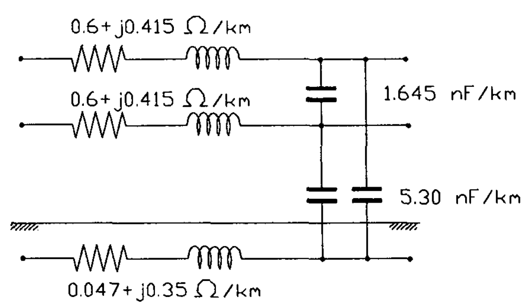


Fig. 2 – Simplified equivalent circuit of a stretch of a SWL . The phase conductors of the main line (rated at 161 kV) are supposed as uniformly transposed. Only the SWL conductors are represented. Characteristics of the shield wire conductors: ACSR cables, Ø = 11.35 mm, S_{Al}=48.57 sqmm, S_{St}=28.33 sqmm , r=0.6 ohm/km at 20 °C.

c) let us disregard the presence of the capacitances between the shield wires and between the shield wires and ground;

d) as already said, let us assume for the moment that the load is lumped at the receiving end of the SWL.

Fig. 3 reports the equivalent circuit of the SWL considered, obtained in the assumptions above. In the equivalent circuit, the voltages applied by the transformer supplying the SWL are represented by ideal generators with emfs E_A, E_B, E_C ; the balanced three-phase load by a star of equal impedances Z_L .

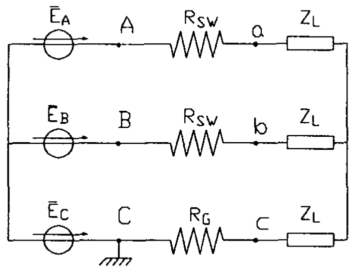


Fig. 3 - Equivalent circuit of a SWL supplying a symmetrical load. Only the series resistances of the SWL are represented. R_{SW}, R_G = resistance of the shield wires and of the ground return circuit, respectively. Z_L= load impedance per phase. E_A, E_B , E_C = voltages applied at sending end of the SWL.

Let us insert now, in series to R_G , two resistances:

- the resistance $R^*=R_{SW} - R_G$
- the resistance $R^\wedge = -R^*$ (singular because it is negative)

Following this modification the regime of the circuit does not change (see Fig. 4) .

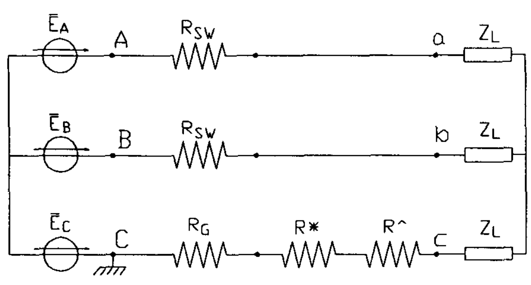


Fig. 4 – Balancing of the series resistances of the SWL. 1st step: insertion in the Fig. 3 circuit of the resistances: $R^*=R_{SW} - R_G$; $R^\wedge = -R^*$

Let us move now, in the circuit in Fig. 4, the degenerate resistance $R^\wedge=-R^*$, by changing the position with that of the impedance Z_L in the same phase, as indicated in Fig. 5.

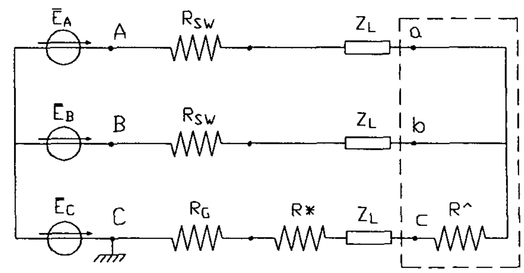


Fig. 5 – Balancing of the resistances of the SWL. 2nd step: transfiguration of Fig. 4 circuit.

In the *a b c* section of the circuit an unbalanced star of impedances is connected. These impedances are degenerate because one of them is made of a negative resistance, the other two are nil. If, in the branches of nil impedances, two reactances, the first inductive $X_L=-R^\wedge/\sqrt{3}$, the second capacitive $X_C = R^\wedge/\sqrt{3}$ are inserted, with proper choice of the phases, as indicated in Fig 6b), the resulting star of impedances, energized with 3-phase symmetrical positive sequence voltages, behaves as it were made of three equal resistances, $R^\wedge/3$ each (Fig. 6c) , thus balancing the whole system.

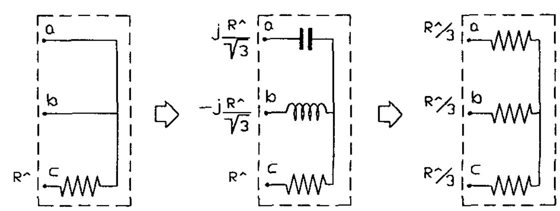


Fig. 6 – Balancing of the resistances of the SWL. 3rd step: a) the unsymmetrical part of the circuit in Fig. 5 is evidenced; b) – balancing of resistance $R^\wedge$ by addition of an inductive reactance, equal to $R^\wedge/\sqrt{3}$, and a capacitive reactance equal to - $R^\wedge/\sqrt{3}$ inserted, with proper choice of the phases on phases a and b. c) equivalent circuit of the star in b).

At this stage, it is possible to move, in the circuit in Fig. 6b), the resistance $R^\wedge$ and the balancing reactances $\pm j\, R^\wedge/\sqrt{3}$ behind the load impedance Z_L (see Fig.7).

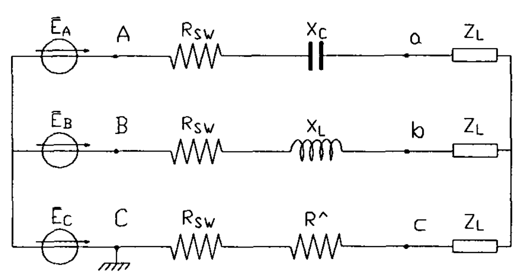


Fig. 7 – Balancing of the series resistances of the SWL. 4th step.

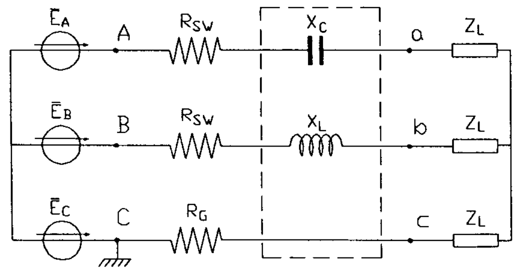


Fig. 8 – Balancing of the series resistances of the SWL. 5th step: The balancing circuit is evidenced in the dotted square. Xc= -j R^/√3, X_L= j R^/√3 = balancing reactances.

Combining R^ with R_{SW} , in the ground circuit, the circuit in Fig. 8 is arrived at:

From Fig. 8 it can be seen that the circuit that is being proposed, balancing the difference of the series resistances in the circuit in Fig. 2, is made of an inductive reactance and a capacitive reactance, whose absolute value is equal to the difference between the value of the total resistance of each shield wire and the one of the ground return, divided by √3, inserted in series, with proper choice of phases according to the sequence of the applied voltages E_A, E_B, E_C, behind the load impedances Z_L.

The circuit behaves as inserting in series in the shield wires a negative resistance and in the ground return circuit a positive resistance of such values as to balance the original resistances. The equivalent resistance of each phase of the circuit after balancing (shield wires and ground return circuit) is equal to: Req = 1/3 ($2R_{SW}+R_G$).

In order to evaluate the size and rating of the balancing reactances, let us consider the case of a SWL 100 km long, equipped with conductors with a unit resistance of 0.6 Ω/km as in Fig. 2. If the ground return circuit has a unit resistance of 0.047 Ω/km, the value of the balancing reactances is:

$X_C = X_L$ = (60- 4.7)/√3=31.9 Ω.

If the SWL carries 1 MW at 34.5 kV, the reactive power absorbed by each balancing reactance is :

$Q_C = Q_L = 31.9 * 17^2$ = 9.2 kVAR (C=100 ηF, L=101.5 mH)

The voltage across the two reactances, at steady state, in normal operation, is: $V_C = V_L$ = 31.9 * 17 = 542 V.

The rating of the balancing components above is thus well acceptable. They should be inserted in series with the shield wires, isolated with respect to ground as in the case of the series capacitor banks.

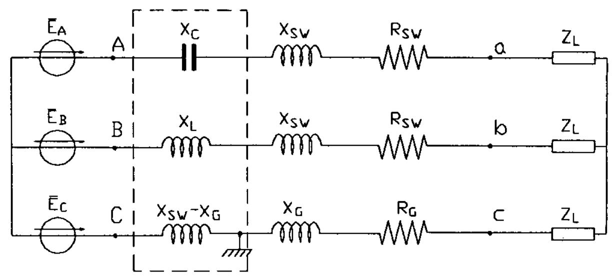


Fig. 9 – Balancing of the resistances and of the reactances of the SWL. 6th step: The balancing circuit is evidenced in the dotted square.

3. BALANCING OF THE SERIES REACTANCES OF THE SWL

The difference between the series reactance of the shield, X_{SW} , and that of the ground return circuit, X_G , may be compensated by inserting in series in the ground return circuit an inductive reactance equal to $X_{SW} - X_G$ [3]. The balancing circuit that is thus obtained is the one evidenced in Fig. 9.

The balancing circuit in Fig. 9 may be easily transformed in the more general form, represented in Fig. 10, where three capacitors X_{comp} were added in series in the three phases. This is equivalent to make a certain degree of series compensation of the line inductance.

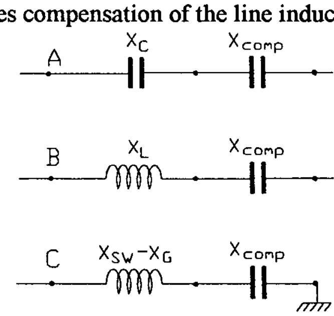


Fig. 10 – SWL balancing circuit in a generalized form. X_{comp}= series capacitor.

If it is taken X_{comp}= - (X_{SW}-X_G) , the circuit in Fig 11 is arrived at, as a particular case. This circuit is particularly interesting because it enables a compensation of the series unsymmetries of the SWL without need of any additional components in the ground return circuit. This condition makes it possible to distribute the compensation devices of the series unsymmetries, along the SWL, if it were convenient (f. i. in the case of loads distributed along the SWL).

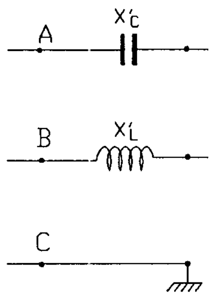


Fig. 11 – Balancing circuit of Fig. 10, in the particular case of $X_{comp}= -(X_{SW}-X_G)$. $X'_L=X_L + X_{comp}$; $X'_C= X_C+X_{comp}$

4. BALANCING OF THE SWL CAPACITANCES

In order to avoid ferroresonance overvoltages and support the voltage, capacitors (AFC) connected between the shield wires and between shield wires and ground were applied in the SWLs built [3] The capacitor bank connected between the shield wires is of capacitance different from that of the other two banks in order to compensate for the differences of the line capacitances (see Fig. 2). This practice may be applied even if the new series balancing circuit is applied. In the assumptions made, i. e. if the load is at the far end of the SWL, three AFC capacitors installed line side of the balancing circuit of Fig. 9 (or of Fig. 10), or along the SWL or at receiving end, according to the voltage control requirements, perform the functions in question.

5. CASE OF LOADS DISTRIBUTED ALONG THE SWL.

In case of loads distributed along the SWL, which is the most frequent case, an almost precise compensation of the series imbalances due to the differences in the series resistances could be obtained, in principle, by applying the balancing circuits proposed in this paper on each stretch of SWL, behind every pick-up points. The circuits should compensate the differences among the resistance of the shield wires and the ground return circuit relevant to each SWL stretch. The compensation of the difference of the inductive reactances of the shield wires and of the ground return circuit may be compensated in an approximate way by inserting a proper inductive reactance at sending end of the SWL, in series with the ground connection of the supply transformer [3]. The reactance should compensate for the difference in question up to the electrical center of the load. By applying the circuit in Fig. 11, it is also possible to perform a compensation distributed, also for the difference of the series inductances (shield wires and ground return circuit).

In practice, in the most common cases, it is sufficient to apply one balancing circuit only at sending end rated in such a way as to balance approximately the circuit, as made in the past, where a balancing circuit, made of a resistor-reactor was foreseen at the sending end of the SWL.

6. PROTECTION OF THE BALANCING CIRCUITS

The insulation of the balancing circuits dealt with in this paper should be protected against the stresses due to the temporary and transients overvoltages (f.i. during the faults, or following switching operations and/or ligthning phenomena). As a first approach to the problem simple spark gaps may be considered for the protection. An in depth analysis of this problem is to be performed in order to assess setting of the gaps and coordination with the breaker protection.

7. ANALYSIS OF A PRACTICAL CASE

The results of the application of the balancing circuit dealt with in this paper to a practical case is presented in the following.

The line configuration assumed is the one represented in Fig. 2. The main line is a 161 kV single circuit line equipped with two ACSR shield wires. The line is supposed to carry a load of 65 MW, $\cos\varphi=1$, i.e. the surge impedance load. A Three-phase-scheme SWL, 120 km long, operated at 34.5 kV originates from the 161/34.5 kV station at the sending end of the line. The phase conductors of the 161 kV line are supposed to be transposed along line at 20 km, 60 km, 100 km.

In the study the following assumption were done:

- A balanced three phase load 6x333 kW= 2000kW, $\cos\varphi=0.9$ was supposed to be supplied by MV/LV transformers connected to the SWL every 20 km along the line.
- The interposing transformer at sending end was assumed to be rated at 3 MVA.
- An AFC bank rated at 400 kVAR was supposed to be installed at 120 km.

Three different compensation means were considered:

a) a resistor reactor inserted in the ground connection of the interposing transformer at sendig end of the SWL, (this case is identified as RL);
b) the new balancing circuit dealt with in Fig. 9 (this case is identified as CLL);
c) the new balancing circuit of Fig. 11 (this case is identified as CL).

In all the cases the balancing circuits were dimensioned in such a way as to compensate for the difference of the series impedances of the shield wires and of the ground return circuit up to the electrical center of the loads. The ATP/EMTP Program was used for the numerical simulations.

Fig 12 shows the shape of the positive sequence component of the voltage and of the negative component along the SWL. From the figures it ensues that :

- in case of balancing circuit type RL, the voltage drop along the line, and across the compensating devices, is equal to 5.4 % while with the circuits type CLL and CL, the drop is more contained, about 3.6 % in both cases.
- The compensation of the negative sequence component of the voltage, V_i, is effective in all the three cases, beeing V_i at the load points always less than 1.1%. The three circuits (RL, CLL and CL) are almost equivalent as regards this point. The low value of V_i proves the proposed circuit works.
- The balancing circuit type RL causes an increase of the active power losses equal to 37.6 kW in comparison with the cases of circuits CLL and CL.
- Reactive power absorberd by the balancing capacitors and reactors in cases CLL and CL is in the range of 20-30 kVAR.

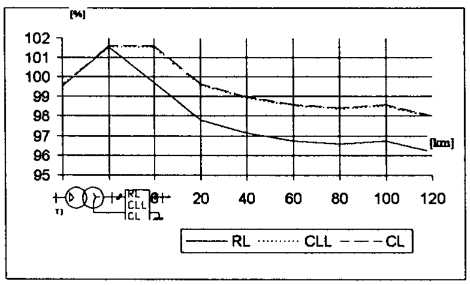


Fig.12- Positive sequence component of the voltage along the SWL in the three cases of balancing circuits considered:RL, CLL, CL. Aggregate load supplied = 2000 kW, cosφ= 0.9.

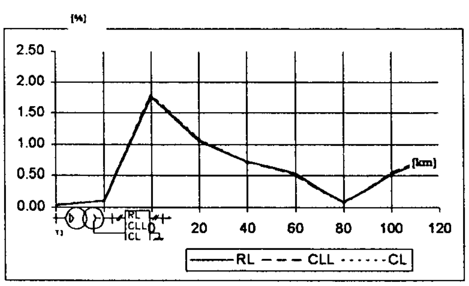


Fig.13- Negative sequence component of the voltage along the SWL in cases of Fig. 12. Load pick-up points at 20, 40, 60, 80, 100, 120 km.

8. CONCLUSIONS

A new balancing circuit is proposed here for the *Three-Phase-Scheme SWLs.* The circuit is presented in two different versions:

- the first, the one of the circuit represented in Fig. 9, that simply compensates the unsymmetry of the series impedances in the equivalent circuit of a SWL;
- the second, the one of the circuit represented in Fig. 10, derived from the circuit of Fig. 9, that, in addition to the functions of the previous circuit, reduces also the SWL reactance by means of a sort of series compensation.

The circuit proposed, in performing the balancing functions of the series impedances of the SWLs, presents some advantages with respect to the systems proposed and/or adopted in the past, i.e.:

a) the one made of a resistor in series with a reactance;
b) the one that makes use of the e.m.f.s at secondary side of special compensating transformers.

In particular, with respect to the first one of the above mentioned balancing methods, that has been applied in the commercial applications of the *Three-Phase Scheme* SWL, it presents the following advantages:

- it is made of lossless, static, low cost components;
- it determines a reduction of the total resistance of the conductors of the SWL, thus limiting the voltage drop;
- it does not make active power losses to increase because of the use of lossy balancing resistor in series.

The circuit represented in Fig. 11, derived from the one in Fig. 10, in addition to the balancing effects, limits also the SWL series reactance, and makes it possible to perform an accurate balancing, distributed along the SWL.

The circuit presented does not performs a balancing action as the transformers in item b), but this does not seem an important limitation, except than in some special cases.

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