Transient Switching Analysis of a Nonconventional Rural Generation System

J.S. Chaves, M.C. Tavares

***Abstract*—This paper introduces a nonconventional rural generation system that extracts energy from high-voltage transmission line surroundings. The system was designed for a 230-kV transmission line and consists of a special 20-km collector line and an innovative substation. The energy is coupled to the collector line and supplied through a resonant circuit. There is no physical contact with the transmission line. A detailed electromagnetic study is described, assuring there is no disturbance at the transmission line and that the rural system delivers high-quality energy. Spark gaps were used to avoid overvoltage along the rural feeder. Transmission line reliability is not compromised.**

***Keywords*—Capacitive coupling, resonant circuit, rural electrification, transmission lines.**

I. Introduction

APPROXIMATELY 1.06 billion people do not have access to electrical services, representing approximately 15% of the global population [1], [2]. In addition, a large number have access to low-quality electrical service, mostly in rural areas [3].

For the specific case of communities without access to energy but close to high- and extrahigh-voltage transmission lines (TLs), the possibility of being electrified is almost nil. The high costs for the construction of a rural substation to supply tenths of MWs does not allow the development of projects for these communities [4]. Therefore, nonconventional projects must be postulated to address this problem [5], [6], [7]. The use of capacitive dividers connected directly to the phases was proposed to supply small loads far from TLs, but this approach can compromise the power system reliability [8]. In the 1980s, the use of insulated shielding wires as feeders that were energized at the subtransmission voltage level was implemented, serving remote communities at a maximum distance from a power substation of 100 km [9], [10].

Another alternative to feed very small remote loads was proposed that was based on insulating sections of TL shielding wires that would behave as a natural voltage divider. Insulated shielding wires (ISWs) were formerly applied to supply microwave repeater and communication facilities in Canada [11], [12], [13], [14]. The same system was also implemented in Peru to serve small rural communities, but it suffered from assembly and load increase problems [15].

Another ISW proposal was analyzed in [7], [16], [17], but further analysis and a pilot project were requested to produce a robust alternative. However, implementing this pilot case demanded a high financial and logistical commitment, since it was necessary to perform interventions in TL assets, which is often extremely delicate. A thorough transient study was performed to ensure that TL reliability and safety were not compromised. A protection philosophy was proposed for the nonconventional rural system.

In the present document, a novel distributed generation system that does not interfere with TL assets is presented. This innovative solution is a further improvement on previous ISW proposals that can be applied to feed off-grid communities around the world to serve as a second supply source for existing rural systems. As the quality level of the proposed alternative will be equal to the TL level, this system will strongly enhance the quality indices of the existing rural distribution systems. This new alternative is known as a coupling generation system and should be treated as nonconventional distribution generation.

II. System under study

The transmission system analyzed in this study is composed of two equivalent systems and a 200 km 230 kV transmission line, as shown in Figure 1(a). This voltage level was chosen because it is largely used all over the world and, in some countries, is the highest available level. The line is considered transposed as depicted: 1/6, 1/3, 1/3 and 1/6 of the total transmission line length. The soil resistivity was taken as 4000 Ω.m [18], which corresponds to an actual value in Brazil. A careful evaluation was implemented for different ground resistivities [19], and no influence was observed, as the energy is provided by the electric field that is not affected by the soil resistivity. See Figure 1(b) for tower characteristics.

The line surge impedance loading (SIL) is 200 MVA, and the power factor is 0.98 lagging. The short-circuit level at the generation station group is 6.0 kA, and at the grid side, it is 4.8 kA. A X/R ratio of 35 and 12 is considered for both equivalents. On each side, a 20 MVAr shunt reactor is installed, with a quality factor of 400. The neutral reactor has $X_h/X_d = 1.5$ (ratio for zero and positive/negative sequence reactances) with a quality factor of 40. These quality factor values are derived from actual Brazilian data.

The nonconventional source is a collector line (CL) that lies within the host TL right-of-way (ROW). Its location was obtained by applying artificial intelligence techniques, specifically, a genetic algorithm that considered the line-induced voltage, the electrical field at the wire surfaces, lightning protection and the delivered power [20]. Due to the low amount of tapped energy, several of the distributed (extracted) power

This study was supported by the research agencies CAPES (code 001), CNPq and FAPESP (2017/20010-1).

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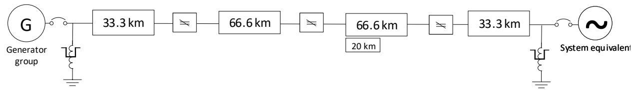
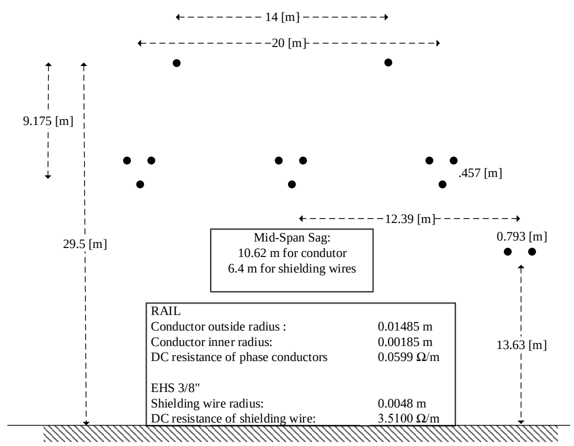


(a) Single line diagram of simulated system.



(b) Tower structure configuration.

Fig. 1. Test power system setup

sources could be replicated along the TL, as they do not compromise the TL power flow. The tapped energy lies in the range of host TL loss, although it is not actually obtained from the line losses.

The CL length was set as 20 km and was formed by a bundle of 2 wires spaced by 0.793 m. The CL should not include a transposition tower [7]. If the CL route involves a transposition tower, each transposition section would produce a different induced voltage. The sum of the induced voltages would result in a lower total voltage than if the collector line is set along the same TL transposition section.

A. Mathematical Model

The collector line wires (CWs) lie within the host TL electrical field and respond as a natural capacitive voltage divider. Hence, the voltage induced on the CW is a function of the TL voltage level and the spatial coordinates of the energized conductor.

Equation (1) describes the induced voltage V_d on the CW, where $\hat{V}_a$, $\hat{V}_b$ and $\hat{V}_c$ are the phase voltages of the TL and C_{km} is the mutual capacitance, where k and m are the phase indexes. These values are calculated based on the shunt capacitance of the TL, considering the collector line as a circuit with insulated wires. Figure 2 shows the equivalent capacitances of the system for the three-phase line.

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

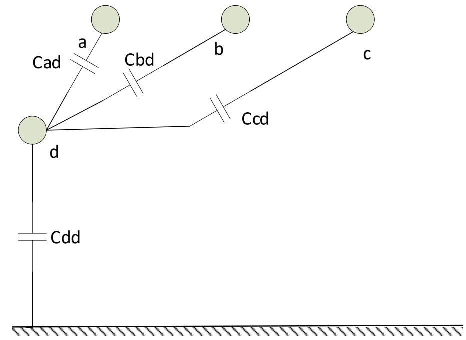


Fig. 2. Equivalent capacitance of the system

Note that $\hat{V}_d$ does not depend on the CW length because the electromagnetic effects are negligible. This means that energy is produced by capacitive coupling and not by electromagnetic coupling and is therefore independent of the TL loading level [16], [19]. The induced voltage for Figure 1(b) is 16 kV in the no-load condition.

The capacitive coupling between TL phases and CW is represented by a Thevenin equivalent with a series capacitance C_d, described by equation $C_d = (C_{dg} + C_{fd})$, where $C_{dg} = \sum_{n=1}^{4} C_{4xn}$ and $C_{fd} = \sum_{n=1}^{3} |C_{4xn}|$, [19].

These values are calculated using the matrix C_{4x4} derived from the shunt capacitance matrix of the TL+CW parameters. The values of equivalent capacitances are per unit length; thus, the power delivered is proportional to the CW length. For the 20 km collector line, the equivalent capacitance is $0.25\ \mu F$. However, this capacitance value is high and compromises voltage regulation. This problem is solved by adding a series inductor to reproduce a resonance condition. The inductance is calculated with equation (2), where l_c is the CL length in [m] and ω is the fundamental frequency in [rad/s]. The resonant system produces a strong source at the point of common coupling (PCC), as shown in Figure 3. It is important to note that $\hat{V_{cl_{op}}}$ in this figure is the voltage on the CW.

$$L_d = \frac{1}{\omega^2 \cdot C_d \cdot l_c} \tag{2}$$

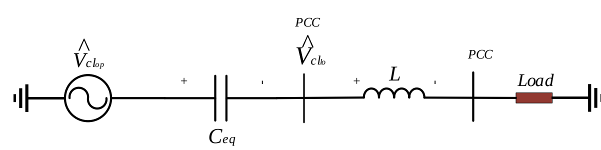


Fig. 3. Equivalent circuit of the capacitive nonconventional generation system with the tuning reactor

Although the induced voltage is not a function of the collector line length, the delivered power is. The naturally induced voltage is only dependent on the TL and CW geometries. However, the voltage at the CW changes with the rural load (load current dependent) due to the resonant system necessary to deliver proper voltage regulation. This means that the optimal tuning reactor changes with the target load, i.e., with the CL length. An adequate design is necessary [20].

This 20 km CL aims to supply 100 kVA for a single-phase rural system. The tuning substation is a nonconventional rural station composed of a tuning reactor that resonates with the CW equivalent. This is a strong system based on a resonant reactor close to 9.77 kΩ. A group of single-phase transformers was conceived to reduce this value to 390.9 Ω, as presented in Figure 4. Three 120 kVA transformers were designed with the following data: leakage reactance of 0.09 pu (quality factor of 100), air core reactance 0.2 pu, knee voltage 1.15 pu, magnetization current of 1% and turn ratios of 40:8 kV, 7.9:20 kV and 20:0.110 kV for T1, T2 and T3, respectively. Both windings of transformers T1 and T2 are grounded. It is important to have the grounding system connected to the host transmission line counterpoise structure to be at the same potential (the tower closest to PCC). This ensures a proper current return path to the single-phase system. An inadequate connection in the return path can decrease the induced voltage on the collector line as the system reference changes. Additionally, there would be the risk of step and touch voltages.

The rural feeder in the tested system consisted of a single-phase line of 50 km with metallic return (two-conductor line) with 19.9 kV nominal voltage. A distribution transformer was positioned at the end of the line, close to the rural load. The long rural system was adopted to illustrate that the rural load may be located far from the host TL route.

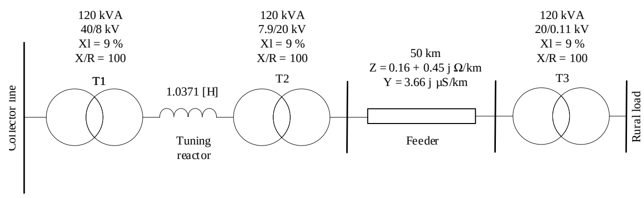
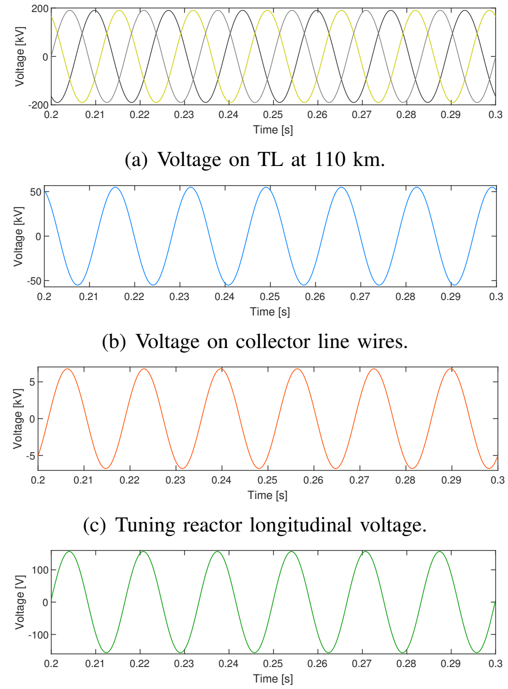


Fig. 4. Diagram of the nonconventional rural generation system.

Based on the premise that isolated communities should acquire low-cost equipment and generate income, once the electrical supply is provided, we define a rural load of 100 kW [7] using the data of energy necessities of nonsupplied communities, considering a 2 kW/house [16]. Figure 5 shows the TL voltage waveform at 110 km, the CW voltage, the tuning reactor longitudinal voltage, and the rural load. These values are used as base peak voltages in transient results. Note that when the system is supplying the target load, no distortion appears along the feeder. The new rural distribution system will have the same quality level as the transmission system, and we can say that the transmission system will transfer the energy quality to the rural system. However, the voltage will be much higher than that under the no-load condition of 40 kV at the CW.

III. Transient Study

The basic premise adopted is that the use of this nonconventional generation system should never compromise the transmission line integrity or reliability. The same approach



(a) Voltage on TL at 110 km.

(b) Voltage on collector line wires.

(c) Tuning reactor longitudinal voltage.

(d) Voltage at rural load.

Fig. 5. Voltages for a 100 kW power supply.

was established when the OPGW (optical ground wire) was formerly used in the TL [5], [7], [21].

A detailed switching study was implemented with *PSCAD* software. The TL was represented with a phase domain model to properly consider the series parameter frequency dependence. The single-circuit TL has 2 grounded shielding wires, and the transposition cycles are actually modeled. Only in the CL section was the TL modeled with the additional nongrounded CW bundle, located as shown in Figure 1(b).

It should be noted that host TL switching will produce high transient overvoltages along the rural feeder. Therefore, it is necessary to properly protect the rural feeder system. A system based on spark gaps was proposed in [7]. The same solution is applied in the present study, installing spark gaps (SG) along the CW at km 0, 10 and 20. The SG breakdown voltage was set to 80 kV.

In the next sections, the most important switching cases are presented. TL energization and rural feeder energization were omitted because overvoltage levels were very low.

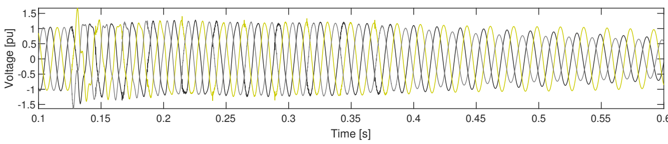
A. Host TL load trip

The scheme for the host TL load trip was implemented considering a statistical opening switch with a uniform distribution over a cycle using 100 shots. The TL loading was 90 % SIL. After a dead time of 200 ms, the sending end circuit breaker (CB) was opened. The results are shown in Table I.

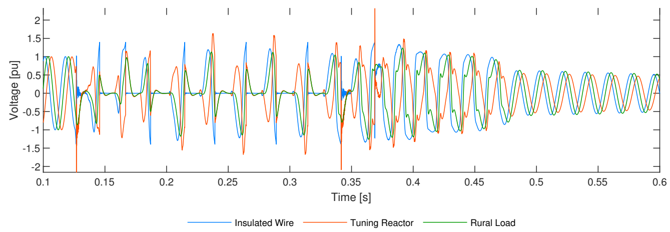
The following is a severe deterministic host TL load trip case. As shown in Figure 6(a) and Figure 6(b), the receiving CB opens at 125 ms, and then a 1.5 pu overvoltage appears

TABLE I. HOST TL LOAD TRIPPING - 100 CASES

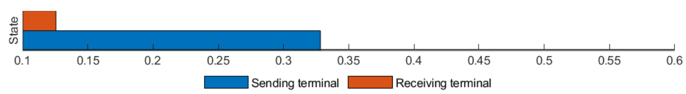
	CW [pu]	Tuning reactor [pu]	Rural load [pu]	TL sending terminal [pu]	TL remote terminal [pu]
Mean:	1.39	2.28	1.22	1.39	1.77
Std Dev:	0.00027	0.10	0.04	0.01	0.04
98% Lvl:	1.39	2.48	1.30	1.40	1.85



(a) Voltage on TL at 110 km point.



(b) Voltage on generation system.



(c) Terminal breaker status

Fig. 6. Host TL load trip case.

along the TL. Once the CB opens, the induced voltage at the collector line rises for 0.8 ms until it overcomes the spark gap breakdown voltage. In this short time, the tuning reactor voltage rises rapidly, reaching a pu value of 2.1, as shown in Figure 6(b). Figure 6(c) shows each line terminal circuit-breaker status under load trip occurrence (high level is closed). Spark gap operations reduce overvoltage almost immediately.

The sudden voltage rise after load tripping induces a very high voltage at the collector line. Spark gaps are conducted, as can be observed by the fast impulses that appear along the feeder. Due to their short duration, they do not endanger the rural system. When the TL voltage reduces, the gap arc extinguishes. After the dead time, no source is connected; then, shunt reactors feed the transmission line with a decreasing voltage ramp. After 5 cycles, the voltage along the feeder presents a sinusoidal form again.

B. Host TL fault

A fault occurrence on the host TL is a severe condition, as the induced voltage can reach a very high value. The induced voltage described by Equation 1 depends directly on the TL phase voltage. Therefore, it is expected that overvoltages on TLs will raise the CL voltage.

A host TL fault statistical case was implemented considering six fault resistance values: 0.1 Ω, 1 Ω, 5 Ω, 10 Ω, 50 Ω, and 100 Ω (with 100 shots for each fault resistance). The fault location is at 110 km (PCC). The fault case consists of applying a fault considering a uniform distribution over a cycle, remote CB tripping after 100 ms, and sending a CB tripping a cycle later. No fault removals or TL reclosings were simulated.

Table II summarizes the fault cases for different fault types. For each fault, the fault resistance was varied, totaling 4200 cases. Severe results are presented (98%). Due to spark-gap protection, collector line voltage does not increase drastically; therefore, voltage along the rural feeder remains within acceptable levels.

The collector line-induced voltage is mainly derived from the phase voltages and mutual capacitance between the phases and CL wires. This means that the closest phase has a higher contribution to the induced voltage. Therefore, faults applied at phases farther from the CL will produce higher overvoltages due to the contribution of the closest healthy phase.

TABLE II. FAULTS AT KM 110 - SEVERE STATISTICAL OVERVOLTAGE RESULTS - 98% - 4200 CASES.

	Collector line		Tuning reactor		Rural load	
	kV	**pu**	**kV**	**pu**	**V**	**pu**
BG	96.07	1.67	19.34	2.51	211.23	1.36
CG	81.27	1.41	21.33	2.76	209.76	1.35
AG	87.00	1.52	26.29	3.40	156.24	1.01
BCG	80.75	1.41	19.85	2.57	216.61	1.40
ABG	74.16	1.30	19.92	2.58	155.37	1.00
ACG	88.11	1.53	21.77	2.82	163.76	1.06
ABCG	67.87	1.18	16.00	2.07	168.95	1.09

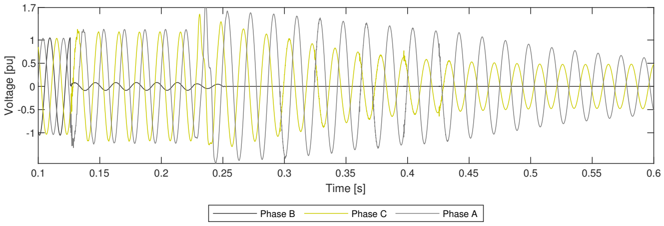
Figures 7(a) and 7(b) show a severe case regarding rural load overvoltage. It consists of a phase B to ground fault (BG) at CW with a fault resistance of 5 Ω. Phase A is the phase closest to the CL due to the transposition cycle.

A fault occurs at 126.04 ms, and afterwards, the voltage along the TL rises up, provoking a higher voltage on the collector line and resulting in spark-gap operation (Fig. 7(c): high level is SG operation). Figure 7(d) shows the circuit-breaker status (high level is closed). The induced voltage is reduced until the gap arc extinguishes, allowing subsequent collector line voltage elevation. However, the voltage rate of rise is not fast due to capacitive coupling. This sequence of events is repeated until the TL is eventually tripped. In this case, the voltage on the collector line remains high, and the spark gap at 10 km remains conducting. Once the collector voltage returns to the normal level, the rural system goes to normal operation. It can be observed that there was no important overvoltage produced by the TL faults under rural loads.

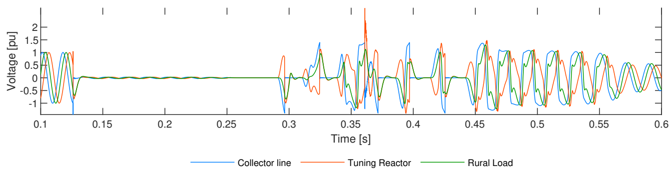
C. Faults at collector line

In this section, the results for fault occurrence at the collector line are presented. The case characteristics are similar to the previous section, where six fault resistances were analyzed: 0.1 Ω, 1 Ω, 5 Ω, 10 Ω, 50 Ω, 100 Ω on a statistic study with 100 shots for each fault resistance using a uniform distribution over a cycle. Faults were applied at the PCC.

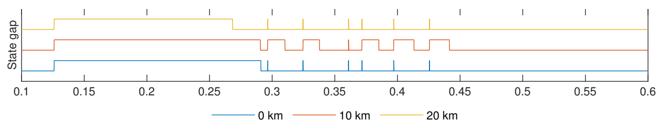
Collector line fault results are summarized in Table III for all the fault resistance values. The statistical results show no



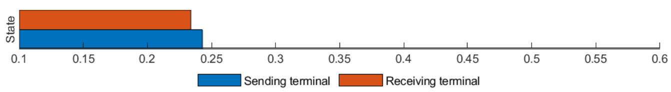
(a) Voltage on TL at 110 km.



(b) Voltage on source system.



(c) Spark gaps status



(d) Terminal CB status

Fig. 7. Line-to-ground fault at 110 km using a 0.1 Ω fault resistance.

TABLE III. COLLECTOR LINE FAULT - 600 SHOTS.

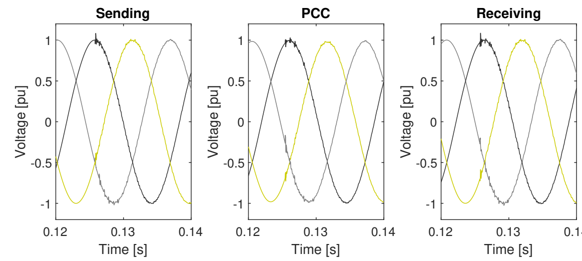
	TL sending [pu]	TL 110 km [pu]	TL receiving [pu]
Max	1.181	1.135	1.131
Mean	1.057	1.041	1.057
Std Dev	0.017	0.009	0.017
98%	1.093	1.031	1.093

variation along host TL. When the collector line is under fault, it is actually grounded, removing the induced voltage and detuning the resonant circuit. The system is discharged slowly, basically as an RL circuit response. However, a small interference on host TL voltages can be observed, without an important effect.

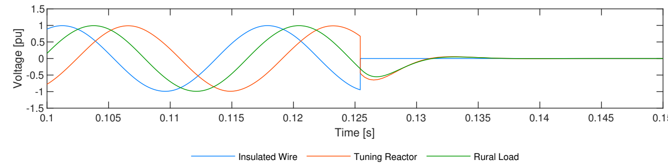
The most severe deterministic case is presented in Figures 8(a) and 8(b), with a fault resistance value of 0.1 Ω. The voltage in the rural system is zero after the fault, without any transient overvoltage. The voltage along the TL presents a small disturbance at the fault instant that lasts for less than half a cycle.

D. Faults at rural load

In addition, a rural load fault analysis was implemented considering different fault resistances: 0.1 $m\Omega$, 1 $m\Omega$, 5 $m\Omega$, 10 $m\Omega$, and 50 $m\Omega$. Again, a statistical study with 100 shots using a uniform distribution over a cycle was implemented for each resistance value, totaling 500 cases.

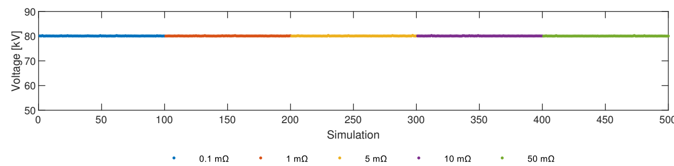


(a) Voltage at TL.

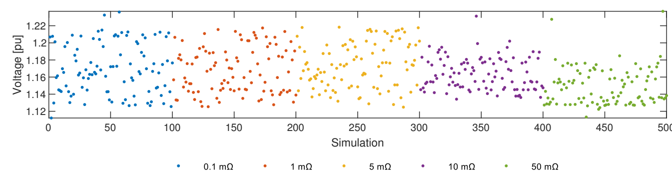


(b) Voltage at rural system.

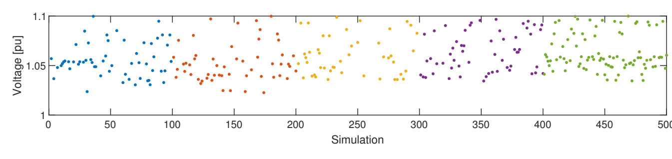
Fig. 8. Collector line fault.



(a) Voltage on CW



(b) Voltage on TL sending terminal.



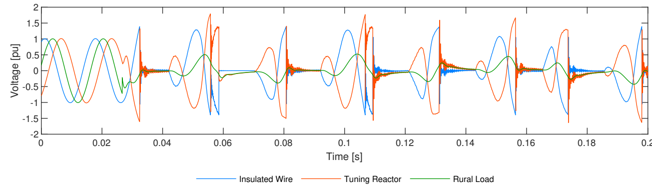
(c) Voltage on TL receiving terminal.

Fig. 9. Rural load fault, statistic analysis

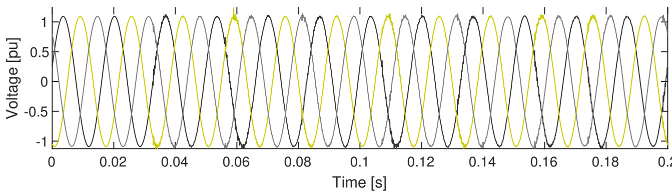
A data cloud is presented in Figure 9 with the simulation results, and each color represents a different fault resistance value. We can identify that all resistance values produce a SG breakdown. On the other hand, there is no impact on the voltages at the TL terminals for all fault resistance values. This implies no impact on the host TL protection performance due to faults along the feeder.

Note that for all resistance cases, the collector line voltage increases until SG breakdown. These SG flashovers induce a small and short disturbance on TL voltage, which is lower than 15 %, as presented in Figure 10.

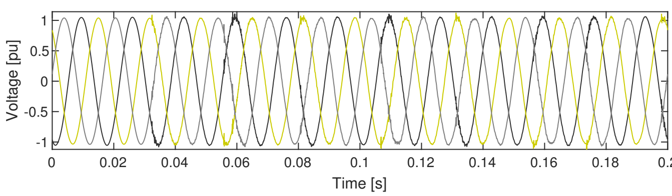
Figure 10 shows a deterministic case result of a fault at rural load. A fault resistance value of 50 $m\Omega$ was used, and the fault was applied at 26.67 ms. It should be noted that



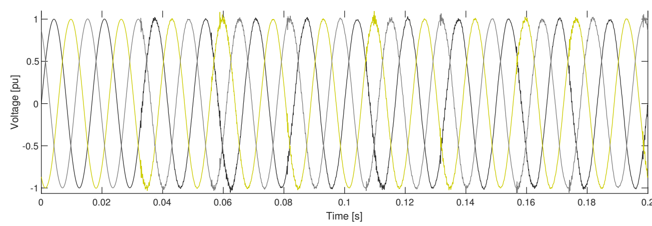
(a) Voltage along the rural feeder.



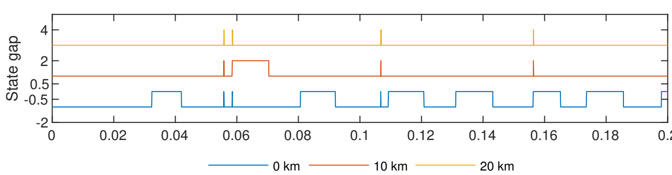
(b) Voltage on sending terminal.



(c) Voltage at 100 km point.



(d) Voltage on remote terminal.



(e) Spark gap status for rural load faults.

Fig. 10. Voltage system for rural load fault

for the simulated permanent rural load fault, the collector line voltage increases to levels that activate the spark gaps. Once this voltage reduces, the system is detuned, and the arc gap extinguishes. However, as the fault is not cleared, the collector line voltage increases again, activating the spark gap once more, as shown in Figure 10(e) (high level is SG operation). This will continue until the fault is cleared. A protection system scheme is necessary to isolate the fault or open the rural feeder circuit.

IV. Final considerations

The proposed generation system is adequate to feed small loads using the assets of an existing host high-voltage transmission line. Based on the capacitive coupling between the line and a collector line placed along the right of way, a low-level voltage is produced without the use of transformers. As presented in [17], the inductive coupling effect is not relevant; therefore, the induced voltage is basically a function of the geometry between the power system and the collector line, with a minor contribution of the host transmission line loading level. The system will provide energy even during a no-load condition.

The position of the collector line, as well as the number of wires, were found using a genetic algorithm that identifies the best position, the best capacitive coupling and the lowest cost, as presented in [20]. Cost optimization is based on the number and type of conductors used for the CL and the whole CL structure. For the case presented in Figure 1(b), the total project cost using a 20 km collector line to feed a 100 kW load is approximately US$ $345,000$. Considering the social and economic benefit this system brings to isolated communities and due to its technical peculiarities, this cost can be considered low, at least compared to a solar panel system, as presented in [20].

In the former stage of this research, the traditional ISW solution was studied for different line configurations [17], [16]. For the present system based on the collector line approach, a protection element was eliminated, and now there is no need to use a spark gap for the tuning reactor.

The use of a group of transformers is still applied, as this drastically reduces the longitudinal voltage across the tuning reactor. Another solution that is considered relevant is the use of spark gaps along the collector line, as they prevent important overvoltages along the rural feeder, allowing a fast rural system to recover after power system switching or fault events, as presented previously.

For some events at the host TL, the collector line spark gaps operate, properly protecting the rural system. However, it is necessary to design a protection scheme that will identify a permanent fault and protect rural system assets, for instance, by interrupting SG operation. New material on protection will be presented in future work.

V. Conclusions

In the present document, we introduce a nonconventional coupling generation system that is composed of a collector line and an innovative distribution substation. The energy is harvested from the electric field in the surroundings of a high-voltage transmission line. This is an evolution regarding the previous proposal of extracting energy from insulated shielding wires. There is no contact with any host transmission line asset, and the proposal can be applied to existing or newly built transmission line structures.

The generation system can provide firm energy in the range of 100 kW. This amount is adequate to serve small off-grid communities and even be considered a second supply source for weak rural systems. It is a low-cost alternative that continuously delivers the installed capacity, different from wind or solar power plants. Additionally, it is not intermittent and has the same quality and reliability level as the host transmission line.

Rural system protection was based on three spark gaps (SGs) installed at the collector line. Typical switches such as load trips and faults along both host transmission lines and rural systems were presented. The SGs were adequate to properly mitigate the overvoltages. For rural feeder faults, very small disturbances appear at TL voltages due to SG operation. Switching when energizing the TL or the generation system did not produce any important disturbance.

Additional studies to interrupt spark-gap operation under permanent fault events at the host transmission line are under development, as is the protection system for the distribution system. Although the CL structure was shielded by TL conductors, a more thorough lightning study is under development and will be presented in the near future.

The extracted power will not compromise the TL power flow and can even be replicated along the TL route. For TL companies, it is very important to supply energy to the off-grid population in the vicinity of a new project, which may facilitate ROW approval. From the rural system side, this is a low-cost high-quality electrical service.

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