

THREE-PHASE AND SINGLE-PHASE ELECTRIFICATION IN DEVELOPING COUNTRIES USING THE INSULATED SHIELD WIRES OF HV LINES ENERGIZED AT MV

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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 loads.

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 $10^{-42} f (\Omega/\text{km})$, i.e. 0.05 Ω/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 reactor 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.

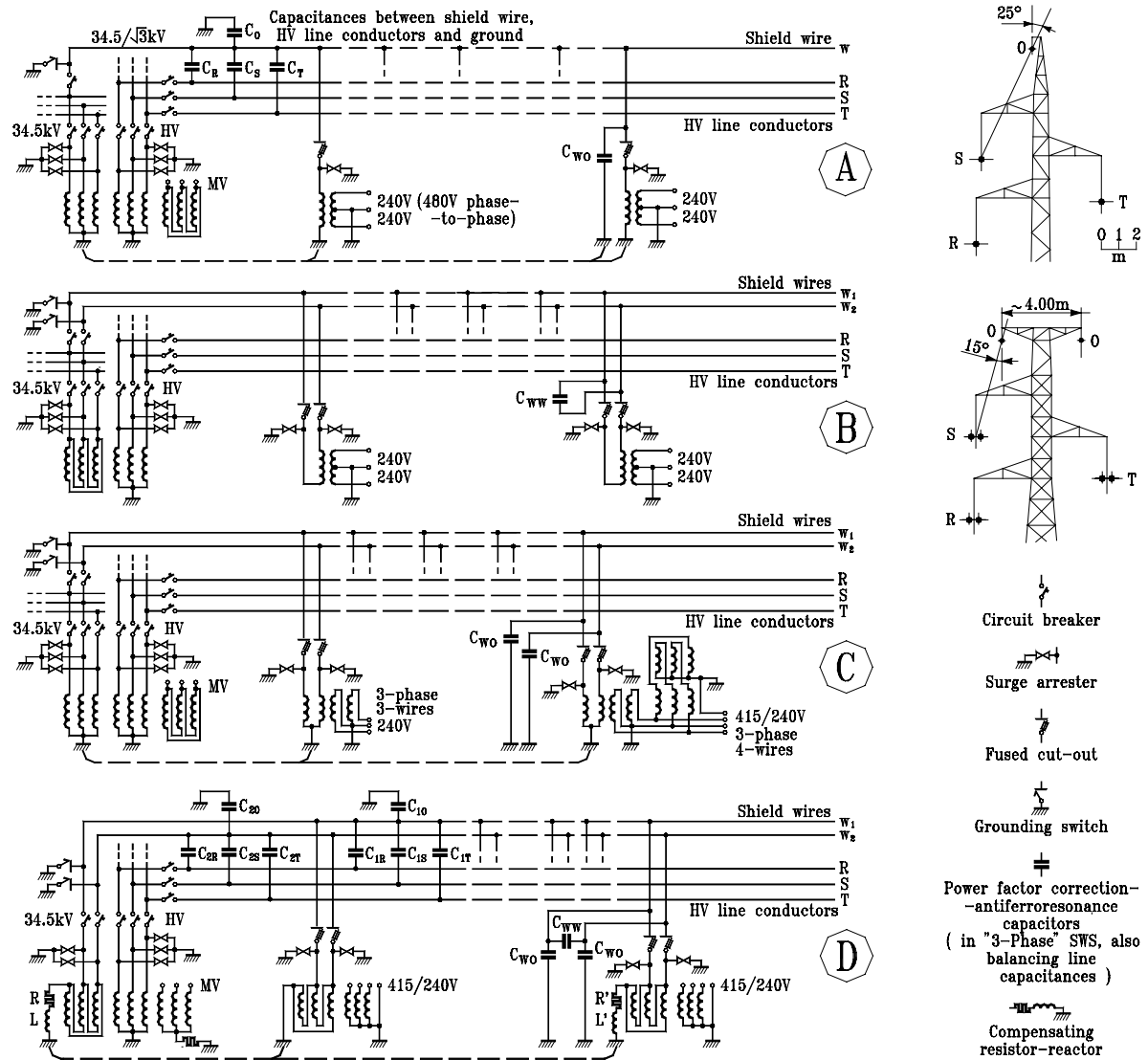


Fig.1- SWSs applicable to a HV (115 to 230 kV) single-circuit line: A = Single-Phase Ground-Return (typical line tower is shown on top right); B = Single-Phase Metallic-Return; C = "V" SWS; D = "3-Phase" SWS (typical line towers for SWSs B, C and D are shown on middle right).

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 SWSs 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 Ω . 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.

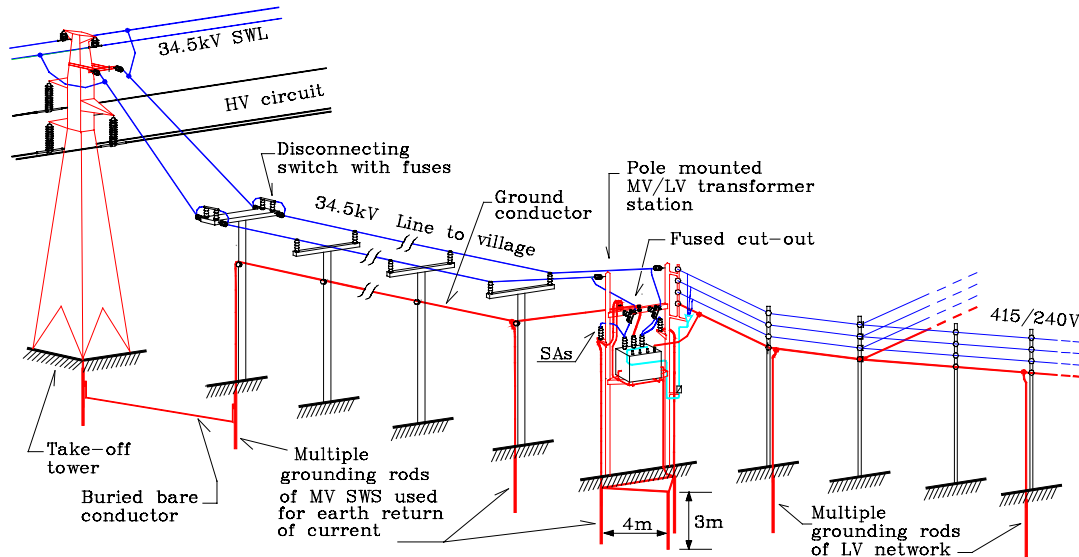


Fig. 2 - Circuit schematic of "3-Phase" SWS distribution in the villages, showing independent earthing of MV and LV networks.

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.:

- limitation of voltage drop at remote end;
- conductor current carrying capacity at temperature limit must not be exceeded;
- economic optimization (Joule losses and initial investment);
- quality of supply (voltage stability for very long SWLs; reasonably low rate of interruption).

An additional technical requirement for SWLs is:

- limitation of the negative-sequence voltage component, V_2 , at all 3-phase customers' premises, generally within 1% of positive sequence voltage (in no case to exceed 2%) in keeping with the regulations for conventional distribution.

For balancing of SWLs, the criterion that has been followed is to apply only solutions that require simple conventional schemes and equipment, entirely devoid of power electronics devices, to provide a reliable service with ordinary operational methods.

Initially the steady-state analysis of the SWSs was performed with the Electromagnetic Transients Program (EMTP). A new method [4] was set up in 1989 for the "V" and "3-Phase" SWLs in order to speed up the calculations of steady-state operation. The method is based on the use of symmetrical components for the system of the two shield wires and the earth return. Two computer programs have been prepared for calculation of the normal operating conditions, of power frequency temporary overvoltages and overcurrents, and optimization of the compensation means.

At the time of writing research is under way by the authors at Rome University for the numerical simulation of a 3-phase system, in particular of SWSs, with any number of asymmetries, in power frequency steady-state conditions, without use of the symmetrical components.

The "3-Phase" SWS has been the most frequently applied. Steady-state analysis allows calculation of locations and ratings of grounding resistor-reactor, and of p.f. correction capacitors performing also the antiferroresonance and balancing functions; the optimal choice of supply phases of the two insulated shield wires is made for minimizing the imbalances.

The "Single-Phase Ground-Return" SWS has been applied in HV lines provided with one shield wire. Only in exceptional cases

(supply from busbars with very low short circuit power) a compensating circuit formed by two MV capacitors and one reactor delta connected, may be required for lowering V_2 at supply busbars to less than 1%.

Parametric analyses of the power carrying capability of SWLs have been presented in [3] and [5]. Fig. 3 shows typical loading capabilities versus length of the "3-Phase" SWSs with rated voltage of 34.5 kV. Two sizes of ACSR shield wires are considered, with loads uniformly distributed or concentrated at the remote end. Capacitors are installed partly at 60% of SWL length from sending end, and partly at sending or receiving end for loads respectively distributed or concentrated. To prevent ferroresonance [3], [5], it is sufficient to install p.f. correction capacitors with a 3-phase kVAR rating of about 25% of the total kVA rating of the MV/LV transformers supplied by the SWL.

An optimized R+jX grounding circuit has been simulated 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 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 of 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).

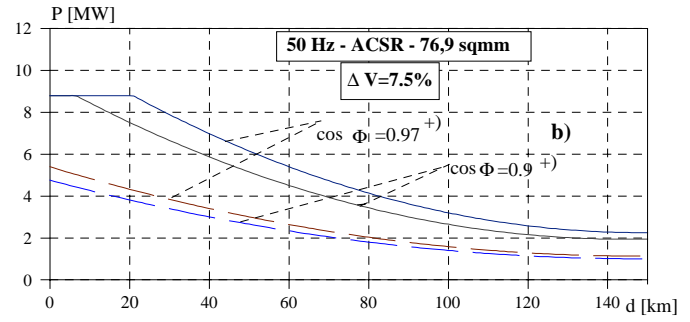
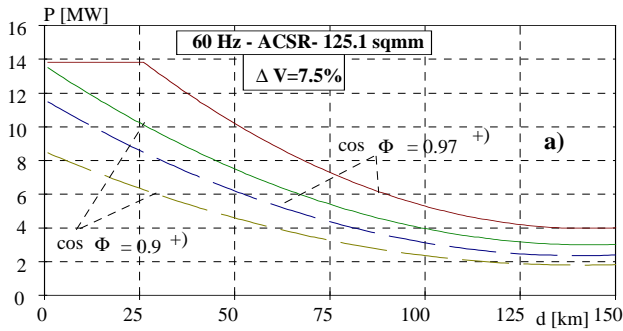


Fig 3 -Loading capability of 34.5 kV "3-Phase" SWLs: **a)** SWLs in 230 kV-60 Hz lines (Brazil) with ACSR shield wires code Penguin: $S=125.1 \text{ sqmm}$; $d=14.31 \text{ mm}$; $r_{40^\circ\text{C}}=0.287 \Omega/\text{km}$; **b)** SWLs in 161 kV-50 Hz lines (Ghana and Sierra Leone) with ACSR shield wires: $S=76.9 \text{ sqmm}$ ($S_{al}=48.57 \text{ sqmm}$; $S_{st}=28.33 \text{ sqmm}$); $d=11.35 \text{ mm}$; $r_{40^\circ\text{C}}=0.646 \Omega/\text{km}$

———— Distributed load ----- Concentrated load; +) load power factor on LV side of MV/LV transformers

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, $I_{1\Phi}$ (kArms symm) and to the SWL length, L (km). If $I_{1\Phi} \times L \leq 200\text{-}250$, 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 Φ -to-Gr voltage; i.e. for a SWS supplied by a 34.5 kV network: 1.2/50 μs impulse test of 170 kV; 60 s -50/60 Hz test of 70 kVrms; SAs with rated voltage of 30 kV.

Insulation design and coordination of "3-Phase" SWSs has required special analyses, the Φ -to-Gr operation voltage being equal to Φ -to- Φ voltage. It is performed on the basis of the calculated temporary and switching overvoltages. Tables I and II summarize the results of the EMTP analyses carried out for various "3-Phase" SWSs.

Table I-"3-Phase" SWSs-Typical energization and re-energization overvoltages on shield wires (1 p.u.= $34.5\sqrt{2}=48.8 \text{ kV}$)

	Energization overvoltages		Re-energization overvoltages
Vmax [p.u.] →	1.60	2.10	1.85
Vmean[p.u.] →	1.31 (a)	1.60 (b)	1.46 (c)
σ [p.u.] →	0.19	0.19	0.125

a) With: MV/LV transf.s, SAs, loads -b) Without: MV/LV transf., SAs, loads

c) 1- Φ -to-Gr fault, simultaneous on same tower in the SWL and HV circuit, followed by 3-phase HSR of SWL and 1-phase HSR of HV circuit; with MV/LV tranf.s and SAs.

Table II - "3-Phase" SWSs-Temporary overvoltages, V, and energy dissipated in SAs, E, due to 1- Φ -to-Gr faults on HV circuit and to contacts between HV circuit and SWL (1 p.u.= $34.5\sqrt{2}=48.8 \text{ kV}$)

1- Φ -to-Gr short circuit on HV circuit, $\Delta t=0.1 \text{ s}$ V[p.u.]/ E[kJ]	Contact between HV circuit and SWL, $\Delta t=0.1 \text{ s}$ V[p.u.]/ E[kJ]
1.51/4.6 (a)	1.60 / 47 (a)

a)With MV/LV transformers and SAs

Insulation of "3-Phase" SWLs has been made so far with rigid string glass insulators suitable to withstand the operation voltage (under rain; with pollution where applicable), and the temporary and switching overvoltages calculated with the MV/LV transformer stations connected (normal operation), as well as all

disconnected (commissioning; tests). In the latter case, SAs are not connected along the SWL.

For the wire-to-Gr operation voltage of 34.5 kV, an insulator string formed by 4 discs with diameter of 255 mm, spacing (from coupling with tower U-bolt and coupling with suspension clamp) of 550 mm, and the following characteristics is applied:

- Wet 50 Hz-60 s withstand voltage 130 kVrms⁺)
 - Dry 1.2/50 μs impulse withstand voltage 270kVpeak⁺)
 - Creepage distance 1200 mm
 - Electromechanical failing load $\geq 50 \text{ kN}$
- +) without arcing horns

Each insulator string is protected by arcing horns with an adjustable distance in the range 20-36 cm, which prevent damage of insulators and fittings by lightning/power arcs. Gap distance is set at 30 and 33 cm for operation at 30 and 34.5 kV wire-to-Gr.

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 Φ -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 (LIPL) of 120-130 kVpeak and a 0.5 kA switching surge impulse 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 Φ -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/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 for 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-Abofoor (Fig.6) was originally a "V" 34.5/ $\sqrt{3}$ 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" SWSs

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.

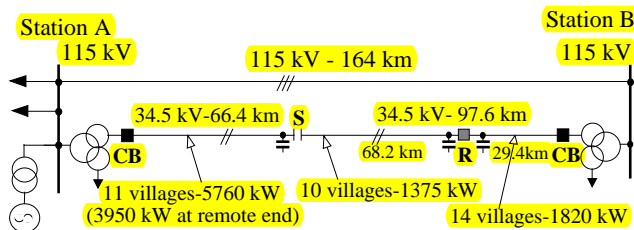


Fig.4 - Single-line diagram of "3-Phase" SWSs simulated for application of HSR and recloser (CB=circuit breaker; R=recloser; S=separation point of SWLs).

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 (C_{10} and C_{20} 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.

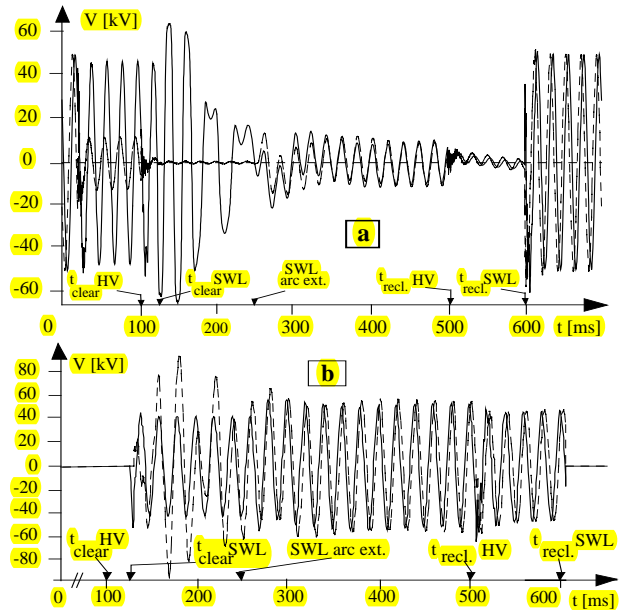


Fig.5- 1- Φ -to-Gr fault on SWL and HV circuit at 62.7 km from sending end, followed by HSR of SWL recloser, and 1-pole HSR of HV circuit. Capacitors, SAs and 5% of year 2001 SWL load simulated. a) Φ -to-Gr voltage of shield wires at SWL receiving end, vs. time. b) TRVs across SWL recloser, vs. time.

Some commercial 36kV and 40.5kV CBs possess a 1.2/50 μ s 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 SWSs 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 SWLs (≤ 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.

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, $V_c \leq 15V$). 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 Ω in the HV/MV supply substations up to a maximum of 3.5 Ω 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_c 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 $\pm 5\%$ 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 (T_m and T_i in Fig.6) have been prototype tested to withstand the short circuit current electrodynamic stresses.

6. APPLICATION OF SWSs IN OTHER COUNTRIES

The good operation experience in Ghana and the very low cost of SWSs has justified the application in other countries, in most cases supported by the International Funding Agencies. The cost for making electricity available at MV with the SWSs to the communities located along the HV lines, is only 10-15% of the cost of the conventional solutions. Of course, the cost of MV/LV transformer stations and of LV networks is practically the same as for conventional distribution.

A supplementary justification of the SWSs 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, in 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 SWSs, 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.

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Energization overvoltages of SWL ($1 \text{ p.u.} = \sqrt{2} V_n$)

SWS	"3-Phase"	"V"	Single-Phase Ground Return
V_{\max} [p.u.] \rightarrow	1.60	2.05	2.25
V_{mean} [p.u.] \rightarrow	1.31 (a)	1.60 (c)	1.57 (d)
σ [p.u.] \rightarrow	$\sigma = 0.19$	0.19	0.30
V_{\max} [p.u.] \rightarrow	2.10		
V_{mean} [p.u.] \rightarrow	1.60 (b)	-	-
σ [p.u.] \rightarrow	0.19		

a) With: MV/LV Transf., SAs, Load - b) Without: MV/LV Transf., SAs, Loads - c) Without: MV/LV Transf., SAs, Loads - d) With: MV/LV Transf., Load; without SAs

HSR switching overvoltages of "3-Phase" SWS (Sierra Leone) ($1 \text{ p.u.} = \sqrt{2} 34.5 \text{ kV}$)

	V_{\max} [p.u.]	σ [p.u.]	V_{mean} [p.u.]
Case-I	1.80	0.158	1.57
Case-II	1.90	0.137	1.61
Case-III	.85	0.129	1.71

- 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

SWS	"3-Phase"	"V"	Single-Phase Ground Return
		(SW floating)	(SW floating)
V_{\max} [p.u.] \rightarrow	1.59	1.85	2.65
V_{mean} [p.u.] \rightarrow	0.86 (b)	0.90 (b)	1.66 (d)
σ [p.u.] \rightarrow	0.27	0.33	0.32

Temporary overvoltages of SWL and energy dissipated on SAs

SWS	"3-Phase"	"V"	Single-Phase Ground Return
	[p.u./kJ]	[p.u]	[p.u./kJ]
1- Φ -to-Gr short circuit on HV circuit, $\Delta t = 0.1 \text{ s}$,	1.51/4.6 (a)	1.50 (b)	1.16 (e)
Contact between HV circuit and SWL, $\Delta t = 0.1 \text{ s}$	1.60/47 (a)	2.25 (b)	1.68 (e)

a) With MV/LV transformer and SAs,
 e.) Without: MV/LV Transf., load, SAs