Transient study of rural electrification using induced voltage at transmission lines' shielding wires.

J. S. Chaves, M.C. Tavares

Abstract-- **Nowadays rural electrification rate has increased around the world due to governmental programs and the use of alternative energy sources, however, isolated communities still lives without electric services. This population, who achieves 1.2 billion of people, demands the use of non-conventional methods to solve this problem. Ironically, part of the isolated villages are localized near to high voltage transmission lines (TL). The low electric load of those communities prevents the construction of a high voltage service station, becoming economically non-viable. These micro loads can be supplied by using the energy loss that is confined near to isolated shielding wires (ISW), in order to avoid the use of large transformers. This paper shows an innovative proposal of rural electrification using induced voltage in ISW from a 500 kV transmission line. A transient study is presented evaluating the possible overvoltages caused throughout the generation system, defining a protection system that allows the feeding of small communities without affecting the transmission line performance. The electrification system presented comply with steady and transient states standards .**

***Keywords*: Isolated shielding wires, rural electrification, transmission lines.**

I. Introduction

CURRENTLY, many transmission lines´ projects are built away from the main highways and their routes cross or make frontier with small towns and villages without electricity supply. When those transmission lines are of high voltage (HV) level, it is technically difficult to reduce the line reliability to feed small loads. The electrical supply of potential consumers present near to HV and extra high voltage (EHV) transmission lines would produce gains for the region, since the service would be a benefit for local small enterprises and could contribute to decrease the migration to nearby major urban centers. A non-conventional method to deal with this issue is the use of isolated shielding wires (ISW).

This technology uses the energy loss confined between ISW and phases conductors voltages in an overhead transmission line to attend small electric loads [1 – 4]. ISW produces a natural capacitive voltage divider by electromagnetic coupling, inducing a lower voltage on ISW. This fact avoids the construction of conventional transformation substations to electrify isolated villages [5].

As transmission lines are commonly exposed to temporary overvoltages because of different nature faults, this research studies transmission lines behavior when using the proposed system under fault.

In the next section a fault study on transmission line and rural feeder is presented. Based on the results, it is possible to observe that this method is a feasible alternative to electrify isolated small loads near to transmission lines without jeopardizing transmission system reliability.

II. Isolated shield wires system model

Some considerations on the non conventional source of the energy should be made: generally, SWs are grounded and no induced voltage appears in those cables. However, there is a permanent small current flowing, which will result in transmission line loss. Nowadays some Brazilian EHV lines (above 500 kV) have their SWs isolated with small insulator to reduce loss. In this project, the idea is to use this energy lost by the lines to feed very small and unattended loads.

Assuming a single circuit transmission line (phases a, b and c) with two SWs, a single shielding wire will be isolated meanwhile the other is grounded [5]. Equation (1) describes the voltage induced on the ISW, where Y_{ad}, Y_{bd}, Y_{cd}, and Y_{dd} are admittances $Y = j\omega C$ associated with other capacitances. Here the ISW is named as phase d.

$$\widehat{V_d} = \frac{\hat{V}_a Y_{ad} + \hat{V}_b Y_{bd} + \hat{V}_c Y_{cd}}{Y_{ad} + Y_{bd} + Y_{cd} + Y_{dd}} = \hat{V}_{thd} \quad (1)$$

$$Y_{thd} = Y_{ad} + Y_{bd} + Y_{cd} + Y_{dd} \quad (2)$$

Capacitive coupling generates the SW voltage V_d. Electromagnetic effects are insignificant due to low contribution of induced voltage in lines with regular lengths (maximum length around 400 km), therefore, voltage on ISW does not depend on insulated SW length. However, the power generated depends on the ISW length.

III. Analyzed system

A. Transmission line

The transmission system studied is composed of a generator unit, step-up transformer, circuit breaker (CB), 300 km 500 kV transmission line, and equivalent terminals network, as shown in Figure 1.

The TL was considered transposed as depicted: 1/6, 1/3, 1/3 and 1/6 of total transmission line length. The line has a 500 kV

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Cross-Rope structure based on an actual Brazilian transmission line data (Tucurui - Marabá). See Figure 2. The soil resistivity is 4000 Ω.m.

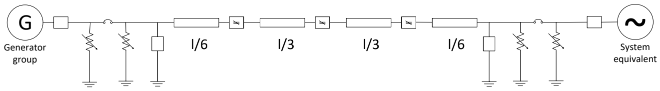


Figure 1.Single line diagram of simulated system.

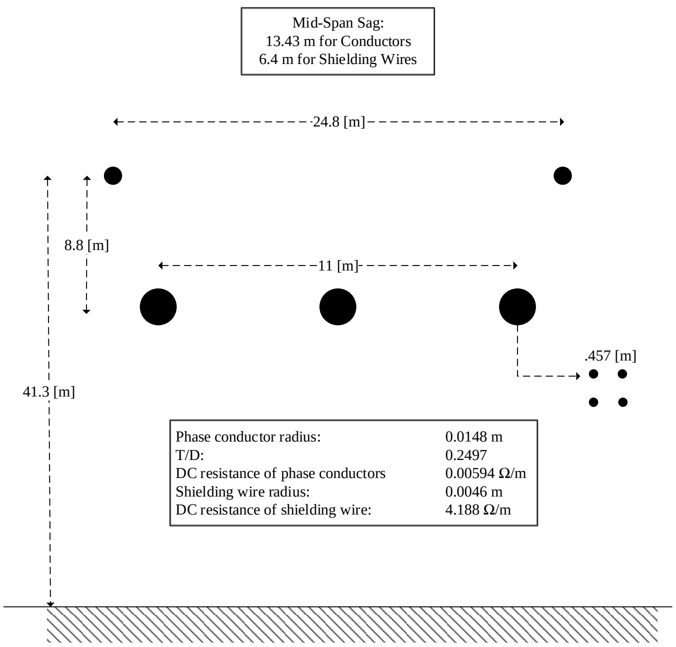


Figure 2. Tower structure configuration.

Based on the physical transmission line characteristics, transversal and longitudinal parameters were calculated in phase domain. As the SWs will be part of the electrical system they cannot be incorporated in the line parameters matrices as in regular studies. In the present study they should be explicitly represented, therefore, TL cannot be represented as a balanced line (or ideally transposed line), as the transposition cycle has major influence in the SW coupled voltage, as will be properly described in forthcoming sections. Thus the transposition towers must be represented explicitly and non-transposed line will have 5 phases.

Table 1 presents the calculated modal values ([7], [8]) for 60 Hz (resistance per unit length, characteristic impedance, propagation speed).

TABLE 1. MODAL PARAMETERS FOR 500 KV NON-TRANSPOSED TRANSMISSION LINE, CALCULATED FOR 60 HZ

Mode	$\boldsymbol{R'_{modal}}$ [Ω/km]	$\boldsymbol{Z_c}$ [Ω]	Propagation speed [km/ms]
1	4.14	986.49	153.33
2	3.59	953.98	159.15
3	0.36	812.54	183.53
4	0.015	206.04	295.96
5	0.014	151.98	296.10

Modes 1 and 2 correspond to ISW, being remarkable the difference in resistance with aerial modes (modes 4 and 5), as well as the lower propagation speed. Mode 3 corresponds to the ground mode (similar to zero sequence), with surge impedance larger than the aerial modes and lower propagation speed. The aerial modes' propagation speeds are close to light velocity.

Simulations were made using PSCAD/EMTDC and the non-transposed line was modeled with frequency depend Phase Model. Shielding wires were represented explicitly, as well as the transposition towers. Therefore, five phases non-transposed line sections were considered, the regular *a*, *b* and *c* and two shielding wires (*d* and *e*). Phase *e* was grounded along the whole TL. Phase *d* was insulated between the transmission tower at km 150 and 250, while grounded at the remainder of the line. Due to transposition effect, the phases configuration on the insulated section changes as presented in Figure 3.

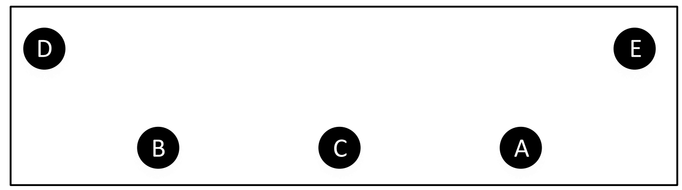


Figure 3. Phases configuration between km 150 and 250.

B. Rural feeder

A rural feeder with 10 km length was designed to connect the isolated communities, see Figure . Feeder height was taken as 12 m with a 13.8 kV wood crosshead of 2.5 m length. A 4/0 AWG cable with resistance of 0.1610 Ω/km was used. An 800 kVA single-phase transformer (TR) was used with a turn ratio of 3.5, leakage impedance of 0.09 pu, and quality factor of 100 (typical in Brazilian system).

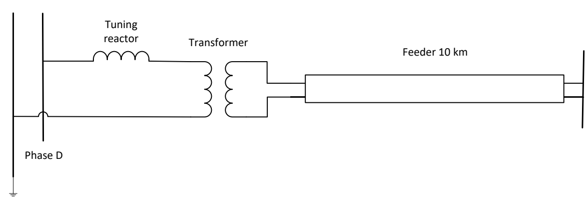


Figure 4. Feeder configuration.

C. Tuning reactor

The present generation system has a high capacitive response, which compromises voltage regulation at the load, see equation (1), preventing direct use of the ISW system to feed a small load. To increase the generation short circuit level it is necessary insert a reactor with a value equal to the Thevenin equivalent system capacitance. This resonant circuit produces a small system equivalent, resulting in a strong source at the point of common coupling (PCC), located at 200 km [5].

To tune the resonance circuit it was specified a reactor of 4165.5 Ω with a quality factor of 200. The protection for the rural feeder system was composed of a spark gap in series with a dump resistance of 50 Ω in parallel with tuning reactor (TR), see Figure 5. The spark gap has a breakdown voltage of 150 kV. Surge arresters were was installed on terminals of the transformer.

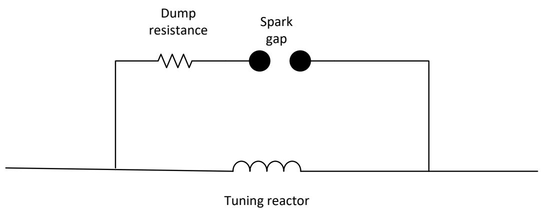


Figure 5. Tuning reactor protection.

D. Rural load

The target load was taken as small towns with less than 1000 people. The houses consumption would be mainly to light, radio and use of some basic household appliances and communication. In these rural areas small engines should also be considered. Thus, a rural load was defined with typical values as shown in Table 2.

TABLE 2 – SINGLE HOUSE LOAD.

	Quantity	Unit power [W]	Total power [W]
Illumination	3	20	60
Outlet	3	180	540
Refrigerator	1	500	500
Motor ¾ HP	1	800	800
Total per house [W]			1900

A target of 260 houses resulted in a power supply of 0.5 MW. This rural load was supposed to be located 10 km away from a 500 kV transmission line.

IV. RESULTS

A. Short circuit at transmission line.

Generally, single-phase faults are the most common in transmission lines [6]. However, two-phases and three-phases faults are considered as well in the present study to identify the response of induced voltage on SW and the behavior of the equipment used. Due to high SW attenuation, fault incident far away from PCC will cause lower overvoltage; therefore, the fault was applied on PCC (km 200).

Statistical analysis was performed with 100 shots and the fault was modelled through of resistor values of 1 Ω, 10 Ω, 20 Ω, 50 Ω and 70 Ω. The fault was supposed transient and three-phase opening/reclosing was applied. A 400 Ω pre-insertion resistor was used during reclosing maneuver. Figure 6. Fault protection scheme. presents the fault protection scheme applied.

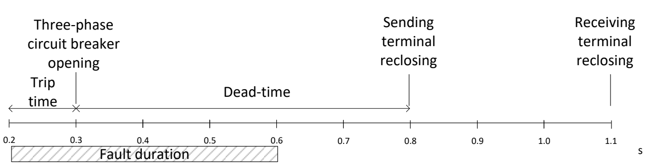


Figure 6. Fault protection scheme.

Initially, simulations were performed without any protection, neither on reactor nor on SW. In Figure 6 presents the overvoltage on ISW at 200 km point for different types of faults and fault resistance values. Besides, Table 3 shows overvoltage results and the statistical study of other points of the system with a fault resistance of 20 Ω.

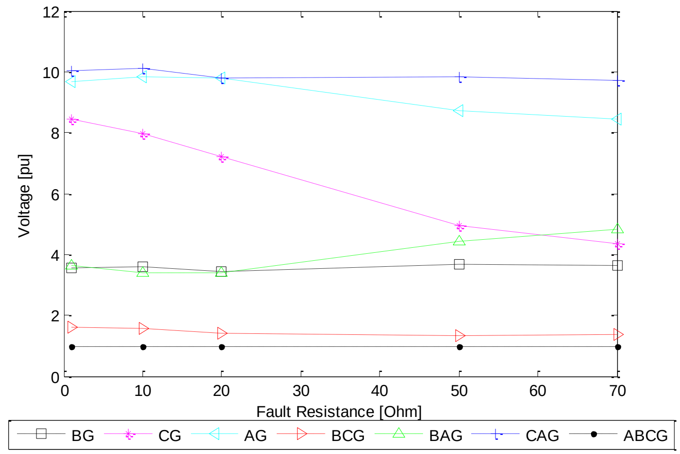


Figure 6. Overvoltage on ISW at 200 km point for different types of fault at transmission line (km 200) without protection.

TABLE 3. 98% PROBABILITY RESULTS FOR FAULTS AT KM 200. NO PROTECTION SYSTEM. FAULT RESISTANCE OF 20 Ω

Type of fault	V SW		I SW		V drop TR	
	kV	pu	kV	pu	kV	pu
BG	423	3.46	230	3.09	398	4.35
CG	885	7.24	395	5.31	848	9.25
AG	1202	9.83	467	6.29	1153	12.58
BCG	175	1.43	119	1.60	163	1.78
BAG	416	3.40	344	3.30	395	4.30
CAG	1206	9.86	481	6.44	1156	12.65
ABCG	198	1.63	84	1.32	109	1.79

The overvoltage at ISW without any protection may reach extremely high values, as 10 pu. However, these extreme values are not physically correct, as a disruption would occur. In the present document the line was modeled considering the air has infinite breakdown voltage and no corona effect was modeled.

Phases farther from isolated SW present the highest overvoltages. Induced voltage on ISW depends mainly on phase voltages and coupling capacitances between phases and SW, see equation (1). As the closest phase to ISW has the greater contribution to the induced voltage, CAG fault provokes highest overvoltage on ISW (phase B is closest from ISW in this transposition section, see Figure 3). Although the influence of fault resistance value on CG and AG generates different overvoltage values, all of them are extremely highly.

Based on this results, the proposed tuning reactor protection together with spark gaps at ISW were considered further on. The ISW spark gaps have a breakdown voltage of 210 kV and should be installed in parallel to each SW insulator.

The most severe case is presented on Figure 7 considering the protection system. Although high voltage appears in healthy phases, no high overvoltage is observed on rural system.

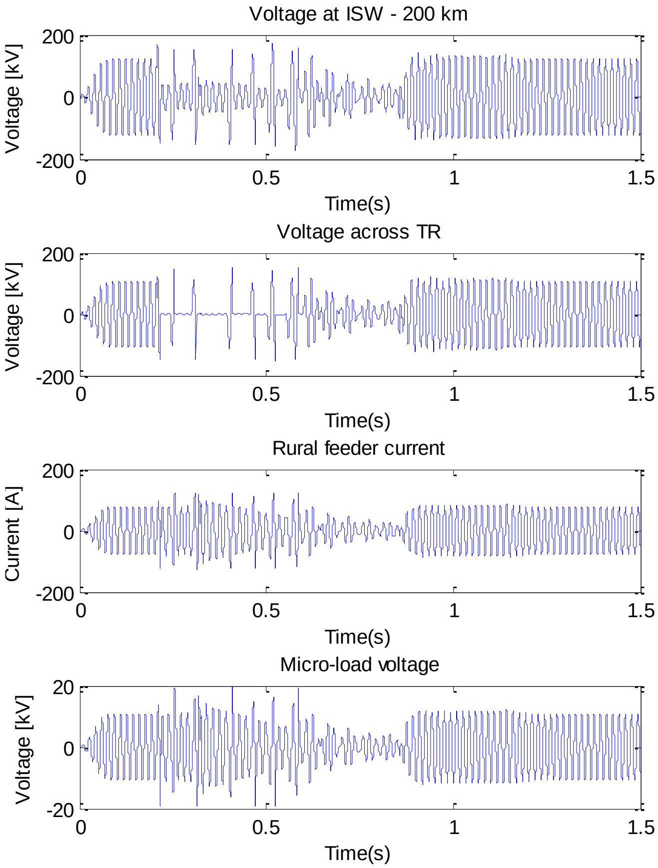


Figure 7. Most severe ACG fault using protection system.

B. Short circuit along the rural feeder.

Faults along the rural feeder can generate high overvoltages because of the resonant circuit, rising the voltage on ISW.

Transient faults along the rural feeder were simulated. The fault duration was 400 ms. Statistical analysis was performed with 100 shots. Additionally, a study of the fault resistance value effect was made using five values: 1 Ω, 10 Ω, 20 Ω, 50 Ω and 70 Ω. Faults on points 150 km, 200 km and 250 km on ISW were considered as well as fault on both terminals of rural transformer and rural load. Three thousand simulations were implemented.

In the present isolated distribution system a major concern is that the transmission system should not have any modification on its reliability figure. The obtained results confirm that there is no disturbance on TL phases voltage derived from faults in the feeder system, as shown in Table 4. Figure 8 shows a deterministic case of a fault in the rural transformer high voltage terminal. It can be verified that even when steep overvoltages appears at ISW due to tuned reactor gap operation, there are no impact on TL voltages.

Figure 9 shows the 98% overvoltage results at some points of rural system. It was observed that the occurrence of fault along the ISW does not result in important overvoltages along rural system. The high impedance of Thevenin source (see Equation 2) together with the protection system cause fast discharge of capacitance equivalent system and the tuned reactor, preventing both reactor and ISW gaps from operating.

TABLE 4. VOLTAGE ON TRANSMISSION LINE AT KM 200 - FAULT ALONG THE FEEDER WITH FAULT RESISTANCE OF 20 Ω - VALUES IN KV.

Values	**Fault location**					
	Micro-load	**TR low side**	**TR high side**	**ISW (km)**		
				150	**200**	**250**
Min.	419.82	419.82	419.81	419.86	419.86	419.86
Max.	419.82	419.82	419.81	419.86	419.86	419.86
Mean	419.82	419.82	419.81	419.86	419.86	419.86
Std deviation	0.00	0.00	0.00	0.00	0.00	0.00
98%	419.82	419.82	419.81	419.86	419.86	419.86

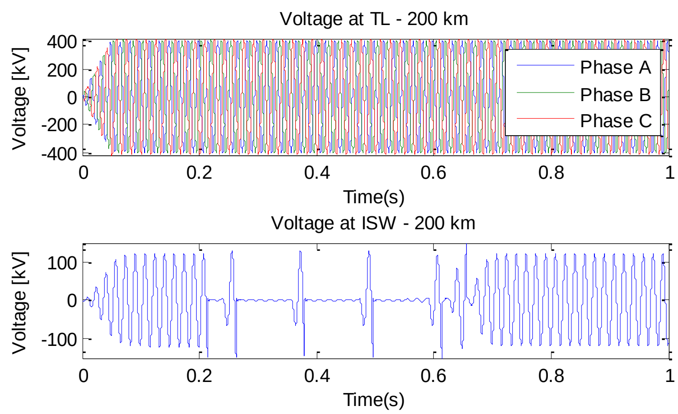


Figure 8. Voltage on transmission line and ISW on 200 km for short-circuit on transformer high voltage terminal with protection system.

For other fault locations the reactor gap always protected the system. Fast variations on tuning reactor current elevate the voltage along the rural feeder due to a resonance phenomena on LC circuit, including the transformer. Overvoltages close to 2 pu on the high voltage transformer side appear derived from faults on feeder and rural load. However those are short duration transients that will not damage the rural assets.

An important aspect to be emphasized is that due to the rapid reactor gap operation, the overvoltages along the feeder remain almost constant regardless of the fault resistance value.

Faults on high voltage transformer terminals generate the highest value on rural load, however, overvoltages do not exceed 1.6 pu for a small fault resistance. Due to a voltage increase across the tuning reactor, the gap discharges promptly. The arc re-ignites several times while the fault is maintained. The voltage on ISW and tuning reactor are controlled, avoiding resonant condition.

Although the rural micro load is subjected to rapid impulses due to arc re-ignition, the maximum voltages in the feeder are neither high nor of long duration. Use of spark gaps avoid the extremely high overvoltages previously presented on the feeder system.

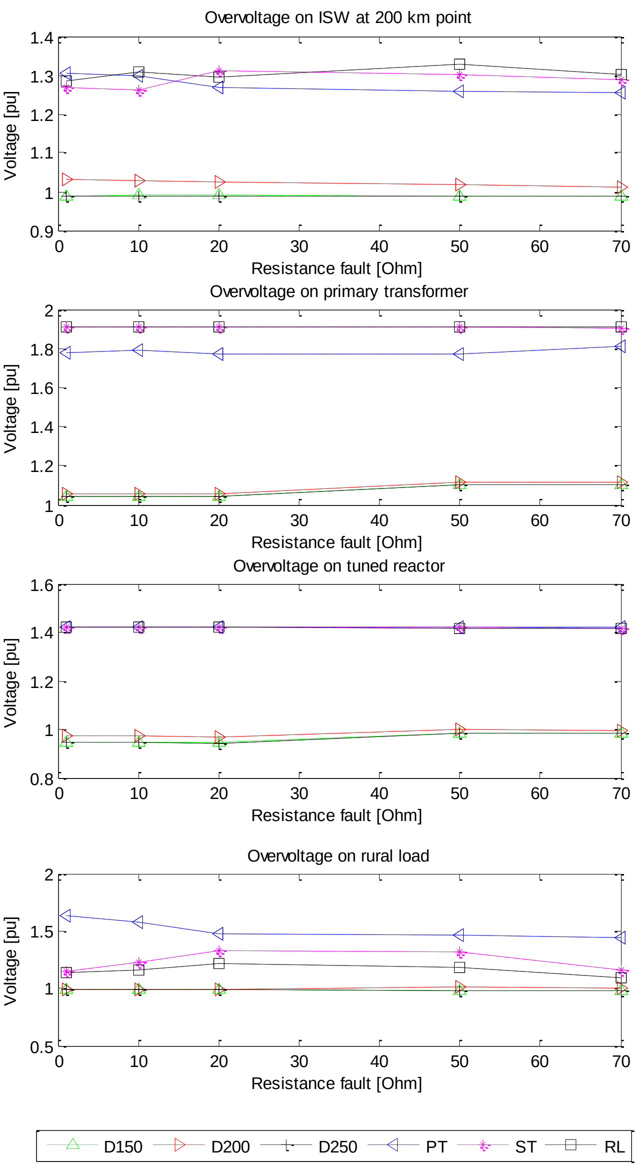


Figure 9. Overvoltage along the rural system for faults along the feeder. D150: Fault on 150 km of ISW, D200: Fault on 200 km of ISW, D250: Fault on 250 km of ISW, PT: Fault on high voltage transformer side, ST: Fault on low voltage transformer terminal, RL: Fault on rural load - 98% probability results.

C. Short circuit on ISW

An important data to analyze is the current fault on ISW. In case of live-line maintenance, the operator will need to ground the ISW. The worst location to ground is close to PCC and it will result in the maximum current, because the energy stored in the reactor will be released and the only attenuation will be ISW resistance.

In Figure 11 are presented the curves of a statistical study performed for the maximum and minimum fault current value at ISW. There is a short voltage spike in each case, because the passive LC circuit elements will discharge. However, this value is reduced to a current lower than 25 Arms for steady state.

Grounding ISW is not a difficult operation, taking advantage of the low short circuit equivalent source level.

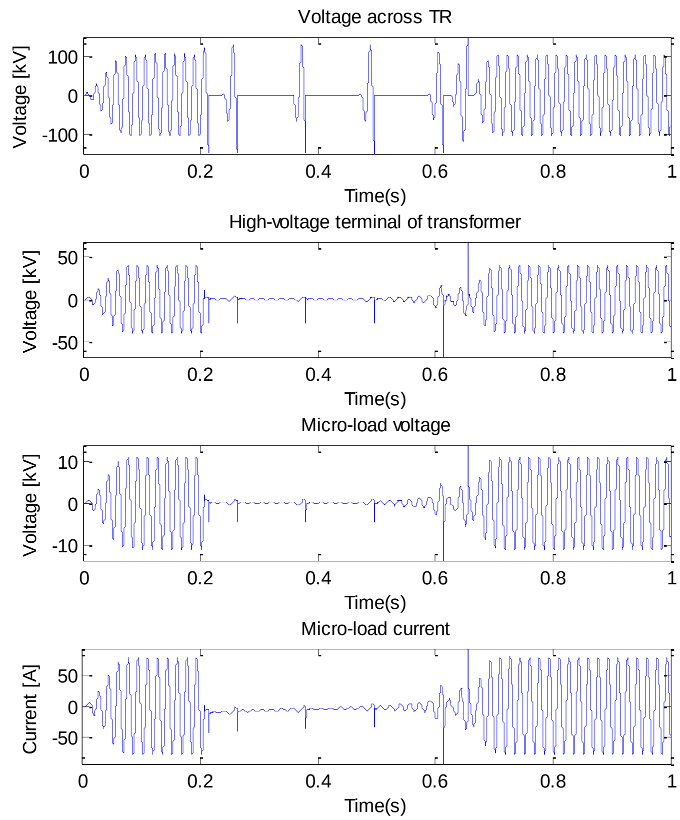
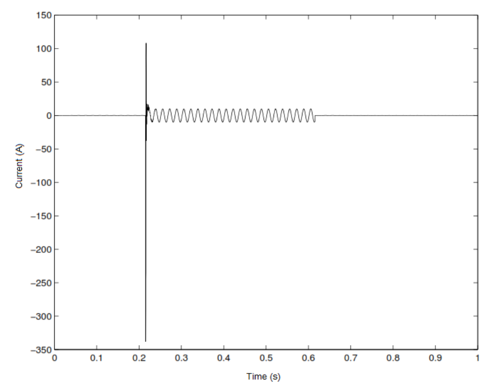
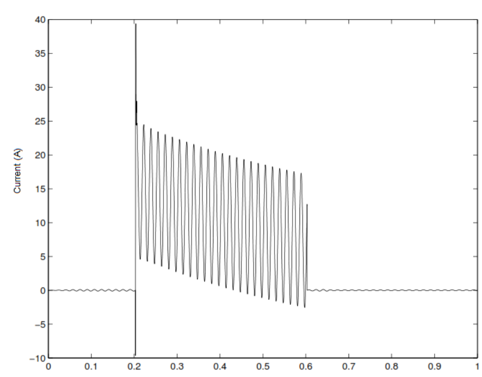


Figure 10. Voltage and current along the feeder for short-circuit on high voltage side of transformer with protection system.



(a) Simulate with maximum current



(b) Simulate with minimum current

Figure 11. Voltage and current along the feeder for short-circuit on high voltage terminal of transformer with protection system.

V. Conclusions

In the present paper a new method to attend very small isolated loads is presented. The energy is obtained from HV or EHV isolated shield wire and is basically derived from transmission line loss. These small loads are in the order of tenths of MW and, if they are located in vicinity of transmission line, the proposed solution can become extremely attractive.

The ISW becomes a natural voltage divider, generating a perfect sinusoidal voltage with the same quality as the one from the transmission system. No energy quality degradation is produced by the generation asset.

The natural generation system is highly capacitive and a tuning reactor was specified to produce a strong generation source. It was also necessary to design a protection system for both the generation equipment, formed by a tuning reactor and rural distribution transformer, and the SW insulators. Both protection systems were based on spark gaps, being necessary to include a damping resistor in the tuning reactor gap circuit.

For a 500 kV example system the voltage is supplied at 30 kV. A single phase distribution transformer was used to reduce the voltage level to the rural feeder. The feeder voltage can be adjusted according to the feeder length. In the present case it was reduced to a 13.8 kV system (8 kV phase to ground).

The most severe disturbances are associated with faults at transmission system and at rural feeder. It can be concluded that:

– No important overvoltage appears at generation system and load during faults at transmission line.
– Transmission line does not identify any disturbance for rural feeder faults.
– Overvoltages along the feeder remain almost constant regardless of the fault resistance value.
– Rural feeder faults are mitigated with the use of spark gaps.

The proposed solution provides a low cost source for isolated micro loads where non-conventional generation, like solar panels, are not adequate. This system needs low maintenance and can also be used as an additional supply source in locations where rural outages are much above acceptable levels.

VI. References

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