ABSTRACT

The paper first describes the technique of 3-phase and single-phase power distribution along HV transmission lines via the insulated shield wires energized at MV (20 to 34.5 kV) from the main HV/MV transformer stations, with ground return of current. The design and operation criteria of shield wire lines which can supply up to 5-6 MW at 34.5 kV to villages/loads at distances up to 100-150 km from the supply station are presented. The latest developments of insulation coordination are presented as well as the operation experience thereof. Application of the high-speed reclosure and possible use of reclosers at intermediate points of shield wire lines are analysed.

10 years' operation experience of shield wire schemes in Ghana is reported. Some information of shield wire schemes implemented in other countries and of schemes at engineering/planning stage is provided.

1. DESCRIPTION OF SHIELD WIRE DISTRIBUTION SCHEMES

There are many minor towns, villages and farms in developing regions which are located along the HV lines supplying the major towns or connecting remote power plants to the system. 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.

The supply of villages by means of capacitively induced voltage on an insulated shield wire of a stretch of HV line is also not feasible where power demand of villages is relatively large and/or a 3-phase supply is required. In fact, this capacitive induction scheme allows only spilling of small single-phase power (say, 0.5 kW per km of a 161 kV single-circuit line). On the other hand, unconventional equipment is needed in each village to keep the supply voltage reasonably constant with variable load.

It has also been proposed to use three capacitor banks connected between each phase of a HV line and ground, instead of an insulated wire, to allow 3-phase supply of a concentrated loads up to 2 MVA. This 3-phase capacitive divider requires a capacitor bank with a kVAR rating of an order of magnitude larger than the load kVA to be supplied. It has voltage regulation problems similar to the capacitive induction scheme. Cost is therefore comparable to that of a conventional T-tapping HV/MV transformer station.

A novel solution has been proposed and applied [1], [2], [3]. It consists of insulating the shield wire(s) from the towers of the HV lines by means of suspension insulators and energizing the wire(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 shield wire(s) and ground for power supply to the load.

The Shield Wire Schemes (SWSs) are shown in Fig.1. SWSs A and B are suitable for single-phase distribution; SWSs C and D require two insulated shield wires and can supply 3-phase loads. If the HV line is provided with one shield wire, only Scheme A is applicable. The SWSs have been developed from a combination of two techniques applied independently in various countries: Use of insulated shield wires in the long EHV lines carrying a large amount of power, to reduce Joule losses caused by the current induced in the steel or alumoweld wires, and/or for power line carrier communications. Application of single-phase single-wire MV distribution lines with ground return of current, to supply small remote loads in rural regions.

The ground return of the current (SWSs A, C, and D in Fig.1) is the most economic concept also in the regions with relatively high soil resistivity, because the cost of grounding electrodes is small in developing countries for the current flow concerned.

The earth return path has a much lower resistance than usual distribution conductors; it is calculated at \(10^{-42}\) \(\Omega/km\), i.e. 0.05 \(\Omega/km\) at 50 Hz, equivalent to a 570 sqmm aluminum cable.

Details on the concept, analysis, compensation and protection of the SWSs are provided in ref. [3], [4], [5]. Only some information is given here.

The ground return SWSs A and C can be supplied directly from the station MV busbars (Fig.1), if the MV feeding system has the neutral solidly grounded, or grounded through either a grounding transformer or a neutral rector of low impedance.

In SWS B, referred to in the following as "Single-Phase Metallic- Return" the earth-return of the current is avoided. It is supplied by two phases of station MV busbars and requires two insulated shield wires, from which the MV/LV distribution transformers are branched off.

SWS C, referred to as "V" Scheme, requires two insulated shield wires energized from two phases of a MV network. There are two single-phase MV/LV transformers branched from each shield wire and ground in part of the distribution stations. The secondary windings are open-delta connected ("V" connection), thus providing, at no-load, a symmetrical 3-phase source that enables the supply of a small amount of 3-phase load in addition to single-phase loads. The LV grounding transformer connected at the secondary terminals of "V" transformers (Fig.1-C), creates the neutral for supply of LV single-phase consumers between one phase and neutral. Where only single-phase loads are to be supplied, one MV/LV single-phase transformer only is installed, branched from one shield wire and ground.

SWS D is referred to as "3-Phase" Scheme. The two insulated shield wires and the ground return path form a 3-phase circuit that is unbalanced, the ground return being used as the 3rd phase conductor. The resistance of the earth conductor is much smaller than the resistance of any practical shield wire cable; the reactance of the earth conductor is usually slightly smaller [3]. The capacitance between wires is much smaller than the capacitance between each shield wire and ground. The concept is to make the "3-Phase" line formed by the two shield wires and the earth path symmetrical, with simple compensating components:

- a series resistor-reactor in the earth path (R-L, in Fig.1-D) so as to raise the earth path voltage drop to about the same value as the voltage drop on shield wires;
- a p.f. correction capacitor branched between the two wires (\(C_{ww}\) in Fig.1-D) somewhat larger than the p.f. correction capacitors branched from each shield wire and ground (\(C_{wo}\) in Fig.1-D), so as to raise the wire-to-wire total capacitance to the same value as the wire-to-ground capacitance.
An alternative lossless compensation scheme which has higher initial cost is also feasible [5].

The supply of “3-Phase” shield wire lines (SWLs) is feasible in two ways:
• From a dedicated MV winding of a HV/MV step-down transformer (Fig. 1-D), operated with one terminal grounded via the compensating R-L circuit (or solidly grounded in short or lightly loaded SWLs where the R-L circuit is not needed). The SWL is switched and protected by a 2-pole circuit breaker (CB).
• Via a MV/MV interposing transformer (Ti) supplied by the MV (10 to 34.5 kV) station busbars. Ti provides the suitable voltage for the SWL (usually 34.5 kV, i.e. the highest of MVs, for the long SWLs); Ti also allows grounding one terminal via the R-L circuit. Several Tis applied in the SWSSs in existence have a rated power of 2 to 7 MVA. A standard feeder CB is used on the supply side of Ti, for switching and protecting as one block the Ti and SWL (no CB is used on SWL side; see Fig. 6).

The “3-Phase” SWS supplies MV/LV distribution transformers operated with one MV terminal permanently grounded (Fig.1-D). This SWS can supply 100% 3-phase load, as a conventional 3-phase distribution feeder. Where desired, it can also be used for single-phase distribution, via MV/LV transformers branched from one shield wire and ground and from the two shield wires. The “3-Phase” SWS absorbs a balanced load from the HV transmission system, if distribution load is balanced.

Capacitors $C_{wo}$ and $C_{ww}$ perform three functions: p.f. correction, prevention of ferroresonance, and circuit balancing in SWS D. These functions and the one of the fast closing grounding switch are described in ref. [3] and [5].

In some cases the communities or farms to be supplied are located at some distance from the HV line route. Supply is then made via lateral MV lines, equipped with one conductor for the “Single-Phase Ground-Return” SWS or with 2 conductors for the “V” or “3-Phase” SWS. The length of lateral lines built so far has been up to 20 km from take-off tower of HV line.

The grounding system for earth-return of current is described in [3]. The largest current flows in the grounding system of the HV/MV substations supplying the SWLs. This does not pose problems because the extensive meshed grounding system of stations generally has a resistance not exceeding 1 or 2 $\Omega$. Fig. 2 shows the arrangement of the “3-Phase” SWS distribution in a village. The grounding system for earth return and its separation from the grounding system of LV networks are also shown.

2. ANALYSIS AND DESIGN CRITERIA OF SWSs

The SWLs are operated as the conventional MV distribution feeders. The “3-Phase” SWL (Fig. 1-D) has practically the same power distribution capability of a conventional MV long feeder of same rated voltage, with conductors of same ohmic resistance.
However, the steady-state and transient analyses of SWSs are somewhat complex, owing to the electromagnetic coupling with the HV circuit, to the earth return of current and to the unbalanced nature of the "V" and "3-Phase" SWLs.

The experience gained in over 10 years of commercial operation of several SWSs in tropical countries allows a drastic simplification of the design analyses for new applications. The same requirements of conventional very long MV radial feeders should be fulfilled, i.e.: a) limitation of voltage drop at remote end; b) conductor current carrying capacity at temperature limit must not be exceeded; c) economic optimization (Joule losses and initial investment); d) quality of supply (voltage stability for very long SWLs; reasonably low rate of interruption).

An additional technical requirement for SWLs is: e) limitation of the negative-sequence voltage component, $V_2$, at the sending end only, to limit $V_2$ anywhere within 1.2% for SWL length up to 100 km. For uniformly distributed loads, the $R+jX$ grounding circuit that minimizes the weighted mean value of $V_2$ along the SWL is rated at about 1/3 of the difference of the series impedances of a shield wire and the earth return path. The effect of electromagnetic induction of HV circuit on SWL (voltage drop; $V_2$) are computed by simulating the HV circuit as normally transposed with a power flow from no-load to SIL; the shield wires are not transposed.

The supply MV of SWLs is assumed to be regulated by means of the on-load tap-changers of transformers from 1 p.u. at no-load up to 1.05 p.u. at full load. The curves of Fig. 3 have been plotted for a voltage drop on SWL of 7.5% from no-load to full load.

Switching and lightning overvoltages have been extensively investigated in the early years of application of SWSs with the EMTP, by using conservatively the methods applied to EHV systems [2] [3] [5]. The knowledge of overvoltages gained from these analyses, validated by many years of operation experience, allows insulation coordination of new SWSs, without repeating for each application the transient analyses of most phenomena.

3. INSULATION OF SWSs

Basic concepts on insulation coordination have been presented in ref. [3] and [5]. It should be noted that the earth-return SWSs are either MV systems with solidly grounded neutral (SWSs A and C, Fig.1) or MV systems with one phase permanently grounded via a low impedance or solidly ("3-Phase" SWS). This allows transformers to be protected effectively with surge arresters (SAs).
An operational rule is that the SWLs should be grounded at the sending end when they are not energized. The fast automatically closing grounding switch at the sending end of SWL assures that it can not remain at floating potential, except for a very short time.

Insulation coordination of SWSs requires attention to be given to the temporary overvoltages induced in the SWL during the 1-Φ-to-Gr faults in the HV circuit, that are approximately proportional to the inducing fault current, \( I_1 \) (kA rms symm.) and to the SWL length, \( L \) (km). If \( I_1 \geq 0.5 \text{ kA} \), the induced overvoltages do not exceed 1.5 p.u.. In these conditions, "\( V \)" and "Single-Phase Ground-Return" SWSs can be implemented with the same insulation levels and SAs applied in conventional MV networks with solidly grounded neutral operated at same 34.5 kVrms. This MCOV assures a sufficient margin above the max. allowed MCOV (max. continuous operation voltage capability) of 55-56 kVrms and a MCOV (max. continuous operation voltage capability) of 38-39 kVrms. This MCOV assures a sufficient margin above the max. allowed \( \Phi \)-to-Gr operation voltage of a 34.5 kV SWL, i.e. 36 kV. In conclusion, commercial SAs rated at 48 kV are safely applicable to 34.5 kV “3-Phase” SWSs.

Main and distribution transformers are protected by SAs. In “3-Phase” SWSs the short duration (<1s) temporary overvoltages can reach 1.5-1.6 p.u. (see Table II), i.e. 52-55 kVrms for a 34.5 kV SWS. Commercial SAs with rated voltage of 48 kV have a TOV (1-s temporary overvoltage capability) of 55-56 kVrms and a MCOV (max. continuous operation voltage capability) of 38-39 kVrms. This MCOV assures a sufficient margin above the max. allowed \( \Phi \)-to-Gr operation voltage of a 34.5 kV SWL, i.e. 36 kV. In conclusion, commercial SAs rated at 48 kV are safely applicable to 34.5 kV “3-Phase” SWSs.

These SAs possess a 10 kA lightning impulse protection level (LIPIL) of 120-130 kVpeak and a 0.5 kA switching surge protection level (SSPL) of 94-100 kVpeak. Equipment, in particular transformers, with a BIL of 200 kV and a 60s - 50/60 Hz withstand voltage of 82.5 kVrms are suitable for operation at 34.5 kV \( \Phi \)-to-Gr and are adequately protected by the above considered SAs. It should be noted that the MV windings of distribution transformers with a BIL of 200 kV can be manufactured with enameled wire, i.e. with the conventional technology of 34.5 kV/MV/LV transformers and the extra cost is therefore very small. The BIL of 200 kV is a standard for conventional 34.5 kV transformers in some countries.

Table I shows that the energization and high-speed re-energization overvoltages of “3-Phase” SWLs do not exceed respectively 1.6 p.u. and 1.85 p.u., if the MV/LV transformers and associated SAs are preconnected to SWL. Energization overvoltages do not exceed 2.1 p.u. if only the SWL is energized. The above specified insulation levels of “3-Phase” 34.5 kV SWLs and distribution equipment are therefore suitable for application. A SA rated at 48 kV has a rated energy capability of 150-200 kJ. Table II shows the energy dissipation in SAs is a small fraction of the capability of most overvoltages. Energy capability could be exceeded only in the case of a contact between one conductor of the HV circuit and a shield wire, if fault is not cleared quickly. This event has never occurred in the operation of the SWLs so far.

In summary it is worth noting that in the “3-Phase” SWS the increase of phase-to-Gr operation voltage by a factor 1.73 in...
comparison with a conventional 34.5 kV distribution system, requires an increase of equipment insulation by a factor of only 1.15-1.20 above the standard levels for 34.5 kV equipment.

These results have been validated by the operation experience in Ghana (see par. 5). The SWS Techiman-Aboofor (Fig.6) was originally a "V" 34.5/√3 kV scheme; equipment had a BIL of 170 kV and a 60s - 50 Hz test voltage of 70 kVrms. This SWS was converted into a "3-Phase" scheme in 1995, with rated voltage of 30 kV, without replacing the 170 kV BIL distribution equipment, the MV lateral lines, etc. Only SAs and transformers were replaced to fit with the higher operation voltage and transformers' ratio. In the SWL, the horn gap of insulator strings has been increased from 23 cm to 30 cm, and an interposing transformer was installed at the sending end. Comparison of operation results before and after the transformation, shows some reduction of transient faults of "3-Phase" SWL and no failures at all in equipment.

4. APPLICATION OF HIGH-SPEED RECLOSURE AND RECLOSERS IN "3-PHASE" SWFS

The operational experience of SWLs shows that practically all the faults are of a transient nature (see par. 5.3). The High-Speed Reclosure (HSR) would therefore be very effective. For a very long SWL the HSR can be compounded by installing reclosers along the SWL, coordinated with the CB at the sending end.

An EMTP study has been performed for some "3-Phase" 34.5 kV SWLs planned for construction in Laos, in particular for a 97.6 km SWL (Fig. 4, from station B to S). The HV line will be operated at 115 kV, will have phase conductors in a triangular configuration and two shield wires with a shielding angle of 15°. The installation of a recloser at 29.4 km from the supply station B (Fig. 4) is being considered. The recloser divides the SWL in two parts with the design total loads indicated in Fig. 4.

The SWL has been simulated in the initial operation, with MV/LV transformers protected by SAs which have a rated voltage of 48 kV. The SWL is equipped with antiferroresonance/p.f. correction/balancing capacitors split in two banks, up-stream and downstream of the recloser, each rated at 2x85 kVAR (wire-to-Gr)+1x112.5 kVAR (wire-to-wire). A small active load has been also simulated (5% of the year 2001 load forecast, i.e. about 2% of design loads shown in Fig. 4). The 3-winding transformers of stations A and B have the winding connection as per Fig.1-D.

Analyses have been carried out for all the significant combinations of fault location, SWL and HV phases involved, operating sequences of recloser and CB of HV circuit. Attention has been focused on the behaviour of the system during the reclosure delay, secondary arc extinction, TRVs and possible cases of induced temporary overvoltages on the disconnected, "floating" shield wires. If the SWL is operated at no-load, the impedance to ground is the magnetizing reactance of the MV/LV transformers connected between the SWL and ground, in parallel with the capacitance to ground of the wires (C10 and C20 in Fig. 1-D). If the overall impedance between shield wires and ground happens to be inductive, the capacitive coupling with the HV circuit can give rise to overvoltages, liable to evolve into ferroresonance due to the saturation of the MV/LV transformers.

The following results have been found:

- Secondary arc currents have values which, on the basis of experience, always self-extinguish.
- During the "worst-case" conditions of the HSR performed by the CB of the SWL or the recloser, with open-phase conditions in both the SWL and HV circuit (following a 1-Φ-to-Gr short circuit on both the SWL and the HV circuit; see Fig.5-a), the highest calculated overvoltage is 1.32 p.u. (65 kV). Even when the SWL is simulated in the unrealistic condition of no-load, there is no build-up of ferroresonance.
- In the case of a 1-Φ-to-Gr or Φ-to-Φ-to-Gr fault in the SWL at the same time as a 1-Φ-to-Gr fault in the HV circuit, relatively high values of TRVs build up across the interrupting device, be it the CB at sending end of SWL or a recloser installed along the SWL (Fig. 5-b): TRVs reach 1.95 p.u. (95 kV) after 36 ms. This occurs with the SWL secondary arc still burning in faulty phase.
- The max. re-energization overvoltages (1.85 p.u., see Tab. I), are consistent with the insulation.

Some commercial 36kV and 40.5kV CBs possess a 1.2/50 µs impulse withstand voltage of 200 kV and a 50Hz-1 minute withstand voltage of 100 kVrms dry (80 kVrms wet). These insulation levels are sufficient for the 3-phase SWFs operated at 34.5 kV phase-to-ground. The TRVs capabilities, to be checked, should be sufficient, taking into account that the short-circuit current is small on SWFs (≤5 kA).

If commercial 36 kV reclosers do not comply with the insulation and TRVs requirements, CBs should be used instead.

In case of recloser installation, part of capacitors must be connected downstream of the recloser, to prevent the onset of ferroresonance in open-phase conditions. SAs are also effective in limiting the open-phase overvoltages, because the energy dissipated by them is much less than their thermal capability.

The above results confirm the feasibility of HSR for both the SWL circuit breaker and the recloser. The simulated means for eliminating the risk of overvoltages (capacitors, SAs and small load) are redundant.
5. 10-YEAR OPERATION RESULTS OF SWSs IN GHANA

5.1 General information

In Ghana (West Africa) the shield wires have been insulated in about 1000 km of 161 kV transmission lines, mostly equipped with two shield wires. The first SWS, a "V" Scheme, was commissioned in 1985. The operation results are reported here for the 5 SWSs of Fig.6, in service for about 10 years in the very long 161 kV transmission line supplying Central-Northern Ghana.

Three SWSs are "3-Phase" schemes, supplied via an interposing transformer (Ti) and operated at 30 kV. These SWSs supply several 3-phase motors rated from 50 to 100 kW (water pumping stations; saw mills; etc.).

Two SWSs are "V" schemes operated at 34.5/√3=20 kV wire-to-ground (34.5 kV wire-to-wire). These SWSs mostly serve single-phase domestic-commercial loads and 5-10% of 3-phase motor loads (corn mills; etc.).

The SWSs of Fig. 6 currently supply a total load of about 6500 kW, providing electricity to an estimated population of 150,000. Power is distributed via 88 MV/LV transformers, all but two being pole mounted. The largest load is at Kintampo (20,000 inhabitants); currently, 1530 kW served by 15 transformers.

5.2 Outage rate of 161 kV lines with insulated shield wires

The 161 kV lines of Northern Ghana with two insulated shield wires, represented in Fig. 6, are single-circuit with conductors in a triangular configuration and 15° shielding angle (see tower outline in Fig.1). Lines are partly routed in hilly densely forested regions and partly in savannah; the kereaual level is high.

In the last 3-year period (1996-98) the three 161 kV lines shown in Fig.6, with a total length of 527 km (of which 480 km with insulated shield wires) have undergone, on average, 2.1 outages per 100 km per year due to transient faults, mostly caused by lightning. The outage rate is higher in the forested areas than in the savannah. Since the HSR is not in service, lines were re-energized manually a few minutes after trip out.

In the region of Kumasi, where the lines with insulated shield wires originate (Fig.6), there are other 161 kV lines of the same design, except that the two shield wires are grounded at each tower. These lines have undergone in the same period, on average, 4.6 outages per 100 km per year due to transient faults.

Operation records for 10 years confirm that the insulation of the shield wires by no means worsens the lightning performance of the HV lines, as expected at the design stage [3]. Actually, the 10-year records in Ghana have constantly shown a lower outage rate in the 161 kV lines with insulated shield wires than in conventional comparable lines. One reason for this better performance may be the care given in the realization of tower grounding of the very long 161 kV radial Northern line of Ghana (Fig.6), for the achievement of a reasonable continuity of service. Another reason may be that the conventional lines considered for the comparison are mostly routed in forested areas, while one part of the lines with insulated shield wires is routed across savannah.

5.3 SWLs insulation performance and outage rate

The 480 km of SWLs in operation for about 10 years (Fig.6), as well as the associated 161 kV circuits, have never undergone a permanent fault.

In the last 3-years (1996-1998) the SWLs have undergone, on average, 29 outages per 100 km per year due to transient faults, mostly caused by thunderstorms. The SWLs have been re-energized manually by the operators, usually 5 minutes after the trip-out, because the HSR is not yet applied.

In the same region of Ghana where the SWLs are in service, there are also 34.5 kV conventional lines originating from the same busbars which supply the SWLs. The 120 sqmm AAC conductors of these lines are supported via suspension insulator strings (3 caps and pin glass insulators) from steel towers with an average span of 235 m; lines are protected by one shield wire. In the last 3 years, the longest of these lines (119 km) has undergone, on average, 52 outages per 100 km per year due to line faults, i.e. 1.8 times the outage rate recorded for the SWLs. About 7% of the faults of conventional MV lines have been of permanent nature (fallen trees; broken shield wire; etc.) requiring, on average, one day for each repair work.

On the basis of experience of the HSR of MV lines in Europe, it can be expected that application of the single-shot HSR of SWLs should lower the outage rate by 70 to 80%, i.e., outage rate should be reduced to less than 10 per 100 km per year.

The reasons for the lower outage rate of SWLs than of conventional equivalent MV lines, and of the absence so far of permanent faults in SWLs, are the same as reported in ref. [5].

Arcing across rod-gaps has always extinguished immediately after line trip-out. Switching of the SWLs and of the 161 kV circuits has never caused a shield wire insulation flashover. SWLs practically require no maintenance (clearing of right-of-way, etc.), since it is performed for the HV line.

5.4 Earth return of current

Multiple grounding rods paralleled via a ground conductor are installed in the villages, in the short MV lines (0.3 to 3 km long) connecting the SWL to the MV/LV transformers, as shown in Fig.2. One rod every 3 or 4 poles is installed, in addition to the normal grounding system of take-off HV tower and of MV/LV transformer stations. This arrangement has provided excellent results with modest cost, also where soil resistivity is rather high.

The measured values of potential of ground electrodes to remote earth, V_e, at the end of the dry season does not exceed

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Fig.6: Single-line diagram of the insulated SWSs in operation in the Northern Ghana 161 kV-527 km long transmission line.
25V at peak load (usually, \( V_e \leq 15V \)). Touch and step voltages do not exceed 7 V (are usually less than 3V). The ground resistances were found in the range from 0.3-0.5 \( \Omega \) in the HV/MV supply substations up to a maximum of 3.5 \( \Omega \) in one village.

The grounding system for earth return of current is independent from the grounding system of the LV distribution networks. The latter is made with multiple rods along the LV feeders as shown for one LV feeder in Fig.2 (transformer LV neutral is not grounded at the MV/LV stations). Induced potential on the neutral of LV networks is generally found lower than 5% of the measured value of \( V_e \) at the site.

5.5 Performance of Power Line Carrier (PLC) telecommunications and line distance relays

PLC is used in the 161 kV Northern lines with insulated shield wires, with the same functions as in all the other lines in Ghana (voice communication; transfer tripping signals for protection; SCADA system). The Northern line is radial and a multi-hop PLC transmission is utilized to the National Control Center.

Operation experience of PLC on the main conductors of the 161 kV lines with insulated shield wires energized at MV is very good, in agreement with the results of the analysis performed at the engineering stage.

Operation of line distance protection relays also proved to be correct. Insulation of shield wires had been taken into account in the calculation of line constants and relay setting.

5.6 Quality of service to consumers

The quality of service to consumers has been good, equivalent or better than the service from conventional 34.5 kV overhead radial lines of same length.

Voltage at the secondary terminals of MV/LV transformers throughout the whole scheme is stable and is in the range from 230 V to 245 V for single-phase supply at the nominal voltage of 240 V. Three-phase motor supplies are affected by variations within ±5% above or below rated voltage.

The negative sequence component of voltage at all customers' supply points is generally 0.4 to 0.6% (always less than 1%) in the "3-Phase" SWSs. It is from 0.7% to 2% in the "V" SWSs.

Voltage drop is only a few percent at start-up of a 75 kW motor at Buipe (remote end of a 104 km long SWL; Fig. 6).

5.7 Equipment performance

No equipment failure has occurred during about 10 years' operation of the SWSs of Northern Ghana (Fig. 6), except in one small LV dry-type grounding transformer of a "V" SWS (applied as shown in Fig.1-C) due to a loose connection.

Use of MV zinc oxide surge arresters to protect all the MV/LV transformers has certainly contributed to the non-occurrence of any failure in these transformers.

In view of the exposure to frequent lightning flashovers of SWLs, as well as conventional 11kV-34.5kV overhead lines, the standardized HV/MV step-down transformers and interposing transformers (Tm and Ti in Fig.6) have been prototype tested to withstand the short circuit current electrodynamic stresses.

6. APPLICATION OF SWSs IN OTHER COUNTRIES

A supplementary justification of the SWs is that it is an effective deterrent to vandalism and theft, because the communities along the HV line also take advantage of electricity supply.

"3-phase" 34.5 kV SWSs are in operation in 230kV-60Hz lines in Brazil (Mato Grosso and Rondonia States [6]). One of these SWSs supplies a load of 4.3 MW located 85 km away from the supply station of SWL.

Three "Single-Phase Ground-Return" 25 kV SWS are in operation in 190 km of 115 kV-50 Hz lines in Laos.

"3-Phase" 34.5 kV SWLs have been implemented in the first 161 kV-50 Hz line in Sierra Leone. One SWL will supply the town of Makeni (4.5 MW) and will also be used for PLC communications. These SWSs are not yet in service due to the revolutionary turmoil in the country.

SWSs to be operated at 34.5kV will be implemented in two 132 kV lines and are planned for an existing 230 kV line in Ethiopia. To ease the application of the "Single-Phase Ground-Return" SWS in existing lines with one shield wire, post type composite insulators will be fitted on top of tower peaks.

Several SWSs, mostly with the "3-Phase" scheme, are planned for construction in Togo, Benin and in Laos, and are considered for application in Tanzania.

A study has shown in principle the feasibility of SWLs by insulating ground wires incorporating fiber optics (OPGWs).

7. CONCLUSIONS

The SWSs dealt with in the paper allow electricity supply to communities located along, or not far from, the HV transmission lines with very little installation and maintenance costs.

10 years' extensive operation experience in Ghana has confirmed the viability of the SWs, which provide a quality of service to consumers not inferior to the one of equivalent MV lines.

Application of the high-speed reclosure to SWLs is proven to be feasible and should eliminate most of transient outages.

Several other SWSs have been implemented in Brazil, Laos, Sierra Leone, and are planned in Togo, Benin, Ethiopia, Tanzania.

REFERENCES

Energization overvoltages of SWL (1 p.u. = √2 V_n)

<table>
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</table>

V_{max} [p.u.] \rightarrow V_{mean} [p.u.] \rightarrow \sigma [p.u.] \rightarrow 1.59 \quad 1.85 \quad 2.65 (a)  
V_{mean} [p.u.] \rightarrow V_{mean} [p.u.] \rightarrow \sigma [p.u.] \rightarrow 0.86 (b) \quad 0.90 (b) \quad 1.66 (d)

HSR switching overvoltages of "3-Phase" SWS (Sierra Leone) (1.p.u. = √2 34.5 kV)

<table>
<thead>
<tr>
<th>Case</th>
<th>V_{max} [p.u.]</th>
<th>V_{mean} [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.80</td>
<td>0.158</td>
</tr>
<tr>
<td>II</td>
<td>1.90</td>
<td>0.137</td>
</tr>
<tr>
<td>III</td>
<td>0.85</td>
<td>0.129</td>
</tr>
</tbody>
</table>

I: 1-phase-to-Gr fault in the SWL, followed by 3-phase opening and HSR.
II: 1-phase-to-Gr fault, simultaneous on same tower in the SWL and 161 kV circuit, followed by 3-phase HSR of SWL and 1-phase HSR of 161 kV circuit.
III: 3-phase trip-out of the SWL, followed by HSR. No fault or switching on 161 kV circuit.

Switching overvoltages on SWL due to the energization of HV circuit

<table>
<thead>
<tr>
<th>SWS</th>
<th>&quot;3-Phase&quot;</th>
<th>&quot;V&quot;</th>
<th>Single-Phase Ground Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>V [p.u.]</td>
<td>Vmean [p.u.]</td>
<td>σ [p.u.]</td>
</tr>
<tr>
<td>1.59</td>
<td>1.85 (a)</td>
<td>0.90 (b)</td>
<td>1.66 (d)</td>
</tr>
<tr>
<td>0.86</td>
<td>0.90 (b)</td>
<td>0.33</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Temporary overvoltages of SWL and energy dissipated on SAs

<table>
<thead>
<tr>
<th>SWS</th>
<th>&quot;3-Phase&quot;</th>
<th>&quot;V&quot;</th>
<th>Single-Phase Ground Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>V [p.u./kJ]</td>
<td>Vmean [p.u./kJ]</td>
<td></td>
</tr>
<tr>
<td>1.51</td>
<td>1.50 (a)</td>
<td>1.16 (e)</td>
<td></td>
</tr>
<tr>
<td>1.60</td>
<td>2.25 (b)</td>
<td>1.68 (e)</td>
<td></td>
</tr>
</tbody>
</table>