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NEW CONCEPTS ON MV DISTRIBUTION FROM INSULATED SHIELD WIRES OF HV LINES

OPERATION RESULTS OF AN EXPERIMENTAL SYSTEM AND APPLICATIONS IN GHANA

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Abstract

The paper deals with the problem of the most cost effective power supply to the villages and communities of developing countries, located along the route of HV lines, up to 100 km distant from the HV/MV transformer stations.

In the first part of the paper a novel solution is presented. This consists of: (i) insulation of the shield wire(s) of an HV line, and wire(s) energization at MV (10 to 34.5 kV) from the closest transformer station; (ii) supply of villages along the line route by means of standard MV/LV distribution transformers connected between the shield wire(s) and ground . Four different schemes are presented, two of them suitable for single-phase distribution, the others for 3-phase supply. The behaviour in steady-state and in transient conditions is analyzed.

The second part of the paper reports the positive results of 33 months of operation of an experimental scheme tested in Ghana for supply of single-phase and 3-phase loads from the two insulated shield wires of a 161 kV line.

Finally the paper describes the distribution schemes along 407 km of new 161 kV lines in Northern Ghana, where the novel solution is applied to supply power to both domestic and industrial loads in 12 small towns with a design aggregate load of 5000 kW

Keywords: unconventional distribution schemes; shield wire; insulation; ground return; line balancing.

1. Introduction

In many cases new HV lines built for the supply of power to the major towns of developing regions, are routed not far from highways, along which there are several villages without electricity. Local inhabitants, therefore, expect to benefit from the supply of power from the HV lines. The problem, however, is how to spill small amounts of power (tens or a few hundred of kW) from the HV lines at reasonable cost.

Several possible solutions have been considered for Northern Ghana where the extension of the 161 kV interconnected transmission network is under construction. It is planned to use the rated voltage of 34.5 kV for subtransmission and distribution in areas with low load density, and 11 kV for distribution in the major towns. The 34.5 kV systems are operated with the neutral solidly grounded or grounded through a grounding transformer, depending on fault current level; the configuration is radial. Distance of villages from the closest planned 161 kV transformer station may be as much as 50-125 km, the planned 161 kV stations being 100-250 km apart.

The following solutions have proven unviable:

- An MV line on the same right-of-way as the HV line cannot be economically justified, if the aggregate load is too small in comparison with distance.
  An MV 3-phase circuit supported by the same towers as the HV line, poses technical problems, the small conductors and phase separation of the MV line being unsuitable for the long spans of an HV line carrying big conductors.
- Supply of villages by means of capacitively induced voltage on an insulated conductor or shield wire of a stretch of HV line. This requires ground return of current and allows to spill only small amounts of power (say, 0.5 kW/km of 161 kV single-circuit line). To keep the supply voltage reasonably constant with variable load, sophisticated equipments are needed in each village (e.g. thyristor controlled reactors). A similar scheme where a capacitor bank connected to one phase of the HV lines is used instead of an insulated wire, is affected by the same drawbacks.
- Use of inductive type potential transformers connected between phase and ground, without protection on the HV side, operating at their thermal capacity. The power output is too small (5-6 kW per single-phase PT) and cost per kW too high.

A novel solution (first proposed by one of the authors in ref. [1]) is presented. It consists of:

- Insulation of the shield wire(s) of an HV line and energization at MV from the closest transformer station.
- Supply of the villages along the HV line by means of fused single-phase or 3-phase transformers, depending on the scheme chosen and on the nature of the load to be supplied (see Fig. 1).

For the ease of reference, this paper also includes some concepts and theoretical analyses presented earlier at a symposium in Africa [2].

The overruling criterion has been to propose solutions that require only conventional distribution equipments, devoid of power electronic devices, to provide a reliable service with simple and ordinary operational methods.

2. Description of the proposed schemes

The proposed schemes are shown in Fig. 1. Schemes A and B are suitable for single-phase distribution; Schemes C and D require two insulated shield wires and can supply also 3-phase loads. The Schemes have been developed from a combination of two different techniques applied independently in the past:

- Use of insulated shield wires in the long EHV lines carrying a large amount of power, to reduce Joule losses caused by the currents induced in the steel or alumoweld wires (U.S.A., USSR, Turkey, etc). In some cases, the insulated shield wires have been used for power line carrier communications.
- Application of single-phase single-wire MV distribution lines with ground return of current, to supply small remote loads, occasionally at distances of over 100km from the HV station. Canada has a long experience with this scheme, while there have also been applications in other countries (Australia, New Zealand, USSR).

The ground return of the current (Schemes A, C and D in Fig. 1) is the most economic concept where the soil has low or medium resistivity, as the cost of grounding electrodes is small for the current flow of interest. In Scheme A, referred to later in the text as "Single-Phase Ground-Return", the ground-return current is 1A for every 20kVA of load at $34.5/\sqrt{3}$ kV.

The earth return path has a resistance much lower than a shield wire: it is calculated at $10^{-4}\ \pi^{2} f$ (ohm/km), i.e. 0.05 ohm/km at 50 Hz, equivalent to a 570 sqmm aluminium cable.

The ground return Schemes A and C are feasible if the MV feeding system has the neutral solidly grounded, or grounded through either a grounding transformer or a neutral reactor of low impedance. The metallic return Scheme B and ground return Scheme D, can be applied also where the supply MV network is operated with ungrounded neutral or high-impedance grounding.

In Scheme B, referred to ahead as "Single-Phase Metallic Return" the earth-return of the current is avoided. It is feasible if the HV line has two insulated shield wires from which the MV/LV distribution transformers are branched.

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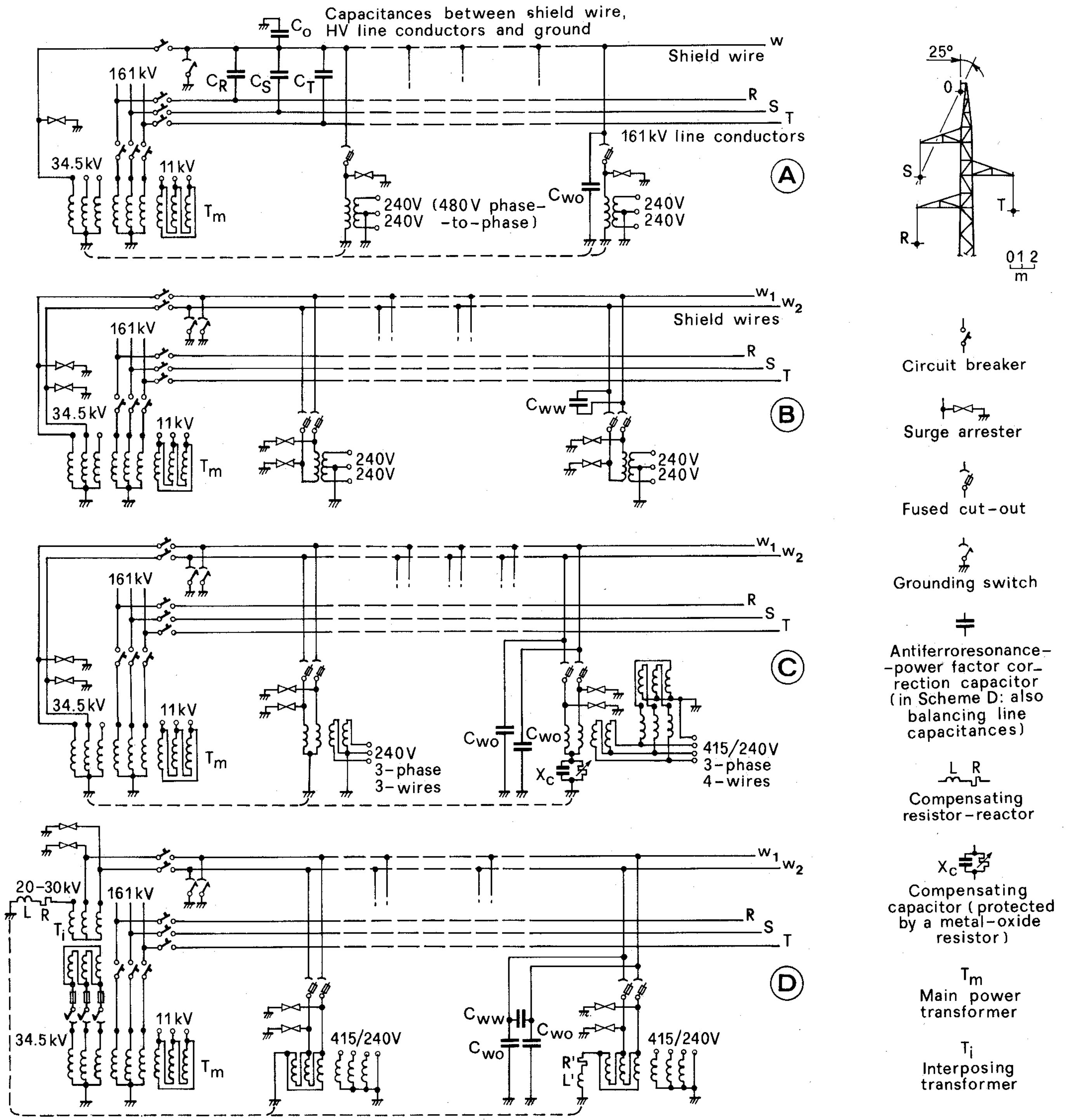


Fig. 1 - Proposed schemes for use of insulated shield wires as MV distribution lines: A = Single-Phase Ground-Return; B = Single-Phase Metallic-Return; C = "V" Scheme; D = "3-Phase" Scheme. Top right: Conductor arrangement of 161 kV normal suspension tower for Scheme A.

Scheme C, referred to as "V" Scheme, requires two insulated shield wires energized from two phases of a grounded neutral MV network. In the distribution stations, there are two single phase MV/LV transformers branched from each shield wire and ground. The secondary windings are open-delta connected ("V" connection), thus providing at no-load, a symmetrical 3-phase source that makes possible the supply of a small amount of 3-phase load in addition to single-phase loads.

Scheme D is referred to as "3-Phase" Scheme. The concept here proposed is to make symmetrical the line formed by the two shield wires and the earth path, with simple compensating components as described in par. 5: a series resistor-reactor in the earth path and a capacitor branched between the two wires (L-R and C_{ww} in Fig. 1-D). This unconventional line is energized with 3-phase symmetrical voltages by means of an interposing transformer (T_i in Fig. 1-D), one terminal phase of which is grounded. Depending on the characteristics of the load, single-phase transformers or 3-phase transformers with one primary-terminal grounded, are connected along the line. Scheme D can supply 100% 3-phase load.

Single-phase distribution with conventional North American equipments (Schemes A and B) is the simplest and cheapest solution for the villages non provided with any electricity supply.

In Northern Ghana there are a few small towns along the new 161 kV lines with existing 3-phase distribution networks, and two isolated industrial plants with 3-phase motors, supplied by Diesel generators. Schemes C and D are being applied in these cases.

3. Lightning performance of HV lines with insulated shield wire(s)

Lightning performance should be checked for the HV circuit and the MV insulated shield wire circuit. It is first necessary to prove that the insulation of the shield wires does not erode the shielding efficiency and does not cause an increase of the back-flashover rate of the HV circuit.

As regards the shield wire distribution circuit, it is necessary to compare the lightning and insulation performance with those of a conventional distribution line of the same rated voltage.

It is known from the application of insulated shield wires in EHV lines that the protection capability remains practically unchanged when arcing horns with a small gap (10 to 50 mm) are mounted in each suspension and tension insulator supporting the shield wires. The wires are usually grounded at one point of each short insulated portion, or several transpositions of two long insulated wires are made, to limit the induced overvoltages. The case under consideration differs from the normal practice as follows:

- the shield wire is energized at 10 to 30 kVrms with respect to ground, on a length up to 100 km;
- insulation should be adequate to withstand the switching overvoltages as discussed later in the paper: arcing horns should have a gap of 100 to 300 mm, the gap depending on the operation voltage.

The potential of the wire is very small in comparison with the potential of a lightning leader approaching the ground. It can thus be expected that the shielding efficiency will not be reduced.

When lightning strikes a shield wire or a tower, the closest protective gaps of the shield wire will sparkover and ground the wire through the arc. The shield wires perform as if they were grounded and thus raise the lightning current level liable to cause back-flashover of the HV circuit. As the wire is energized in the transformer station, the gap sparkover will initiate a short circuit to ground. Then the protection relay will trip off the shield wire line, unless the power arc selfextinguishes quickly, as may occur if the fault current is small. This behaviour should not be a concern because it is typical of all conventional MV lines.

After the wire disconnection a secondary arc current may flow in the ignited gap. This current is maintained by the capacitive and electromagnetic induction from the HV circuit. Analysis shows that maximum secondary current occurs in conjunction with a single-phase-to-ground fault on the HV circuit (caused by a back-flashover or lightning stroke to a conductor), or a one-open phase condition, due to voltage and current imbalances.

The secondary arc current on insulator gaps must be extinguished quickly, to prevent damage to the equipment and to allow power supply restoration from shield wires. Experimental laboratory and field investigations (see par. 4 and 10) have shown that self-extinction of the secondary arc does occur in the insulated shield wires that are up to at least 100 km long.

The height above ground of the insulated shield wires is greater than that of the conductors of a conventional MV line. This fact may cause an increase of the lightning flashover rate, for an assigned line insulation level, due to:

(i) the direct lightning strokes, owing to the larger exposed swath of the line;

(ii) the overvoltages induced by lightning striking the ground close to the line, the overvoltage amplitude being approximately proportional to the conductor height above ground.

Volta River Authority (VRA) typical 161 kV lines are designed with conductors in triangular configuration (see Fig. 3a) and average span of 385 m; the average shield wire height is about 20 m above ground. The mean height of the upper conductor of a 34.5 kV line with average span of 225 m, is about 10 m.

Calculations show that a height increase from 10 m to 20 m causes an increase from 20% to 40% in the flashover rate due to lightning striking the line directly (item (i)), with current intensities in the range of 10 kA to 100 kA.

Concerning the lightning induced overvoltages (item (ii)), calculations have been performed with the method reported in ref. [3], for conductors insulated with a BIL of 200 kV, typical of a 34.5 kV line. Let us assume that 5% of lightning occurrences exceed 100 kA, and an average front duration of 5 μs. The calculated flashover rate due to induced overvoltages increases by 1-2 per 100 km of line per year, when the conductor height is raised from 10 m to 20 m, and a keraunic activity of 4 strokes per square km per year is assumed, as estimated for Ghana.

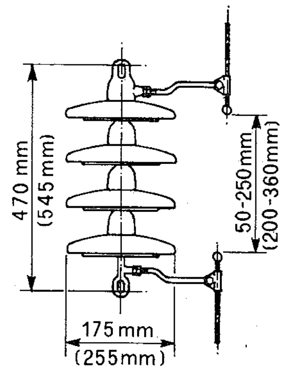
The estimate of risk of insulation failure should also take account of the fact that the high position of the shield wires – installed by design above the HV conductors – reduces insulation failures which otherwise can be caused by contacts with trees and overgrown brush or foreign objects, and insulator bridging by animals that climb the towers. These faults may contribute considerably to the outage rate of MV lines, and are frequently of longer duration (non self-extinguishing). This explains why in the experimental shield wire line in Ghana (see par. 10) the recorded outage rate is much lower than that of the conventional 34.5 kV lines in the same area, in spite of the fact that the average height of the shield wires is 28 m (see tower scheme in Fig. 9).

4. Selfextinction of arcs across insulator rod gaps

In the case of Scheme A (Fig. 1-A), with 5 distribution transformers each rated at 167 kVA and a shield wire length of up to 100 km, a secondary arc current on the wire of 3-4 A has been calculated during an asymmetrical short circuit on the HV line. When the HV line returns to normal 3-phase operation, the secondary arc current drops to less than 2 A. Normally, lightning strokes which hit the shield wire should not cause back-flashover on the HV conductors, and the secondary arc current will be less than 2 A from the beginning. The steady state recovery voltage of shield wire after arc extinction is less than 15 kV rms.

With the above values of arc current and recovery voltage, the rod-gap selfextinction is expected to occur in less than 1 s after the shield wire breaker has opened, if there is no fault on the HV line, or shortly after the successful reclosure or final disconnection of the HV line, if this is also affected by a fault. The shield wire should be re-energized, automatically or manually, as a normal MV line. In the rare event of persistent secondary arcing on the shield wire, the grounding switch should be closed in the sending station.

Laboratory tests have been carried out at Rome University with an artificial circuit, to check the arc selfextinction capability of the rod gaps. The tested insulators (Fig. 2) are composed of four toughened glass 175 mm diameter cap and pin insulators arranged in a rigid string to keep the gap spacing constant, which can be set in the range of 5 to 25 cm. To form a rigid string, the cap of one disc and the pin of the adjacent disc are made of one piece.



– Disc size [mm]	175	255
– Dry impulse withstand+) [kVcrest]	210	260
– Wet 1-minute 50 Hz withstand+) [kVrms]	85	130
– Creepage distance	760	1200
– Electromechanical failing load [kN]	⩾40	⩾40

+) Without arcing horns

Fig. 2 - Rigid string toughened glass insulator string applied in the experimental 34.5 kV Cape Coast-Kissi line (175 mm discs) and in the insulated shield wire lines in Northern Ghana (255 mm discs).

The test circuit to check the secondary arc extinction consisted of two series connected capacitors supplied by a transformer, the insulator string being connected in parallel with one capacitor to simulate the recovery voltage. Arc currents up to 6 A rms and recovery voltages up to 19 kVrms were generated. The results of the test are summarized as follows:

- Vertical string: selfextinction occurred in all the tests (at least 10 per case) within the following limits:

arc current	recovery voltage	gap spacing
⩽3 Arms	⩽15 kVrms	10-20 cm
⩽6 Arms	⩽12.5 kVrms	10-20 cm

- Horizontal string: selfextinction occurred in all the tests (at least 10 per case) up to the highest currents and recovery voltage simulated (6 Arms and 19 kVrms) and any gap spacing in the range of 5 to 20 cm.

The Fig. 2 insulator assemblies have been applied in the distribution schemes from the shield wires in Ghana.

5. Analysis of the Schemes for 3-phase load supply

Let us consider a 161 kV line of standard VRA design, with two shield wires. The wires are insulated ACSR cable; conductor configuration and distances are indicated in Fig. 3a. The equivalent circuit of 1 km of the line formed by the shield wires and the ground return path is shown in Fig. 3b; the influence of the 161 kV main conductors has been neglected. The ground-return path has a series reactance of 0.35 ohm/km, close to the reactance of the shield wires; the resistance is very small in comparison with that of the insulated shield wires.

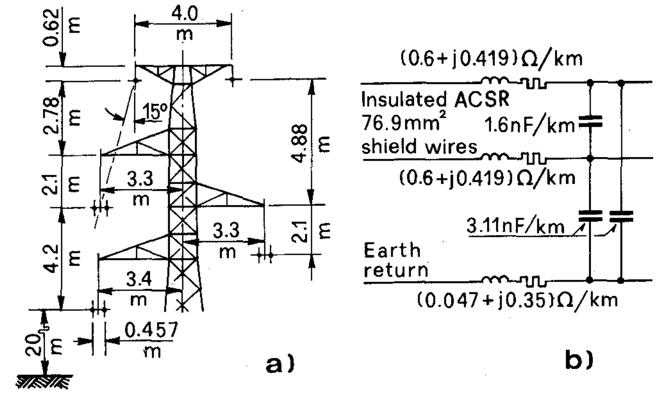


Fig. 3 - a) Conductor arrangement in the 161kV twin bundle conductor line Techiman-Tamale; b) Simplified equivalent circuit, per unit length of line, of the shield wire line.

The circuit is useful for the physical explanation of the phenomena that occur when the shield wires are energized with the "V" Scheme or with the "3-Phase" Scheme.

"V"-Scheme *(for single-phase and small 3-phase loads)*

The 3-phase load that can be supplied from the "V" Scheme (Fig. 1-C) via the secondary windings of "V" connected transformers is limited by the negative-sequence voltage, V_2, that causes overheating of the induction motors. In Europe, a generally accepted limit for V_2 in continuous operation is 2%. This causes a negative-sequence current circulation of 10 to 15% of motor rated current.

An approach to limit the 3-phase supply voltage imbalance would be to identify the most efficient balancing circuits with mathematical simulations. The result would probably be rather complex circuits, not suitable in rural distribution. The approach applied consists in the choice of the most simple balancing circuits and measures, and in the computer analysis of their effectiveness in the practical applications.

It can be assumed that the shield wires are energized from a symmetrical system, i.e. with phase-to-ground voltages of equal rms values and 120° phase shift. If the currents in the shield wires along the line have the same intensity and an equal phase shift with reference to the respective phase-to-ground voltage vector, the voltage drop vectors in the series impedance of each wire have the same rms value and 120° phase shift. Under these conditions, if the ground return impedance were nil, the two shield wire-to-ground voltages would maintain the same rms value and a constant phase shift of 120° at any point along the line, as the applied voltages at the sending end. In other words, if the ground return impedance is rendered nil by some means, and the loads are split at any station along the line into two equal single-phase loads branched between each shield wire and ground, the 3-phase voltages of the secondary windings of no-load "V" connected distribution transformers (see Fig. 1-C) remain symmetrical, regardless of the magnitude of single-phase loads supplied by the shield wires.

The capacitance of the wires to ground (see Fig. 3b) and of any couple of equal capacitors connected between the wires and the ground, behave as balanced single-phase loads and do not cause voltage asymmetry. On the other hand, the wire-to-wire capacitance causes current flow in phase opposition in the two wires; the associated voltage drops are in phase opposition and result in a voltage asymmetry. These capacitive currents are however small (less than 1A for a 50 km - 34.5 kV line) and their effect is negligible.

To apply the above described concept usefully, the equivalent impedance of the ground return path should be compensated for. The resistance being small, it is sufficient to compensate for the reactance only. This can be done by capacitor(s) connected between the neutral of the "V" connected transformers and ground (see Fig. 1-C). The capacitor reactance is, therefore, selected so as to compensate the voltage drop in the reactance of ground-return path, in particular to the location where the 3-phase loads are installed.

If the shield wire line supplies only loads at the receiving end or if the various loads branched along the line vary proportionally and maintain the same power factor, the neutral capacitors provide an exact compensation of reactive voltage drops. If loads depart from these conditions the compensation is approximate.

As already noted, the residual uncompensated resistive voltage drop in the earth path is small because the resistance is small. The capacitors have small ratings and should be protected, preferably by a metal-oxide resistor branched in parallel.

The supply of 3-phase loads by means of "V" connected transformers causes the flow of current components in phase opposition in the two shield wires. The associated voltage drop in the wire impedances causes voltage asymmetry. However, the negative-sequence voltage does not exceed the 2% limit, if the three-phase loads very distant from the HV/MV stations are a small part of total load.

If total load and 3-phase loads of a "V" Scheme are modest, the 2% imbalance limit can be complied with, even without use of compensating capacitors. This is the case with the "V" experimental system at Cape Coast in Ghana (see par. 10).

"3-Phase" Scheme *(for 100% 3-phase load)*

The two insulated shield wires and the ground return form a 3-phase circuit that is of course unbalanced. Typical differences of the series impedances and shunt capacitances are shown in Fig. 3b. The resistance of the earth conductor is smaller than the resistance of any practical shield wire cable; the reactance of the earth conductor is slightly smaller. The capacitance between wires is about one-half of the capacitance between each shield wire and ground.

A section of line can be rendered symmetrical by compensating the series impedance imbalance with a series resistor-reactor inserted in the earth path (R-L in Fig. 1-D), and by connecting a capacitor between the two wires(C_{ww} in Fig. 1-D), so as to raise the wire-to-wire capacitance to the same value as the wire-to-ground capacitance. The series resistor-reactor can be inserted in the earth path only at the sending end, and at the receiving MV/LV transformers in the villages.

The following points may be made on the accuracy of compensation that can be achieved in a real line:

- For shield wire lines used as distribution circuits not exceeding 100-125 km in length, a practically precise compensation can be obtained by concentrating the compensating components at one location only.
- If the load is connected at no more than two points along the line (as in the case of supply of Yapei and Buipe from Tamale, see Fig. 12), an exact compensation is obtained by locating an R-L circuit at the sending end (Tamale) to compensate the first stretch of line, and an R'-L' circuit at the remote end (Buipe) to compensate the second stretch of line (Fig. 1-D).
- If loads are branched at several points along the line, a precise compensation can be obtained only if they all vary proportionally and maintain the same power factor. This requires the insertion of an appropriate R-L circuit in the grounded phase of the MV/LV distribution transformer in each station.
- Calculations performed for practical applications (see par. 11) show that, even if load conditions differ from those considered above, it is possible to limit the negative-sequence voltage to less than 2% with an approximate compensation. The simplest consists of a single R-L circuit installed at the sending end, calculated such as to compensate the voltage drop difference of the aggregate load, assumed to be concentrated at the electrical gravity centre.

To supply a 3-phase line where one phase conductor is the earth, with symmetrical voltages, it is necessary to use an interposing transformer. A possible connection is shown in Fig. 1-D.

In the "3-Phase" Scheme the 3-phase loads are supplied by conventional delta/grounded star (or star/ grounded zig-zag) connected MV/LV transformers, that have to be designed for continuous operation with one primary terminal grounded and the other terminals with a voltage to ground equal to the phase-to-phase voltage.

The single-phase distribution is to be supplied by single-phase transformers, which are to be distributed among the phases, so as to obtain a balanced load, as practised in North America. However, as the line has no neutral, it is necessary to branch part of the transformers between the two shield wires, and this requires transformers with two HV bushings.

The "3-Phase" Scheme has some disadvantages in comparison with the "V" Scheme. These are summarized as follows:

- The wire-to-ground voltage is equal to wire-to-wire voltage, and therefore a greater insulation is needed in the line and station equipment, for assigned voltage percent drop and power losses.
- The interposing transformer calls for additional investment with higher power losses, voltage drops, and possible risk of failure, as in any other ordinary transformer.
- The compensating resistors cause non negligible power losses. Investigations are under way on possible alternative low-loss equipments, that must however be simple and reliable.

6. Steady-State operation

A parametric study of the steady-state behaviour has been performed for the four Schemes of Fig. 1. An untransposed 161 kV single-circuit transmission line has been considered, with 400 sqmm ACSR conductors, in triangular configuration (see Fig. 3a), protected by one or two insulated shield wires. The following two shield wire alternatives have been considered:

- galvanized steel: S = 60 sqmm; Ø = 10 mm (7 x 3.33 mm); r = 2.77 Ω /km at 30 °C.
- ACSR cable; S = 76.9 sqmm; S_{Al} = 48.57 sqmm; S_{St} = 28.33 sqmm; Ø = 11.35 mm (12 Al x 2.27 mm + 7 St x 2.27 mm); r = 0.617 Ω /km at 30° C.

The analysis has been performed with BPA's Electromagnetic Transients Program (EMTP). For Schemes A, B and C of Fig. 1, it has been assumed that the shield wire(s) is (are) energized at constant voltage of $34.5/\sqrt{3}$ kV phase-to-ground and 34.5 kV phase-to-phase. In the case of Scheme D of Fig. 1, two alternative symmetrical voltages of 20 kV and 30 kV, have been considered (phase-to-phase and phase-to-ground rms voltages are equal); voltage was assumed constant on the primary side of the interposing transformer.

The loads along the line have been simulated on the primary side of the MV/LV transformers, at a power factor of 0.9 or 1.0 For the "V" Scheme, 10% of load was assumed to be 3-phase and 90% single-phase; the latter was considered to be supplied in equal parts by the two transformers "V" connected. For the "3-Phase" Scheme, the loads were assumed to be 100% three-phase, symmetrical, as in conventional 3-phase European distribution.

The aggregate power that can be supplied by the shield wire(s) for the various schemes of Fig. 1, is plotted versus distance in Fig. 4, for a line length ranging between 20 km and 100 km, with the following additional assumptions:

- Loads are connected to the shield wires at 20 km intervals. The number of equal loads varies from 1 to 5 for line length from 20 to 100 km.
- The voltage drop in the shield wire line does not exceed 10% for Schemes A, B and C of Fig. 1. Drop is reduced to 7.5% for Scheme D, to allow for a voltage drop of 2.5% in the interposing transformer. The supply busbars are in any case regulated at 34.5 kV constant voltage.
- The electromagnetic coupling between the shield wire (s) and the conductors of 161 kV circuit is simulated by considering the 161 kV line operated at no-load or at SIL. Line is assumed untransposed in the stretch where the shield wires are insulated.
- The shield wire line is balanced as described in par. 5 when the "3-Phase" Scheme is analysed.The "V" Scheme is uncompensated.
- Earth resistivity is assumed to be 100 Ω m; grounding resistance of MV/LV stations is assumed to be 2 Ω .

The curve chart of Fig. 4 refers to 60 sqmm steel shield wires and

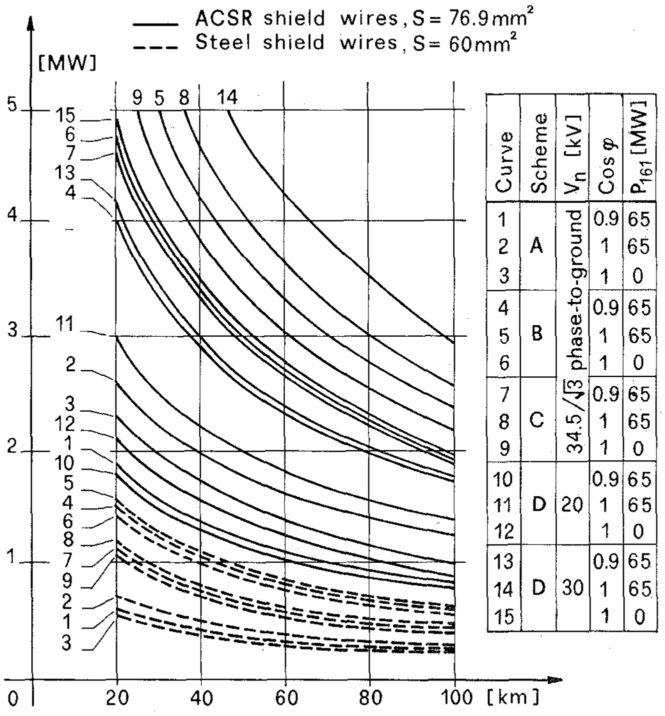


Fig. 4 - Transmissible power of typical steel and ACSR shield wire lines, versus length. Loads connected every 20 km. Shield wires are energized as per schemes of Fig. 1, at the rated voltage V_n.

76.9 sqmm ACSR shield wires, respectively. The diagram shows that the transmissibile power ranges from about 0.3 MW up to 5 MW, depending on type of cable, line length and scheme.

The resistive voltage drop is predominant in the steel wires, and therefore the power carrying capacity, as limited by voltage drop, is about the same with load power factor of 0.9 and 1.0.

The power distribution capacity of the steel wires is also limited by the power losses and by the low short circuit current, which limits the load current consistent with fault detection capacity. Even if the steel shield wires possess a non-negligible current carrying capacity at the thermal limit (about 85 A for a 60 sqmm wire), this can be used only partly, say one half, owing to voltage drop and power loss.

The "V" Scheme possesses the greatest capacity, more than twice the capacity of the "3-Phase" Scheme for the same shield wire-to-ground voltage. These two schemes possess the same capacity, if the phase-to-ground voltage is raised by a factor 1.5 in the "3-Phase" Scheme.

Scheme B has a capacity much greater than Scheme A, because it is supplied by the phase-to-phase instead of phase-to-ground voltage.

The main conductors of the 161 kV line induce non negligible voltages in the shield wires which depend on the geometrical arrangement of cables, the applied voltage and current flows. When the 161 kV line is loaded at SIL, the induced voltages were calculated up to 700-800 V for a 100 km stretch of shield wires. They add vectorially to the voltages applied at the sending end, and to the voltage drop due to current flow on shield wires, thereby raising or reducing the overall voltage drop and negative sequence component in three-phase Schemes. Differences of voltage drop up to 5-7% have been calculated in some cases, depending on phase(s) chosen to energize the shield wire(s).

The curve chart of Fig. 4 shows that the voltages induced in the shield wires from the 161 kV line currents, partly compensate the voltage drop caused by the power flow on shield wires, thereby raising the wire power carrying capacity (see curves 2 and 3; 5 and 6; 8 and 9). The energizing phases have been selected in such a way as to lower the overall voltage drop.

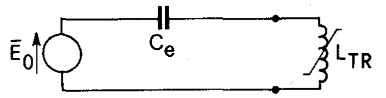
The negative-sequence voltage calculated for the "V" and "3-Phase" schemes are not reported here. Compensation to reduce negative sequence voltage should be optimized for specific applications, as reported in par. 10 and 11.

7. Temporary overvoltages induced in the insulated shield wires

7.1 Ferroresonance

Let us consider first Scheme A (Fig. 1). When the breaker supplying the shield wire is open, a series ferroresonance phenomenon might occur in the circuit formed by the capacitances between shield wire and HV conductors (C_R, C_S, C_T), and the saturable magnetizing impedances of the MV/LV transformers which are in parallel with the capacitance to ground of the shield wire (C_O). The phenomenon may build up when transformers operate at no-load or low-load.

Fig. 5 provides the equivalent circuit for the case of an open circuit shield wire at both ends, with the transformers at no-load. The Thevenin equivalent, as seen from the transformer terminals, is obtained by neglecting the line series impedances. For the case of Scheme A (Fig. 1), with a line length of 100 km, the calculations give: $E_O = 7.73$ kV and $C_e = 0.68$ μF.



$$\bar{E}_0 = \frac{C_R \bar{E}_R + C_S \bar{E}_S + C_T \bar{E}_T}{C_e} \qquad C_e = C_R + C_S + C_T + C_0$$

Fig. 5 - Thevenin equivalent circuit for physical interpretation of ferroresonance phenomenon. L_{TR} is the magnetizing inductance of MV/LV transformers.

The circuit analysis performed with the EMTP has confirmed that the ferroresonance may build up in the above described conditions, and could be ignited by the following transients: switching-off the shield wire with the 161 kV line in normal operation; switching-off one phase of the 161 kV line; extinction of the secondary arc on the shield wire with the secondary arc burning in one disconnected phase of the 161 kV line. Overvoltages ranging from 1.2 p.u. to 2.1 p.u. have been calculated.

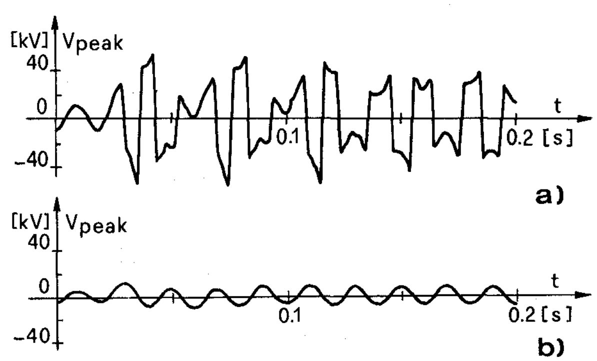


Fig. 6 - Voltage-to-ground of the shield wire switched-off at sending end. Scheme A, line length 100 km; 5 x 167 kVA transformers at no-load connected to shield wire at 20 km intervals: a) single-phase opening of 161 kV line; b) as case a), but with a capacitor rated 1.68μF connected between shield wire and ground at 100 km.

A simple counter-measure to ferroresonance has been studied, consisting in the connection of a capacitor between the shield wire and ground (Fig. 1). A capacitor rated 1.68μF (210 kVAR at 34.5/$\sqrt{3}$ kV) prevents the phenomenon and reduces the induced voltage on the open ended shield wire to non harmful values for equipments.

Fig. 6 illustrates the ferroresonance overvoltage calculated with the EMTP in a case of interest. Diagrams show that the phenomenon is drastically damped by a power factor correction capacitor.

Ferroresonance may occur in a similar way in the other shield wire schemes, and may be prevented by the application of antiferroresonance capacitors connected as indicated in Fig. 1. The capacitors also ensure power factor correction and, in the "3-Phase" Scheme (Fig. 1-D), they balance the line shunt capacitances.

7.2 Overvoltages induced by the short circuit current of HV line

The overvoltage induced in a shield wire is approximately proportional to the short circuit current flowing in the HV circuit underneath and to the exposed length of wire. The higher values occur during the 1-phase-to-ground short circuit in the uppermost phase, with fault located at the end of the insulated shield wire stretch. The induced voltage adds vectorially to the shield wire operating voltage.

A parametric analysis for a 161 kV line with insulated shield wires on a 100 km stretch energized at 34.5/$\sqrt{3}$ kV to ground has already been dealt with in ref. [2]. It showed that, if the short circuit power P_{sc} of the feeding 161 kV busbar is large, say $P_{sc} = 5000$ MVA, exceedingly large overvoltages may be induced, up to 2.7 p.u. wire-to-ground (1 p.u. = 34.5/$\sqrt{3}$ kV rms), that cannot be tolerated by the station equipments and consumers supplied from the wires and ground (Schemes A, C, and D of Fig. 1).

As regards Scheme B of Fig. 1, the induced overvoltages between the two shield wires, where consumers are branched, are small, because similar overvoltages are induced in each wire. Thus MV/LV transformer saturation and overvoltages on LV consumers do not occur. There remain, however, the phase-to-ground overvoltages referred to above, which stress all the insulations to ground and may destroy the surge arresters.

A practical approach for determining the maximum acceptable overvoltage, is to calculate the induced voltage in a conventional double-circuit line, when a 1-phase-to-ground fault affects one circuit and the other circuit is open at the remote terminal. Calculations performed for the 34.5 kV double circuit line equivalent in length and supply conditions, indicate maximum overvoltages in the healthy circuit of 1.4 – 1.5 p.u., which is consistent with the earth fault factor 1.4 p.u. stipulated by the IEC recommendations for the effectively grounded networks.

The analysis referred to above [2] has shown that the induced overvoltages are contained within 1.45 p.u. for the 161 kV-34.5/$\sqrt{3}$ kV Schemes of Fig. 1, if the short circuit power at the 161 kV supply station does not exceed 350 MVA and 600 MVA (assumed ratio $X_o/X_1 = 1$) for the insulated shield wire length of 100 km and 50 km, respectively.

In the developing regions, where the application of the novel distribution scheme is proposed, the short circuit power is usually very low and therefore the induced overvoltages are deemed acceptable.

In Northern Ghana, the 161 kV system under construction at the time of writing, has a low short circuit power at the stations supplying the shield wire schemes (see Fig. 11): Psc = 600 MVA at Kumasi; 335 MVA at Techiman; 175 MVA at Tamale and 121 MVA at Bolgatanga, with $X_o/X_1 = 0.8$ to 1.2. The calculated maximum induced overvoltages during a 1-phase-to-ground short circuit in the worst location are summarized as follows for the two most exposed lines (see single-line diagram in Fig. 12).

Shield-wire line and length	Scheme	1-Phase-to-G fault location on 161 kV line	Faulty Phase	Max. ind. overvoltage on shield wire, phase-to-ground [kVrms]	[p.u.]
Techiman-Soronuasi	"V"	Soronuasi	R	29.0	1.45
			S	30.0	1.50
L=72 km	V_n=34.5/$\sqrt{3}$kV		T	30.0	1.50
Tamale-Buipe	"3-Phase"	Tamale	R	27.0	0.90
			S	25.5	0.85
L=104 km	V_n=30 kV		T	30.0	1.00

The table shows that the induced overvoltages are about the same for the two schemes; values in p.u. reach the upper limit accepted in the "V" Scheme. No overvoltages occur in the "3-Phase" Scheme because it is supplied via an interposing transformer.

7.3 Overvoltages due to contacts between a shield wire and a conductor of HV circuit.

The contacts between conductors of an MV and HV circuit may cause the largest temporary overvoltages affecting the MV system. The risk of occurrence is small, but not negligible in the proposed scheme, like in the case of lines where an HV and MV circuit are supported by the same towers. For the application in Ghana, this risk has been estimated from the operation records of shield wire breakages of 161 kV lines.

Calculations have been made for the shield wire schemes of Northern Ghana, described in par. 11. Saturation of transformers, that would reduce the overvoltages, has been conservatively neglected on the grounds that MV/LV transformers may be disconnected due to the melting of protective fuses. The maximum calculated power frequency overvoltages are summarized as follows, with reference to the single-line diagram of Fig. 11.

Scheme and voltage to ground	P_{SC} at Kumasi [MVA]	Location of contact between shield wire and 161 kV line conductors	Max. overvoltage on shield wire line [kVrms]	[p.u.]
"V"–34.5/$\sqrt{3}$kV	600	Soronuasi	45	2.25
"3-Phase" 30 kV	600	Buipe	66	2.20
	400	Buipe	64	2.13

The above temporary overvoltages may cause surge arrester failure but are not expected to affect equipment insulation, that is tested at a higher 50Hz voltage.

8. Transient overvoltages

Switching overvoltages affect the shield wire distribution schemes during the energization of the wires themselves and the HV circuit. Transient overvoltages may also be induced in the wires when faults occur in the HV circuit.

An energization overvoltage study has been performed with the EMTP for the shield wire schemes of Northern Ghana (Fig. 12). The cumulative overvoltage distributions are plotted in Fig. 7 for the Techiman - Tamale 161 kV line and the associated Techiman - Soronuasi "V" shield wire line and Tamale - Buipe "3 Phase" shield wire line.

The distributions on the right side of Fig. 7 refer to the no-load energization of the shield wire lines with the 161 kV circuit in normal operation; the Tamale - Buipe shield wires are assumed energized at the rated voltage of 25 kV wire-to- ground. Overvoltages are very low and the probability of exceeding 2 p.u. is less than 2.5%. This performance is attributable to the presence of the antiferroresonance capacitors along the lines, which reduce the transient overvoltages to lower values than in conventional lines.

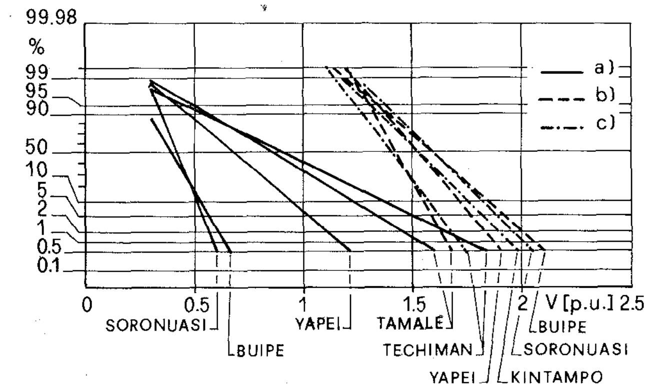


Fig. 7 - Distributions of switching overvoltages in the shield wire lines Techiman-Soronuasi and Tamale-Buipe: a) shield wire lines open ended, ungrounded, at switching-on the 161 kV line Techiman-Tamale; b) energization of the line Tamale-Buipe; c) energization of the line Techiman-Soronuasi; 1 p.u. = nominal crest phase-to-ground voltage.

The distributions on the left side of Fig. 7 provide the induced overvoltages at the no-load energization of the Techiman - Tamale 161 kV line; the shield wires are assumed to be out of service (open ended at both terminals), but not grounded (i.e. floating). The overvoltages are low ($V_{50\%}$ = 0.95 p.u.; σ = 0.45 p.u.) for the assumed status of the shield wires prior to switching.

If the shield wires are energized prior to the energization of the 161 kV circuit, large switching overvoltages may build-up when the 161 kV line has a large shunt compensation. The study has shown that this may occur if resonance or near resonance conditions exist between the capacitance of the wires to the 161 kV line conductors, on the one side, and the inductance equivalent to the shunt reactor in parallel with the phase-to-ground capacitance of 161 kV line conductors, on the other. Under this circuit condition, the live shield wires may induce a relatively high potential on the floating conductors of the 161 kV line. This in turn causes an increase of the overvoltages induced in the shield wires when the 161 kV line is energized. The phenomenon is illustrated by the cumulative overvoltage distribution of Fig. 8, that refers to an insulated shield wire 100 km long, in Scheme A of Fig. 1, coupled with a 185 km long 161 kV line, compensated with a 15 MVAR shunt reactor. The curve *a* of Fig. 8 shows that the no-load energization of the 161 kV line, with the shield wire previously energized at 34.5/$\sqrt{3}$ kV to ground, causes overvoltages that can exceed 4 p.u. in 5% of cases.

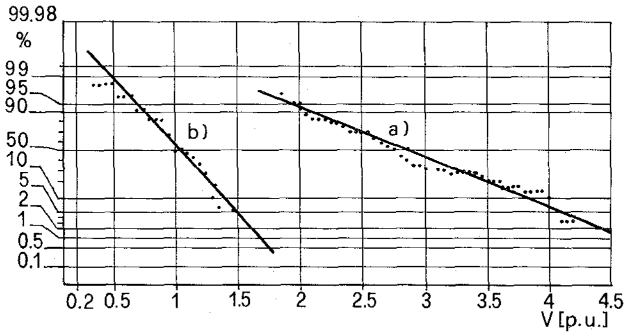


Fig. 8 - Distributions of switching overvoltages induced in 100 km of shield wire at 3-phase energization of a 185 km long 161 kV line equipped with single 400 sqmm conductors and shunt compensated: a) shield wire is energized at 34.5/$\sqrt{3}$ kV prior to 161 kV circuit energization; b) shield wire open-ended at both terminals prior to 161 kV circuit energization.

The 161 kV lines of Northern Ghana where the shield wire distribution schemes are being applied (Fig. 12), are equipped with line connected shunt reactors. Even if resonance conditions are unlikely to occur, it was decided that energization of the 161 kV line will be permitted only when the shield wire line is de-energized to avoid the above described phenomenon.

9. Ground return of current. Tower grounding

The grounding electrodes and continuous current flow through the ground must be checked as regards soil heating, step and touch voltages and interference with telephone lines. The solution of these problems is facilitated by the low values of current flowing in each MV/LV station and, on the other hand, by the large dimensions of the grounding system of the feeding HV/MV stations where greater currents flow.

It is necessary to prevent the earth from drying out near the electrodes, because an uncontrolled increase in resistance would occur (thermal instability). To check that this phenomenon will not occur, the Ollendorff formula can be applied:

$$V_e = \sqrt{2\,\lambda\,\varrho\,\vartheta_e} \tag{1}$$

where: V_e = potential of electrode with respect to remote earth (V); ϑ_e = temperature rise of electrode and contiguous soil above ambient temperature (°C); ϱ = resistivity of soil (ohm m); λ = heat conductivity of soil (W/m °C). The formula (1) is applicable to electrodes of any shape in soil of uniform electrical and thermal resistivities.

Assuming an ambient temperature of 40°C, ϑ_e should not exceed 60° to prevent fast evaporation of moisture. Then, by assuming λ = 1 W/m °C, formula (1) yields the following maximum acceptable values of V_e:

V_e = 50 V for ϱ = 20 ohm m
V_e = 110 V for ϱ = 100 ohm m
V_e = 345 V for ϱ = 1000 ohm m

If the ground current is 10 A or 50 A (200 kVA or 1000 kVA at 34.5/$\sqrt{3}$ kV) and the lower electrode potential limit of 50 V is applied, the grounding resistance limit is 5 ohm or 1 ohm, respectively. The corresponding step and touch voltages are low (usually a small fraction of 50 V).

These design criteria are in keeping with those applied in Canada. The Electrical Utility Regulations in Alberta [4] stipulate the following limits in ground return distribution systems: current infeed in individual grounding systems ⩽ 10A; potential rise of electrodes

⩽ 50 V; grounding resistance ⩽ 6 ohm. For reasons of safety multiple electrodes, well separated and loop interconnected, are recommended. A typical design in soil with low or medium resistivity consists of 3 interconnected steel rods (ø = 19 mm), about 3 m long, placed at the corners of a triangle with 3 m sides. In sandy, gravely or rocky soil, deep-driven rods are applied to reach permanent moisture conditions, or grounding system is duplicated and paralleled one span apart.

The grounding electrodes of the experimental shield wire line in Ghana have been designed with the above criteria. The operation results reported in par. 10 prove that these criteria are applicable also for soil conditions in Ghana.

The insulation of the shield wires causes some increase of the line zero-sequence reactance and the induced voltages in parallel telephone lines. However these effects are of little importance for the planned lines where short circuit power is small.

The insulation of shield wires also causes an increase in the equivalent ground resistance as seen from any tower, because the grounding contribution of nearby towers through the wires is eliminated, unless the gaps sparkover. During a 1-phase-to-ground fault of the HV line in a tower, without gap sparkover in the wire, the step and touch voltages will be greater. On the other hand, the short circuit current of the HV system consistent with the prospective distribution from shield wire is quite low, as discussed in a previous paragraph. This helps compliance with safety regulations for tower grounding.

10. Experimental distribution system in Ghana. Operation results

10.1 Description of the scheme

To check the performance of the novel distribution from insulated shield wires of HV lines, an experimental scheme was put in service in 1985 by Volta River Authority (VRA) in Ghana.

The scheme was implemented by insulating the two shield wires on 31 km of the 161 kV line Cape Coast-Takoradi, using Cape Coast Substation as the sending end. This line is 64 km long and has been in service since 1965. Towers are double-circuit (see Fig. 9) but only one circuit is strung. Two alumoweld shield wires, with a cross-section of 36 sqmm, are also strung. The line is routed not far from the ocean shore (see map in Fig. 12) and near several villages without any electricity supply. The terrain is rolling or flat and vegetation height (bush and trees) is generally much less than tower height.

The shield wires have been insulated by means of rigid insulator strings of the type shown in Fig. 2, with small size glass discs (175 mm) and rod-gap set at 23 cm.

The circuit schematic diagram of the experimental project is shown in Fig. 9. The Bronybima and Atabadzi villages are supplied in single-phase ground-return (Fig. 1 - A), by one 100 kVA - 19900 V $\pm$ 2 x 2.5% / 252 V standard North American distribution transformer. The consumers at Kissi village are also supplied in single-phase; however two 100 kVA transformers are branched between each shield wire and ground, with ground-return of current.

At the end of the insulated shield wires stretch, the scheme supplies the TV Broadcasting station of South-West Ghana. This is a 3-phase load of 60 kW, with induction motors rated up to 5 HP. The "V" Scheme, uncompensated, is applied (Fig. 1 - C), with two transformers rated at 100 kVA.

The "V" Scheme provides a 3-phase supply without neutral. To make available a 415/240 V, 3-phase supply with neutral, as provided by the local Diesel generators, a small LV dry-type grounding transformer has been installed, designed for a continuous current of 10 A per phase and a low zero-sequence impedance voltage (0.67 + j0.25 ohm).

Calculations with the EMTP had shown that to contain the negative sequence voltage at the 415 V busbars of the TV Broadcasting station to less than 2%, from no-load to full forecast load (75 kW of 3-phase load), the following simple remedies should suffice:

(i) connect a 10 kVAR-415 V capacitor between two properly selected phases of the 415 V busbars

(ii) set the off-load tap-changer of the transformer connected to the wire with higher voltage, at ratio one step (2.5%) higher than the other.

These measures compensate for the asymmetries of the line and "V" connected transformers, because asymmetries (i) and (ii) produce opposite effects, that are jointly almost equivalent in size.

The shield wires of the 161 kV line chosen for the experiment have a small section (36 sqmm) and high ohmic resistance (2 ohm/km at 20° C). It is thus important to protect the wires effectively against short circuit and overload currents which could cause dangerous extrasagging and permanent degrading of mechanical characteristics. Their maximum continuous current carrying capacity in a tropical environment is about 50 A. A low setting instantaneous over-current relay and inverse time overload relay perform the protective functions.

The transformer stations require only conventional single-phase distribution equipments. The transformers are protected on the HV side with a fuse cutout and a surge arrester.

A suspension tower with insulated shield wires and typical single phase ground return MV/LV transformer station are shown in Fig. 10.

Antiferroresonance capacitors rated at 200 kVAR at 19.9 kV, are connected between each shield wire and ground, in the locations shown in Fig. 9. The capacitors, which also provide power factor correction, are connected solidly (without fuses), to avert the risk that fuse melting may expose the system to dangerous ferroresonance overvoltages.

The grounding system to which is connected one terminal of the MV/LV transformers for the ground return of current, is independent from the grounding system of the 240 V distribution network. Each grounding system is formed with rods, ø = 19 mm, about 3 m long, placed at the corners of a triangle with 3 m sides. Where possible, the earth return electrodes are connected via a buried counter-

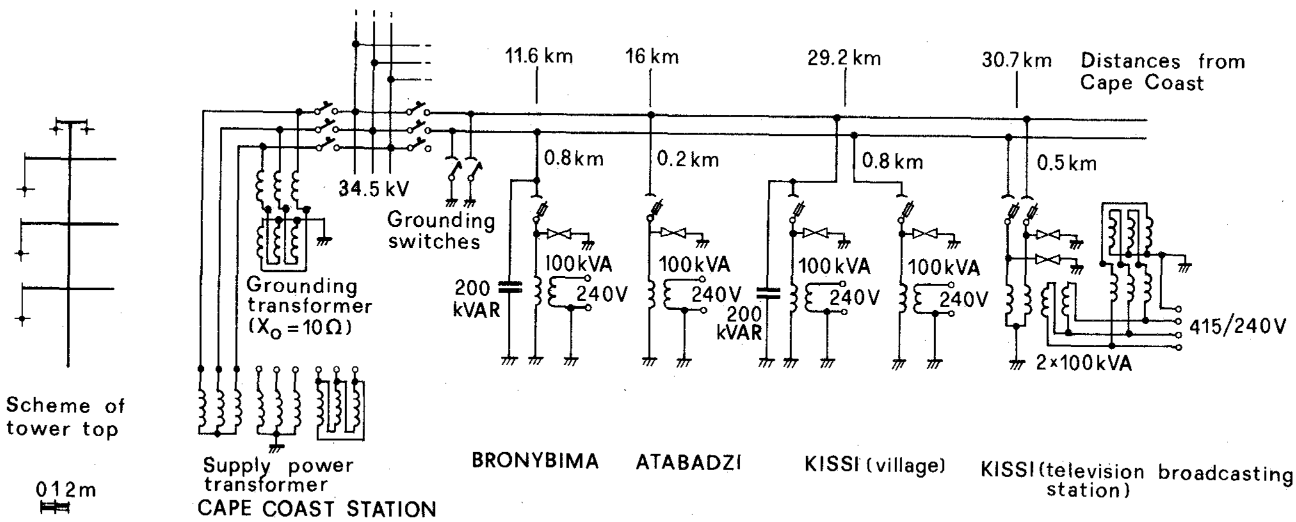


Fig. 9 - Circuit schematic of the experimental distribution scheme from shield wires at Cape Coast. Meaning of symbols is the same as in Fig. 1.

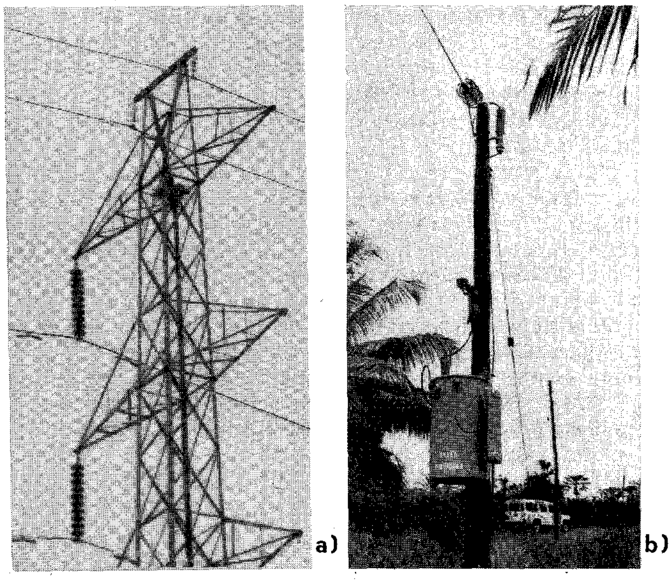


Fig. 10 - a) A suspension tower with insulated shield wires; b) Atabadzi single-phase ground-return transformer station.

poise to the grounding system of the 161 kV branch-off tower, thereby markedly reducing the ground resistance.

10.2 Operation results

At the time of writing, the experimental system has been in continuous operation for 33 months and has performed very well since its inception. Details on operation performance are provided below.

(i) *Lightning performance of 161 kV line.* The line crosses an area with moderately high keraunic level. The average outage rate of the 161 kV Cape Coast-Takoradi line recorded in the last 33 months has not been higher than that recorded during the five years prior to insulation of shield wires. Comparison with the outage rates recorded for the 161 kV lines of the region with same tower configuration (Cape Coast-Winneba and Takoradi-Tarkwa) also confirms that lightning performance has not changed after shield wire insulation.

(ii) *Shield wire insulation performance.* The insulator strings and rod-gaps did not suffer any damage and ensured a good operation performance of the 31 km shield wire line.

In 33 months, there was only one forced outage of the shield wire line, probably caused by lightning which did not disturb the operation of the 161 kV circuit.

There is also evidence that in a few cases, lightning strokes caused a flashover of shield wire insulation, but the follow-up power arc selfextinguished and shield wire tripout did not occur; the 161 kV circuit was not tripped out either. Coincident tripouts of the 161 kV circuit and shield wire line have never occurred.

There are no reported cases that the rod-gaps did not selfextinguish immediately after arc ignition. Switching of the shield wires and of the 161 kV circuit never caused a shield wire insulation flashover.

(iii) *Grounding systems.* The ground return of current was a matter of concern, because of lack of experience with local soil, mostly laterite and long dry seasons.

A favourable fact is the cost saving ensured by installing good grounding systems with local labour and materials. Another fact is that the terrain at the villages, where earth current injection occurs, is usually flat and soil resistivity is relatively low all year round.

The following Table summarizes the measured ground resistances (R_g) and soil resistivities (ϱ) at the end of the dry season; the range of current infeed to earth (I_g) and max. electrode voltage to remote earth (V_e); the max. value of ground resistance acceptable according to the Ollendorff formula, such as to avert the risk of soil drying out by fast evaporation ($R_{g,M}$).

The Table shows that in all the stations $R_g < R_{g,M}$ and $V_e < 50$ V. No inconvenience, of any kind, has been reported in relation to the earth return of current.

After insulation of the shield wires, an improvement was made

Location	R_g [ohm]	ϱ [Ωm]	I_g [A]	V_e [V]	$R_{g,M}$ [ohm]
Cape Coast	2	–	10-13	26	—
Bronyibima	4	(365)+)	10-11	44	19.6
Atabadzi	3	30	0.5-3	9	20.6
Kissi (village)	0.5-1	15	10-12	12	3.5
Kissi (TVstation)	1.5	12	0.5-3	4.5	12.6

+) At 161kV tap-off tower, located on top of hill

in the grounding system of three 161kV towers which had resistances of 29 to 45 ohm and could be lowered to 4 to 18 ohm. This measure was adopted for the safety of the local people.

(i v) *Measurements of reactances and resistances of shield wires and ground return path.* The electrical constants of the simplified equivalent circuit of the line formed by two independent shield wires with earth return, had been calculated with the EMTP, i.e. by applying standard methods and formulae, and by assuming a uniform earth resistivity of 100 ohm m.

Field measurements were made in the experimental line, to check the series resistances and reactances depending on the ground return path, that in the applied shield wire schemes control the steady-state electrical operation. Three measurements were made, by short circuiting the shield wires at Kissi as shown in Fig. 11: (a) one phase-to ground; (b) phase-to-phase (c) phase-to-phase-to ground. At Cape Coast the circuit was energized at 240V or 415V-50 Hz. The 161 kV line was put out of service and ungrounded at both terminals; the MV/LV transformers and capacitors were disconnected.

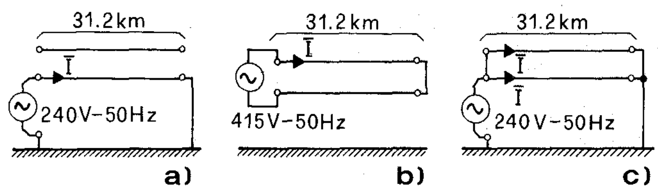


Fig. 11 - Circuit arrangement for measurements of series impedances of the Cape Coast-Kissi experimental shield wire line.

The series resistances and reactances obtained with simple formulae from the measured currents and voltages, are compared below with the series impedance calculated with the EMTP. Differences range from 1 to 6%.

Series impedance	Measured [ohm/km]	Calculated [ohm/km]
insulated shield wires	2.1+j0.43	2.08+j0.415
ground return path	0.045+j0.37	0.047+ j0.35

(v) *Temporary overvoltages.* The antiferroresonance capacitors performed their function as expected. A field test was made by tripping at Cape Coast the breaker of the shield wires, at low load. The induced voltage measured from the shield wire to ground, was about 1 kV rms.

The 50 Hz induced voltage from short circuit current flow on the 161 kV line did not cause flashover of shield wire insulation and never damaged the lightning arresters.

So far, no contacts have occurred between the 161 kV line conductors and the insulated shield wires.

(v i) *Equipment performance.* During 33 months of operation, no equipment failure has occurred, except the shattering of the 20 kV bushing of a 200 kVAR capacitor, caused by a cobra, that climbed the pole onto the capacitor.

(v ii) *Quality of service to consumers.* The number of domestic service connections was limited, from the beginning, to 250 (about 2500 people) because of the experimental nature of the scheme. The total power supplied is 150 kW, including the TV station.

The quality of service to consumers has been good, equivalent to the service from a conventional 34.5 kV line.

Voltage at the secondary terminals of MV/LV transformers throughout the whole scheme, is in the range from 233 V to 247 V. The supply voltage at Cape Coast is maintained almost constant, at $33/\sqrt{3}$ kV. The line resistance voltage drop is the controlling component, because the shield wires have a high resistance. This reduces

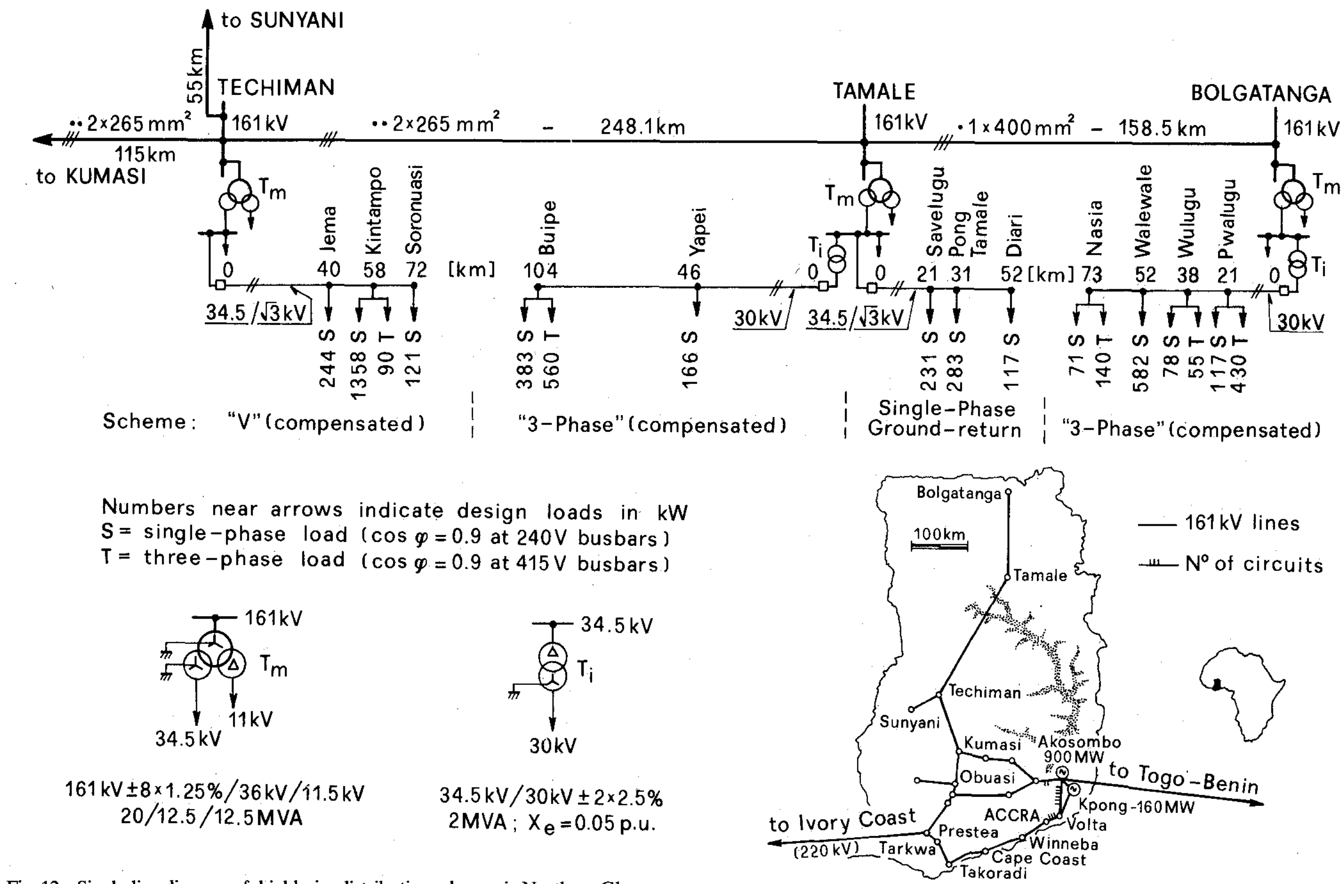


Fig. 12 - Single-line diagram of shield wire distribution schemes in Northern Ghana.

the efficacy of power factor correction capacitors. If the load is greatly increased, it will be necessary to raise the sending end voltage by means of the transformer on-load-tap-changer.

(v iii) *3-Phase supply of Kissi TV broadcasting station.* During the commissioning tests, the start up and operation of a 15 kW squirrel cage induction motor was checked. With the motor operated at no-load, the negative-sequence voltage at the terminals was less (by about 20%) than before connecting the motor, as expected, owing to the low negative-sequence impedance of the motor.

The major concern was voltage imbalance. Measurements were made over a long period, in all the load conditions at the villages and the TV station. They proved that the negative sequence component of the voltage at the 415 V busbars of the TV station never exceeded 1.5%.

11. Commercial distribution in Northern Ghana using the insulated shield wires.

On the strength of the positive operation results of the experiment discussed in par. 10, VRA has decided to utilize the novel scheme commercially in Northern Ghana. This will supply power initially to 12 villages and some industrial loads. The new 161 kV lines from Kumasi to Bolgatanga through Tamale, 522 km long, are routed close to the highway and these villages.

Fig. 12 is a single-line diagram of the Northern Ghana shield wire distribution systems, under construction at the time of writing. The tower head outline of the 161 kV lines is shown in Fig. 3a, depicting two shield wires, typical of the VRA transmission lines, to provide effective shielding as the keraunic level in the region is considered rather high.

Fig. 12 also shows the distances between the villages and the nearest 161/34.5 kV transformer station as well as loads to be served. The largest 3-phase load demand is located at Buipe, 104 km south of the Tamale transformer station.

The assumed design loads (Fig. 12) are those forecast for the year 2005, with an aggregate load projection of 5025 kW to be supplied by four shield wire lines. The initial 1989 load, which is estimated at 3040 kW, will serve a population of about 80000, or 8000 households. This is 13% of the population initially to be supplied from the electrification extension under way. The 3-phase loads shown in Fig. 12 are presently supplied by diesel generators and are forecast to remain constant throughout the planning horizon (1989-2005).

The significant industrial 3-phase loads at Buipe and Pwalugu (Fig. 12) led to selection of the "3-Phase" Scheme for the associated shield wire lines, with grounding resistor-reactor compensation, to drastically limit the negative sequence voltage components. One of the shield wire lines will supply only small 3-phase loads (corn mills at Kintampo); the "V" Scheme compensated with a small grounding capacitor will be applied. The fourth shield wire line will supply only single-phase loads. These will be served by the "Single-Phase Ground Return" Scheme, applied in both shield wires. This will allow the possibility of supplying future small 3-phase loads with the "V" connected transformers.

The insulated shield wires are ACSR conductors with a total cross-sectional area of 76.9 sqmm (see par. 6 for detailed data). The suspension insulators are rigid strings as illustrated in Fig. 2. The large disc size (dimensions in brackets in Fig. 2) have been used because in the "3-Phase" Scheme the selected phase-to-ground operating voltage is 30 kV (in the "V" Scheme, it is 19.9 kV). Tension strings are similar to suspension strings, but an antiperching steel blade is mounted in the rod-gap.

Antiferroresonance-balancing-power factor correction capacitors are applied as follows:

- "3-Phase" Scheme (ref. Fig. 1-D):
  - at Buipe: C_{ww} = 170 kVAR; C_{wo} = 2 x 130 kVAR
  - at Walewale: C_{ww} = 215 kVAR; C_{wo} = 2 x 190 kVAR
- "V" and "Single-Phase Ground Return" Schemes (ref. Fig. 1-C and 1-A):
  - at Kintampo: C_{wo} = 2 x 175 kVAR initial (2x350 kVAR in year 2005)
  - at Tamale: C_{wo} = 2 x 75 kVAR initial (2x125 kVAR in year 2005)

In the "3-Phase" Schemes, a compensating resistor-reactor is

Table I - "3-Phase" Schemes - Positive and negative sequence voltages at no-load and year 2005 peak load, and power losses

Location and distance from supply station	P [kW]	V_1 [%]	V_2 [%]	v_1 [%]	v_2 [%]	ΔP [%]
Tamale	—	93.3	0.5	—	—	—
—	—	100.3	0.5	—	—	7.70
Yapei	0	94.3	1.5	101.7	1.5	
(46 km)	166	95.3	1.0	100.2	1.0	
Buipe	0	95.7	1.0	105.5	1.0	
(104 km)	943	92.0	1.1	98.8	1.1	
Bolgatanga	—	95.3	0.3	—	—	—
—	—	99.7	0.2	—	—	4.30
Pwalugu	0	96.0	0.7	103.4	0.7	
(21 km)	547	96.7	0.6	99.5	0.6	
Wulugu	0	96.3	0.5	104.1	0.5	
(38 km)	133	96.3	0.3	99.5	0.3	
Walewale	0	97.0	0.4	104.6	0.4	
(52 km)	582	95.7	0.2	100.7	0.2	
Nasia	0	97.0	0.5	104.6	0.5	
(73 km)	211	95.7	0.3	101.2	0.3	

P = load, assumed 3-phase balanced at each village; $\cos\phi=0.9$.
V_1, V_2 = positive and negative sequence voltage along shield wire line; 100% = 30kV.
v_1, v_2 = positive and negative sequence voltage at the LV winding terminals of MV/LV transformers; 100% = 415V.
ΔP = shield wire line losses, in percent of total 2005 feeder load, including compensating resistors and interposing transformer. The effect of coupling with the 161kV main circuit has been neglected in loss calculation.

Table II - "V" Scheme and "Single-Phase ground return" Scheme - Voltages at no-load and year 2005 peak load, and power losses

Location and distance from supply station	P_S [kW]	P_T [kW]	V_R/V_S [%]	v_R/v_S [%]	v_1 [%]	v_2 [%]	ΔP [%]
Techiman	—	—	99.4/ 99.4	—	—	—	
—	—	—	103.4/104.4	—	—	—	7.2
Jema	0	0	100.4/100.4	102.9/100.4			
(40 km)	240	0	93.9/101.4	100.8/102.9			
Kintampo	0	0	100.9/100.9	103.3/100.8	102.2	1.50	
(58 km)	1358	90	90.4/100.4	100.4/100.8	100.7	1.05	
Soronuasi	0	0	101.4/101.4	103.3/100.8			
(72 km)	121	0	91.4/100.4	99.6/102.1			
Tamale	—	—	97.9/ 97.9	—	—	—	
—	—	—	103.9/102.9	—	—	—	1.3
Savelugu	0	0	97.9/ 94.4	100.0/100.4			
(21 km)	231	0	103.9/102.9	102.1/101.3			
Pong Tamale	0	0	97.9/ 94.4	100.0/100.4			
(31 km)	283	0	103.9/102.9	101.7/100.4			
Diari	0	0	97.9/ 94.4	100.0/100.4			
(52 km)	117	0	103.9/102.9	101.7/100.4			

P_S, P_T = single-phase and three-phase loads; $\cos\phi=0.9$.
V_R, V_S = phase-to-ground voltages of two energized shield wires; = 100% = $34.5/\sqrt{3}$kV.
v_R, v_S = secondary voltages of MV/LV transformers branched between each shield wire and ground; 100% = 240V.
v_1, v_2 = positive and negative sequence voltage at the LV winding terminals of MV/LV "V" connected transformers; 100% = 415V.
ΔP = shield wire line Joule losses, in percent of total 2005 feeder load.

installed only at the sending end (R-L in Fig. 1-D). Ratings are as follows: (52 + j 6.2) ohm - 25A - 32.5 kW at Tamale; (22 + j 2.7) ohm - 30 A - 19.8 kW at Bolgatanga; a 5s - 500A and 5s - 700A temporary rating is also required, respectively.

In the "V" Scheme, a compensating capacitor rated at 24 ohm - 50A - 60 kVAR and protected by a metal-oxide-resistor, is required only at Kintampo, where it will be traversed by the total earth current. At Kintampo, a 415V zig-zag connected grounding transformer, rated at 30A continuous current per phase, will provide a 415/240V, 4-wire 3-phase supply from two "V" connected transformers (see Fig. 1-C).

Phase loadings were selected in the 34.5kV system supplying the "V" and "Single-Phase Ground-Return" Schemes to keep the load imbalance in the 161 kV feeding network to very small values.

The main results of the steady-state operation analysis are summarized in the Tables I and II. The whole Fig. 12 system has been simulated with the EMTP, at no-load and peak load for the years 1989 and 2005. The load power factor was assumed to be 0.9 at the 415 V and 240 V terminals of the MV/LV transformers. These have been simulated with ratings selected according to normal distribution practice and an impedance voltage of 4%.

The assumption has been made that the voltage of the 34.5 kV supply busbars in the main stations, will be raised by 5-6% from no load to peak load condition. This will be done by the on-load-tap-changer of the step-down transformers.

The position of the off-load-tap-changer of MV/LV transformers was preselected, at each location, so as to obtain an average LV value as close as possible to the rated voltage (415 V and 240 V). In addition, in the "V" Scheme, the taps of the two MV/LV single-phase transformers branched between the two shield wires and ground, have been staggered by one or two steps, to reduce the average imbalance of 3-phase secondary voltages.

The maximum voltage drop in the shield wire lines is 5% to 8.3% in the "3-Phase" Schemes, for the 1989 to 2005 peak loads. The most important results summarized in Tables I and II, are as follows:

- The voltage at the LV terminals of all the MV/LV transformers remains in the range 0.98 p.u. to 1.05 p.u. in the "3-Phase" Schemes, and 0.99 p.u. to 1.03 p.u. in the "V" Schemes, from no-load to maximum load of year 2005 by taking advantage of the tap-changer voltage control of 34.5 kV busbars, as mentioned above.
- The negative-sequence voltage at the secondary terminals of the MV/LV transformers is generally less than 1% in any loading condition; it was found to be 1.5% in two locations, at no-load.

This voltage imbalance is small but not nil. In the "3-Phase" Schemes, it is caused by the imperfect line compensation adopted which is concentrated in the sending end only and by the non symmetrical electromagnetic coupling between the shield wire line conductors and 161 kV line conductors.

- The shield wire line Joule losses, including the compensating equipments and, in the "3-Phase" Schemes, the interposing transformers, range for the various lines from 0.7% to 5.4% for the 1989 load and from 1.3% to 7.7% for the 2005 load.

The above results are satisfactory for the length of the distribution lines dealt with (up to 104 km).

Single-phase distribution proved very economical for the electrification of villages where there were no 3-phase networks supplied by diesel generators. To limit the voltage drops and the losses on LV distribution lines, 3-wire lines are utilized, which are supplied by single-phase transformers with two 240 V secondary windings (see Fig. 1). This provides 240 V between each of the two phase conductors and neutral, and 480 V between the two phase conductors. The 240 V domestic consumers are equally divided among the two circuits.

The temporary and switching overvoltages which may affect the shield wire schemes of Fig. 12, have been reported briefly in par. 7 and 8.

In the "V" and "Single-Phase Ground Return" Schemes, the equipment insulation levels are the standard in use for the 34.5 kV networks with grounded neutral, i.e.: BIL = 170 kV; 50 Hz withstand at 70 kVrms; surge arresters rated at 27 kV. In the "3-Phase" Schemes, somewhat higher insulation levels have been specified, because of the higher phase-to-ground operation voltage.

Attention must be paid to providing protection against the high-resistance phase-to-ground faults. In normal MV radial networks operated with grounded neutral, the protection is provided by low-setting homopolar overcurrent relays. These are sensitive to the ground current which circulates only during the ground faults. In the earth-return distribution, the ground overcurrent relay must of course be set above the load current, thereby reducing the sensitivity.

In the shield wire lines under construction at the time of writing, a complementary protection to high-resistance ground faults will be provided by a relay sensitive to the difference of the intensities of the currents in the two shield wires at the sending end. In normal operation the current difference is nil or small; in the presence of a wire-to-ground fault, a current imbalance will occur and the relay will pick-up.

In the 161/34.5 kV supply stations, the ground return current will be in the range of 30 to 50 A. The calculated station grounding resistances are in the range from 0.3 to 1 ohm, with measured soil resistivity in the range of 90 to 400 ohm m. Total ground mesh voltage to remote earth is less than 50 V. It is deemed that there is no need to improve the grounding systems for the continuous ground return of current.

In the villages, the ground current is generally less than 12.5 A with the exceptions of Kintampo (42 A) and Buipe (20.5 A). In these two towns, several MV/LV transformers are required, scattered over a relatively large area. Multiple grounding systems will be built, one for each MV/LV transformer station, interconnected via a ground overhead conductor running along the phase conductors feeding the transformers.

It has been specified that the grounding resistance of the 161kV line towers shall not generally exceed 10 ohm, and exceptionally 20 ohm in rocky areas.

The total additional cost of the two insulated shield wires in the VRA 161kV lines is U.S. $ 300 per km (contract awards made in July 1987). This cost difference accounts for insulators, because the installed cost of the 76.9 sqmm ACSR shield wires is the same as for the 60 sqmm steel cables used as standard non insulated shield wires. The cost of an independent 34.5 kV standard VRA line is over U.S. $ 20000 per km. Construction of independent lines could have been justified and afforded for only very few of the villages that will be supplied by the shield wire lines. Therefore the new concepts will have a considerable social impact.

12. Conclusions

About 3 years of operation of an experimental system in Ghana have confirmed the viability of the novel scheme for earth-return power distribution via the insulated shield wires of a 161 kV line, energized at $34.5/\sqrt{3}$ kV from a main station. The scheme utilizes only standard North American distribution equipments and also supplies a 3-phase load at the remote line end. It has provided the same quality of service as a conventional distribution system and no problems have been caused by the earth-return of current. The shield wires, although insulated and energized, still prove to serve their primary function of protection against lightning.

Four shield wire schemes are proposed, one of which is applicable to HV lines with one shield wire, and the others where two shield wires are available. Two of the schemes allow supply of 3-phase loads. Simple compensating equipments are proposed (grounding resistor-reactors or capacitors) to keep the voltage imbalance to acceptable values when significant 3-phase loads are supplied.

The capabilities of the schemes and the design and operation restrictions to be observed, have been studied by computer analysis with the EMTP and can be summarized as follows:

- The shield wire schemes can supply significant power, up to 3 MW distributed along 100 km of line energized at 30 kV, if two ACSR shield wires are available.
- The "3-Phase" and "V" Schemes can supply 3-phase loads (100% of capacity or, respectively, a small part) while keeping the negative sequence voltage to less than 1-1.5% in all conditions and locations.
- Temporary overvoltages can be induced on the shield wires by unsymmetrical short circuits on the HV line, by contacts with an HV conductor or following tripout of shield wire(s). Countermeasures are indicated in the paper.
- The switching overvoltages are generally small, except rare phenomena that can be prevented by a switching restriction on shield wires.
- The proposed scheme is applicable to the HV lines in the areas where the short circuit current is relatively modest. This limits the induced overvoltages on shield wires during the short circuits on the HV circuit. It also compensates for the increases of step and touch voltages near the towers and the induced voltages in parallel telecommunication circuits, that are caused by the use of insulated shield wires.

The proposed system is the least costly of any so far applied for power distribution to the villages along HV lines. The application of this system to 466 km of new 161 kV lines in Northern Ghana required an additional investment of only U.S.$ 300 per km of line, and modest extracosts for the grounding systems and compensating equipments. With an additional "V" Scheme planned in the Kumasi-Techiman 161kV line, the shield wire lines will serve 17 villages with a total population of 115000.

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DISCUSSION

ABDUL M. MOUSA (British Columbia Hydro, Vancouver, B. C., Canada): I wish to congratulate the authors for a very interesting paper. This is the first time that the use of shield wires as a distribution circuit has received such extensive theoretical and experimental analysis. The concept itself, however, is not new. A 1960 paper by Andrews and Oakes [5] reported on the use of the shield wires of some 230 kV lines of the Idaho Power Company as a 40 kV, 1-phase, distribution circuit ($69/\sqrt{3}$). The scheme employed earth return and a 25.4 cm gap across each 40 kV insulator string, and the problems of ferroresonance and heating of soil were briefly addressed. The authors' response to the following comments and questions would be appreciated:

1. Insulating the shield wires is also being done for other reasons including reducing power losses, providing a communication channel, and reducing the corrosion of the foundation of the line structures located near the substations. In each of those applications, it has usually been stated that the low level insulation of the shield wires should not adversely affect their lightning protection function. It is pleasing that this point has finally been proven by the field observations reported in this paper.
2. The regulations of the Province of Alberta, Canada, are quoted in the paper in support of the 50 V steady-state voltage rise criterion adopted for the electrodes carrying the ground return current. It should be noted that another Canadian (Federal) Standard [7] has adopted a 15 V limit. This would limit the body current to 10 mA for the typical case of a 1500 Ω body resistance. Where higher steady-state voltages exist, the above standard requires the use of ground mats to eliminate the touch voltage problem.
3. It would be useful if the authors give a reference for the Ollendorff formula and a photograph or a diagram of the "antiperching" steel blade mounted in the rod-gap of tension strings.
4. The statement that "simultaneous tripouts of the 161 kV circuit and the shield wire line have never occurred" is valid only for systems having a low short circuit level. In the general case, simultaneous tripouts might occur. This, however, should not be objectionable because:
   (a) reliability requirements of distribution circuits are usually lower than those of HV/EHV circuits;
   (b) as reported in the paper, the problem is alleviated by the reduction of the outages caused by contact with trees to which typical distribution circuits are exposed.
5. Where part of the subject distribution circuit is carried on separate poles, the capacitance-to-ground of the wires in that part will help reduce the electrostatically induced voltage, thus controlling ferroresonance. This may eliminate the need for installing a capacitor between shield wire and ground.
6. Based on an analysis of the data by Andrews et al. [6], a conservative relation was earlier proposed regarding the length of the gap (d; meters) needed to interrupt a capacitive current [8]:

$$d \propto (\text{kV.A}) \qquad \ldots(2)$$

$$= 0.01 \times (\text{kV.A}) \qquad \ldots(3)$$

   where (kV.A) is the product of the interrupted current (amperes) and the recovery voltage (kV). The lab tests reported in this paper indicate that a 0.1 m gap can interrupt a 6 A capacitive current against a 12.5 kV recovery voltage. The above data allows a better estimate of the constant in relation (2):

$$d = 0.0015 \times (\text{kV.A}) \qquad \ldots(4)$$

   Equation (4) should be applicable at least to the shorter gaps.
7. Based on the overvoltage levels of Fig. 8, the paper recommends that the 161 kV circuit be energized prior to energizing the shield wire circuit. Since the automatic reclosing of the 161 kV circuit following a lightning tripout means performing switching in the "wrong sequence", the above precautionary measure does not appear to be adequate. Perhaps a better approach would be to eliminate the resonance condition either by changing the shunt reactance or by adding a small shunt capacitor. In any case, the problem may not be as serious as Fig. 8 suggests because of the following:
   (a) Digital overvoltage studies tend to underestimate the damping and hence exaggerate the overvoltage levels.
   (b) The voltage of the distribution circuit is only about 20% of that of the HV circuit. It is doubtful that this can induce in the 161 kV circuit a voltage high enough to make the subsequent energizing of the 161 kV circuit hazardous.

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F. Iliceto, E. Cinieri, L. Casely-Hayford, G. Dokyi The authors wish to thank the discussor for his comments and appreciation of the paper.

When the single-phase earth-return insulated shield wire schemes presented in the paper were devised, in 1981, aiming to accelerate rural electrification in Ghana, a bibliographical research was at first made, to look for the support of previous experience before starting the application. No literature could be found and it was decided to make the experimental scheme described in the paper prior to the commercial applications. In fact the magazine "Electric Light and Power" (ref. [5]) was not within the electrotechnical bibliography available to the authors. The experimental scheme was mentioned in previous papers by the authors (CIGRE report N. 37-11 of the 1984 Session and ref. [2]); the scheme was also visited by several engineers from other countries, but the authors did not have notice of any previous similar proposal or application until the above discussion was received.

As pointed out in par. 2 of the paper, the scheme has been conceived as a combination of two different techniques applied in the past: insulation of shield wires of EHV lines; single-phase MV distribution with earth return of current. The concept of power distribution from insulated shield wires is thus straightforward. On the other hand, the functional aspects and mutual interaction between HV transmission circuit and shield wire distribution circuit are rather complex phenomena, that have required analysis with an approach usually applied to EHV systems, and field checks.

Without diminishing the credit due to Messrs. D.L. Andrew and P.A. Oakes for their pioneering work, it is to be noted that the information on the 1960 experiment reported in ref. [5], refers only to single-phase distribution from two insulated shield wires of a stretch of a 230 kV line; ref.[5] did not report system analysis and field results; ferroresonance was mentioned as a phenomenon that should not be of concern in the specific application; a BIL of 350 kV was conservatively assumed for the 40 kV step-down transformer supplied by the shield wire.

Concerning question 2 by the discussor, the authors note that the 50 V maximum steady state voltage rise to remote earth adopted for the design of electrodes carrying the ground current, as stipulated by the regulations of the province of Alberta (Canada), is in keeping also with the italian regulations and is deemed sufficiently conservative. In fact, the step and touch voltages are usually a fraction of total voltage to remote earth, Ve. On the others hand, the Table in par. 10.2 of the paper shows that Ve is less than 15 V in three out of five stations of the experimental scheme. The measured step and touch voltages are less than 15 V in all the five stations, as advocated by the discussor.

References of the Ollendorff formula are provided in [9] and [10].

A photograph of the tension strings used in Ghana, with "antiperching" steel blade is shown in Fig. 13.

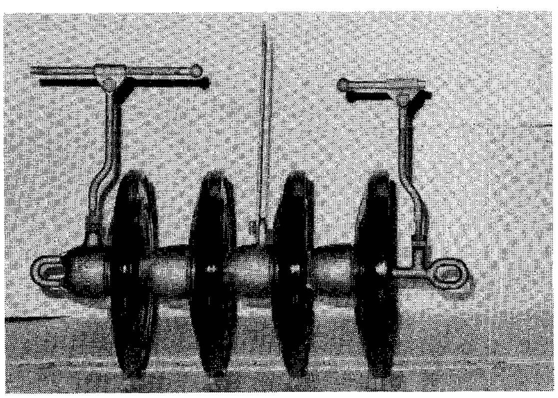

Fig. 13 - Tension strings with "antiperching" steel blade for insulated shield wire lines.

With reference to point 4 of discussion, the authors wish to point out that their statement that "simultaneous tripouts of the 161 kV circuit and the shield wire line have never occurred", is made in par. 10.2 (Operation results) specifically as a field record of the experimental scheme in Ghana, where short circuit currents are low. This is not a general statement. In reality, at the occurrence of a lightning stroke to shield wire or tower peak followed by back flashover of the 161 kV conductors, both circuits will undergo a flashover, regardless of the short circuit current level. Only when the fault current to ground of shield wire circuit is very low, say less than 50-60 A, the follow-up power frequency arc on shield wire has a high probability of self-extinction; if the arc on shield wire self-extinguishes, tripout by the overcurrent protection will not occur because some delay to tripping is provided where fault current is small. This behaviour is typical of the MV lines of the networks with neutral insulated or grounded via a high impedance. There is another possibility of arc self-extinction, where the lightning arc is ignited when the power frequency voltage is close to zero.

The authors agree with the statements (a) and (b) of point 4 of discussion.

As a reply to question 5, it should be noted that the capacitance to ground of each conductor of a MV branch-off line supplied by the shield wire line and carried on separate poles, may be 40 to 60 nF for a 10 km lateral line. This capacitance is in general too small for prevention of ferroresonance. In the Northern Ghana shield wire distribution schemes, capacitors rated at least 600 nF were found necessary. The authors' computer analysis has shown that ferroresonance may occur in conjunction with rare but credible transient phenomena despite the presence in the above cases of capacitors rated over 1200 nF. To avoid rating the capacitors above the values required for power factor correction and avert any risk of persistent overvoltages, it was decided for some of the shield wire lines that the grounding switches installed at the energizing end, will be automatically closed following the opening of the shield wire breaker. This is simply achieved by using, as grounding switches, commercial MV load interrupters equipped with a fast closing mechanism, spring operated.

The authors' test results on the self-interruption of small capacitive currents in air gaps are valid for the specific gap configuration used in the shield wire insulator strings. Performance is more favourable for the horizontal than for the vertical string arrangement. The self-interruption capacity seems to be markedly influenced by the gap electrode configuration and the associated thermal-dynamic actions on the arc.

Although there are hesitations to make a generalized extrapolation of the authors' laboratory results to determine the coefficient in formula (4) of the discussion, there is no doubt that the coefficient assumed in formula (3) is exceedingly conservative. This is confirmed by the extensive operation experience of the MV distribution networks of Italy, that are operated with insulated neutral. Consequently, the single-phase to ground faults cause the circulation of small capacitive currents. Self-extinction of transient line faults occurs in all the cases in the 20 kV networks, if the fault current is 10 A or less, with a recovery voltage of $20/\sqrt{3}$ kV; line insulators have a BIL of 125 kV. The protection relays sensing the ground faults (zero-sequence reactive power directional relays) are delayed 0.3-0.5 s; one reason for delay is to avoid unnecessary line tripouts when the power frequency arc is self-extinguished.

Concerning point 7 of discussion, it should at first be noted that the high overvoltages of curve (a) in Fig. 8, are induced in the shield wires (not in the HV circuit), assumed to be under tension at the moment of 3-phase energization of a 185 km-161 kV shunt compensated line, with a situation of rather sharp resonance, that in practice rarely occurs. This may cause also an increase of the energization overvoltages of the 161 kV conductors (not reported in Fig. 8), owing to the induced charges on 161 kV conductors from the preenergized shield wires.

Concerning the high speed reclosure, only the single-pole reclosure is foreseen in the radial 161 kV system of Fig. 12. The increase of the induced overvoltages in the shield wires due to the above referred resonance is possible also in conjunction with the one-pole re-energization, but has not been analysed in detail. The conservative decision was taken to trip, along with the faulty phase of 161 kV circuit, also the associated shield wires, because the high-speed reclosure is usually successful in case of flashovers caused by lightning, and on the other hand this phenomenon may simultaneously cause the trip-out of the shield wires. The shield wires may be reclosed after the HV conductor, either automatically at high speed (by the same autoreclosing apparatus, with a short delay) or manually by the operators. Some unnecessary trip-outs of shield wire circuits are acceptable, owing to the modest importance of MV in comparison with HV lines.

The discussor's proposed addition of 161 kV capacitors to detune the above resonance condition, without need of opening the shield wires, is not practical; it would cause large expenses and would partially cancel the shunt compensation, that is selected as a trade-off of other more important functional requirements of HV circuits.

The authors agree with the discussor that the overvoltage studies tend to underestimate the damping factors. Field tests of line energization and high-speed reclosure are planned. The assumed operation restriction could be removed, if lower acceptable overvoltages are recorded.

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