Rural electrification method based on floating wires induced voltage: Technical and economical analysis

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***Abstract*—This article presents a non-conventional voltage-transforming system that extracts energy from transmission line (TL) electrical field. The generation system consists in a 20 km collector line built within the right-of-way of a 230 kV transmission line to attend a 100 kW load. A non-conventional substation is conceived to provide adequate voltage regulation. This voltage-transforming system can be replicated at both sides of the TL to feed small remote loads or become an additional supply source for existing rural systems. No intervention on the existent line is necessary. Important results regarding transient, quality and reliability indexes cost evaluation of the system are provided.**

***Keywords*—Capacitive Coupling, Collector Line, Tuning Reactor, Rural Electrification.**

I. Introduction

The United Nations has defined 17 global goals to be reached by 2030 known as *The Sustainable Development Goals* (SDGs), with the aim of reducing poverty, hunger, climate change, lack of energy and improve health, among others. Specifically, regarding electrification, it is proposed to effectively expand the access to modern and reliable energy services, using the necessary methods to promote the use of renewable energies [1].

Access to electrical power is considered by the international community as an asset against poverty that promotes economic growth, entrepreneurship and human development in isolated areas. Countries with high levels of poverty tend to have low levels of electrification. Therefore, access to electrical service is crucial to achieve the proposed goals of SDGs by 2030.

Currently, around 1.2 billion people do not have access to electrical service, representing around 15% of the total population in the world. Likewise, about 3.04 billion people continue to rely on sources based on fuels, such as gasoline and kerosene, for cooking and heating, which present high levels of indoor pollution and a high mortality rate, especially for children and women [2], [3].

Human and social development in small communities have been confronted to difficulty of access to electricity. Rural electrification is necessary for expansion and intensification of agricultural activities [4]. So, it is necessary to provide a service with quality that meets the physical requirements of these populations based on government programs and development policies [5].

In the specific case of communities without access to energy, but close to the routes of extra high voltage (EHV) transmission lines (TL), the possibilities of being electrified are almost null. The high costs for the construction of a distribution substation for those EHV levels to supply hundredths of MW do not allow the development of projects for these communities [6], [7]. Therefore, unconventional projects must be postulated to address this problem [8], [9].

Rural electrical distribution systems (EDS) are often connected to the electric system through a single substation. These rural systems can reach even 100 km, causing high rates of unplanned outages. Utility companies are penalized if they do not comply with the expected quality level, but the access to the second power supply, which would ensure a minimum continuity of the service, may not exist, even if there are EHV or Ultra-High-Voltage (UHV) lines in the surroundings.

On the other hand, in the same way that telecommunication companies take advantage of TL assets, transmission lines may provide energy to isolated communities without the construction of regular substation. The use of capacitive dividers connected directly to the phases is a proposal that allows to supply small remote loads, but may compromise the power system reliability [10]. In the 80s isolated shielding wires were energized at low voltage level, feeding remote communities at a maximum distance of 100 km [11]. In some cases regular Extra High Strength (typical shielding wire) conductor was replaced by Penguin conductors (typical phase conductors) [12]. Those systems are still in service in Africa and Brazil.

Shielding wires (SW) are designed to protect overhead TL from lightning strikes. EHV and UHV TL typically use two shielding wires per transmission tower, either in single- or double-circuit. Since these wires are not meant to carry power, they are usually made of steel, therefore, they can have low electrical conductivity and are much cheaper than phase conductors. Normally, one of the shielding wires is an optical fiber composite ground wire (OPGW) that is used for telecommunication and line teleprotection [13]–[15].

An alternative based on insulated sections of transmission line's shielding wire was proposed by Hydro Quebec to feed small remote loads. This configuration behaves as a natural voltage divider in the TL. Isolated shielding wires (ISW) were applied to supply microwave repeater and communication facilities in Canada [16]–[19]. The same system was also implemented in Peru to attend small rural communities, but presented assembly problems and load increase, and eventually was discontinued [20].

This article introduces a new proposal to address the above main technology characteristics without intervening with an already existing host TL structure. A collector line composed of floating wires is installed within a 230 kV

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TL right-of-way (ROW) to reproduce the previous isolated shielding wire. Besides, a non-conventional substation is used to feed a 100 kW load. It is possible to produce an adequate supply source to feed small loads without any physical contact with the existing TL structure, no additional ROW impact and no additional CO2 emission due to energy generation (low-carbon emission). Additionally, the paper presents an economical analysis, highlighting the feasibility of the proposed non-conventional voltage-transforming system.

II. Coupling Source Supply

Energized host TLs' wires produce electrical charges in their surroundings. The quantity of charges depends on the voltage level at the conductors. If a floating conductor is located within the ROW electric field, an electrical potential will appear [21]. Thus, based on this effect it is proposed to built a collector line within this electric field region in order to produce a source supply. The use of this coupling source supply (CSS) is a promissory alternative to rural communities without any electric service, or with low quality access.

The interaction of induced voltage and electrical charges on a three-phase TL with a collector line is described on equations (1) and (2).

$$\vec{V} = \mathbf{P}\vec{Q} \tag{1}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \end{bmatrix} = \begin{bmatrix} P_{aa} & P_{ab} & P_{ac} & P_{ad} \\ P_{ba} & P_{bb} & P_{bc} & P_{bd} \\ P_{ca} & P_{cb} & P_{cc} & P_{cd} \\ P_{da} & P_{db} & P_{dc} & P_{dd} \end{bmatrix} \begin{bmatrix} Q_a \\ Q_b \\ Q_c \\ Q_d \end{bmatrix} \tag{2}$$

$$P_{kk} = \frac{1}{2\pi\varepsilon_0} \ln \frac{2h_k}{r_k} \quad F^{-1}\text{-km}, \tag{3}$$

$$P_{kl} = \frac{1}{2\pi\varepsilon_0} \ln \frac{D_{kl}}{d_{kl}} \quad F^{-1}\text{-km}, \tag{4}$$

Where,

V_a	Voltage on phase A
V_b	Voltage on phase B
V_c	Voltage on phase C
V_k	Phase voltage on conductor k
Q_k	Charge per km on conductor k
P_{kk}	Self-potential coefficient of conductor k
P_{kl}	Mutual-potential coefficient between conductor k and l
h_k	Height of conductor k
r_k	Radius of conductor k
d_{kl}	Distance of conductor k to conductor l
D_{kl}	Distance of conductor k to image conductor l

Note that equation (2) can be expanded to include more circuits and sub-conductors. Since the values in $\mathbf{P}$ matrix derive only from the host TL geometry, the induced voltage on the collector line is function of the voltage at phases' conductors and their position in space. Equation (2) is used to calculate the induced voltage on the collector wire. Note that the electrical charge on each phase of the TL is unknown, whereas the charge of a floating wire is null. Equation (5) presents a system with 4 variables and 4 equations, assuming $\mathbf{C}$ as capacitance matrix of the transmission line. Equation (6) determines the induced voltage V_d that depends on the phases' voltages and the capacitance, which is a function of the geometry.

$$\begin{bmatrix} C_{aa} & C_{ab} & C_{ac} & C_{ad} \\ C_{ba} & C_{bb} & C_{bc} & C_{bd} \\ C_{ca} & C_{cb} & C_{cc} & C_{cd} \\ C_{da} & C_{db} & C_{dc} & C_{dd} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \end{bmatrix} = \begin{bmatrix} Q_a \\ Q_b \\ Q_c \\ 0 \end{bmatrix} \tag{5}$$

$$V_d = -\frac{V_a C_{da} + V_b C_{db} + V_c C_{dc}}{C_{dd}} \tag{6}$$

Figure 1a shows the equivalent capacitances of the system for the three-phase line represented in (2).

Figure 1b shows an equivalent of the system in Figure 1a. It is composed by a voltage source f, an equivalent mutual (coupling) capacitance C_{fd} and the ground capacitance of wire d (C_{dg}). The voltage at phase d is calculated using (5) or (6). The values of the capacitances C_{dg} and C_{fd} are calculated as:

$$C_{dg} = \sum_{n=1}^{4} C_{4xn} \tag{7}$$

$$C_{fd} = \sum_{n=1}^{3} |C_{4xn}| \tag{8}$$

$$C_{eq} = (C_{dg} + C_{fd}) \cdot l_c \tag{9}$$

where the 4x4 matrix C_{4x4} is the capacitance matrix of transmission line and l_c is the total length of the floating wire.

An equivalent circuit can be obtained. Note that the equivalent capacitance value is per unit of length, thus the CSS power is proportional to the floating wire length.

The presented system has a natural high impedance source value, what compromises the voltage regulation at the load. A strong source must have a low impedance to prevent large deviation from the nominal value when the load changes. This implies that it is impossible to feed small loads through a simple floating wire, being necessary to promote a strong source.

To solve this problem it is proposed to include a series inductive reactor with equal value to the source reactance (Figure 2). This will produce a series resonant circuit, reducing the impedance of the circuit.

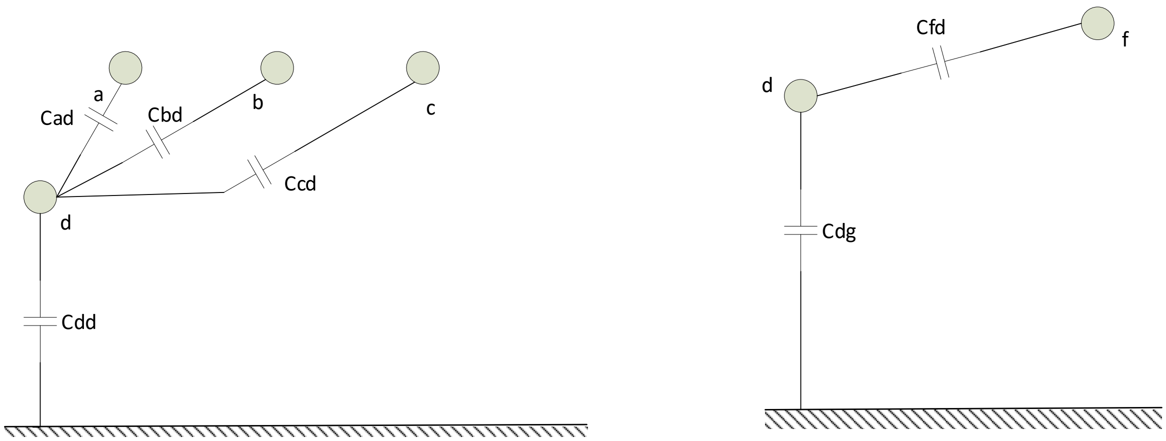
The proposed method produces a strong power source at the point of common coupling (PCC), where the load or the rural feeder is connected.

The reactor can be calculated by the following equation:

$$L = \frac{1}{\omega^2 \cdot (C_{dg} + C_{fd}) \cdot l_c} \tag{10}$$

Through the previous equation it can be verified that the larger the floating wire the smaller the size of the tuning reactor.

The impedance response (Z(ω)) at the Figure 2 load node is shown in Figure 3. The circuit exhibits a band-pass filter



(a) Equivalent capacitance of the system

(b) CL wire equivalent capacitance

Fig. 1: Capacitance model considering host TL and CL wires.

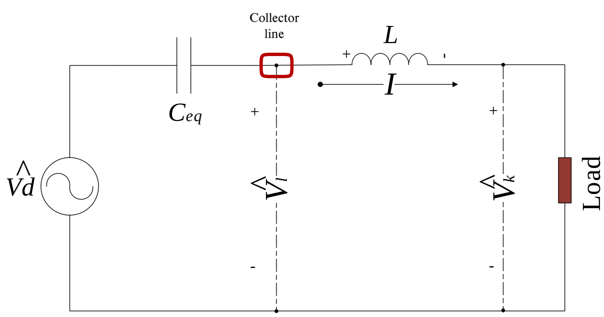


Fig. 2: Equivalent circuit of the capacitive generation system with the tuning reactor.

characteristic tuned at fundamental 60-Hz frequency. This property is important as it effectively blocks high-frequency signals from being transferred to the load, ensuring reliable operation on transient events on the host TL.

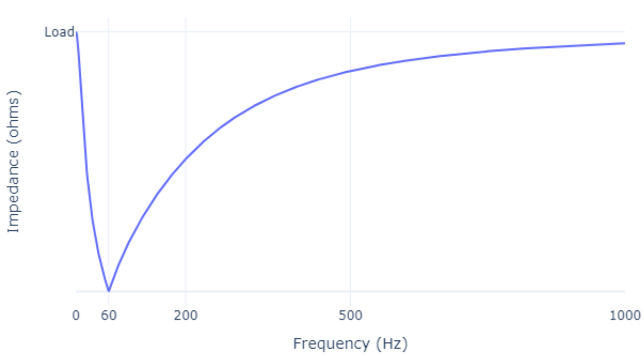


Fig. 3: Impedance response at Fig. 2 load bar.

III. Definition of the Coupling Source Supply

The use of the coupling source supply (CSS) as a method to supply energy for small rural communities close to a TL ROW has been studied in recent years focusing on the isolated shielding wires [9], [22], [23]. However that approach demands modifying the existing TL structure, which is a mayor concern to power utility companies.

In order to overcome this problem, it has been proposed the construction of a collector line composed of an asset of parallel wires (floating wires) within the transmission line right-of-way (ROW). This alternative increases the generation source cost, but does not compromise the TL asset and can be installed near existent TLs [24].

However, positioning the collector line (CL) is not a straightforward procedure. The optimum position must attend some restrictions and objectives. In this way, the positioning of the parallel wires was obtained by solving an optimization problem related to maximizing the induced voltage on the parallel conductors, maximizing the equivalent capacitance C_{eq}, and minimizing the assembly costs, subject to the following constraints:

- Transmission line shielding wire should shield CL from lightning. The protection zone was identified with the electrogeometric model.
- Collector line height cannot be higher than phases wires' height.
- No CL wire can stay under phase cables, avoiding any contact in the event of a fall. Also they cannot be positioned within the tower.
- The CL height must respect the minimum distances to the ground at middle span.
- The magnitude of the electric field must not exceed the values that generate corona effect, considering both TL phases and CL wires.

The optimization is modeled as a mixed-integer non-linear multi-objective problem that requires specialized methods [25] to be solved. The general procedure used to optimize the problem follows the pseudo code presented in Algorithm 1. Since the main focus of this paper is not the optimization problem and its mathematical model, here it will not be explained in detail. The detailed mathematical model and specific operators of the GA are presented in [26].

There, it is evidenced that the optimal configuration of the collector line is represented as a mixed-integer non-linear multi-objective optimization problem that considers mechanical and geometrical restrictions (such as number of conductors, clearance distance, conductor radius, and wind velocity), as well as electrical constrains (such as open circuit voltage, voltage at full load, electric field at the surface of the conductors, and lightning protection). In this sense, Algorithm 1 starts by creating solutions that met all the restrictions (feasible region). Then, to increase the diversity of the population of solutions, 10% of new random solutions ($\mathbf{P_a}$) are introduced to the original population ($\mathbf{P_o}$). Afterwards, the best solutions are selected by using a modified tournament. From the selected solutions, new solutions are created by using crossover and mutation operators. If the process is in the last generation, all the solutions are evaluated and the best ones are selected. Otherwise, the process of introduction of random solutions, natural selection, crossover, and mutation is repeated.

Algorithm 1 Collector line optimization

```
Initialize parameters and limits
P_o ← N random solutions inside the feasible region
it ← 1
while it ≤ max(generations) do
    P_a ← N/10 random solutions in the feasible region
    P_o ← P_o ∪ P_a
    Evaluate all solutions in P_o
    P_o ← Natural selection of P_o
    S_o ← Crossover of P_o with 90% of probability
    S_o ← Mutation of S_o with 5% of probability
    P_o ← P_o ∪ S_o
    if it = max(generations) then
        Evaluate all solutions in P_o
        P_o ← Natural selection of P_o
    it ← it + 1
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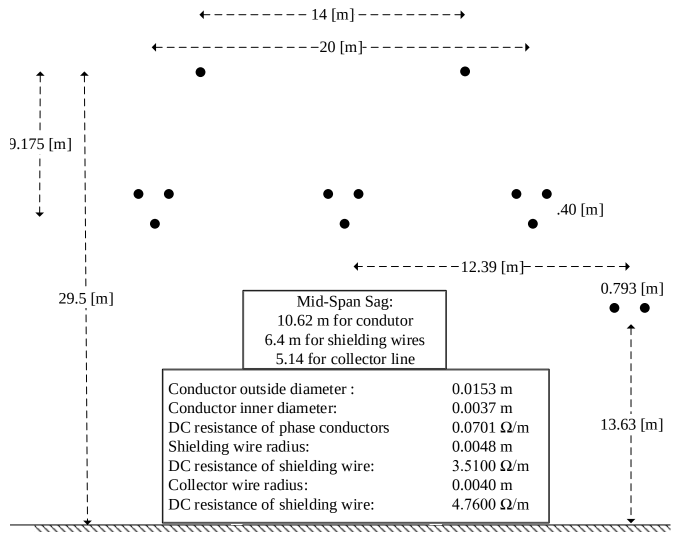
For this study, a 230 kV TL is considered, as presented in Figure 4. The collector line length is a parameter defined as an input to the algorithm, set as 20 km. The optimized collector line structure is presented in Figure 4. The collector system is formed by a bundle of 2 wires spaced by 0.793 m. The shielding wires of the host TL were considered as grounded (regular design). The voltage induced in the CL is 41 kV (without load). This non-conventional system can attend a 100 kW load. Due to the low amount of energy extracted, the proposed system can be replicated at both sides and several times along the TL ROW. The only constraint is that it should avoid transposition tower vicinity [24].

The tuning reactor is located at the non-conventional distribution substation. The reactor resonates with the equivalent capacitance of the collector line, promoting an equivalent strong voltage source that can feed larger loads. Nevertheless, the reactor value is close to 12.32 kΩ. To reduce the reactor to a more feasible size, a group of transformers was considered (Figure 5), and the new value is 392.14 Ω. The best topology was identified for the insulated shielding wire system at [27] and was adopted in the present



Conductor outside diameter :	0.0153 m
Conductor inner diameter:	0.0037 m
DC resistance of phase conductors	0.0701 Ω/m
Shielding wire radius:	0.0048 m
DC resistance of shielding wire:	3.5100 Ω/m
Collector wire radius:	0.0040 m
DC resistance of shielding wire:	4.7600 Ω/m

Fig. 4: 230 kV tower with the collector line. Distances at tower structure

system. The apparatus parameters are defined as: transformers' power: 120 kVA, leakage reactance: 0.09 pu, knee voltage point: 1.3 pu and rated voltage set as: T_1: 41/8.2 kV, T_2: 7.9/20 kV, T_3: 20/0.110 kV; tuning reactor: 1.0466 H with quality factor of 200. The rural feeder consists of a 50 km single-phase line with metallic return and 19.9 kV nominal voltage (phase-to-ground voltage at 34.5 kV system). The distribution transformer (T_3) was positioned at the end of the feeder.

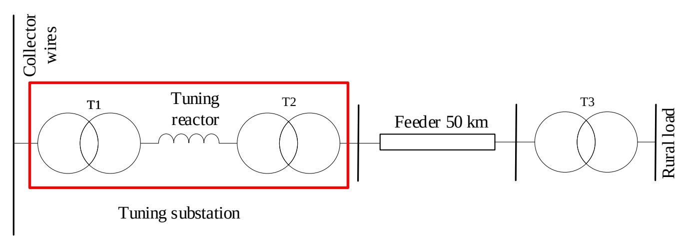


Fig. 5: Single-line diagram of the non-conventional distribution rural system.

A load variation was implemented to monitor the CL voltage and the voltage across the reactor, as presented in Figure 6. These values increase as the load increases due to the resonant circuit. As a result, the voltage on the CL for a maximum power of 100 kW is not greater than 41 kV, which allows the use of insulator string of 69 kV voltage level. The voltage across the reactor also increases, but it does not exceed 6 kV.

Figure 7 shows the voltage at the load for different power supply levels. It is possible to observe an adequate voltage regulation, below 10% for the entire load range.

Figure 8 presents the total harmonic distortion (THD) of the voltage at load. As shown, when the system is providing the target load the distortion is not important, reproducing the quality level from the transmission system. However, for loads above the target load (100 kW) the system quality performance fails. This derives from high voltages experienced at transformer terminals, promoting saturation and highly

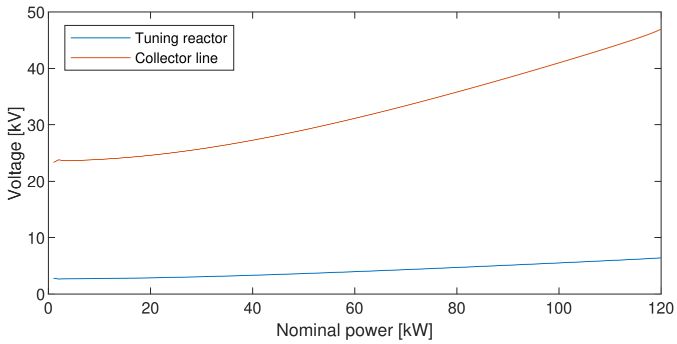


Fig. 6: Voltage at collector wires and across the tuning reactor - Load variation.

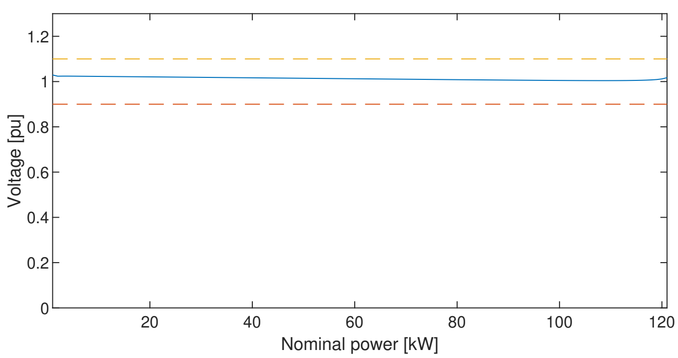


Fig. 7: Load voltage profile for rural load variation.

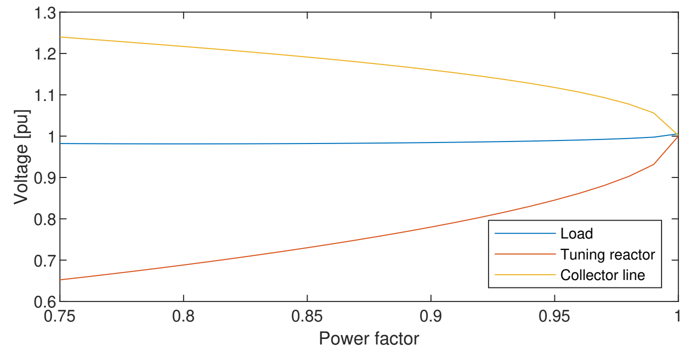


Fig. 9: Voltage at feeder for power factor variation in a 100 kVA load.

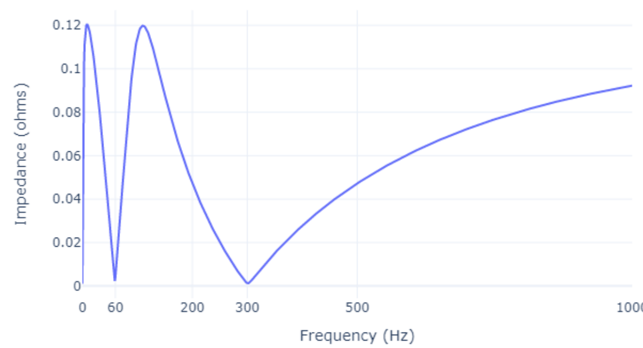


Fig. 10: Z(ω) measured at the load.

deformed waveform. It is necessary to establish a maximum load that can be attended (upper load limit).

For light or no-load condition the transformers operate in saturated region, resulting in substantial distorted waveform, however, high THD disappear fastly when rural load increases.

A power factor (pf) analysis is performed for a 100 kVA inductive load. Results are shown in Figure 9, where the base voltage is the obtained for the unitary pf. For lower pf the collector wire voltage rises up to 1.25 pu, that is not an issue. Most important, the voltage at rural load remains constant.

By performing the Z(ω) analysis at the load side a distinct behavior is presented, as shown in Figure 10. An additional frequency band emerges at the fifth harmonic frequency. This particular behavior can be attributed to the natural frequency response of the rural feeder.

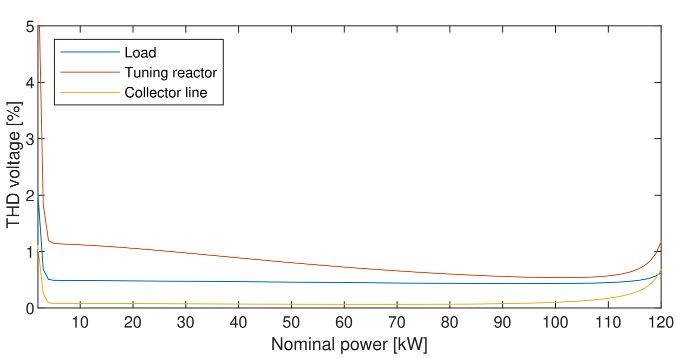


Fig. 8: Voltage total harmonic distortion.

The observed response is directly influenced by the geometry of the feeder. It is necessary to evaluate the feeder impedance response in order to avoid low frequency resonances. The larger the feeder, the lower will be the resonant frequency. For instance, for a 100 km feeder the resonance was at 210 Hz and for a 20 km feeder the resonance was at 480 Hz. In the present study a single feeder was considered, but in real life more lateral branches would be necessary, modifying the frequency response. A great potential of the present rural system is to attend small communities situated in a large region along the ROW. As such, detailed studies should be conducted for any new projects, in order to ensure optimal design and performance.

IV. Transient Analysis: Faults on TL

The non-conventional voltage-transforming system is subjected to transients due to regular switching operations or fault events in the host transmission line as well as in the rural system, demanding the specific apparatus, as detailed in [28].

Three spark-gaps were installed along the collector line, two at the terminals and one in the middle. These gaps prevent high overvoltages from jeopardizing the rural load. The test system was simulated in PSCAD. The spark-gaps were modeled as voltage-controlled breakers with a series 5 Ω resistor. The gap activation is controlled by voltage (80 kV), and it is deactivated when its current is below 20 A.

One of the most severe faults on the system is the single-line to ground fault near the substation. This fault is characterized by having the two healthy phases with sustained overvoltage that contaminates the collector line voltage. This phenomenon can be further understood by examining the Equation 6. The overvoltages can exceed the collector line voltage, resulting in prompt operation of the spark-gaps.

Figure 11 shows a AG fault on the host transmission line at 110 km. The fault impedance is 1 Ω. The fault duration is set to 50 ms.

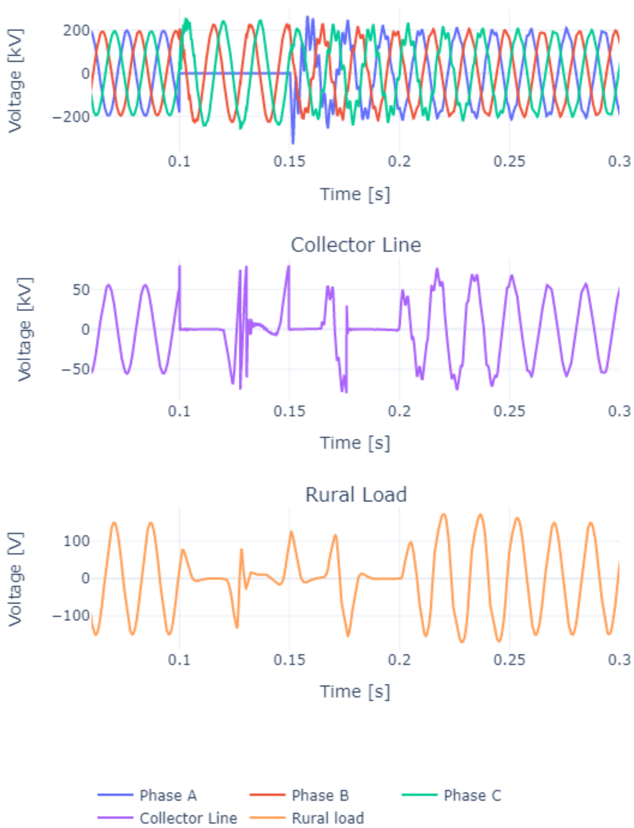


Fig. 11: Single-line to ground fault on the host transmission line.

The transmission line voltage experiences a long transient interval and this behavior is partially reproduced in the collector line and in the rural load. The collector line gaps prevent high overvoltage and momentarily detune the system, protecting the rural system. As can observed, the waveform at the rural load does not have high-frequency harmonics mostly due to the band-pass filter substation layout. The rural system returns to normal operation smoothly.

V. Economic analysis

Although isolated shielding wires could be considered to supply this small load, that would imply in modifying the TL structure. This is not a trivial solution, as it is difficult to reason about increasing the chance of having a failure in the TL due to a contingency at the rural generation system. Therefore an isolated system, that has no physical contact with any asset of the TL, was proposed.

The cost of the proposed project with a 100 kW power supply is presented on Table I. The power is provided using 20 km collector line within a 230 kV transmission line ROW.

TABLE I: Case project cost

CL line (20 km)	US$ 275,014.75
Coupling substation	US$ 70,848.54
Total project cost (20 km)	**US$ 345,863.15**
Power	100 kW = 0.100 MW
Power/MW cost	US$ 3,458,632.87 /MW
Life time	30 years
Annual rate	12%
O&M cost	2% investment cost
Variable cost	40/MWh
Project cost/year	US$ 429,367.34 /MW year
Project cost/MWh	US$ 49.01 /MWh
O&M cost	US$ 7.90 /MWh
Energy cost	US$ 40.00/MWh
Total unit cost	**96.91/MWh**

Variable cost is set using Brazilian data, however this value may be much lower in countries with a cheaper electricity cost.

In order to provide a comparison basis, an economical evaluation was implemented to a photo-voltaic (PV) system that would attend a similar load, i.e. 100 kW continuously (2400 kWh/day). This supply demands a PV system with 600 kWp of installed capacity. Therefore, solar infrastructure should be designed with a battery system to provide 24 hours supply, like the proposed system. Table II summarizes the total cost of a solar system.

Summing up, the solar system cost would become around US$ 1,200,000. However, this system demands sunny days every day, and is not able to supply the load if there are rainy days in a roll. Despite the high price, solar system can be built wherever the climate conditions are adequate, while the proposed CSS is bounded to the existence of a nearby transmission line route.

The reliability and quality of CSS rural electrification are huge advantages. Outages, voltage regulation and supply hours restriction are not expected problems once the proposed system will take profit of the TL energy quality. The low reliability on communities using solar system electrification has been considered a limitation, as well as the extremely

TABLE II: Solar cost

Installed capacity	100 kW
Energy per day	2400 kWh
Average produced value	4 kWh/kWp
PV system necessary	600 kWp
Solar panel	
Solar panel 330 W	162.00 USD/per unit
Minimum units required	1818 Units
Total cost panels	294,516.00 USD
Inverts	
Inverts 100 kWp	12,500.00 USD/per unit
Units required	6 Units
Total cost inverts	75,000.00 USD
Structure cost	
Cost per kWp	90.00 USD/kWp
Total cost structure	54,000.00 USD
Battery system	
Ion battery system	300.00 USD/kWh
Total cost battery	720,000.00 USD
Shipping and electrical equipment	
Cost	52,500.00 USD
Solar system total	**USD 1,196,016.00**

high cost of kWh produced with this technology [29]. CSS may be installed as the main electrification method to small communities or combined as a second supply source to electrified both on-grid and off-grid system, taking advantages of its reliability.

VI. Conclusions

In the search of a rural electrification method for unattended communities, it is proposed to build a collector line in the right of way (ROW) of a transmission line, together with a non-conventional substation. This non-conventional voltage-transforming system can also be considered as a second source of supply for existing rural system with low reliability. The energy is extracted from the electrical field around the TL.

The amount of energy extracted (hundredths of MW) is not significant to transmission companies, but it is extremely appealing to the distribution sector and even more to attend off-grid population. Thus, we can give an additional economic value to TL ROW.

The natural capacitive system produces a very weak source, and to provide adequate voltage regulation it was specified a series resonant system, based on a series reactor. This layout behaves as a band-pass filter that resonates for the fundamental frequency and blocks the remainder, including switching transients.

The proper design and location of the collector line (CL) was obtained with an optimization process focusing on enlarging the induced voltage and respecting TL safety distances. A 20 km CL was conceived at a 230 kV transmission line ROW to attend a 100 kW load. A non-conventional substation was considered with two transformers and the series reactor. The voltage values at the collector wires and tuning reactor are moderate, and commercial insulators can be used.

Steady-state results present a great regulation voltage performance. The voltage at collector line wires is defined by transmission line geometry and higher voltage levels will generate larger power supply. The proposed rural system has very high quality and reliability indexes, as it mimics the transmission line system quality.

Transient analyses performed in recent years indicate satisfactory response during faults on the host line and the rural system itself [28]. The 3-gap configuration is essential for mitigating overvoltages on the collector line during high voltage surges on the host TL.

The CSS case under study costs US$ 350,000.00 to attend a 100 kW load. The system is able to provide non-weather dependent energy 24 h per day (2400 kWh/day). A solar panel (PV) system with similar requirements would have a much higher cost US$ 1,200,000.00, because a battery system is necessary. However, the proposed CSS is bounded to the existence of a nearby transmission line route.

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References

[1] ONU, "Transforming our world: the 2030 Agenda for Sustainable Development," *General Assembly*, vol. 16301, no. October, pp. 1–35, 2015.

[2] T. World_Bank, *State of electricity access report 2017*. Washington DC: 2017 International Bank for Reconstruction and Development, 2017.

[3] A. U. Rehman, S. M. A. Shah, S. A. R. Shah, S. Badshah, and M. A. Khattak, "Prospects of rural electrification of Balochistan province with renewable energy sources," *2017 3rd International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET)*, pp. 95–100, 2017.

[4] H. Ding, C. Qin, and K. Shi, "Development through electrification: Evidence from rural China," *China Economic Review*, apr 2018. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S1043951X18300488

[5] D. R. Thomas and J. Urpelainen, "Early electrification and the quality of service: Evidence from rural India," *Energy for Sustainable Development*, vol. 44, pp. 11–20, jun 2018.

[6] Lloyd Mandeno, *Rural Power Supply Especially in Back Country Areas*. Wellington: Proceedig of the New Zealand Institution of Engineers, Vol.33, 1947.

[7] M. Chaves, "A contribution to the study of the use of unconventional techniques for the supply of small loads in the vicinity of high voltage transmission lines. [In Portuguese]," Ph.D. dissertation, University of Campinas, Brazil, 1995.

[8] R. Karhammer, A. Sanghvi, E. Fernstrom, M. Aissa, J. Arthur, J. Tullock, I. Davies, S. Bergman, and S. Mathur, "Sub-Saharan Africa: Introducing Low Cost Methods in Electricity Distribution Networks," *ESMAP Technical Paper 104/06*, 2006.

[9] S. Chaves and M. C. Tavares, "Micro-loads electrification: Use of insulated shielding wires of a 500 kV transmission line." *Energy for Sustainable Development - Elsevier*, 2017.

[10] H. G. Sarmiento, R. de la Rosa, V. Carrillo, and J. Vilar, "Solving electric energy supply to rural areas: The capacitive voltage divider," *IEEE Transactions on Power Delivery*, vol. 5, no. 1, pp. 259–265, 1990.

[11] F. Iliceto, Cinieri E., and Caseley-Hayford L., "New concepts on MV Distribution from insulated shield wires of HV Lines," *IEEE Transactions on Power Delivery*, vol. 4, no. 4, pp. 2130–2144, 1989.

[12] J. Ramos, A. Piantini, V. A. Pires, and A. D'Ajuz, "The Brazilian experience with the use of the Shield Wire Line technology (SWL) for energy distribution," *IEEE Latin America Transactions*, vol. 7, no. 6, pp. 650–656, 2009.

[13] J. Wang, Y. Wang, X. Peng, X. Li, X. Xu, and X. Mao, "Induced voltage of overhead ground wires in 50 0-kV single-circuit transmission lines," *IEEE Transactions on Power Delivery*, 2014.

[14] G. Kochan, K. Lenarczyk, K. Kiczkajło, and B. Dudek, "Replacement of existing ground wire with OPGW under live-line conditions new training polygon in Olsztyn," in *ICOLIM 2014 - 11th International Conference on Live Maintenance*, Budapest Hungary, 2014, pp. 21–25.

[15] R. Vasquez-Arnez, M. Masuda, J. Jardini, and E. Nicodem, "Tap-off power from a transmission line shield wires to feed small loads," in *2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America.*, Sao Paulo, Brazil, 2010, pp. 116–121.

[16] R. Berthiaume and R. Blais, "Microwave repeater power supply tapped from the overhead ground wire on 735 kv transmission lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-99, no. 1, pp. 183–184, Jan 1980.

[17] L. Bolduc, B. Bouchard, and G. Beaulieu, "Capacitive divider substation," *IEEE Transactions on Power Delivery*, vol. 12, no. 3, pp. 1202–1208, 1997.

[18] L. Bolduc, S. Member, Y. Brissette, and P. Savard, "IVACE : A Self-Regulating Variable Reactor," *IEEE Transactions on Power Delivery*, vol. 19, pp. 387–392, 2004.

[19] R. Blais and R. Berthiaume, "Supplying fixed and stroboscopic light beacons from the overhead ground wire on 735 kv transmission lines," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-99, no. 1, pp. 181–182, Jan 1980.

[20] F. Llanos Sifuentes, "Use of energy in the shielding wire as an alternative for feeding small loads [In Spanish]," *Comisión 2: "Energía y uso racional de Recursos" - Lima-Peru*, 1981.

[21] R. Horton, M. Halpin, and K. Wallace, "Induced voltage in parallel transmission lines caused by electric field induction," in *ESMO 2006 - 2006 IEEE 11th International Conference on Transmission Distribution Construction, Operation and Live-Line Maintenance*, Oct 2006, p. 2.

[22] J. S. Chaves and M. Tavares, "Transient study of rural electrification using induced voltage at transmission lines' shielding," in *IPST - International Conference on Power Systems Transients*, Seoul-South Korea, 2017, p. 8. [Online]. Available: http://www.ipstconf.org/papers/Proc{_}IPST2017/17IPST098.pdf

[23] J. S. Chaves and M. C. Tavares, "Rural electrification using capacitive induced voltage on transmission lines' shield wires," in *IEEE PES*

Asia-Pacific Power and Energy Engineering Conference, Xian-China, 2016, p. 8.

[24] J. S. Chaves, M. C. Tavares, and P. Mestas, "Rural electrification based on capacitive coupling using a collector line," in *IAPE - International Conference on Innovative Applied Energy*, Oxford-UK, 2019, p. 8.

[25] J. S. Acosta and M. C. Tavares, "Enhancement of overhead transmission line capacity through evolutionary computing," in *2018 IEEE PES Transmission Distribution Conference and Exhibition - Latin America (T D-LA)*, Sep. 2018, pp. 1–5.

[26] J. S. Chaves, J. S. Acosta, and M. C. Tavares, "Optimal transmission line coupling generation system design for rural electrification," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, pp. 1964–1973, 2021.

[27] J. S. Chaves H. and M. C. Tavares, "Analyzing rural electrification topologies based on induced voltage at insulated shielding wires," *IEEE Transactions on Power Delivery*, vol. 34, no. 1, pp. 53–62, Feb 2019.

[28] J. Chaves and M. Tavares, "Transient switching analysis of a nonconventional rural generation system," *Electric Power Systems Research*, vol. 196, p. 107245, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378779621002261

[29] X. Lemaire, "Off-grid electrification with solar home systems: The experience of a fee-for-service concession in South Africa," *Energy for Sustainable Development*, vol. 15, no. 3, pp. 277–283, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.esd.2011.07.005