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RURAL ELECTRIFICATION IN DEVELOPING COUNTRIES WITH THE SHIELD WIRE SCHEME. APPLICATIONS IN LAOS

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ABSTRACT

Firstly, the paper briefly describes the technique for 3-phase and single-phase power distribution along HV (115-330kV) transmission lines via the insulated shield wires, energized at MV (20-34.5kV) from the main HV/MV transformer stations, using the ground as a MV phase conductor.

A new computer program based on phase coordinates is presented, expressly developed for the analysis of this unconventional low cost grid based rural electrification technique, referred to as the "Shield Wire Scheme" (SWS).

The paper then describes the eight SWSs in operation in Laos. In particular, the planning and engineering criteria, and the commissioning results are reported for five "3-Phase" SWSs, put into operation in 2002-3 and providing electricity to over 100 villages, to some small towns and to a provincial capital.

Brief information is given on SWSs in operation, under construction and planned in other developing countries.

Keywords: unconventional distribution scheme; shield wire; analysis; line balancing; engineering; field experience

1. BRIEF DESCRIPTION OF THE INSULATED SHIELD WIRE DISTRIBUTION SCHEMES

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

A very low cost solution is the Shield Wire Scheme (SWS) first conceived by one of the authors [1] and applied commercially in Ghana [2] [3] [5]. The SWS consists of insulating the shield wire(s) (SW(s)) of the HV lines from the towers and energizing the SW(s) at MV (20-34.5 kV) from the HV/MV transformer station at one end of the HV line. MV/LV transformers are connected between the SW(s) and ground for power supply to the loads.

The applicable SWSs, presented in previous papers [2] [3], are shown in Fig. 1: Scheme A – "Single-Phase Earth-Return"; Scheme B – "Single-Phase Metallic Return"; Scheme C – "V"; Scheme D – "3-Phase".

Scheme A is applicable on HV lines provided with one shield wire. Schemes B, C and D are feasible on HV lines provided with two shield wires. Schemes A and B perform single-phase distribution with earth return and metallic return of current, respectively. Scheme C and D perform 3-phase distribution, the 3rd conductor being the earth path.

The "3-Phase" scheme is the most frequently used because it supplies the same loads as a conventional 3-phase distribution system, including large induction motors, without restrictions. The "V" scheme is simpler, but has limited application, because voltage symmetrization is less accurate than in the "3-Phase" Scheme, thus enabling the supply of only a small amount of 3-phase load (say, 10% of total) in addition to single-phase loads.

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The “Single-Phase Earth-Return” Scheme has been applied on HV lines already built or designed with one SW only.

Laboratory investigations [2], EMTP-ATP computer analysis [7], [9] and 14-years of extensive field experience [5] have proven that the insulation for MV of the SWs of HV lines (V≥115 kV) and energization at MV (up to 34.5 kV) does not erode the lightning shielding efficiency of the SWs and has a negligible effect on the back-flashover rate of the HV circuit. When lightning strikes a SW insulated for MV or a tower peak, a flashover occurs across the arcing horns of the SW insulator. Then SW(s) are grounded via the arc and behave for the HV circuit as conventional SWs. The lightning current amplitude liable to cause the back-flashover is reduced by only 1 to 5 % depending on the ratio of lightning impulse insulation levels of line HV conductors and SWs [7] [9].

The ground return of the current is also the most economic concept in regions with relatively high soil resistivity, because the cost of grounding electrodes is small in developing countries for the current flow of interest. The earth return path has a much lower resistance than usual distribution conductors. It is calculated at $10^{-4}\pi^2$ f (Ω/km), i.e. 0.05 Ω/km at 50 Hz, equivalent to a 570 sqmm aluminium cable.

In the "3-Phase" Scheme (Fig.1-D), the two insulated SWs and the ground return path form a 3-phase circuit which is supplied at MV from a HV/MV station by a transformer winding with one terminal permanently grounded. Consequently, the wire-to-ground (w_1-Gr and w_2-Gr) rms voltages are equal to the wire-to-wire (w_1-w_2) rms voltage. The shield wire line (SWL) is a 3-phase unsymmetrical circuit, with the ground return being used as the 3rd phase conductor.

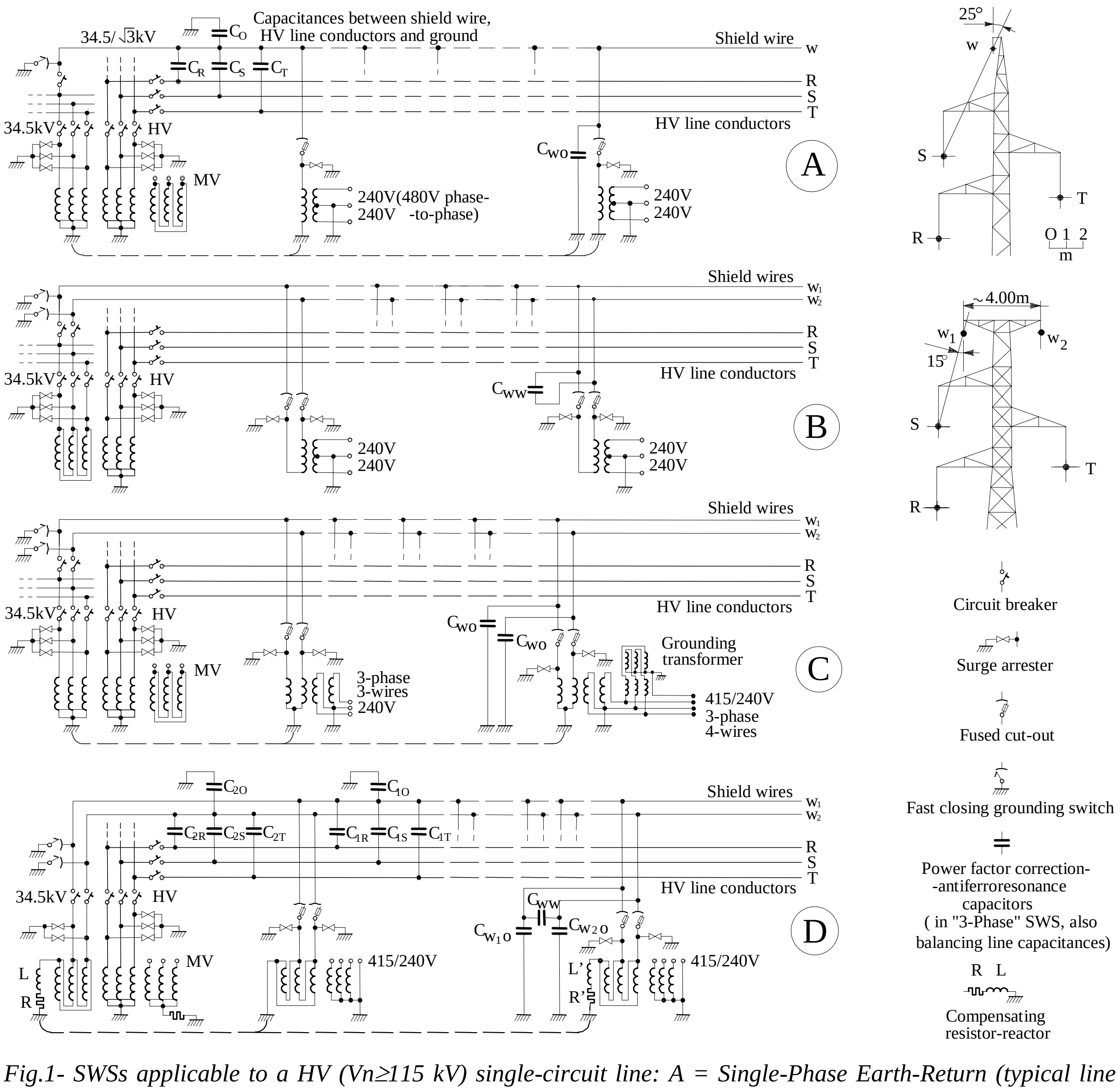


Fig.1- SWSs applicable to a HV (Vn≥115 kV) single-circuit line: A = Single-Phase Earth-Return (typical line tower is shown on top right); B = Single-Phase Metallic-Return; C = "V" SWS; D = "3-Phase" SWS (typical line tower for SWSs B, C and D is shown on middle right).

As pointed out above, the resistance of the earth path is much smaller than the resistance of any practical SW cable; the reactance of the earth path is usually slightly smaller [2]. The capacitive leakage currents terminating to the SWs and earth path (3rd phase of SWL) are unbalanced owing to diversity of the partial capacitances and of the currents capacitively induced by the HV conductors.

The applied concept is to make the "3-Phase" circuit formed by the two SWs and the earth path symmetrical, with simple compensating components, which introduce complementary asymmetries tailored to cancel out or drastically reduce the inherent asymmetries of the SWL, thereby limiting the negative sequence component of voltages generally within 1% (in no case to exceed 2%). This is achieved by:

- a series resistor-reactor in the earth path (R-L in Fig.1-D) in order to raise the earth path voltage drop to about the same value as the voltage drop on SWs;
- a p.f. correction capacitor branched between the two wires (C_{ww} in Fig.1-D) which is larger than the p.f. correction capacitors branched from each SW and ground (C_{w10} and C_{w20}), so that the total capacitive currents flowing to the SWs and to the earth (leakage currents in the air from wires, earth and HV conductors; capacitors currents) are about of equal amplitude and phase shifted by 120^{o} and 240^{o}.

The supply of “Single-Phase Earth-Return” and of “V” SWLs [2], [3], [4] is usually made directly from the MV busbars of a HV/MV substation, via a circuit breaker (CB).

The supply of “3-Phase” SWLs is feasible: i) from a dedicated MV winding of a HV/MV step-down transformer via a MV 2-pole CB as shown in Fig.1-D; ii) alternatively, via a MV/MV interposing transformer providing galvanic insulation and the suitable voltage for SWL. The supply winding of SWL is in any case operated with one terminal grounded via the compensating R-L circuit. When a MV/MV interposing transformer is used, this is supplied via a standard MV 3-pole CB, for switching and protecting, as one block on primary side, the interposing transformer and the SWL [4], [5].

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

Capacitors C_{ww}, C_{w10} and C_{w20} perform three functions: p.f. correction, prevention of ferroresonance and circuit balancing in “3-Phase” SWS. These functions and the one of the fast closing grounding switch (Fig. 1) are described in ref. [2], [3].

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 Earth-Return" SWS or with 2 conductors for the "3-Phase" SWS. The length of lateral lines built so far has been up to 25 km from HV line take-off tower.

The grounding system for earth-return of current is described in [2] and operation experience is reported in [3] [4] [5]. The largest current flows in the grounding system of the HV/MV substations supplying the SWL(s) (Fig.1). This does not pose problems because the extensive meshed grounding system of HV stations generally has a resistance not exceeding 1 or 2 Ω. Field experience has shown that, with a current flow in the grounding system of HV/MV stations of up to 100 A (load of 6 MVA in a 34.5 kV "3-Phase" SWS), the step and touch voltages generally do not exceed 7 V.

The "3-Phase" SWL (Fig.1-D) has practically the same power distribution capability of a conventional MV long feeder of the same rated voltage, with conductors of the same ohmic resistance. 34.5 kV, 50 Hz-100 km long SWL formed by two ACSR SWs of 76.9 sqmm (S_{al}=48.57 sqmm; S_{st}=28.33 sqmm; $r_{40°C}$=0.646 Ω/km) can supply up to 4 MVA of distributed load, including large induction motors (rated up to 200 kW).

The single-phase SWSs, A and B in Fig. 1, are seen by the HV supply network as single-phase loads. When two or more such SWSs are supplied from the same HV/MV substation, or from substations of the same region, the unbalance is minimized by connecting the SWLs to different MV phases. Where this is impracticable or insufficient, a MV L-C circuit can be branched in parallel with the SWL, designed for compensating the negative sequence currents produced by the single-phase load [3].

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.

2. DESCRIPTION OF THE PROGRAM FOR SWSs ANALYSIS

The unsymmetrical configuration of SWSs requires, for an accurate analysis of its operation, the simulation of all the electrostatic and electromagnetic couplings between the conductors of HV circuit, the insulated SWs energized at MV and the earth path used for return of current.

Initially, the steady-state operation analysis of SWSs has been performed with the ATP-EMTP (Alternative Transients Program–Electromagnetic Transients Program), a powerful and accurate tool, the use of which is however quite complex. Moreover, the ATPs load-flow option is not very efficient, especially when dealing with radial systems with low X/R ratios, both these features being typical of distribution systems.

As an alternative to the EMTP, special programs based on the 2-phase symmetrical components transformation were developed in 1989 [10] for the steady-state, temporary overvoltage and short circuit analyses of the "V" and "3-Phase" SWSs. These programs had the merit of simplicity of use, but were based on some simulation approximations of SWS symmetrization.

To overcome these limitations, a new program has recently been developed [8] that uses the phase coordinates, expressly implemented for the accurate analysis of any type of SWS.

The program firstly builds the nodal admittance matrix, in phase coordinates, of each system component (multiconductor line, transformers, induction motors, constant power and constant impedance loads, etc.).

The total nodal admittance system matrix, [**Y**], is then assembled without any topological constraint, by mapping the individual "component" matrices into the global one. The network is described by the linear system [**I**]=[**Y**][**E**], where [**I**] and [**E**] are the nodal injected currents and applied voltages, respectively. By partitioning the [**Y**] matrix into "known" and "unknown" voltage nodes (suffixed "k" and "u", respectively) the following system of equations is obtained:

$$\begin{bmatrix} \mathbf{I}_k \\ \mathbf{I}_u \end{bmatrix} = \begin{bmatrix} \mathbf{Y}_{kk} & \mathbf{Y}_{ku} \\ \mathbf{Y}_{uk} & \mathbf{Y}_{uu} \end{bmatrix} \begin{bmatrix} \mathbf{E}_k \\ \mathbf{E}_u \end{bmatrix} \tag{1}$$

System (1) yields the following expressions of the unknown voltages [$\mathbf{E}_u$]:

$$[\mathbf{E}_u] = [\mathbf{Y}_{uu}]^{-1}\{[\mathbf{I}_u] - [\mathbf{Y}_{uk}][\mathbf{E}_k]\} \tag{2}$$

Since actual operation generally requires simulation of loads in steady-state conditions as constant active and reactive power, their equivalent current injection depends on the nodal voltage. The solution therefore requires an iterative method. An initial estimate of the nodal voltages is required in order to calculate the injected currents, based on equations:

$$\mathbf{I}_i = -\left(\frac{\mathbf{N}_i}{\mathbf{E}_i}\right)^*, \tag{3}$$

where $\mathbf{N}_i$ is the complex power at node 'i'. System (2) is then solved iteratively: the [$\mathbf{I}_u$] vector estimated by equation (3) is substituted in (2) to obtain the unknown voltages [$\mathbf{E}_u$]. By multiplying those voltages by the estimated currents, the powers absorbed by the (P, Q) loads are calculated. If the convergence condition is not fulfilled for all the constant-power nodes, i.e. the calculated power is not within the prescribed tolerance, the voltage vector is used to calculate another set of current injections and the cycle is repeated.

The voltage initialization is simply performed by solving system (2) without injected currents, i.e. by neglecting the (P, Q) loads: this yields an initial voltage estimate which is not very different from the actual values and which is an excellent starting point for the iterative process. The importance of this fact should not be overlooked, especially when dealing with unbalanced networks and/or loads, where the phases of the voltages have a significant impact on the convergence of load flow calculations.

In "3-Phase" SWSs, the shield wires' phase-to-ground voltages are equal to the phase-to-phase voltages. Moreover, the phasors of these voltages, with respect to the HV reference, can vary widely depending on the transformers vector group and on the adopted connection scheme. The latter statement can also be extended to the LV terminals of the MV/LV distribution transformers branched from the SWs. The above described automatic load-flow initialization avoids any need for recognition of "conventional" or "unconventional" nodes.

The described algorithm has shown to be very efficient and robust. In fact, convergence is obtained in a few iterations even in presence of large unbalanced conditions. This feature can also be used for the simulation of unsymmetrical faults. The algorithm nevertheless requires the knowledge of both phase and amplitude of the applied voltages. It is not usually possible in actual systems to assign the phase angle values to more than one three-phase node. For this reason, the algorithm is essentially suited to the analysis of networks with a single point of supply, i.e. the SWSs and distribution systems, although it is not restricted to radial networks.

The analysis of three-phase induction motor loads and small three-phase generators operated at constant p.f. requires a hybrid approach combining the above described phase value modelling with sequence-value representation of the rotating devices. It should be pointed out that the Y-bus solution method is unaffected neither by these changes nor by the limitation of the single point of supply.

The new program has the capacity to calculate the unsymmetrical shunt capacitors to be connected to the "3-Phase" SWS which, besides providing p.f. correction and preventing ferroresonance [2] [3], make the total capacitive currents flowing to the two SWs and to the earth almost equal in amplitude and phase shifted by 120° and 240°, thereby optimising the shunt symmetrization.

The program has been up-rated very recently at Rome University by including an algorithm for the automatic identification of the optimal value of the grounding impedance of one terminal of the transformer at sending end and, where applicable, at another location along the "3-Phase" SWL (R-L and R'-L' circuits in Fig. 1-D). The program minimizes the average value of the residual negative-sequence voltages at the LV terminals of MV/LV transformers along the SWL, the average being weighted on the basis of the load active powers.

3. RURAL ELECTRIFICATION IN LAOS USING THE SWSs

3.1 General information

EDL-Electricité du Laos has applied the SWSs for power supply to a large number of villages and to some towns located along the 115kV transmission lines of Northern Laos or at a distance up to several kilometres from HV line route. EDL's 115kV transmission network and the SWLs in operation as of December 2003 are shown in Fig. 2.

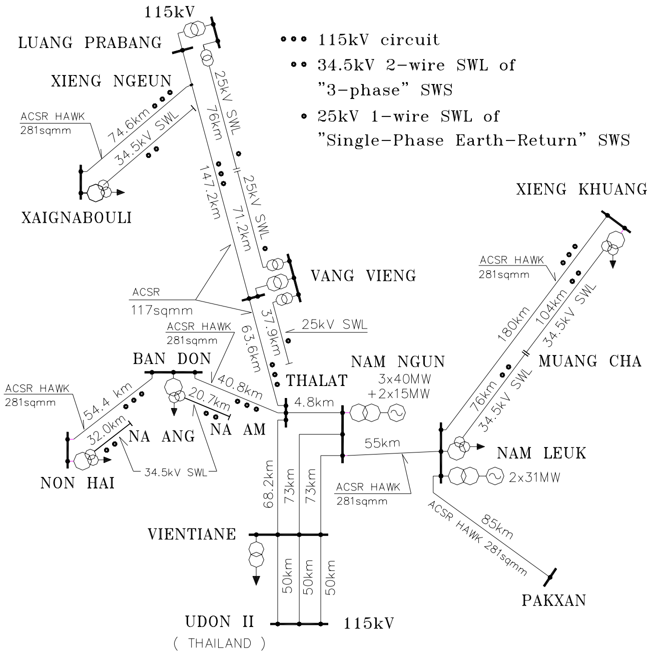


Fig.2-Single-line diagram of the 115 network of Laos showing the SWSs

The regions crossed by the 115kV lines equipped with the SWSs are mostly mountainous, covered by tropical forest, with sharp slopes and few access roads. Nature is intact and beautiful, but it is very difficult for construction and maintenance of transmission and distribution lines. The main roads follow the valleys, where the prevailing cultivation is rice and where the villages are located.

Construction of HV lines in these mountainous regions is less penalized than construction of MV lines. In fact, the tower spotting of HV lines supported by lattice galvanized steel towers can take advantage of the profile by crossing valleys with long spans. MV lines have the span length limited, on the one hand, by the loading capability of locally fabricated concrete poles and, on the other hand, by the small separation between phase conductors. Transport and erection of concrete poles on the sides or tops of mountains is difficult. Contractors therefore prefer to build MV lines which closely follow the winding roads and end up being much longer than the point-to-point distance and more expensive. The SWS overcomes these problems in Laos, because it provides a MV circuit along the HV circuit at very little cost. Other reasons justifying the use of the "3-Phase" SWSs are the following:

- The "3-Phase" SWLs operated at 34.5 kV (max. voltage in use for distribution) have a loading capability of some MW and reach can exceed 100 km (see Fig. 4 and Table I) [3] [4].
- Earth-return of current has been used many decades for single-phase rural electrification and 14 years in commercial SWSs. This technique does not pose problems even if the soil resistivity is high as it is in many places in Laos. The earth is an ideal conductor in rural areas of developing countries because: (*i*) cost is very small (cost items are grounding rods and grounding conductors, installed for performing also other functions); (*ii*) power losses are very small; (*iii*) unlike a conventional line conductor, it is neither exposed to insulation failures nor to interruptions; (*iv*) maintenance has negligible cost.
- Although the analysis of SWSs is somewhat complex, operation is simple because only conventional distribution equipment is used, with ordinary operational methods and without electronic power devices.
- Although the phase–to-Gr operation voltage in the "3-Phase" SWS is higher by a factor of $\sqrt{3}$ = 1.732 in comparison with the conventional lines, the required increase of insulation is only 15-20 % above the standard for conventional MV lines and equipment (BIL of 200 kV instead of 170 kV for the 34.5 rated voltage) [3] [4] [5].

- SWLs are part of the HV line. They are therefore inherently much more reliable than conventional MV lines and do not require specific maintenance, except for visual inspection of SW insulators during HV line patrolling. MV lines require frequent clearing of right-of-way (ROW) in tropical forests.
- Cost of making electricity available at MV with the SWSs to communities located along the HV lines is only 10-15 % of cost of independent MV lines on the same ROW.
- If an optical ground wire (OPGW) is applied in the HV line for telecommunications, the SWS can be realized as well by insulating the OPGW for the operation voltage of the SWLs.
- SWLs have practically no environmental impact. Independent MV lines on same ROW of an HV line require widening of ROW and cause more disturbances to forestry and farming.
- SWLs have proven to be a deterrent to vandalism and theft of HV lines, because the communities along the HV line must preserve the integrity of the line to ensure power supply to themselves from the SWL.
- Insulation of SW(s) for application of SWSs is compatible with power line carrier telecommunication, used in all the HV lines in Laos.
- The low values of short circuit currents in Laos limit to well acceptable values the overvoltages induced in the SWLs during the asymmetrical phase-to-Gr faults in the associated HV circuit and the touch and step voltages near the grounding systems of HV towers with insulated SWs dispersing the short circuit currents.

The first SWS application in Laos was planned in 1991-92 for the Thalat-Vang Vieng – Luang Prabang 211 km long, 115kV line. When this application of SWS was decided, the 115 kV line had already been designed with one SW. The Single-Phase Earth-Return SWS (Fig. 1-A) was therefore implemented and commissioned in 1996.

The second, more extensive, application of the SWSs has been performed along the following 115kV lines: Nam Leuk – Xieng Khuang, 180 km long; Xieng Ngeun – Xaignabouli, 74 km long; Thalat – Ban Don – Non Hai, 95 km long. These radial lines cross tropical regions, partly at high altitude (up to 2000 m), in areas of high keraunic level. They have therefore been protected by two SWs. The 3-Phase SWS (Fig. 1-D) has been applied in all these new lines. The project was planned in 1996-98 and commissioned in 2002-2003.

3.2 Single-Phase Earth-Return SWSs

Operation voltage of the "Single-Phase Earth-Return" SWSs in Laos is 25 kV. Each of the three SWSs in operation in the Thalat-Vang Vieng – Luang Prabang 115 kV line (see Fig. 2) is supplied via a single-phase 22 kV/25kV±2x2.5% interposing transformer. The Vang Vieng-Luang Prabang 115 kV line is equipped with an ACSR SW, with cross section of 76.9 sqmm (S_{Al}=48.57 sqmm; S_{St}=28.33 sqmm). The Thalat-Vang Vieng 115 kV line is equipped with a galvanized steel SW with a cross section of 60 sqmm. SW is insulated with rigid toughened glass suspension and tension insulator strings. Tower head outline is as shown in Fig. 1 (top right).

When the load of the single-phase SWLs exceeds 50% of final design load, a static L-C circuit may be connected to the 22kV busbars which supply the SWLs, to produce negative sequence currents in phase opposition with those caused by the single-phase loads of SWLs, thereby minimizing the voltage unbalance on supply network [3]. A typical circuit consists of two capacitors and one reactor, delta connected, performing also p.f. correction to unity; total kvar rating of capacitors and reactor will be about 50% of SWL load.

The three "Single-Phase Earth-Return" SWSs in operation in Laos (Fig. 2) supply 47 villages via about 90 MV/LV single-phase transformers rated at 20, 30, 50 and 100 kVA. Fig.3 shows some details of the longest single-phase SWS. The p.f. correction-antiferroresonance capacitor is pole mounted at about the mid point of SWL.

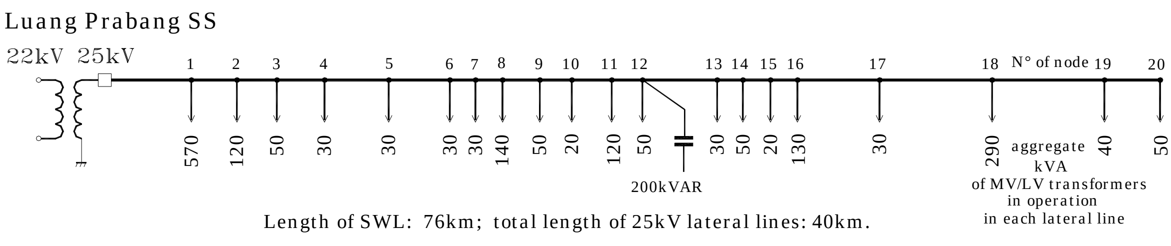


Fig. 3- Single-Phase Earth-Return 25 kV SWL supplied from Luang Prabang substation

3.3 "3-Phase" SWSs

There are five "3-Phase" SWSs in operation in Laos, located as shown in the HV grid diagram (Fig. 2). Details of the SWSs are provided in Fig.4. The Xieng Khuang–Muang Cha SWS (Fig. 4-A) supplies 42 villages at a distance up to 129 km (SWL of 104.4 km extended at remote end by a 25 km lateral line).

The Nam Leuk–Muang Cha SWS (Fig. 4-B) supplies several villages and, at the receiving end, a provincial capital, formerly served by a 22 kV network supplied by a diesel station, now replaced in the initial stage by a 3 MVA – 34.5/22 kV step-down transformer. Final load of this SWS is forecast to reach 5 MW. In addition to the grounding resistor of 19 Ω at sending end of SWL, an R-L circuit (14+j 4 Ω) is installed at Muang Cha.

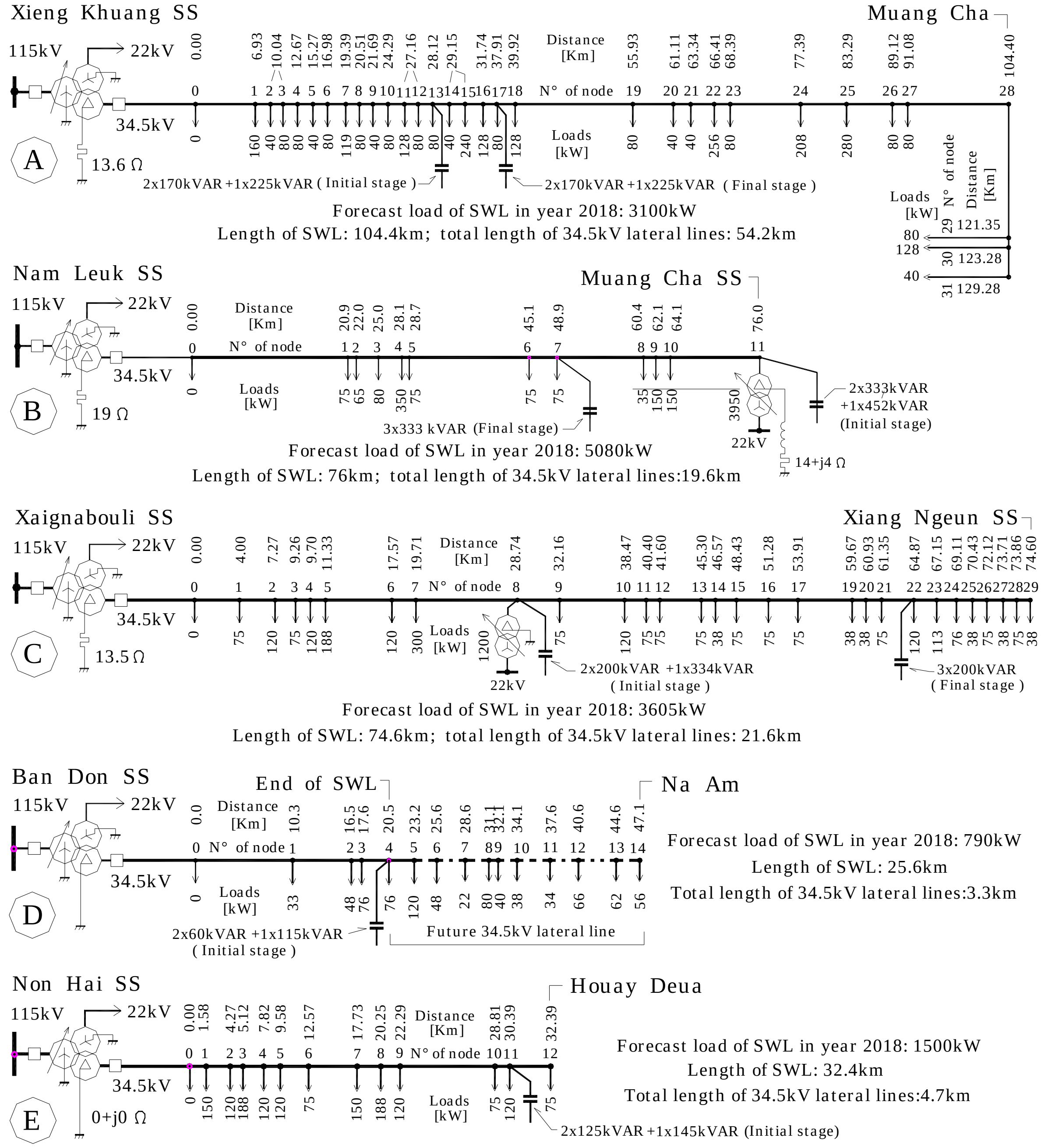


Fig. 4- Single-line diagrams of 34.5 kV "3-Phase" SWSs in Laos

The Xaignabouli – Xiang Ngeun SWS (Fig.4-C) supplies 30 villages; it also supplies the Muang Nam town via a 34.5/22 kV step-down transformer. Location and ratings of L-R grounding circuits and of shunt capacitors, and forecast loads in year 2018 are shown in Fig. 4.

The Ban Don-Na Am SWS (Fig.4-D) and Non Hai-Houay Deua SWS (Fig.4-E) are shorter and supply fewer villages. These SWSs do not require the R-L grounding circuit for the forecast loads.

Table I summarizes the results of the steady-state operation analysis of the longest "3-Phase" SWS. It shows that the voltages at the LV terminals of the MV/LV transformers are well regulated in all locations and loading conditions. The negative-sequence component voltages, $100(V_2/V_1)$, have been calculated by assuming that the HV grid supply voltages are balanced. The transpositions of the 115 kV lines have been simulated. Table I shows that the calculated unbalance does not exceed 0.5 % and 1 % at no-load and maximum load, respectively. A similar or better performance has been computed for the other "3-Phase" SWSs.

Short circuit and temporary overvoltage analyses have been performed with the program described in par. 2. Switching and lightning overvoltage analyses have been performed for one of the SWS with the ATP-EMTP.

The 115 kV lines are equipped with single conductors code Hawk in each phase in triangular configuration, shielded by two SWs. Suspension tower head outline is shown in Fig.2 (middle right). In order to ensure a low back-flashover rate, tower grounding resistance is specified to be ≤ 10 Ω anywhere practicable.

Table I- Results of steady-state operation analysis of Xieng Khuang-Muang Cha SWS

Active power flow on 115 kV circuit				0 MW		10 MW		37 MW (SIL)	
SWL load in % of year 2018 peak load of 3100 kW Load power factor on LV side of MV/LV transformers				0% -		50% 0.9		100% 0.9	
Node	Village/Town	Year 2018 peak load [kW]	Distance from Xieng Khuang [km]	Phase-to-neutral positive sequence voltage, V_1, and voltage unbalance K_i=100V_2/V_1 on LV side of MV/LV transformers					
				V_1 [V]	K_i=[%]	V_1 [V]	K_i=[%]	V_1 [V]	K_i=[%]
1	B. Nano, B. Xa, B. Namtom	160	6.93	231.6	0.39	228.8	0.64	230.9	1.00
2	B. Dong Dane	80	10.04	231.9	0.32	228.8	0.54	230.3	0.88
3	B. Thakek	40	10.04	231.9	0.32	228.6	0.54	229.9	0.88
4	B. Phonxai, B. Hoy, B. Tham	80	12.67	232.2	0.28	228.8	0.47	229.9	0.78
5	B. Gnoun	40	15.27	232.4	0.24	228.6	0.41	229.1	0.69
6	B. Kosi	80	16.98	232.6	0.21	228.8	0.38	229.3	0.63
7	B. Nong Nam, B. Koua	119	19.39	232.9	0.16	228.8	0.31	228.8	0.49
8	B. Phang	80	20.51	232.9	0.16	228.8	0.31	228.8	0.49
9	B. Na Ou	40	21.69	233.1	0.14	228.6	0.28	228.2	0.44
10	B. Xang	80	24.29	233.4	0.12	228.9	0.26	228.3	0.36
11	B. Nasay	80	27.16	233.5	0.12	228.9	0.25	228.1	0.29
12	B. Siphom	128	27.16	233.5	0.12	229.1	0.25	228.5	0.29
13	B. Phosi, B. Thum	80	28.12	233.6	0.12	228.9	0.25	227.9	0.27
14	B. Phaivat, B. Phon, B. Nasy	240	28.12	233.6	0.12	228.9	0.25	227.9	0.27
15	B. Hongsi	40	28.12	233.7	0.13	228.7	0.25	227.5	0.24
16	B. Naho	128	31.74	233.9	0.16	229.2	0.23	227.9	0.10
17	B. Keokhuang	80	37.91	228.2	0.19	229.0	0.26	227.0	0.04
18	B. Kafe	128	39.92	228.3	0.20	229.2	0.27	227.3	0.08
19	B. Xieng Khong	80	55.93	228.8	0.28	229.2	0.49	225.8	0.39
20	B. Vieng Thong	40	61.11	228.9	0.31	229.0	0.56	230.7	0.48
21	B. Nasay, B. Nasong	40	63.34	228.9	0.31	229.0	0.56	230.7	0.48
22	B. Dong, B. Nahong	256	66.41	229.1	0.33	229.5	0.62	231.3	0.55
23	B. Phonhom	80	68.39	229.1	0.34	229.3	0.63	230.7	0.58
24	B. Kohai	80	77.39	229.3	0.37	229.0	0.65	230.0	0.70
25	B. Namla	128	77.39	229.3	0.37	229.3	0.65	230.4	0.70
26	B. Nadi, B. Na Mouang, Muang Om	280	83.29	229.5	0.40	228.8	0.66	229.4	0.79
27	B. Thamlo	80	89.12	229.6	0.43	228.8	0.67	229.1	0.85
28	B. Pialuang	80	91.08	229.7	0.44	228.7	0.68	229.0	0.87
29	Muang Ao Kang	80	121.35*	230.0	0.50	228.4	0.73	228.1	1.03
30	Muang Ao Nua	128	123.28*	230.0	0.50	228.7	0.73	228.5	1.03
31	Muang Ao Tai	45	129.28*	229.9	0.49	230.1	0.70	231.1	0.97
Total peak load [kW]		3100							
Transformers' tap position: 115 kV±8x1.25%/23 kV/34.5 kV±2x3.75% MV/LV 34.5 kV±2x2.5%/400-231 V				0 / - / -1x3.75% 0% / +1x2.5%		0 / - / 0 0% / +1x2.5%		0 / - / +1x3.37% 0%/-1x2.5%/-2x2.5%	
Grounding impedance (all loading conditions) located at Xieng Khuang: $\mathbf{Z}_c$ = 13.6 + J 0 Ω									
P.f. correction-antiferroresonance-balancing capacitors located at Phaivat, sufficient up to ~ 50% of the final load: $C_{W,Gr}$ = 2x170 kvar ; $C_{W,W}$ = 1x225 kvar Additional capacitors with 100% of final load, to be located in future at Naho: $C_{W,Gr}$ = 2x170 kvar ; $C_{W,W}$ = 1x225 kvar									

*) 24.72 km long 34.5 kV 2-wire lateral line taking off from the 115 kV line at km 104.56. Distance of the other villages from 115 kV line is generally less than 1 km, except 3 villages located at 1.5 to 5.5 km.

The SWs are ACSR conductors code Petrel, S=81.7 sqmm (S_{Al}=51.6 sqmm; S_{St}=30.1 sqmm; stranding 12x2.34 mm Al+7x2.34 mm St), d=11.7 mm, $r_{20°C}$=0.56 Ω/km.

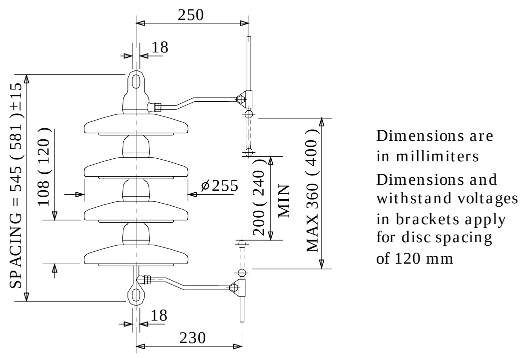
Fig.5 shows the toughened glass rigid insulator strings applied for SWs. Tension strings are provided with a bird antipercing spike. Distance between arcing horns is set at 33.5 cm and 36.5 cm for altitude up to 1000 m and above 1000 m, respectively.

Each of the 5 "3-Phase" SWLs (Fig.4) is supplied by the 34.5kV winding of a 3-winding 115kV±10x1.25%/34.5kV±2x3.75%/23 kV - 16/6/13 MVA transformer. Tap changer on 34.5 kV winding is off-voltage type. In view of the exposure to frequent short circuits of the 22 kV networks and of the long 34.5 SWLs, the 1st fabricated transformer has been tested to withstand the short circuit electrodynamic forces.

At the sending end, each SWL is switched and protected by a CB performing also the automatic reclosure. Fig. 6 shows the single-line diagram of the standard SWL supply bay.

Fig.7 describes a typical distribution arrangement in a village. It shows how multiple grounding is realized for an economic and efficient limitation of grounding resistance and of touch/step voltages. Fig. 7 also shows that neutral of LV networks is grounded only in poles along the LV lines to realize separation with the grounding systems for earth return of current.

At take-off from the HV line, each lateral line to a village is sectionalized by a bipolar disconnecting switch and protected by two HRC type fuses with replaceable silver fuse link.



- Wet 50 Hz-60 s withstand voltage — 130 (143) kVrms +)
- Dry 1.2 / 50 μs impulse withstand voltage — 270 (295) kVpeak +)
- Creepage distance — 1200 mm
- Electromechanical failing load — ≥ 50 kN

+) without arcing horns

Fig. 5-Rigid toughened glass insulator string for 34.5 kV "3-Phase" SWS

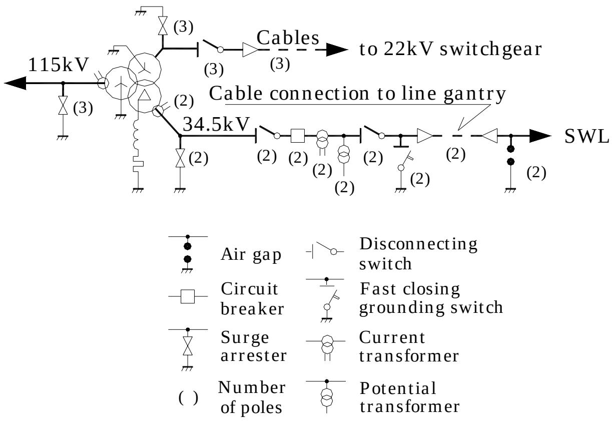


Fig.6- Single-line diagram of the 34.5 kV supply bay of "3-Phase" SWLs

All the MV/LV transformers are pole mounted (See Fig.7), sectionalised and protected by two single-phase fused cut-outs. A CB is provided on the LV side of transformer. LV feeders are protected by fuses. Most of initially installed MV/LV transformers are rated at 50 kVA and 100 kVA; some are rated at 160 kVA and a few at 250 kVA. The LV distribution cabinet is not shown in Fig.7.

Common features of the SWSs of Fig. 4-A, B and C are the long length of the SWLs, the large number of MV/LV transformers supplied by each SWL and the long total length of the lateral 34.5 kV lines. Long lateral lines are equipped with two conductors and are designed with longer spans than 3-wire MV lines. The 3rd ground conductor is installed only in 0.5-1 km of lateral line close to the MV/LV transformer stations, to perform the multiple grounding for earth return of current (a grounding rod every 3 poles, paralleled by the overhead ground conductor, see Fig.7).

Lateral lines are exposed to transient and permanent faults as conventional MV lines. In order to achieve a low outage rate of the SWL, it is necessary to ensure a good coordination of protection relays supervising the 34.5 kV CB at sending end of SWL, of fuses at take off from SWL and of fuses protecting the MV/LV transformers. It is planned in the future to split the long SWLs by means of a recloser at an intermediate point, in order to increase the continuity of service to consumers.

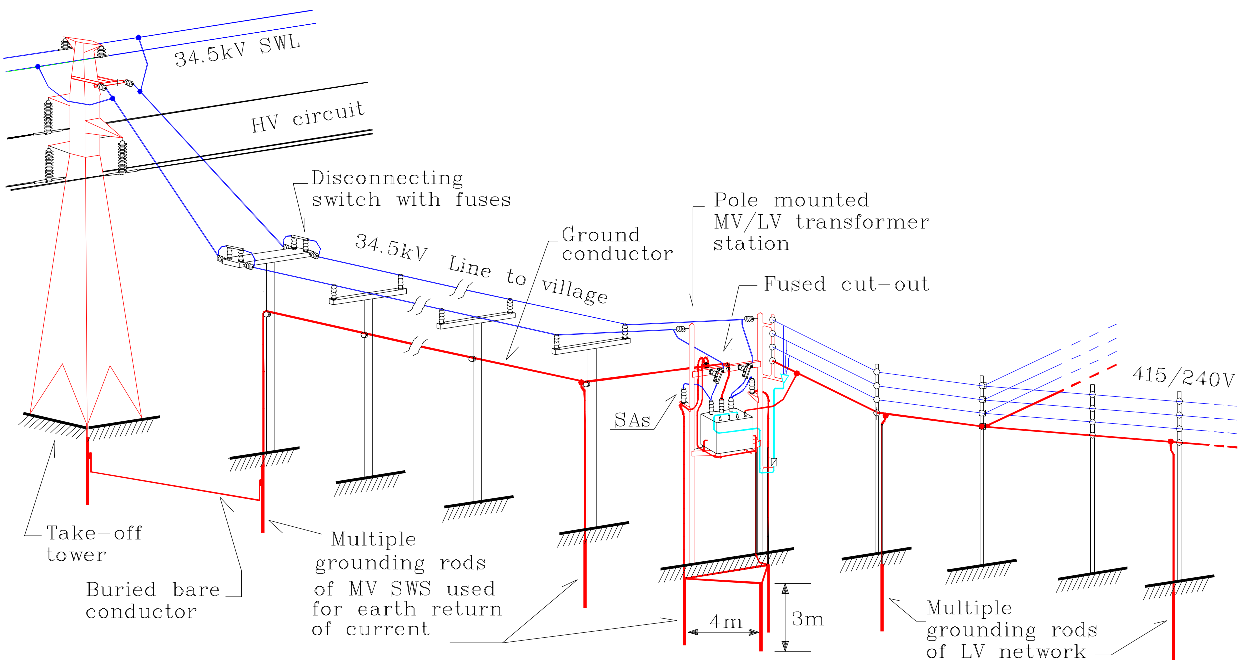


Fig.7- Circuit schematic of "3-Phase" SWS distribution in the villages, showing independent earthing of MV and LV networks

4. OPERATION EXPERIENCE

The "Single-Phase Earth-Return" SWSs have provided a well regulated and stable voltage to consumers. However, customers using motor drives prefer the 3-phase supply, because procurement of single-phase motors is not easy and is expensive in Laos. On the other hand, as time goes by, the number of customers and load are increasing more than forecast at the planning stage. Distribution capacity of the 25 kV single-phase schemes is limited, in particular where a steel SW has been used for the SWL.

EDL has therefore decided to only apply the "3-Phase" SWS in the 2nd SWS project. A brief summary is reported here of the commissioning and 1st year of operation of the "3-Phase" SWSs.

The SWLs are switched on and off as conventional MV lines, with all the distribution transformers connected.

Voltages measured phase-to-neutral at the LV terminals of all the MV/LV transformers are found in the range from 220 to 230 V. Voltage unbalance is very low, in keeping with calculations. With the present light load, the negative sequence voltage of the SWL referred to in Table I has been measured in the range from 0.1% to 0.4%. Similar values have been measured in the other SWLs. Voltage is stable in all locations, even during start-up of the largest motors.

Checking of the adequacy of grounding systems for earth return of current is very simple in a SWS in service, because there is a continuous current injection to the ground, I_g. It is therefore sufficient to measure I_g with a clamp-on ammeter in the villages and substations, and the potential to remote earth, V_e, with a multimeter. The ratio $R_g=V_e/I_g$ is the ground resistance. Touch and step voltages are measured with a multimeter and readily recalculated for the maximum design current, $I_{g,max}$, by multiplying by the ratio $I_{g,max} / I_g$.

Measured values of R_g have been found in the range from 0.5-1 Ω for the 115 kV substations up to 8 Ω for MV/LV transformer stations with a low power rating. Values of V_e, referred to $I_{g,max}$, do not generally exceed 30 V. Step and touch voltages, measured conservatively by assuming infinite the resistance of human body, do not generally exceed 7V with $I_{g,max}$, with one exception at Muang Cha substation fence where a value of 15 V is estimated in dry season when current will reach $I_{g,max}$ =50 Arms. In some cases the Contractor has been requested to improve the grounding system with the addition of grounding rods and buried connecting cables.

Coordination of protection tests have been performed by creating artificial 2-phase and 3-phase short circuit in 3 of the 5 SWSs of Fig.4, in the most critically located 34.5 kV lateral line and at the MV terminals of a MV/LV transformer connected to the same line. Where necessary, settings of overcurrent relays at sending end of SWL and rated current of fuses have been modified, so as to ensure that the SWL will not be tripped in the event of faults in lateral lines.

No permanent faults have occurred so far in the SWSs. Transients faults on SWLs can be caused almost solely by lightning. Owing to the location on top of towers, energized SWs cannot undergo arcing to vegetation; the wire-to-wire faults that are caused by wind, birds etc. in conventional MV lines, are not possible in SWLs, due to the large distance between the two SWs; bush fires affect HV conductors rather than SWs.

The recorded rate of faults per 100kmxyear is lower for the "3-Phase" SWLs than for conventional MV lines of same rated voltage, in spite of the higher exposure to lightning of SWLs. Fault rate in lateral 34.5 kV lines is of same order as recorded for conventional MV lines of same voltage.

5. APPLICATIONS OF SWSs IN OTHER COUNTRIES

Ghana. The first pilot and commercial applications were made in Ghana in the late 1980s. About 1000 km of 161 kV-50 Hz transmission lines are provided with SWSs, half of which have been in operation for 14 years (30 kV "3-Phase" and 34.5 kV "V" SWSs). The good operational experience has justified the application in other countries, in most cases supported by the International Funding Agencies.

Brazil. "3-Phase" SWSs have been in operation since 1995 in a long 230 kV-60 Hz line. One of the SWSs supplies the town of Jaru (load was 4.3 MW in 1995) located at a distance of 85 km from the supply substation of the SWL.

Sierra Leone. "3-Phase" 34.5 kV SWSs have been implemented in 150 km of the first 161 kV-50 Hz line of the country. One SWL will supply 4.5 MW to the town of Makeni and will be used for power line carrier communications. The SWSs are not yet in service due to turmoil in the country.

Ethiopia. "Single-Phase Earth-Return" 34.5 kV SWSs have been applied on 200 km of 132 kV-50 Hz lines. The galvanized steel SWs of an existing 230 kV line have been replaced by ACSR SWs for application of the "3-Phase" 34.5 kV SWSs. Use of the "3-Phase" SWSs has been planned for a new 200 km long 132 kV line.

Togo. "3-Phase" 34.5 kV SWSs are under implementation in 265 km of new 161 kV-50 Hz lines. One of the SWs will be an insulated OPGW.

Benin. "3-Phase" 34.5 kV SWSs are planned for construction in about 300 km of 161 kV-50 Hz lines. One of the SWs will be an insulated OPGW.

Burkina Faso. "3-Phase" 34.5 kV SWSs are planned for construction in a new 225kV-50Hz-330 km long line.

Mozambique. A feasibility study has been performed for the application of "3-Phase" 34.5 kV SWSs in about 550 km of existing 220 kV lines in the North of the country.

Cambodia and Malawi have also expressed interest in the use of the SWSs.

6. CONCLUSIONS

The unconventional grid based rural electrification technique dealt with in the paper, referred to as the SWS, allows electricity to be made available at MV to communities located along the HV transmission lines, with an installation cost that is only 10-15% of cost of independent MV lines on the same ROW. Environmental impact and maintenance costs of SWLs are negligible.

14 years of operational experience in Ghana has confirmed the viability of the “3-Phase” SWSs, which provide a quality of service to consumers not inferior to the one of equivalent conventional MV lines. On the basis of this field experience, Electricité du Laos firstly implemented three “Single-Phase Earth-Return” SWSs and has recently commissioned five “3-Phase” SWSs serving a large rural population. The latter provide a well regulated and balanced 3-phase supply in all locations. Earth return of current does not pose problems. Faults on SWLs are practically all of transient nature, generally caused by lightning.

The use of the automatic reclosure is expected to eliminate the vast majority of faults in the very long “3-Phase” SWLs in Laos (one is 129 km long and supplies 42 villages). Application of a recloser in an intermediate point of long SWLs is also foreseen, when loads will exceed certain values, in order to increase the continuity of supply.

No royalties are due for application of SWSs, which have been conceived for promoting rural electrification in developing countries.

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