# BALANCING METHODS OF THE "3-PHASE" SHIELD WIRE SCHEMES

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*Abstract*-- **Insulation of shield wire(s) of HV (115-230 kV) transmission lines and their energization at MV (20-34.5 kV) from a HV/MV transformer station at one line terminal and use of the ground as a MV phase conductor, allows the setting-up of long unconventional MV distribution feeders for 3-phase or single-phase low cost electrification along the route of the HV line. This technique has been applied in various tropical countries and is referred to as the "Shield Wire Scheme" (SWS).**

**The "3-Phase" SWS, that is the most applied scheme, is an inherently unsymmetrical 3-phase system. The paper deals with the methods to reduce the negative sequence voltage at the consumer terminals generally within 1%.**

**Firstly, the paper presents a brief description of the "3-Phase" SWS for those readers not familiar with this technique. Then the paper deals with the compensating method using a series impedance in the earth return path and a shunt capacitance connected between the two shield wires.**

**A general purpose accurate method is presented for the calculation of the compensating impedances, implemented in a computer program developed by the authors.**

**The results of an application to a "3-Phase" SWS planned for construction in Western Africa is finally presented.**

*Index Terms*— **Unconventional Distribution Schemes, Shield Wire Schemes, Negative Sequence Voltage, Balancing Impedance and Capacitance.**

## 1. Introduction

IN many cases, new HV lines built for the supply of power to major towns in developing countries, or for connecting remote power plants to the system, are routed not far from the highways along whom are several minor towns, villages and farms without electricity. The distance of these communities from the closest HV/MV transformer station may exceed 100 km. Owing to the small amount of power to be supplied at long distances, conventional 3-phase MV lines and/or addition of HV/MV stations are not feasible from an economic point of view.

A very low cost solution is the Shield Wire Scheme, first proposed in ref. [1], [2]. The SWS consists of insulating the shield wire(s) (SW(s)) from the towers of the HV lines and energizing the SW(s) at MV (20-34.5 kV) from the HV/MV transformer station at one end of the HV line. MV/LV transformers are connected between the SW(s) and ground for power supply to the loads.

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The applicable SWSs presented in previous papers [2], [3], [4] are four: Single-Phase Earth-Return (applicable in HV lines with one SW); Single-Phase Metallic-Return, "V" Scheme and "3-Phase" Scheme, the latter three being feasible in HV lines equipped with two SWs.

In this paper, only the most frequently used "3-Phase" SWS will be considered (Fig.1). In the "3-Phase" SWS (Fig.1) the two insulated SWs and the ground return path form a 3-phase circuit which is supplied at MV from a HV/MV station.

The supply of "3-Phase" Shield Wire Line (SWL) is feasible:

i) from a dedicated MV winding of a HV/MV step-down transformer via a MV 2-pole CB, as shown in Fig.1;
ii) via a MV/MV interposing transformer providing the suitable voltage for SWL. The SWL supply winding is in any case operated with one terminal grounded.

The "3-Phase" SWS supplies MV/LV conventional distribution transformers operated with one MV terminal permanently grounded (Fig.1). This SWS can supply 100% 3-phase load, as a conventional 3-phase distribution feeder.

The loading capability of the "3-Phase" SWLs is controlled by the same phenomena as long MV conventional lines, i.e.:

- voltage drop,
- thermal limit of conductors,
- voltage stability (only for very long lines),
- economic aspects (Joule losses, initial investment),

and, in addition, by the voltage unbalance. In fact, as the "3-Phase" SWL is an unsymmetrical system, a negative-sequence voltage, $V_2$, arises at the consumer terminals.

The value of $V_2$ must be contained within 1-2% of the positive sequence voltage $V_1$, for a correct operation of user equipment.

The balancing of $V_2$ can be obtained by applying different methods (see Par.2), but the most simple, using only static components, utilizes a series resistor-reactor in the earth path (R-L in Fig.1) and capacitors branched between the two SWs ($C_{ww}$ in Fig.1) and between each SW and ground ($C_{w10}$ and $C_{w20}$ in Fig.1). Capacitors $C_{ww}$, $C_{w10}$ and $C_{w20}$ then perform three functions: p.f. correction, prevention of ferroresonance and circuit balancing in "3-Phase" SWS [2], [3], [4].

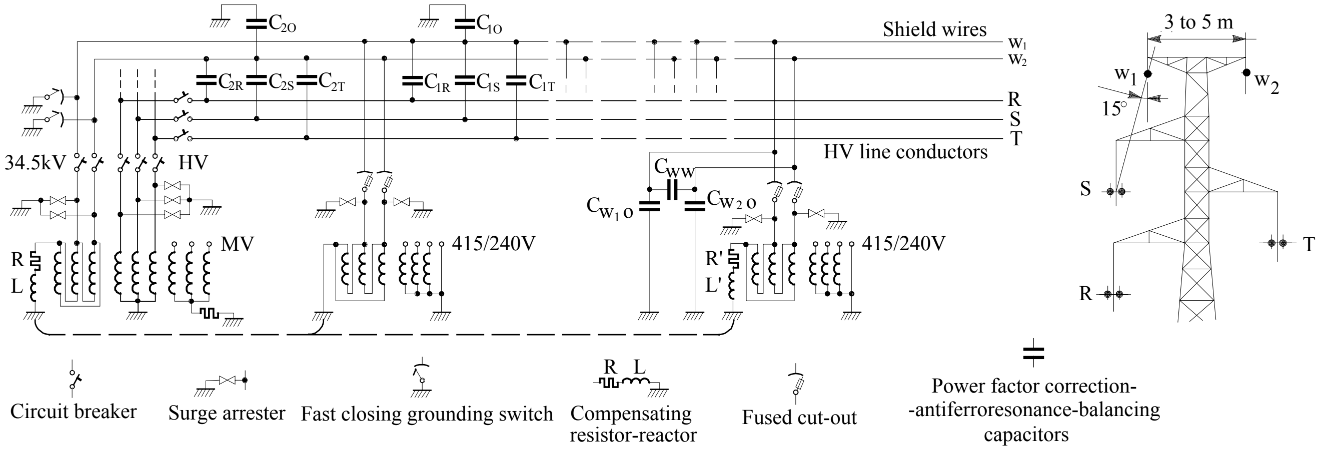


Fig.1- "3-Phase" SWS and typical HV (115-230 kV) line tower with two insulated SWs

The following paragraphs describe the phenomenon that causes voltage unbalance in the “3-Phase” SWSs and the means to reduce it. Par. 3 presents a general method that allows to compensate the negative sequence voltage at any specified consumer terminal. A parametric study is then performed for a “3-Phase” SWS.

## 2. MINIMIZATION OF THE NEGATIVE SEQUENCE VOLTAGE IN “3-PHASE” SWSS

### 2.1. Methodology

In the "3-Phase" SWS (Fig.1), the two insulated SWs and the ground return path form a 3-phase circuit which is supplied at MV from a HV/MV station by a transformer winding with one terminal permanently grounded. Consequently, the wire-to-ground (w1-Gr and w2-Gr) rms voltages are equal to the wire-to-wire (w1-w2) voltage.

The major cause that can generate asymmetries is the fact that the resistance of the earth path is much smaller than the resistance of any practical SW cable, while the reactance of the earth path is usually slightly smaller [2].

The capacitive leakage currents terminating to the SWs and to earth path (3rd phase of SWL) are unbalanced owing to diversity of the partial capacitances and of the currents capacitively induced by the HV conductors.

The source and the LV loads do not usually cause significant asymmetries because the network feeding the SWL is symmetrical and the LV loads are reasonably balanced in the three phases.

In order to make symmetrical the "3-Phase" circuit formed by the two SWs and the earth path, the simplest solution is to apply complementary asymmetries tailored to cancel out or drastically reduce the inherent asymmetries of the SWL.

The methods proposed to reduce the asymmetries are the following:

1a) inserting a proper series impedance $\mathbf{Z}_c$ in the earth path as shown in Fig.2.1a [2];
1b) inserting two series reactances, $X_1$ and $X_2$ as shown in Fig.2.1b [10].
2) connecting a p.f. correction capacitor between the two shield wires ($C_{ww}$ in Fig.1) larger than the p.f. correction capacitors branched from each SW and ground ($C_{w10}$ and $C_{w20}$ in Fig. 1), so that the total capacitive currents flowing to the SWs and to the earth are of equal amplitude and phase shifted by 120° and 240°.
3) using appropriate e.m.f.s at the secondary side of special compensating transformers [9] (Fig.2.1c).

Methods 1a) and 2), that use simple static low cost compensating components, are described in detail in the following paragraphs.

### 2.2. Series impedances installed in the earth path

Let us consider a “3-Phase” SWS feeding a load at the receiving end of the SWL as shown in Fig. 2.2.1a. By disregarding all the capacitances and the magnetic coupling between the SWs and the HV line conductors, the equivalent circuit of the system is the one shown in Fig. 2.2.1b.

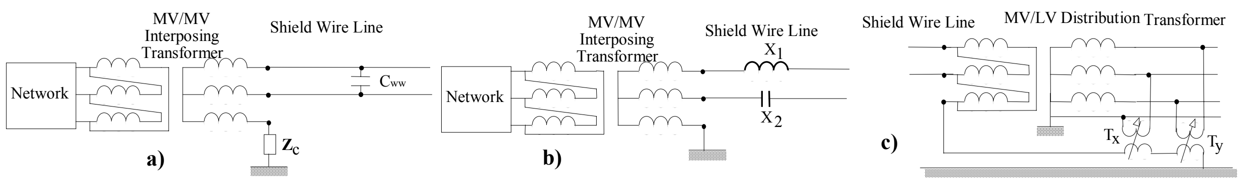
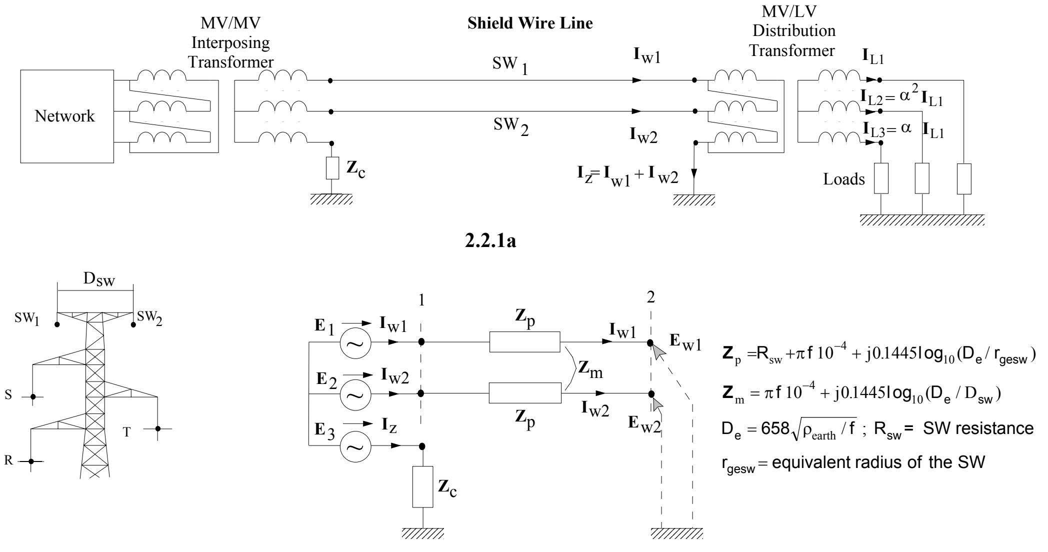


Fig. 2.1 – Alternative methods to reduce the asymmetries in 3-Phase SWSs: a) by capacitances between SWs and an earth-path impedance; b) by two reactors in series with the SWs; c) by special compensating transformers.




Fig, 2.2.1- Single line diagram of the SWL and corresponding equivalent circuit

In order to make nil the negative sequence component of voltages at section 2 of the SWL, the voltage $\mathbf{E}_{w1}$ and $-\mathbf{E}_{w2}$ must have the same amplitude and must be shifted by 120º ,i.e:

$$\mathbf{E}_{w1} = e^{-j120^\circ}(-\mathbf{E}_{w2}) = e^{j60^\circ}\,\mathbf{E}_{w2} \qquad (2.2.1)$$

The circuit of Fig.2.2.1b yields the following equations:

$$\mathbf{E}_{w1} = \mathbf{E}_1 - \mathbf{E}_3 - \mathbf{Z}_p\,\mathbf{I}_{w1} - \mathbf{Z}_m\,\mathbf{I}_{w2} - \mathbf{Z}_c\,(\mathbf{I}_{w1}+\mathbf{I}_{w2})$$

$$\mathbf{E}_{w2} = \mathbf{E}_2 - \mathbf{E}_3 - \mathbf{Z}_m\,\mathbf{I}_{w1} - \mathbf{Z}_p\,\mathbf{I}_{w2} - \mathbf{Z}_c\,(\mathbf{I}_{w1}+\mathbf{I}_{w2}) \qquad (2.2.2)$$

Taking into account that $\mathbf{I}_{w2}=e^{-j120^\circ}\mathbf{I}_{w1}$ and equation (2.2.1), the compensating impedance $\mathbf{Z}_c$ can be calculated with the following formulas:

$$\mathbf{Z}_c = R_c + j\,X_c = \mathbf{Z}_p - 2\mathbf{Z}_m = (R_{sw} - R_{ea}) + j\,(X_p - 2X_m) =$$
$$= R_{sw} - \pi^2 f 10^{-4} + j\,0.1445\,\log_{10}[D^2_{sw}/(r_{gesw}\,D_e)] \qquad (2.2.3)$$

where: $R_c$ is the difference of the SW conductor and earth return resistances; $X_c$ is the difference between the self-reactance of the SWs and twice the SWs mutual reactance.

In reality the SWL supplies several loads along the line. Then, by applying the same procedure, the following expression of $\mathbf{Z}_c$, which makes nil the negative sequence voltage at the far end of the SWL, is obtained:

$$\mathbf{Z}_c = (\mathbf{Z}_p - 2\,\mathbf{Z}_m)\sum_{i=1}^{N_L} l_i\,\mathbf{I}_{Li} \Big/ \sum_{i=1}^{N_L}\mathbf{I}_{Li} \qquad (2.2.4)$$

where: $N_L$ is the number of the supplied loads; $l_i$ and $\mathbf{I}_{Li}$ are the distance from the SWL sending end and the current of the $i^{th}$ load, respectively.

Formula (2.2.3) and (2.2.4) always yield a compensation impedance, $\mathbf{Z}_c$, which is inductive because the self and mutual capacitances of the SWs have been neglected.

To take into account these capacitances, let us consider the equivalent circuit of the SWL shown in Fig. 2.2.2.

Applying again the procedure leading to formula (2.2.3), the following expression of $\mathbf{Z}_c$ is obtained:

$$\mathbf{Z}_c = \frac{(\mathbf{Z}_p e^{-j60^\circ} - \mathbf{Z}_m)\mathbf{I}_{w1} - (\mathbf{Z}_p - \mathbf{Z}_m e^{-j60^\circ})\mathbf{I}_{w2}}{\mathbf{I}_z e^{-j120^\circ}}, \qquad (2.2.5)$$

where:

$$\begin{cases} \mathbf{I}_{w1} = \mathbf{I}_{L1} + j\omega\dfrac{C_o + C_m}{2}\mathbf{E}_{w1} - j\omega\dfrac{C_m}{2}\mathbf{E}_{w2} \\ \mathbf{I}_{w2} = \mathbf{I}_{L2} + j\omega\dfrac{C_o + C_m}{2}\mathbf{E}_{w2} - j\omega\dfrac{C_m}{2}\mathbf{E}_{w1} \\ \mathbf{I}_z = -[\mathbf{I}_{L1} + \mathbf{I}_{L2} + j\omega C_o(\mathbf{E}_{w1} + \mathbf{E}_{w2})] \end{cases}$$

are the currents flowing in the SWs and in $\mathbf{Z}_c$, respectively. $\mathbf{I}_{w1}$ and $\mathbf{I}_{w2}$ are calculated by using equation (2.2.1). It can be noted that formula (2.2.5) yields formula (2.2.3) if $C_o$=$C_m$=0

Calculation of the compensation impedance, $\mathbf{Z}_c$, with the above equations, obtained without making the balancing of leakage currents terminating on the SWs, yields values of $\mathbf{Z}_c$ strongly depending on supplied load, with imaginary capacitive part, i.e. not acceptable in a distribution system.

It is therefore necessary to evaluate the balancing capacitances and their best location along the SWL in order to make, as much as possible, $\mathbf{Z}_c$ not affected by the load.

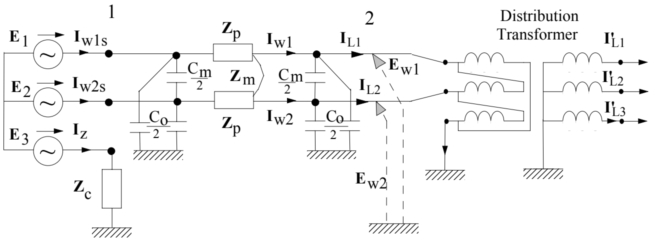



Fig. 2.2.2- Equivalent circuit of the SWL taking into account the capacitances of the shield wires

### *2.3. Balancing methods of "3-Phase" SWSs capacitive currents*

A HV line with "3-Phase" SWS has 5 insulated conductors: three HV phase conductors, R, S and T, and two shield wires, $w_1$ and $w_2$, as shown in Fig. 2.3.1a.

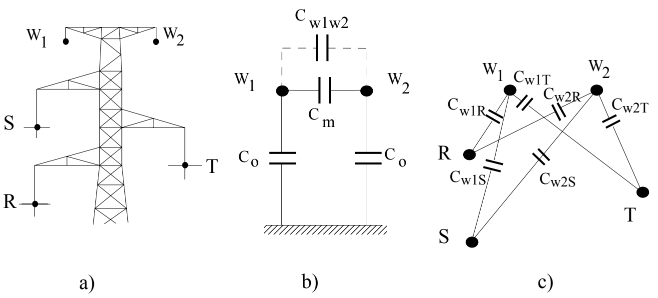



Fig. 2.3.1- a) HV tower head of SWL; b) capacitances between the shield wires and to ground; c) capacitances between the SWs and the HV circuit

Disregarding the electric coupling between SWs and HV conductors, the leakage capacitances of SWs are shown in Fig. 2.3.1b. Since the SW to ground capacitance, $C_o$, is always greater than the capacitance between the SWs, $C_m$, to make symmetrical the SW capacitive circuit it is sufficient to connect the following capacitance between the SWs:

$$C_{w1w2}=C_o - C_m$$

On the other hand, taking into account the mutual coupling capacitances between SWs and HV line conductors (Fig.2.3.1c), the capacitive currents flowing to each conductor, $\mathbf{I}_i$, can be calculated with the following equations:

$$\begin{bmatrix} \mathbf{I}_R \\ \mathbf{I}_S \\ \mathbf{I}_T \\ \mathbf{I}_{w1} \\ \mathbf{I}_{w2} \end{bmatrix} = j\omega \begin{bmatrix} \gamma_{R,R} & \gamma_{R,S} & \gamma_{R,T} & \gamma_{R,w1} & \gamma_{R,w2} \\ \gamma_{R,S} & \gamma_{S,S} & \gamma_{S,T} & \gamma_{S,w1} & \gamma_{S,w2} \\ \gamma_{R,T} & \gamma_{S,T} & \gamma_{T,T} & \gamma_{T,w1} & \gamma_{T,w2} \\ \gamma_{w1,R} & \gamma_{w1,S} & \gamma_{w1,T} & \gamma_{w1,w1} & \gamma_{w1,w2} \\ \gamma_{w2,R} & \gamma_{w2,S} & \gamma_{w2,T} & \gamma_{w1,w2} & \gamma_{w,,w2} \end{bmatrix} \begin{bmatrix} \mathbf{E}_R \\ \mathbf{E}_S \\ \mathbf{E}_T \\ \mathbf{E}_{w1} \\ \mathbf{E}_{w2} \end{bmatrix} \quad (2.3.1),$$

where $\mathbf{E}_i$, and $\gamma_{ij}$ are the conductor-to-Gr voltages and the induction matrix coefficients, respectively, and $\omega$ is the network angular frequency.

The capacitive currents flowing to the shield wires can be obtained from the two last equations of (2.3.1):

$$\begin{cases} \mathbf{I}_{w1} = j\omega[\gamma_{w1,R}\mathbf{E}_R + \gamma_{w1,S}\mathbf{E}_S + \gamma_{w1,T}\mathbf{E}_T + \gamma_{w1,w1}\mathbf{E}_{w1} + \gamma_{w1,w2}\mathbf{E}_{w2}] \\ \mathbf{I}_{w2} = j\omega[\gamma_{w2,R}\mathbf{E}_R + \gamma_{w2,S}\mathbf{E}_S + \gamma_{w2,T}\mathbf{E}_T + \gamma_{w2,w1}\mathbf{E}_{w1} + \gamma_{w2,w2}\mathbf{E}_{w2}] \end{cases} \quad (2.3.2)$$

By assuming that: $\mathbf{E}_S=\alpha^2\ \mathbf{E}_R$, $\mathbf{E}_T=\alpha\ \mathbf{E}_R$, $\mathbf{E}_{w1}=-\alpha^2\mathbf{E}_{w2}$; from (2.3.2) it follows that $\mathbf{I}_{w1}$ and $\mathbf{I}_{w2}$ generally have different amplitudes and are shifted by an angle lower than 120°. In order to obtain that $\mathbf{I}_{w1}$ and $\mathbf{I}_{w2}$ are part of a positive sequence symmetrical system (1, $\alpha^2$, $\alpha$) the following two procedures may be applied, depending on whether the HV circuit is fully transposed or untransposed along the SWL length.

*Transposed HV circuit*

If the HV circuit is fully transposed along the SWL length, the mutual capacitances between each shield wire and the HV conductors are equal to the arithmetic mean value:

$$C_{wi,c} = -\gamma_{wi,c} = -(\gamma_{wi,R} + \gamma_{wi,S} + \gamma_{wi,T})/3 \qquad (i = 1,2)$$

The capacitive currents flowing to the shield wires are thus:

$$\begin{cases} \mathbf{I}_{w1} = j\ \omega\ [\gamma_{w1,c}(\mathbf{E}_R + \mathbf{E}_S + \mathbf{E}_T) + \gamma_{w1,w1}\mathbf{E}_{w1} + \gamma_{w1,w2}\mathbf{E}_{w2}] \\ \mathbf{I}_{w2} = j\omega\ [\gamma_{w2,c}(\mathbf{E}_R + \mathbf{E}_S + \mathbf{E}_T) + \gamma_{w2,w1}\mathbf{E}_{w1} + \gamma_{w2,w2}\mathbf{E}_{w2}] \end{cases}$$

As $\mathbf{E}_R+\mathbf{E}_S+\mathbf{E}_T=0$, these equations yield:

$$\begin{cases} \mathbf{I}_{w1} = j\omega[\gamma_{w1,w1}\mathbf{E}_{w1} + \gamma_{w1,w2}\mathbf{E}_{w2}] \\ \mathbf{I}_{w2} = j\omega[\gamma_{w2,w1}\mathbf{E}_{w1} + \gamma_{w2,w2}\mathbf{E}_{w2}] \end{cases} \quad (2.3.3)$$

Furthermore, since $\gamma_{w1,w1}\cong\gamma_{w2,w2}=\gamma_{w,w}$ the total capacitive currents flowing to the shield wires, $\mathbf{I'}_{w1}$ and $\mathbf{I'}_{w2}$, become equal in magnitude and 120° phase shifted by adding the following capacitance between the shield wires (see Fig. 2.3.2):

$$C_{w1,w2} = \gamma_{w,w} + 2\gamma_{w1,w2} \qquad (2.3.4)$$

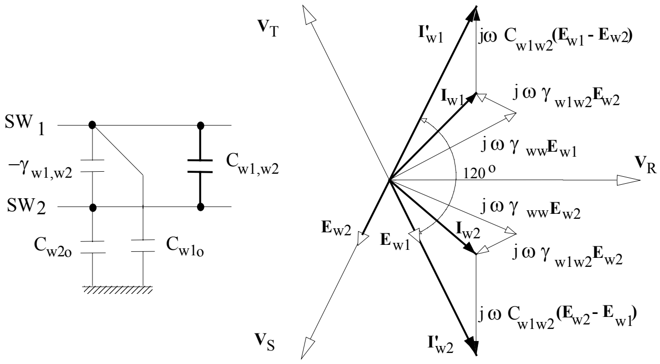



Fig. 2.3.2- Vector diagram in case of a HV transposed line .

*Untransposed HV circuit*

When the HV circuit is untransposed, the simplification of equations (2.3.2) in (2.3.3) is not possible because the sum of the capacitive currents between each SW and the HV conductors is not nil.

Equations (2.3.2) can be rewritten as follows:

$$\begin{cases} \mathbf{I}_{w1} = \mathbf{I}_{w1,RST} + j\omega[\gamma_{w1,w1}\mathbf{E}_{w1} + \gamma_{w1,w2}\mathbf{E}_{w2}] \\ \mathbf{I}_{w2} = \mathbf{I}_{w2,RST} + j\omega[\gamma_{w2,w1}\mathbf{E}_{w1} + \gamma_{w2,w2}\mathbf{E}_{w2}] \end{cases} \quad (2.3.5)$$

where:

$$\begin{cases} \mathbf{I}_{w1,RST} = j\omega\ [\gamma_{w1,R}\mathbf{E}_R + \gamma_{w1,S}\mathbf{E}_S + \gamma_{w1,T}\mathbf{E}_T] \\ \mathbf{I}_{w2,RST} = j\omega[\gamma_{w2,R}\mathbf{E}_R + \gamma_{w2,S}\mathbf{E}_S + \gamma_{w2,T}\mathbf{E}_T] \end{cases}$$

are the sum of the capacitive currents flowing from the shield wires to the HV conductors.

The following four different cases should be considered:

*i)* $|\mathbf{I}_{w1}| < |\mathbf{I}_{w2}|$ *and* $\mathbf{I}_{w1}$ *leads* $\mathbf{I}_{w2}$

Two balancing capacitances are needed: one between the shield wires, $C_{w1,w2}$, the other, $C^*_{w1,o}$ between shield wire 1 and ground, so that $\mathbf{I}'_{w1} = \alpha\, \mathbf{I}'_{w2}$:

$$\mathbf{I}_{w1} + j\omega[C_{w1,w2}(\mathbf{E}_{w1} - \mathbf{E}_{w2})) + C^*_{w1,o}\mathbf{E}_{w1}] =$$

$$= \alpha[\mathbf{I}_{w2} + j\omega C_{w1,w2}(\mathbf{E}_{w2} - \mathbf{E}_{w1})]$$

that is:

$$\mathbf{I}_{w1} - \alpha\mathbf{I}_{w2} = j\omega\alpha^2(\mathbf{E}_{w1} - \mathbf{E}_{w2})C_{w1,w2} - j\omega C^*_{w1,o}\mathbf{E}_{w1}$$

$$\mathbf{I} = \mathbf{A}C_{w1,w2} + \mathbf{B}C^*_{w1,o} \qquad (2.3.6)$$

where:

$$\begin{cases} \mathbf{A} = j\omega\alpha^2(\mathbf{E}_{w1} - \mathbf{E}_{w2}) = A_r + jA_i \\ \mathbf{B} = -j\omega\mathbf{E}_{w1} = B_r + jB_i \end{cases}$$

The complex equation (2.3.6) yields the two following algebraic linear equations for the calculation of the unknown balancing capacitances $C_{w1,w2}$ and $C^*_{w1,o}$:

$$\begin{cases} I_r = A_r\, C_{w1,w2} + B_r C^*_{w1,o} \\ I_i = A_i\, C_{w1,w2} + B_i C^*_{w1,o} \end{cases} \qquad (2.3.7)$$

Fig 2.3.3 shows the vector diagram of the voltages and currents and the connection of compensating capacitances.

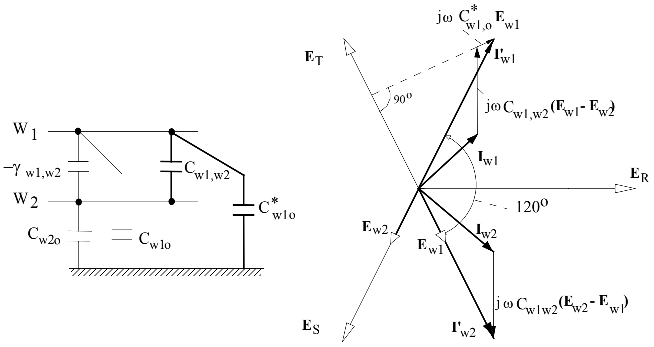



Fig. 2.3.3- Vector diagram in case of a HV untransposed line

*ii)* $|\mathbf{I}_{w1}| < |\mathbf{I}_{w2}|$ *and* $\mathbf{I}_{w2}$ *leads* $\mathbf{I}_{w1}$

In order to have $\mathbf{I}'_{w1} = \alpha^2\mathbf{I}'_{w2}$, by applying the same procedure as for case i), the following equation is obtained:

$$\mathbf{I}_{w1} + j\omega[C_{w1,w2}(\mathbf{E}_{w1} - \mathbf{E}_{w2})) + C^*_{w1,o}\mathbf{E}_{w1}] =$$

$$= \alpha^2[\mathbf{I}_{w2} + j\omega C_{w1,w2}(\mathbf{E}_{w2} - \mathbf{E}_{w1})]$$

which readily yields algebraic equations as (2.3.7).

*iii)* $|\mathbf{I}_{w1}| > |\mathbf{I}_{w2}|$ *and* $\mathbf{I}_{w1}$ *leads* $\mathbf{I}_{w2}$

In order to obtain $\mathbf{I}'_{w1} = \alpha\, \mathbf{I}'_{w2}$, two capacitances must be added, the first one between the two SWs, $C_{w1,w2}$, and the second one, $C^*_{w2o}$, between shield wire 2 and ground:

$$\mathbf{I}_{w1} + j\omega C_{w1,w2}(\mathbf{E}_{w1} - \mathbf{E}_{w2})) =$$

$$= \alpha[\mathbf{I}_{w2} + j\omega C_{w1,w2}(\mathbf{E}_{w2} - \mathbf{E}_{w1}) + j\omega C^*_{w2,o}\mathbf{E}_{w1}]$$

which readily yields algebraic equations as (2.3.7).

*iv)* $|\mathbf{I}_{w1}| > |\mathbf{I}_{w2}|$ *and* $\mathbf{I}_{w2}$ *leads* $\mathbf{I}_{w1}$

In this case it should be $\mathbf{I}'_{w1} = \alpha^2\, \mathbf{I}'_{w2}$, i.e.:

$$\mathbf{I}_{w1} + j\omega C_{w1,w2}(\mathbf{E}_{w1} - \mathbf{E}_{w2})) =$$

$$= \alpha^2[\mathbf{I}_{w2} + j\omega C_{w1,w2}(\mathbf{E}_{w2} - \mathbf{E}_{w1}) + j\omega C^*_{w2,o}\mathbf{E}_{w2}]$$

which readily yields algebraic equations as (2.3.7).

### *2.4 Compensation method by earth path impedance and shunt capacitances*

A good compensation of the "3-Phase" SWS can be obtained by using the earth path impedance, $\mathbf{Z}_c$, combined with the capacitances between the two SWs and one SW and ground.

For example, if the HV line is transposed, once calculated $C_{w1w2}$, the best location where to install it and the value of $\mathbf{Z}_c$ must be determined. If the load and $C_{w1w2}$ are both located at the SWL receiving end (Fig.2.2.2), $\mathbf{Z}_c$ can be calculated using formula (2.2.5), considering the following expressions of $\mathbf{I}_{w1}$ and $\mathbf{I}_{w2}$:

$$\begin{cases} \mathbf{I}_{w1} = \mathbf{I}_{L1} + j\omega\left[\dfrac{C_o + C_m}{2} + C_{w1,w2}\right]\mathbf{E}_{w1} - j\omega\left[\dfrac{C_m}{2} + C_{w1,w2}\right]\mathbf{E}_{w2} \\ \mathbf{I}_{w2} = \mathbf{I}_{L2} + j\omega\left[\dfrac{C_o + C_m}{2} + C_{w1,w2}\right]\mathbf{E}_{w2} - j\omega\left[\dfrac{C_m}{2} + C_{w1,w2}\right]\mathbf{E}_{w1} \end{cases}$$

For the SWL of Fig. 2.2.2 Table I reports the values of $\mathbf{Z}_c$ when the compensating capacitance, $C_{w1w2}$, calculated with (2.3.4), is installed at the far end of the SWL.

TAB.I- VALUES OF COMPENSATING IMPEDANCE $\mathbf{Z}_c$ FOR 3-PHASE" SWLS WHEN $C^*_{w1w2}$ =678 nF IS INSTALLED AT THE RECEIVING END OF SWL

| 120 km-SWL with galvanized steel SW-Φ=10.5mm - $R_{40°}$=2.53 Ω/km *) | | | 120 km SWL with ACSR SW– Φ=12.25 mm - $R_{40°}$=0.65 Ω/km **) | | |
|---|---|---|---|---|---|
| $C_o$/ $C_m$ [nF/km] | $P_L$+j$Q_L$ [kW+jkvar] | $\mathbf{Z}_c$ [Ω] | $C_o$/ $C_m$ [nF/km] | $P_L$+j$Q_L$ [kW+jkvar] | $\mathbf{Z}_c$ [Ω] |
| Not cons. | – | **291.8+j22.6** | 0 / 0 | - | **66.6+j22.6** |
| 6.156/0.504 | 0+j0 | 282.5+j38.6 | 6.156/0.504 | 0+j0 | 66.5+j38.6 |
| " | 100+j50 | 279.9+j38.1 | " | 200+j100 | 61.9+j39.8 |
| " | 200+j100 | 277.3+j36.8 | " | 600+j300 | 54.1+j33.1 |
| " | 500+j250 | 272.9+j29.2 | " | 1000+j500 | 54.6+j26.5 |
| - | - | - | " | 2000+j800 | 59.6+j22.7 |

*) $\mathbf{z}_p$=2.53+j 0.806 [Ω/km]; $\mathbf{z}_m$=0.049+j 0.309 [Ω/km]
**)$\mathbf{z}_p$=0.65+j 0.806 [Ω/km]; $\mathbf{z}_m$=0.049+j 0.309 [Ω/km]

Tab. I shows that $\mathbf{Z}_c$ is little affected by the load variation. This result suggests to install the compensating capacitance(s) at the line end or, in case of several load supplied along the SWL, in the electric center of the loads, thus balancing the currents flowing along the SWs. This solution presents the further advantage of reducing the voltage drops in the SW conductors caused by the current drawn by loads.

## 3. A GENERAL APPROACH FOR CALCULATING THE COMPENSATING IMPEDANCE AND CAPACITANCE

The procedures described in sections 2.2, 2.3 and 2.4 can be applied with relatively simple hand calculation, also in the cases of several load supplied by the SWL. Nevertheless they do not consider the magnetic coupling of the SWL with the HV phase conductors and take into account only approximately the electric coupling.

To calculate accurately $\mathbf{Z}_c$ and the compensating capacitance, $C_{w1w2}$, that make nil the negative sequence voltage at a specified section of the SWL, the following general approach can be applied.

The system formed by the HV circuit and the "3-Phase" SWL (Fig.3.1) can be represented in the phase coordinate domain by its admittance matrix [$\mathbf{Y}$].

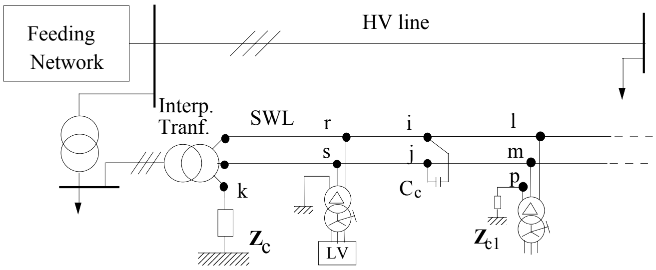



Fig. 3.1- Single line diagram of the "3-Phase" SWS

The SWS is supplied by only one source and the loads can be modelled as constant impedances. The following nodal network equations can therefore be written:

$$[\mathbf{I}] = [\mathbf{Y}]\,[\mathbf{E}] = \begin{bmatrix}[\mathbf{I}_g]\\ [0]\end{bmatrix} = \begin{bmatrix}[\mathbf{Y}_{gg}] & [\mathbf{Y}_{gL}]\\ [\mathbf{Y}_{Lg}] & [\mathbf{Y}_{LL}]\end{bmatrix}\begin{bmatrix}[\mathbf{E}_g]\\ [\mathbf{E}_L]\end{bmatrix}, \qquad (3.1)$$

where: [$\mathbf{I}_g$] and [$\mathbf{E}_g$] are the vectors of nodal currents and voltages of the 3-phase source; [$\mathbf{E}_L$] is the voltage vector of the load busses which have nil nodal currents as each load impedance is included in the system admittance matrix.

### *3.1. Calculation of the compensating capacitance*

The task is the calculation of the admittance, $\mathbf{Y}_s$, that, connected between the nodes i and j of the SWs, makes nil the negative sequence voltage at the nodes r-s-ground of the SWL. This occurs if the following conditions are complied with:

a) In case of MV/LV distribution transformers with one terminal directly grounded (Fig.3.1):

$$\mathbf{E}_r = e^{\pm j60^\circ}\,\mathbf{E}_s \qquad (3.1.1)$$

b) In case of a MV/LV distribution transformer with one terminal grounded via an impedance ($\mathbf{Z}_{c1}$ in Fig.3.1).

$$\mathbf{E}_l - \mathbf{E}_p = e^{\pm j60^\circ}\,(\mathbf{E}_m - \mathbf{E}_p) \qquad (3.1.1')$$

The concept is to take into account the change of the mutual admittance, $\mathbf{Y}_{ij}$, of nodes i and j, where the compensation admittance $\mathbf{Y}_s$ is connected, by evidencing the auxiliary unknown $A_i=\mathbf{Y}_s(\mathbf{E}_i-\mathbf{E}_j)$. In this case from system (3.1), by eliminating the source nodes at fixed voltage, and adding the condition (3.1.1), the following equations are obtained:

$$\begin{bmatrix}\mathbf{I}_4\\ \cdots\\ \mathbf{I}_r\\ \mathbf{I}_s\\ \cdots\\ \mathbf{I}_i\\ \mathbf{I}_j\\ \cdots\\ \mathbf{I}_n\\ 0\end{bmatrix} = \begin{bmatrix}\mathbf{Y}_{44} & .. & \mathbf{Y}_{4r} & \mathbf{Y}_{4s} & .. & \mathbf{Y}_{4i} & \mathbf{Y}_{4j} & .. & \mathbf{Y}_{4n} & 0\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & ..\\ \mathbf{Y}_{r4} & .. & \mathbf{Y}_{rr} & \mathbf{Y}_{rs} & .. & \mathbf{Y}_{ri} & \mathbf{Y}_{rj} & .. & \mathbf{Y}_{rn} & 0\\ \mathbf{Y}_{s4} & . & \mathbf{Y}_{sr} & \mathbf{Y}_{ss} & .. & \mathbf{Y}_{si} & \mathbf{Y}_{sj} & .. & \mathbf{Y}_{sn} & 0\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & ..\\ \mathbf{Y}_{i4} & .. & \mathbf{Y}_{ir} & \mathbf{Y}_{is} & .. & \mathbf{Y}_{ii} & \mathbf{Y}_{ij} & .. & \mathbf{Y}_{in} & 1\\ \mathbf{Y}_{j4} & .. & \mathbf{Y}_{jr} & \mathbf{Y}_{js} & .. & \mathbf{Y}_{ji} & \mathbf{Y}_{jj} & .. & \mathbf{Y}_{jn} & -1\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & 0\\ \mathbf{Y}_{n4} & .. & \mathbf{Y}_{nr} & \mathbf{Y}_{ns} & .. & \mathbf{Y}_{ni} & \mathbf{Y}_{nj} & .. & \mathbf{Y}_{nn} & 0\\ 0 & 0 & 1 & -e^{j\pm 60^\circ} & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\mathbf{E}_4\\ \cdots\\ \mathbf{E}_r\\ \mathbf{E}_s\\ \cdots\\ \mathbf{E}_i\\ \mathbf{E}_j\\ \cdots\\ \mathbf{E}_n\\ [\mathbf{Y}_s(\mathbf{E}_i-\mathbf{E}_J)]\end{bmatrix}$$

(3.1.2)

where all the unknowns are load node voltages and $\mathbf{A}_i=[\mathbf{Y}_s(\mathbf{E}_i-\mathbf{E}_j)]$. Solution of system (3.1.2) yields the following equation for calculation of $\mathbf{Y}$s:

$$\mathbf{Y}_s = \frac{[\mathbf{Y}_s(\mathbf{E}_i-\mathbf{E}_J)]}{\mathbf{E}_i-\mathbf{E}_J} \qquad (3.1.3)$$

If the MV/LV distribution transformer has a terminal grounded via an impedance $\mathbf{Z}_{c1}$, the last equation of (3.1.2) must the replaced by (3.1.1').

### *3.2. Calculation of the compensating impedance $\mathbf{Z}_c$*

The compensating impedance, $\mathbf{Z}_c$, which connected at the grounded terminal of the interposing transformer makes nil the negative sequence voltage at nodes r-s-ground of SWL, can be calculated by introducing the auxiliary unknown $\mathbf{A}_1=\mathbf{E}_k/\mathbf{Z}_c$ and setting the same conditions (3.1.1) or (3.1.1').

In this case the following equations are arrived at:

$$\begin{bmatrix}\mathbf{I}_4\\ \cdots\\ \mathbf{I}_r\\ \mathbf{I}_s\\ \cdots\\ \cdots\\ \mathbf{I}_k\\ \cdots\\ \mathbf{I}_n\\ 0\end{bmatrix} = \begin{bmatrix}\mathbf{Y}_{44} & .. & \mathbf{Y}_{4r} & \mathbf{Y}_{4s} & .. & \mathbf{Y}_{4k} & .. & .. & \mathbf{Y}_{4n} & 0\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & ..\\ \mathbf{Y}_{r4} & .. & \mathbf{Y}_{rr} & \mathbf{Y}_{rs} & .. & \mathbf{Y}_{rk} & .. & .. & \mathbf{Y}_{rn} & 0\\ \mathbf{Y}_{s4} & . & \mathbf{Y}_{sr} & \mathbf{Y}_{ss} & .. & \mathbf{Y}_{sk} & .. & .. & \mathbf{Y}_{sn} & 0\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & ..\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & ..\\ \mathbf{Y}_{k4} & .. & \mathbf{Y}_{kr} & \mathbf{Y}_{ks} & .. & \mathbf{Y}_{kk} & .. & .. & \mathbf{Y}_{kn} & 1\\ .. & .. & .. & .. & .. & .. & .. & .. & .. & 0\\ \mathbf{Y}_{n4} & .. & \mathbf{Y}_{nr} & \mathbf{Y}_{ns} & .. & \mathbf{Y}_{nk} & .. & .. & \mathbf{Y}_{nn} & 0\\ 0 & 0 & 1 & -e^{j\pm 60^\circ} & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\mathbf{E}_4\\ \cdots\\ \mathbf{E}_r\\ \mathbf{E}_s\\ \cdots\\ \mathbf{E}_i\\ \mathbf{E}_j\\ \cdots\\ \mathbf{E}_n\\ [\mathbf{E}_k/\mathbf{Z}_c]\end{bmatrix}$$

(3.2.1)

then $\mathbf{Z}_c$ can be easily calculated with the following formula:

$$\mathbf{Z}_c = \frac{\mathbf{E}_k}{[\mathbf{E}_k/\mathbf{Z}_c]} \qquad (3.2.2)$$

In some cases, where very long SWLs supply many intermediate loads, in order to contain in the specified range the negative sequence voltages along the SWL, in addition to the grounding impedance $\mathbf{Z}_c$, an appropriate $\mathbf{Z}_{c1}$ (R,L circuit) may be used to connect to ground a MV terminal of a distribution transformer (Fig.3.1). In this case $\mathbf{Z}_{c1}$ is calculated to make nil the negative sequence voltage at its installation point, by imposing another condition (3.1.1') and using the auxiliary unknown $\mathbf{E}_p/\mathbf{Z}_{c1}$. The solution of equations allows to calculate simultaneously $\mathbf{Z}_c$ and $\mathbf{Z}_{c1}$. It is noteworthy that the impedance $\mathbf{Z}_{c1}$ reduces only the negative sequence voltage of the node where it is installed.

### *3.3. Proposed automatic procedure*

In order to compensate the unbalance of the SWL with a grounding impedance, $\mathbf{Z}_c$ (R, L circuit), and shunt capacitance between SWs, $C_{w1w2}$, the following procedure can be applied:

a) Choose the installation point of the compensating capacitance: at receiving end of the SWL or at the electrical center of the loads.
b) By considering the SWL at no-load, calculate, according to the procedure (3.1), the compensating capacitance $C_{w1w2}$, i.e. the imaginary part of $\mathbf{Y}_c$.
c) After having connected $C_{w1w2}$ calculated at step b), evaluate the compensating impedance $\mathbf{Z}_c$ (ref. par. 3.2);
d) Ground the terminal of interposing transformer with the calculated $\mathbf{Z}_c$ at step c), repeat step b) to find once again $C_{ww}$.
e) With final values of the $\mathbf{Z}_c$ and $C_{w1w2}$, perform the study of the SWS behaviour, under SWL variable loads and with different load conditions of the HV line, to check that the negative sequence voltages at the consumers' terminals are generally lower than 1%, in no case larger than 2%. On the other hand, if the specified limit of the negative sequence voltage is exceeded for a specific load, the addition of a local R, L grounding circuit can be considered.

The above procedure has been implemented by the authors in an automatic program and an application to some "3-Phase" SWSs planned in Western Africa is reported in the next paragraph.

## 4. An application of the "3-phase" SWSs planned in Western Africa

The procedure described in Par.3.3 has been applied for some "3-Phase" SWSs planned in Western Africa, to be implemented in a 225kV-50Hz-338 km long transmission line with an intermediate substation at 134 km from the sending end, as shown in Fig 4.1. The 225kV line is equipped with AAAC conductors with Φ=31.04 mm, $R_{20°C}$=0.0583 Ω/km, whereas the SWs are ACSR conductors with Φ=10.02 mm, $R_{20°C}$=0.58 Ω/km.

Fig. 4.2 shows the outline of the 225 kV line tower head.

The four SWLs will supply 17 villages/towns along the line route.

One of the SWSs originates from the 33 kV busbar of the 225/33 kV sending end substation through a 2MVA interposing transformer. The second and the third SWSs, which originate from the intermediate substation, are supplied by the 34.5 kV delta winding of a 3-phase 3-winding 225/33/34.5 kV transformer and are 45 km and 96 km long respectively.

The fourth SWL, supplied by the 34.5 kV delta winding of a 3-phase 3-winding 90/33/34.5 kV transformer installed at the receiving end substation of the 225 kV line, is 83 km long.

Tab.II shows the values of the balancing capacitances and compensating impedances obtained by applying the proposed procedure and located as shown in Fig.4.1.

Tab. II – Compensating impedance $\mathbf{Z}_C$ and balancing capacitances for the SWSs of Fig.4.1 calculate by the proposed procedure

| '3-Phase' SW Scheme | Balancing capacitances $C_{ww}/C_{wi,Gr}$ [kVAR] | Compensating impedance $\mathbf{Z}_c$ [Ω] |
|---|---|---|
| 1 | 150/2x50 | 0 |
| 2 | 150/2x50 | 16+ j6 |
| 3 | 200/2x100 | |
| 4 | 70/2x50 | 33+j 7 |

In Table III are reported the positive-sequence voltages, $V_1$ and v1, the negative-sequence voltage $V_2$ and the voltage unbalance, $V_2=100V_2/V_1$ and $v_2=100v_2/v_1$, along the 34.5kV SWL and at the LV terminals of distribution transformers, respectively, at full load operation of the SWSs .

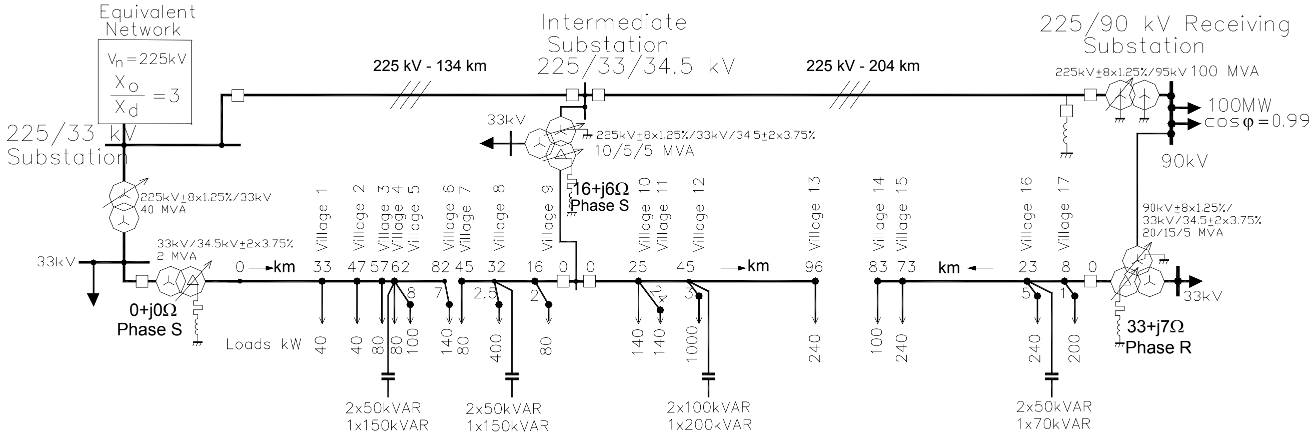


Fig. 4.1- 225kV-34.5kV-50 Hz "3-Phase" SWSs to be implemented in Western Africa

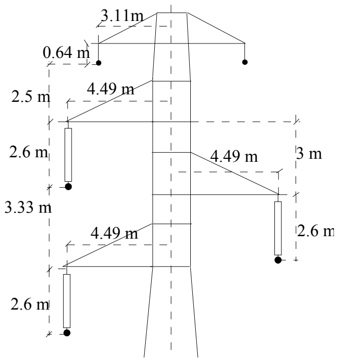



Fig. 4.2 – Outline of 225 kV transmission line tower head

The voltage unbalances at consumer terminals are always lower than 1%, in most cases lower than 0.5 %.

The performed analysis at no load and at 50% of the SWS load, with the 225 kV line carrying 0 MW and 59 MW, have also pointed out that the voltage unbalances are always not greater than 0.7%, in most cases lower than 0.5%.

TABLE- III- POSITIVE SEQUENCE VOLTAGE AND VOLTAGE UNBALANCE ALONG THE SHIELD WIRES AND AT LV OF DISTRIBUTION TRANSFORMERS

| Active power flow on 225 kV circuit: 112 MW SWL operated at forecast loads | | | | | | | |
|---|---|---|---|---|---|---|---|
| Village / Town | Load [kW] | Positive sequence voltage, $V_1$, and voltage unbalance $V_2$=100$V_2$/$V_1$ along the 34.5kV shield wire line | | | Positive sequence voltage, $v_1$, and voltage unbalance $v_2$=100$v_2$/$v_1$ on LV side of MV/LV transformers | | |
| | | $V_1$ [%] | $V_1$ [$kV_{rms}$] | $V_2$ [%] | $v_1$ [%] | $v_1$ [$V_{rms}$] | $v_2$ [%] |
| 1 | 40 | 101.37 | 34.97 | 0.58 | 101.23 | 233.78 | 0.60 |
| 2 | 40 | 101.24 | 34.93 | 0.47 | 101.09 | 233.45 | 0.49 |
| 3 | 80 | 101.15 | 34.90 | 0.45 | 101.19 | 233.69 | 0.46 |
| 4 | 80 | 101.11 | 34.88 | 0.47 | 101.15 | 233.59 | 0.48 |
| 5 | 100 | 101.07 | 34.87 | 0.49 | 101.61 | 234.66 | 0.50 |
| 6 | 140 | 101.07 | 34.87 | 0.34 | 100.75 | 232.68 | 0.35 |
| Total | 480 | | | | | | |
| 7 | 80 | 102.21 | 35.26 | 0.40 | 99.59 | 229.99 | 0.41 |
| 8 | 400 | 102.13 | 35.23 | 0.13 | 99.51 | 229.81 | 0.13 |
| 9 | 80 | 102.30 | 35.29 | 0.29 | 99.68 | 230.21 | 0.30 |
| 10 | 140 | 101.02 | 34.85 | 0.89 | 101.39 | 234.15 | 0.91 |
| 11 | 140 | 100.88 | 34.80 | 0.89 | 101.25 | 233.82 | 0.91 |
| 12 | 1000 | 99.98 | 34.49 | 0.65 | 99.70 | 230.25 | 0.67 |
| 13 | 240 | 99.95 | 34.48 | 0.57 | 99.95 | 230.83 | 0.58 |
| Total | 2080 | | | | | | |
| 14 | 100 | 102.64 | 35.41 | 0.35 | 100.54 | 232.19 | 0.36 |
| 15 | 240 | 102.63 | 35.41 | 0.19 | 100.05 | 231.05 | 0.19 |
| 16 | 240 | 103.11 | 35.57 | 0.35 | 100.53 | 232.17 | 0.36 |
| 17 | 200 | 103.32 | 35.64 | 0.46 | 100.61 | 232.34 | 0.47 |
| Total | 780 | | | | | | |

## 5. CONCLUSION

The paper has firstly presented a short description of the unconventional low cost "3-Phase" SWS for electrification of towns and villages located along the route of the HV transmission lines of developing countries.

As the "3-Phase" Shield Wire Scheme is an inherently unsymmetrical 3-phase system, the paper deals with the methods to reduce negative sequence voltage at the consumer terminals.

The authors have concentrated their attention on the method using simple static components like balancing capacitances between shield wires and a compensating impedance in the earth path return of the current.

Approximate but simple formula are presented for manual calculation of above capacitances and impedance.

The paper proposes a precise general procedure for the calculation of the compensating capacitances and impedance.

The procedure, implemented in an automatic program developed by the authors, allows a quick optimization of the symmetrization of the "3-Phase" SWS.

The application of the method to several "3-Phase" SWSs under construction in Western Africa has confirmed its robustness and reliability.

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## 7. BIOGRAPHIES

**Francesco Iliceto** (SM '71; F '85) was born in Padua (Italy) in 1932. He received a doctor degree (Hons) in Electrical Engineering in 1956 from Padua University. From 1956 to 1965 he worked with two power utilities, on the design and construction of steam thermal power plants (Milan, Italy), of the HVDC link between Sardinia and the Italian mainland and HVAC transmission (Rome, Italy). In 1965 he received the Professor degree of Power System Analysis from the Ministry of Education (Rome, Italy) and joined the Faculty of Engineering of Rome University, where he is currently Ordinarius Professor and Head of the Electrical Engineering Department. In 1966 and 1971 he was visiting professor in Sweden and in the USA.

Since 1968 he has been consultant to the Turkish Electricity Authority. In this capacity, he contributed substantially to the planning, design and operation of the EHV and HV systems of Turkey and interconnections with neighbouring countries, up to the present stage, and to research.

Since 1977 he has been consultant to the Volta River Authority for planning, design and operations of Ghana's national power system and extensive rural electrification.

At the request of the World Bank, of the European Investment Bank, the Inter American Development Bank, the Asian Development Bank and of National Electricity Corporations, he has served as technical consultant in several other countries (Zaire, Portugal, Togo, Benin, Canada, Egypt, Burkina Faso, Northern Cyprus, Sierra Leone, Pakistan, India, Costa Rica, Panama, Honduras, Nicaragua, Brazil, Laos, Senegal, Mali, Mauritania, Ivory Coast, Germany, Ethiopia, Finland, China, Mozambique).

His main fields of interest are EHVAC and EHVDC transmission, power system analysis, power system planning and design, rural electrification with a new low cost technology. He is author or co-author of more than 100 technical papers and tutorial books (5 volumes). He has served as chairman or member of various national and international Technical Committees.

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**Stefano Lauria** (M' 99) was born in Rome, Italy, in 1969. He received the doctor degree and the Ph.D. in electrical engineering from the University of Rome "La Sapienza" in 1996 and in 2001, respectively. In 2000 he joined the Department of Electrical Engineering of University of Rome "La Sapienza" as a Researcher. His main research interests are in power systems analysis, distributed generation, power quality and electromagnetic transients. He is a member of AEI (Italian Electrical Association) and a registered professional engineer in Italy.

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