# Analyzing Rural Electrification Topologies Based on Induced Voltage at Insulated Shielding Wires

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***Abstract*—This paper analyses low-cost techniques for rural electrification based on the use of insulated shielding wires of extra-high-voltage transmission lines. The main idea is to use the line capacitive coupling as an auxiliary power supply to remote rural systems. The insulated shielding wire (ISW) will behave as a capacitive voltage divider, promoting low voltage on it. We introduce a comparison of different low-cost electrification methods used over the last years and present a careful analysis of different topologies, which have a major impact on rural voltage regulation. A transient study was implemented to observe the behavior of both the transmission system and the rural feeder under typical switchings.**

***Index Terms*—Capacitive coupling, rural electrification, transmission lines, insulated shielding wire, electromagnetic transients.**

## I. Introduction

SHIELDING wires (SW) are designed to protect overhead transmission lines against lightning strikes. Typically, in extra-high-voltage (EHV) and ultra-high-voltage (UHV) lines, two shielding wires are used per transmission tower, whether single- or double-circuit. These cables are usually made of steel, do not carry energy, can have low electrical conductivity, and are much cheaper than phase conductors, which will transmit power. A shielding wire normally has one or more optical fibers inside it, being usually an optical fiber composite ground wire (OPGW) type. The electrical system tele-protection uses circuits composed by OPGW [1].

OPGWs are used in several countries to transmit communication data, allowing the connection of people previously segregated from the virtual world. Communication companies have identified an economic value to SW that differs from its initial function, which was protecting the asset of energy companies, the transmission lines (TL) [2]. Thus, OPGWs are used in several countries such as Brazil to digitally connect populations, allowing access to mobile telephony for almost the entire nation. The benefits of using the electric power infrastructure to transfer digital data are immense since the lines cross regions often inhospitable and difficult to access.

Rural distribution systems are often connected to the electrical system through a single substation. These rural lines can be around 100 km long, showing high rates of unplanned outages. Companies are penalized when they do not reach a quality level, but the access to a second power supply, which would ensure a minimum continuity of service, may not exist, even if the region is near an EHV line route.

Similarly, very small villages, with just a dozen houses, may have no access to electricity even if they are near to EHV lines. The size of these loads does not allow conventional solutions such as the installation of a step-down substation. It is impossible to feed loads of tenths of MW from 230-kV lines [3], [4]. Thus, unconventional solutions must be postulated.

In this article, we will examine some low-cost rural electrification methods, identifying main problems and proposing solutions. One of these methods uses insulated shielding wires (ISW) as rural feeders through capacitive coupling with phases of high-voltage transmission lines [5]. We analyze the transmission line modeling with one of the insulated shielding wires in Section III. Moreover, we will show results of the rural system performance for different loading levels under normal operating conditions. We also examine some feeding system topologies, describing the ones we found most suitable. Furthermore, we show some results of the electromagnetic transient study. Nevertheless, caution is advised when modeling lines with ISW, as shown in the study.

It is possible to use the ISW as a second power supply of a rural feeder or to feed previously unattended loads. This is a low-cost solution that can be quickly implemented and used in an integrated manner with other solutions, such as solar panel supply.

## II. Low-Cost Rural Electrification Methods

Rural electrification projects demand specific techniques according to the situation. In many of them, the initial cost is the most important factor, which ultimately end up preventing the use of better methods that could represent integral solutions for a given community. The following section shows a summary of the main techniques that have already been applied at different scales in some countries.

### A. Single Wire Earth Return (SWER)

SWER is a rural load-feeding technique based on a single cable as feeder to attend loads far away from service station

Manuscript received November 6, 2017; revised April 14, 2018 and July 28, 2018; accepted October 27, 2018. Date of publication November 9, 2018; date of current version January 22, 2019. This work was supported by the research agencies CAPES, CNPq (306351/2017-0), and FAPESP (2017/20010-1). Paper no. TPWRD-01362-2017. *(Corresponding author: Joan Sebastian Chaves Huertas.)*

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Digital Object Identifier 10.1109/TPWRD.2018.2880427

centers. An important feature of this configuration is the use of the ground as a return path for the current, avoiding the use of an additional wire and thus reducing assembly costs.

This scheme is composed by a wire that is energized by a single-phase transformer on the high-voltage winding, while the other winding is connected to ground. The load protection is implemented through conventional elements of traditional systems [4], [6].

Although SWER criteria are defined by the size of the rural load to be energized, a capacity lower than 480 kVA with a voltage of 19.1 kV is suggested. In addition, an evaluation of load increment should be made in no more than 10 years, to promote system flexibility [4]. SWER line characteristics impose a simplicity in construction, avoiding problems of safety distances with other phases.

Maintenance costs are also reduced because the system protection uses traditional elements. Distances to trees and vegetation are easier to control, which means less maintenance. Ground resistance must remain constant and be monitored at least once a year, even though, based on past findings, no great changes were observed over time [6].

Some countries in Oceania, such as New Zealand and Australia, have already built SWER lines. SWER systems around the world can achieve line lengths longer than 300 km, although showing voltage regulation problems. Controllable shunt reactors were used to mitigate the issues previously mentioned, as presented in [7].

### B. *Shield Wire Scheme (SWS)*

The SWS system is one of the most effective methods for powering small loads near to transmission lines and service stations when an auxiliary service bus is accessible.

For providing low-cost energy to feed small communities near transmission lines, Professor Francesco Iliceto from the University of Rome presented the SWS system in the 1980s. The magnitude of these loads is lower than 10 MVA. The project proposed to insulate and energize shielding wires (SW), which are mostly grounded through tower's metallic structures. These cables would be fed by the medium distribution voltage, optimizing the purpose of these wires and assigning them a second function [8], [9].

SW are energized with voltages between 20 kV to 34 kV from the nearest high-voltage substation. The high-voltage transmission line is also used as a rural feeder mechanism, and bifurcations are placed along the length of the energized SW. Voltage regulation at distribution side is adequate.

Currently, there is an African community 21.5 km from a transmission line powered by a 34.5 kV SWS system [4], [9]. In Brazil [8] a 5 MVA load located 100 km from service station is attended in Amazon Region. Another example is presented by Iliceto in [9], using SWS in northern Ghana in a 161-kV transmission line. The voltage for transmission and distribution used in the SW for low-load density areas was 34.5 kV. For larger settlements, a voltage of 11 kV was used. Systems operating at 34.5 kV are solidly grounded. Distances between villages and the 161-kV substation were approximately 50 and 125 km. The proposed SWS system uses conventional distribution equipment, avoiding high-cost electronic elements. Both SWS phase wires are energized by the secondary winding using a medium voltage transformer, and the third-phase is grounded through an RL arrangement to balance transformer currents in a compensated V-shaped configuration.

The cost is an important factor and can be considered as an advantage of SWS systems. As a fundamental criterion, the transmission line cost is not changed, since just an additional investment, in addition to the medium distribution voltage insulator used on SW, is needed.

As SW are exposed to lightning, spark gaps must be installed in parallel to insulators. The gap will close in case of overvoltage, protecting the main line (the high-voltage transmission line) by discharging the energy to the ground.

### C. *Capacitive Voltage Divider (CVD)*

In communities far from service stations, the use of energized wires becomes insufficient due to the voltage regulation in rural loads, being economically unfeasible. However, systems based on capacitive coupling may be an alternative energy extraction method. These capacitive voltage dividers, when directly connected to TLs, aim to reduce voltage without power transformers [10].

Capacitive coupling energy extraction systems have large Thevenin impedance, which represents a poor voltage regulation for larger loads. As a solution, a series inductance can be connected to the load to partially or fully compensate the capacitive effect of the voltage divider.

The main drawback of this approach is the intervention to the transmission line itself, which may compromise the line reliability. The rural load size is limited to dozens of kVA, but could be either single- or three-phase load.

### D. *Insulated Shielding Wires (ISW)*

On the region surrounding the transmission line, electrical charges appear as a function of the electric field between line phases and the ground. An induced voltage will appear on an isolated conductor positioned near the phases, derived from the capacitive coupling effect [3].

However, to avoid the costs of launching a new conductor or the problems of having an energized one below phase conductors, the SW can be used as energized wire with a voltage defined by capacitive coupling. Then, the SW must be insulated according to the transmission line voltage level and its physical and geometrical characteristics.

The use of insulated shielding wires is a methodology of rural supply focused on communities without any electric service, where these alternative solutions are not available. For instance, small villages that are located on the rivers vicinity usually experience supply deficit along the year when fed by portable generator. This derives from poor kerosene supply because of dry season that prevents river transportation. Analogous conditions can be observed with solar panels when rainy months provides few sunny hours per day. Solution allows a transmission line reliability based on a distribution line to villages located close of TL better than an isolated generation. On the other hand, ISW also can help to increase the SAIDI and SAIFI indicators as a second power supply.

Back in the late 1970s, Hydro-Québec implemented a system to provide energy to communication equipment, as microwave assets, wherever distribution systems were not available. For that Hydro-Québec used isolated shielding wires on an overhead 735 kV TL. A shunt-switching electronic regulator was proposed. That control reduced energy loss and provided higher energy level per unit of ISW length. This system also powered stroboscopic lamps that identified TL route, to prevent aircraft collision [11]. The system was adequate to power small loads up to 35 kW for a couple of decades; however, because of the high failure rate, maintenance was high, which demanded interventions. Eventually, the system was renewed.

By 2001, the company decides to launch IVACE project (Inductance Auto-Controlée à Entrefers), which consists of the implementation of a voltage regulator based on a transformer arrangement that sets the shielding wire voltage accordingly to deliver a defined power range. Although this improvement allows handling larger loads, it is subject to TL geometry and phase voltage. Its configuration generates certain deformations in the voltage waveform, with a total harmonic distortion of 6% [12].

ElectroPerú is a Peruvian electrical company that implemented the original technology in the 1980s to feed small loads, in the order of tenth of MW. The project considered 138 kV and 230 kV TLs with single- and double-circuit. A 230 kV double-circuit line provided up to 5.9 kW/km, imposing the use of both ISW as well as some additional cables [13]. According to the published results, the system was cost-effective when compared to the construction of a diesel power plant, equivalent in power and service. However, the proposed voltage regulation system was not adequate and it did not consider the natural load expansion (or better, explosion) that occurs whenever energy is supplied to an unattended region. High harmonic levels arose and eventually the project was discontinued.

Our proposal will use the ISW, but will present a different syntonizing circuit, as depicted in the next section.

## III. Basics of Insulated Shielding Wires System

Phase conductors' voltages in an EHV overhead transmission line induce voltage in insulated shielding wires due to capacitive coupling. The energy available in those cables is actually the line capacitive coupling loss but it can have an important economic value for distribution companies and even for transmission line owners, as it can become an important way to feed small off-grid communities that often hinder the release of TL corridors. An important aspect to be highlighted is the fact that the electrical load of isolated communities is comparable with the losses of a transmission line, being a very small power portion that the line will deliver additionally.

Some considerations on this source of energy should be made: generally, SWs are grounded, and no induced voltage appears in those cables. However, there is a permanent small current flowing. Nowadays, some EHV lines (above 500 kV) have their SWs isolated with a small insulator for reducing such loss. In some countries, to obtain a better use of TLs, one of the OPGW is grounded in each tower. As a method for reducing TL losses, the second SW is isolated over almost the entire TL, but grounded in some towers, thus avoiding the induced voltage elevation on the isolated cable [1], [14], [15]. In this study, we propose to use the energy that is confined in an isolated SW to enhance rural systems' continuity and quality figures, as well as to feed unattended communities. The proposed system brings the former solution to a higher level, as is depicted in next sections.

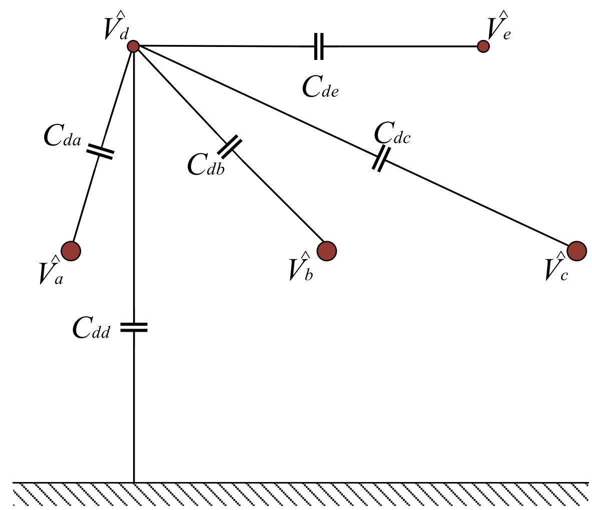



Fig. 1. Capacitance arrangement on transmission line using ISW.

Figure 1 shows capacitance between an ISW (Phase D) and transmission line phases with two SWs (second SW named Phase E is ground). These capacitances are dependent on transmission line geometry.

Note that $\hat{V_d}$ is described by equation (1) that reproduces the influence of phases' voltage on induced phase $D$ voltage. The SW-induced voltage will increase with line voltage level. However, this voltage will decrease with rising of SW self-admittance

$$\hat{V}_d = \frac{\hat{V}_a C_{ad} + \hat{V}_b C_{bd} + \hat{V}_c C_{cd}}{C_{ad} + C_{bd} + C_{cd} + C_{dd}} \tag{1}$$

To analyze the model it is necessary to calculate the Thévenin equivalent voltage, $\hat{V_{thd}}$ to phase $D$, shown in equation (1), and the Thevenin capacitance, presented in equation (4). This equivalent is obtained for a transmission line with a single ISW.

$$C_{dg} = \sum_{n=1}^{4} C_{4n} \tag{2}$$

$$C_{fd} = \sum_{n=1}^{3} |C_{4n}| \tag{3}$$

Where $C_{4x4}$ is the transverse capacitance matrix of the single circuit transmission line with a single ISW. Then:

$$C_{thd} = (C_{dg} + C_{fd}) \tag{4}$$

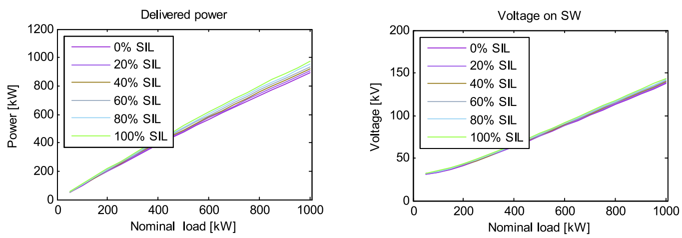



Fig. 2. Rural load variation for different SIL values.

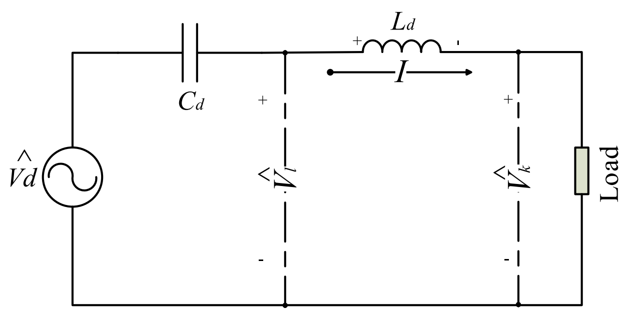



Fig. 3. Equivalent circuit of energy generation using ISW with tuning reactor.

Capacitive coupling generates the SW voltage $V_d$. Power flow has no influence on voltage regulation due to low contribution of induced voltage in lines with regular lengths (maximum length around 400 km) [3], [16], as shown on Fig. 2 that shows an example case for 500 kV transmission line by SIL variation. Therefore, voltage on phase D does not depend on ISW length. The unit of capacitance of equation (4) is F/km, which means that the delivered power depends on the ISW length [16].

Analyzing the equation (4) we verified that a low capacitance $C_{thd}$ compromises load voltage regulation. This means that it is not possible to use just the ISW cable to feed the small load, being necessary to make this source stronger.

To increase the short circuit level of the capacitive source, a reactor with an equal value to the Thevenin equivalent system capacitive reactance should be inserted in series with the generation circuit. This will produce a resonant circuit. Thus, the equivalent feeding system impedance will be small, making the load voltage almost equal to the equivalent source voltage, producing a stronger source at the point of common coupling ($PCC$) [10].

The reactor is calculated with equation (6). The following equations are obtained analyzing Fig. 3:

$$\hat{V_d} = \hat{I}\left(\frac{1}{j\omega C_{thd}}\right) + \hat{I}j\omega L_d + \hat{V_k} \tag{5}$$

where $L_d$:

$$L_d = \frac{1}{\omega^2 C_{thd}} \tag{6}$$

Table I summarizes the main characteristics of the presented methods. ISW appears as a viable solution for loads far from transformation centers. The main idea is that the distribution company uses the second ISW, which was not used by the telecommunication company. The power supplied will have the transmission energy quality, including low outage rates, with a small TL design change. Furthermore, it will be much cheaper than building a distribution substation, which is often impossible because of technical constraints related to extremely low load size.

TABLE I
MAIN CHARACTERISTICS OF RURAL ELECTRIFICATION METHODS

| Method | Target population | Advantages | Disadvantages |
|---|---|---|---|
| **SWER** | Sparsely population and low load density. | Low initial capital cost. Design simplicity. Easy construction. Excellent reliability level. Low maintenance cost. | Special requirements for isolating transformer. Low-resistance earth bank. Restricted load capacity. Possible interference to metallic communication systems. |
| **SWS** | Small cities. Load lower than 4 MVA. | Cost about 15% of a conventional power line. Use conventional transformers. Maintenance on transformation center. | Used to attend load up maximum to 100 km from station. Voltage rise up at transformation centers. |
| **CVD** | Unattended communities. | Cost lower than conventional service stations. Simple installation. | Possible ferroresonance occurrence. High maintenance cost. Interfere in transmission line reliability. |
| **ISW** | Rural loads lower than 0.1 MVA. Unattended communities. | No impact on TL reliability. Voltage quality follows TL quality. Small modification of TL configuration. | Use of voltage regulation system. |

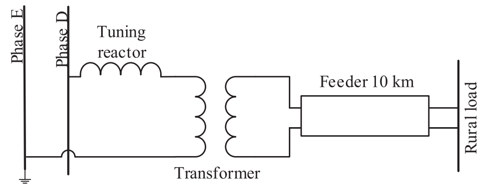
## IV. FEEDER TOPOLOGY

Figure 3 shows the basic principle of the ISW electrification system. We can observe that with the resonant system, load voltage is equal to the internal voltage supply (induced voltage). The power system would consist of the equivalent of the ISW source, the tuning reactor (TR) and the load. In fact, the power system will be connected to a rural feeder that may have nominal voltage of 13.8 kV or 34.5 kV, depending on the feeder length. As the power supply is single-phase, the rural feeder will also be single-phase. We propose the use of a single-phase feeder comprising two conductors, as we have not considered the ground return.

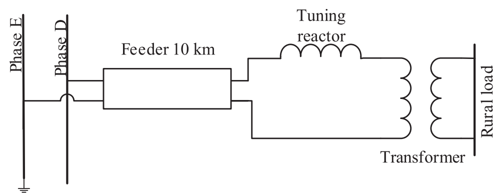
The induced voltage after attending the load will rise, as shown in the next section, requiring lowering of the voltage to distribution level. Some alternatives are proposed in Fig. 4. Some topologies use only a step-down transformer, which can be located at the ISW side (Case 1) or in the rural network connection point (Case 2 and 3). In these last two cases, the rural feeder can be located next to the ISW (before the TR (Case 2) or right after the tuning reactor (Case 3). If the tuning reactor is on the high side of the circuit it will have a very high value, provoking Case 4, which uses more transformers than the previous alternatives but allows the TR to be placed in the low-voltage side, significantly reducing its size.

It is desired to find the best configuration that minimizes the voltage at the ISW and across the tuning reactor, and maximizes the delivered power.

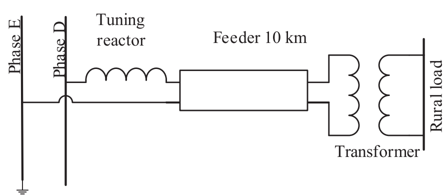
Based on the premise that isolated communities should acquire low-cost equipment and generate income once the electrical supply is provided, we proposed a basic rural load house



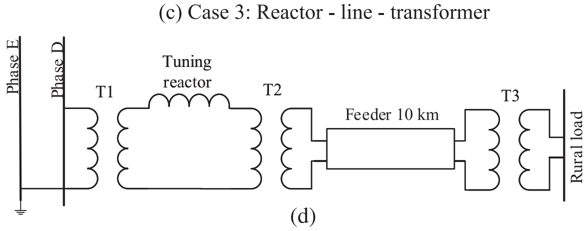

(a) Case 1: Reactor - transformer - line




(b) Case 2: Line - reactor - transformer




(c) Case 3: Reactor - line - transformer




(d) Case 4: Transformer - reactor - transformer - line - transformer

Fig. 4. Rural feeder topologies under study.

TABLE II
TL ENERGIZATION WITH FEEDER CONNECTED

| | Quantity | Unit Power [W] | Total Power [W] |
|---|---|---|---|
| Lighting | 3 | 20 | 60 |
| Outlet | 3 | 180 | 540 |
| Refrigerator | 1 | 500 | 500 |
| Motor 3/4 HP | 1 | 800 | 800 |
| Total per house | | | 1900 |

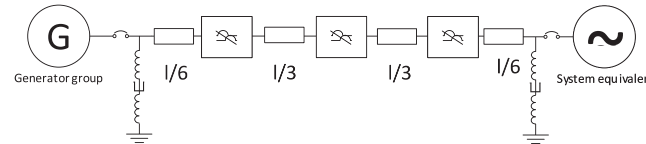
using necessities' data of rural villages with less of 1000 people [16] as is present in Table II.

Considering an exponential grown of the population on electrified communities, 260 houses were considered defined a 500 kW rural load. The following sections present the performance evaluation of these topologies for a 500 kVA rural load [17] using a 500 kV transmission line.

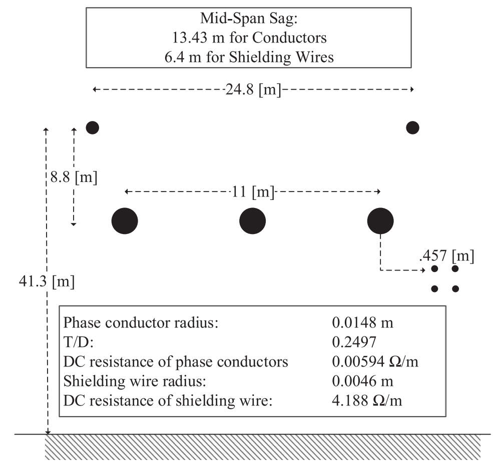
## V. Analyzed System

### A. Transmission System

The transmission system analyzed was composed of two equivalent systems and a 300 km transmission line, as shown in Fig. 5(a). The line was considered transposed as depicted: 1/6, 1/3, 1/3 and 1/6 of total transmission line length. The line had a 500 kV Cross-Rope structure based on an actual Brazilian transmission line (Tucurui-Marabá). The average soil resistivity




(a) Single line diagram of simulated system.




(b) Tower structure configuration.

Fig. 5. Test power system setup.

was 4000 Ω.m [18]. See Fig. 5(b) for tower characteristics. Line surge impedance loading (SIL) is 1420 MVA, power factor 0.98 lagging. The short-circuit level at generation station group was 6.0 kA and at grid-side was 4.8 kA. A quality factor of 35 and 12, respectively, was considered for both equivalents. At each side 220 MVAr reactive shunt compensation was installed, with quality factor of 400. The neutral reactor had $X_h/X_d = 1.5$ with a quality factor of 40.

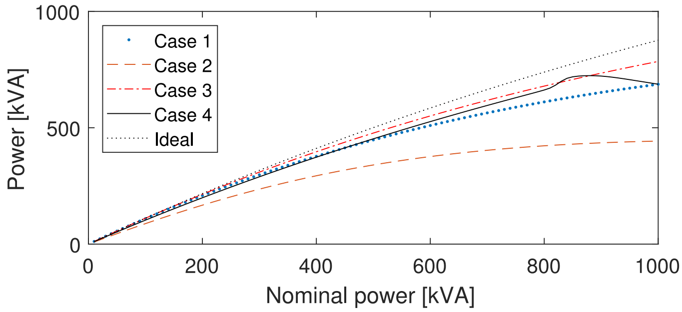
Based on the transmission line physical characteristics, line parameters were calculated. Those parameters cannot be calculated considering the line as ideally transposed with SW implicitly represented, as it is usually done in electromagnetic transient studies. The line must be modeled as a 5 conductor line. The transposition towers must be represented explicitly. Also as one SW will be grounded and the other will be isolated, their connection must be properly represented at each line section terminals.

This transmission line induces 28 kV voltage in the single ISW. A 100 km insulated wire section is used from 150 km to 250 km, where there is no transposition tower, maximizing the induced voltage [16], [19].

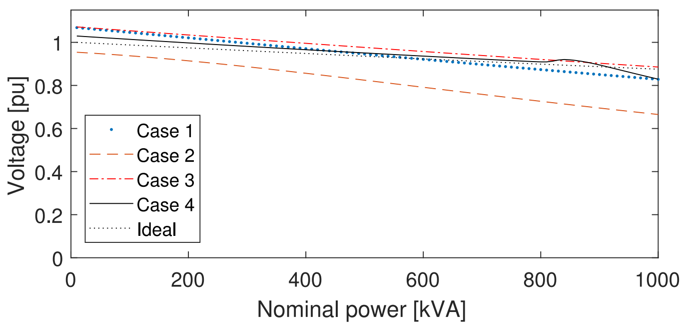
### B. Rural Feeder Parameters

The point common coupling where the feeder is connected to the insulated shielding wire is 200 km. For all cases, a 10 km rural feeder was used. Feeder height is 12 m with a 13.8 kV wood crosshead of 2.5 m length (single-phase voltage is 7.98 kV). A 4/0 AWG cable with resistance of 0.1610 Ω/km was used.

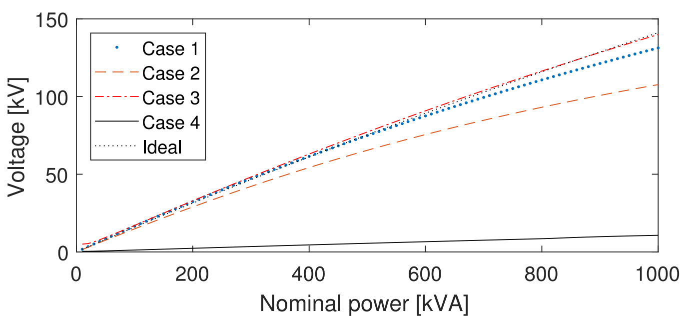
The tuning reactor was specified to generate a resonance with the source equivalent capacitance. For cases 1 to 3 the value used was 11.76 H whereas for case 4 it was 90.23 mH. For both values a quality factor of 200 was considered.



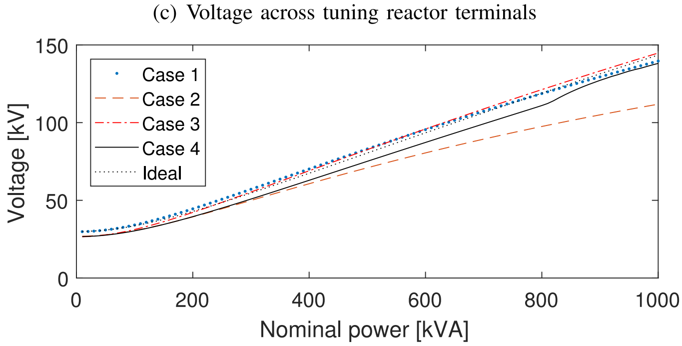

(a) Delivery power




(b) Load voltage




(c) Voltage across tuning reactor terminals




(d) Voltage at Insulated Shielding Wire

Fig. 6. Rural load variation for different feeder topologies.

The 800 kVA single phase transformers used in the first three cases have turn ratio of 28:8 kV and leakage reactance of 0.09 pu (quality factor of 100), air core reactance 0.2 pu, knee voltage 1.4 pu and magnetizing current of 1%. Case 4 presents an arrangement with three 800 kVA transformers, all of them with a reactance of 0.09 pu and quality factor of 100, same magnetization data as previous transformers. T1, T2 and T3 of Fig. 4(d) have turn ratios of 80:8 kV, 3:30 kV and 28:8 kV, respectively.

TABLE III
TOPOLOGIES CASES COMPARISON

| | **ISW voltage** | **Load voltage** | **Tuning reactor voltage** | **Delivery power** |
|---|---|---|---|---|
| **Case 1** | Very high voltage | Lower to high loads<br>Bad regulation voltage | Lower to high voltage | The closest to ideal case |
| **Case 2** | The lowest value | Outside the minimum limits for loads greater than 200 kW | Resistance feeder detunes ressonance point<br>Higher voltage | High loss on feeder<br>The lowest delivery power |
| **Case 3** | Very high voltage | Lower to high loads<br>Bad regulation voltage | Lower 5% than case 1 | The closest to ideal case |
| **Case 4** | High voltage<br>Lower than case 1 and case 3 | The closest to ideal case | 10x lower than ideal case | Non-linear to high loads<br>Lower than case 1 and case 3 |

## VI. RESULTS

### A. *Steady-State Study*

Sensitive steady-state analysis was performed aiming at a target load of 0.5 MW, varying the load range up to 1 MW.

Figure 6 shows the results for all four topologies considering the rural load has a unit power factor. The ideal case consists of connecting the load directly to the tuning reactor. The Table III summarizes the result of all cases.

The power delivered is presented in Fig. 6(a). It can be observed that the delivered power at Case 2 is just 90% of the target load.

Case 3 topology results in a 5% increase in the delivered power value when compared with Case 4. The worse Case 1 response may be explained by not properly generating a resonant circuit when the rural feeder is connected between the capacitive source equivalent and the tuning reactor. That makes Case 3 the worst solution for delivered power and voltage regulation aspects.

Case 4 is very close to ideal case response for load values below 0.7 MW, where there seems to be a threshold. This may be provoked by a very high voltage at transformers, above the saturation knee (see Fig. 6(d)). If the load increases much above the target level the system will not operate properly.

Case 4 topology is considered the best alternative since load voltage regulation has a better performance (Fig. 6(b)). Another important aspect is the voltage across the tuning reactor. For topologies 1 to 3 the voltage for target load is around 80 kV, whereas for Case 4 TR voltage is 15 kV. This topology needs a much smaller reactor that will be insulated for lower voltage level, but will need higher investment because of the two extra transformers. It is important to verify that the ISW induced voltage will rise to 80 kV for target load.

Based on previous analysis we considered Topology 4 the most adequate. The transient study was performed for this elected alternative.

*1) Soil Resistivity Effect:* Around world different soil value is used, for instance, Europe, North America, and Asia a 100 Ω-m is a mean value. In large Brazilian regions, this parameter is set at 4000 Ω-m as the mean value.

In order to analyze the effect of soil resistivity is presented in the Fig. 7, comparing those both soil resistivity value for ISW system. Results show no-effect is presented on induced voltage due to soil resistivity.

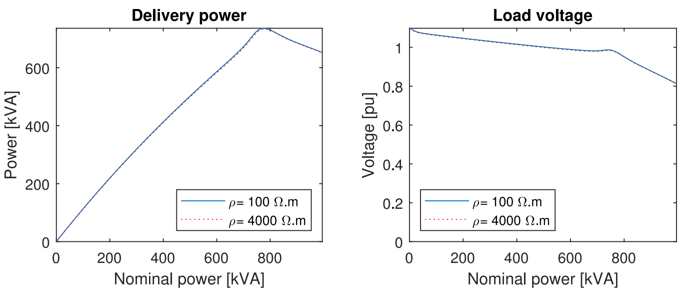



Fig. 7. ISW variation for different soil resistance.

TABLE IV
TL ENERGIZATION WITH FEEDER CONNECTED

| | ISW [kV] | Tuning reactor [kV] | Rural load [kV] |
|---|---|---|---|
| **Minimum:** | 129.42 | 8.93 | 11.89 |
| **Maximum:** | 136.99 | 9.76 | 12.14 |
| **Mean:** | 133.88 | 9.49 | 12.04 |
| **Std Dev:** | 1.62 | 0.197 | 0.049 |
| **98% Level:** | 137.22 | 9.89 | 12.15 |

### B. Transient Study

A basic premise is that the use of ISW by rural distribution companies should never compromise the transmission line integrity or reliability. The same approach was established when the OPGW was formerly used in the TL [1], [3], [16].

Some switching studies were performed using the *PSCAD* software. The line was represented with phase domain model to properly consider the series parameter dependence with frequency. It was modeled as a five conductors' line, the three phases plus the two shielding wires. SWs were grounded at each line terminal whenever needed. The line was represented as non-transposed and the phase transposition was added manually.

The rural system (Fig. 4(d) configuration) was represented with nominal 500 kVA load, power factor 0.9 lagging.

Statistical TL energization with rural feeder already connected was simulated to consider the randomness of the line breaker with 100 shots [20]. A 400-Ω pre-insertion resistor is considered, using a 2 ms standard deviation and main breaker closing after 8 ms.

Table IV summarizes the TL energization result (feeder connected). Note that there is no significant overvoltage at the ISW, nor on the tuning reactor. The load voltage has a minimum increase of 6.9% in the worst case. Statistical data of transient studies is present with a confidence interval that might contain the true value of the population chosen. Then, 98% level is associated with the confidence of observing overvoltages lower than that value for each specific maneuver.

Figure 8 shows the deterministic worst case. It can be observed that the load voltage quality is very high, with harmonic content near zero and no important overvoltage observed. It is also important to highlight that the transient response at the feeder is quickly attenuated due to capacitive equivalent circuit, see Fig. 3. TL energization transient will cause no important disturbance on rural system when it is already connected.

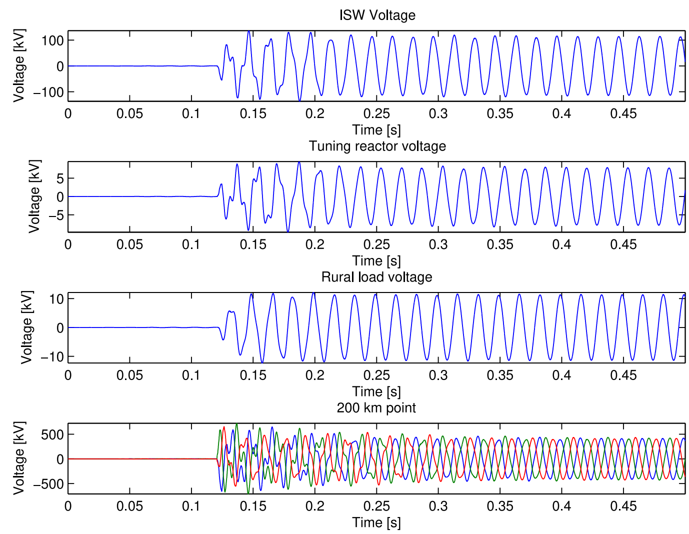



Fig. 8. Voltage along the rural feeder for TL energization with feeder connected.

TABLE V
FEEDER ENERGIZATION

| | ISW [kV] | Tuning reactor [kV] | Rural load [kV] |
|---|---|---|---|
| **Minimum:** | 114.22 | 7.881 | 11.37 |
| **Maximum:** | 114.43 | 7.897 | 11.38 |
| **Mean:** | 114.34 | 7.891 | 11.37 |
| **Std Dev:** | 0.064 | 0.0040 | 0.0033 |
| **98% Level:** | 114.47 | 7.900 | 11.38 |

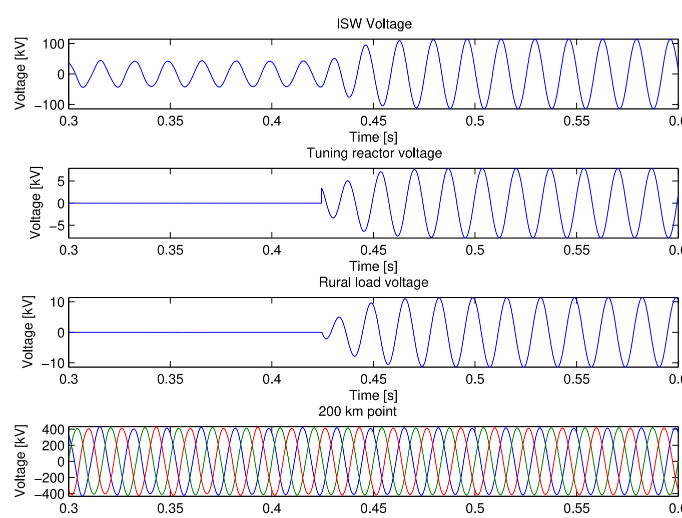



Fig. 9. Voltage along the rural feeder for feeder energization.

The next case analyzes the feeder energization with TL on service. Statistical switching was performed using the same configuration as the last case, results are present in Table V.

Feeder energization causes no harm along the rural feeder. Rural load and the tuning reactor does not present any overvoltage because the system capacitance damps the voltage rise. Fig. 9 shows a severe deterministic case for this switching. Due to feeder energization the ISW induced voltage rises, but no

TABLE VI
TL LOAD TRIPPING

| | ISW [kV] | Tuning reactor [kV] | Rural load [kV] |
|---|---|---|---|
| **Mean:** | 148.19 | 10.90 | 12.78 |
| **Std Dev:** | 0.15 | 0.24 | 0.63 |
| **98% Level:** | 148.67 | 10.76 | 15.14 |

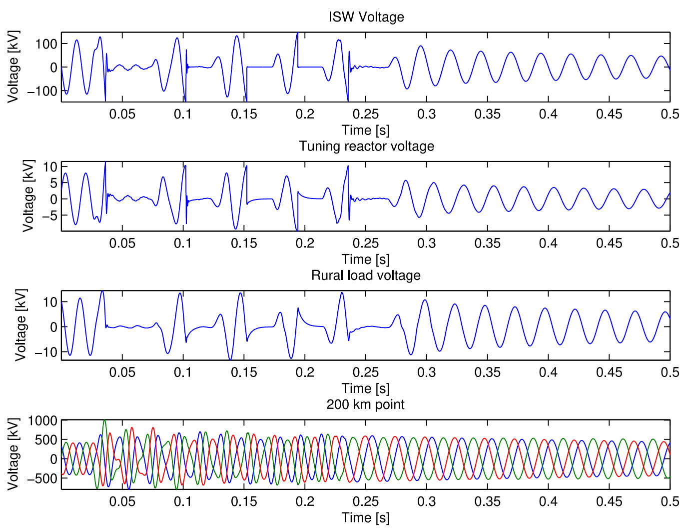



Fig. 10. Voltage along rural system for TL load trip.

high frequency transient is observed. The induced voltage has the same quality as the TL.

An important fact to highlight on the last graphic of Fig. 9 shows that rural energization provokes no disturbance on the TL.

It should be noted that TL switching will produce high transient over-voltages along the rural feeder. Therefore, it is necessary to properly protect the rural feeder system. A system based on SW insulators' spark gaps was considered in [16]. The gap breakdown voltage was set up as 150 kV. Spark gaps should be installed along the ISW. In the simulation three spark gaps were installed at 150, 200 and 250 km.

A TL load trip case study was implemented considering statistical switching. This case consists on circuit breaker opening at receiving terminal for loading level of 90% SIL. Results are presented in Table VI.

Figure 10 presents a severe deterministic case for load trip. Remote breaker opens at 30 ms and local breaker opens at 230 ms. The sudden voltage rise after load tripping induces very high voltage at ISW. Sparks gaps will conduct, as can be observed by the fast impulses that appear along the feeder. Due to their small duration, they will not endanger rural system. When TL voltage reduces the gap arc will extinguish. Sinusoidal voltage are observed in rural feeder produced by TL charging.

Based on equation (1), any overvoltage on TL system will affect directly the rural system safety. As shielding wires have high resistance, it is expect that overvoltage closer to PCC will provoke stronger disturbance along the feeder. Therefore, line-to-ground and three phase faults were analyzed at that location. A statistical analysis was implemented for 100 shots and a 10 Ω fault resistance. The fault case consists of applying fault at 30 ms, remote circuit-breaker tripping after 100 ms dead-time, and 20 ms later sending end breaker tripping.

TABLE VII
FAULTS AT 200 km - SEVERE STATISTICAL RESULTS - 98%

| | Rural load | | Tuning reactor | | ISW | |
|---|---|---|---|---|---|---|
| | kV | pu | kV | pu | kV | pu |
| **AG** | 14.25 | 1.26 | 11.79 | 1.48 | 149.65 | 1.30 |
| **BG** | 17.52 | 1.56 | 11.84 | 1.49 | 148.81 | 1.29 |
| **CG** | 15.41 | 1.37 | 11.85 | 1.49 | 148.30 | 1.30 |
| **ABG** | 15.64 | 1.39 | 10.82 | 1.36 | 152.25 | 1.32 |
| **ACG** | 13.98 | 1.24 | 12.85 | 1.62 | 150.51 | 1.30 |
| **BCG** | 13.15 | 1.17 | 11.47 | 1.44 | 151.34 | 1.31 |

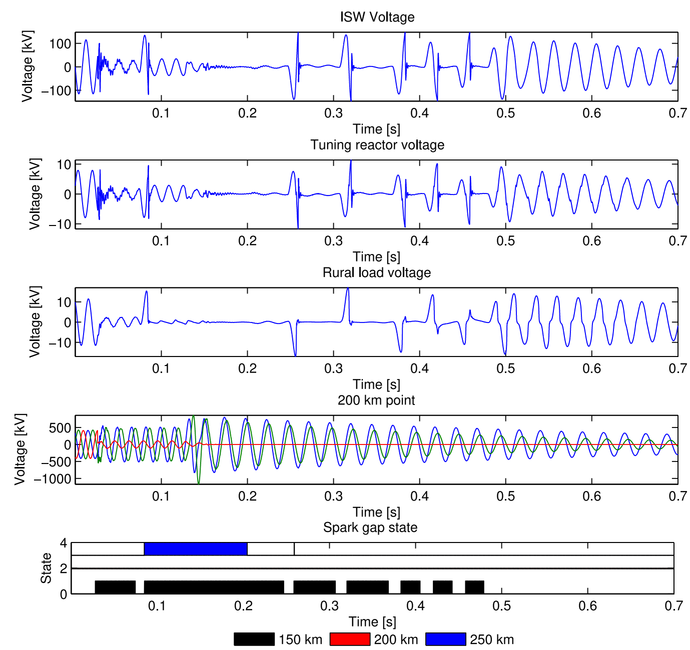



Fig. 11. Voltage along rural system for BG fault at PCC.

Table VII summarizes the statistical study of line-to-ground fault results for different fault types. Severe results are presented (98%). Due to spark-gap protection, voltage on ISW does not increased drastically, therefore, voltage along the rural feeder remains within acceptable limits for those severe cases. Fig. 11 shows the most severe case regarding load overvoltage. It consists of phase B to ground fault (BG) at PCC, which will be the closest phase to ISW at PCC due to transposition cycle.

The sequence of events after fault occurrence is as follows: TL sound phases voltages will rise up, provoking higher ISW induced voltage that will result in spark-gap operation. Induced voltage is reduced and gap arc extinguishes, allowing ISW voltage elevation. This sequence will continue until TL is tripped. The last graphic in Fig. 11 shows spark-gaps operation cycle. Only gaps at 150 and 250 km operate.

Eventually, to explore the rural protection system response, TL energization under BG fault at PCC was simulated. A statistical study was implemented as follows: fault occurrence at 30 ms, breaker trips the line at 130 ms, the fault is permanent and fault resistance is 10 Ω. A 400 Ω pre-insertion resistor was

TABLE VIII
TL ENERGIZATION UNDER BG FAULT AT PCC

| | Rural load [kV] | ISW [kV] | 0 km [kV] | 300 km [kV] | 200 km [kV] | Tuning reactor [kV] |
|---|---|---|---|---|---|---|
| **Max:** | 16.28 | 150.43 | 665.79 | 950.58 | 958.52 | 13.27 |
| **Mean:** | 10.79 | 142.60 | 612.70 | 885.43 | 903.25 | 11.15 |
| **Std Dev:** | 4.45 | 9.09 | 25.43 | 35.12 | 36.22 | 1.01 |
| **98%:** | 19.92 | 161.26 | 664.92 | 957.56 | 977.63 | 13.22 |

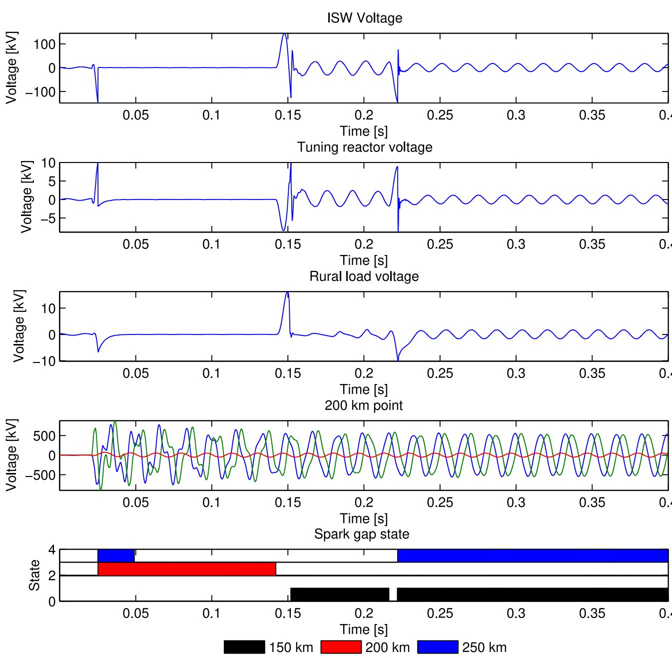



Fig. 12. Voltage along rural system for TL energization under BG fault at PCC.

considered. Table VIII summarizes the statistical results. Fig. 12 shows a severe deterministic case.

Once sending terminal is closed, both sound phases' voltages increases almost above 2 pu. ISW voltage grows until spark occurs (gaps at 150 and PCC). Due to capacitive coupling, the electric arc will keep on, resulting in zero voltage and current along the rural feeder. Eventually PCC gap opens and ISW induced voltage returns. This low voltage will keep on until fault is cleared.

## VII. CONCLUSIONS

In the present document we propose a second use of shielding wires as an alternative for feeding small unattended communities near TLs or as an alternative source for existing long rural feeder. This will prevent the high costs of a rural distribution substation in isolated areas, which is most often unfeasible due to technical and economical constraints.

The proposal evaluated consists of insulating the non-OPGW in such a way that rural distribution companies could take advantage of capacitive coupling. Thus, we can ascribe an additional economic value to the shielding wires.

In this study, we analyzed unconventional ways of feeding rural loads using shielding wires. We focused on insulating the SW to produce a voltage similar to the distribution voltage, without, however, accessing any conductor phase. Thus, we did not compromised the transmission power system reliability or safety.

We evaluated some alternatives to the rural feeder system configuration and identified the most appropriate regarding the need for smaller equipment and better voltage regulation.

In addition, we conducted transients tests to demonstrate that frequent transmission line switching does not produce severe disturbances in the rural distribution system, using the spark gap along the ISW as protection method, neither, the rural system affect the reliability of the power system.

We understand that, just as the OPGW is used for data transmission and has a high economic value for telecommunications, the second shielding wire can have a higher aggregated value when used by rural distribution companies. This technology does not compromise the performance of transmission lines and can transport power to populations which have poor service or remain unattended.

We understand the economic analysis is an important topic however, it is out of the focus of the paper. The proposed system aims to serve isolated communities that do not have the possibility of installing solar panels or wind turbines. In some cases, isolated communities have access to electricity using fuels, which in many cases do not have a continuous supply along the year.

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