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Ferroresonance mitigation for the unconventional rural electrification system[☆,☆☆]

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ABSTRACT

This paper presents a solution to the observed ferroresonance (FRR) phenomenon for both energization switching and load shedding conditions in an unconventional rural electrification system. The energy is extracted from the electric field surrounding an extrahigh voltage transmission line. Ferroresonance occurs in the power transformers of the distribution substation, and the existing solution cannot be directly applied. The mitigation method consists of the insertion of a shunt resistor when the FRR starts. The robustness of the method is shown in a time-domain simulation implemented in PSCAD/EMTDC.

1. Introduction

An electrical power system has characteristics that lead to defining it as a complex network due to its composition, and it is possible to find different subsets of electrical, mechanical, hydraulic, electronic and control components. With an adequate configuration of this equipment, it is feasible to send large blocks of power from generation centres to several consumption centres, always aiming to minimize environmental damage, reduce the ecological footprint, and seek the lowest investment and maintenance costs. Therefore, there must be high efficiency and reliability of the transmission and/or distribution lines throughout the useful lifetime of the system. However, even considering the best conditions and projects, the initial investment cost to build transmission lines is considered the highest and one of those with the longest-term return on capital (more than 30 years) when compared with other systems (water, gas, communication, among others) [1].

Developing electrification projects in rural communities without access to electricity but close to a transmission line becomes unfeasible, mainly due to the high cost of building a small-scale transformation centre (hundreds of kVA) [2]. Additionally, an important aspect is the eventual reduction of reliability and safety of a transmission system when an intervention is implemented to attend to a small rural load. In the literature, several proposals have been highlighted to overcome this situation, such as the unconventional projects presented by [3–11].

In this research, the system studied corresponds to the model proposed by [10], specifically, floating conductors are immersed in the electric field surrounding an extra high voltage transmission line to extract (harvest) electrical energy. The collector line is formed by isolated cables, and an unconventional substation reduces the voltage to the distribution level and stabilizes the voltage. The rural substation has a step-down transformer, a tuning reactor and a step-up transformer. The energy is supplied to the rural load through a regular rural feeder. Due to capacitive coupling, the proposed generation system has a capacitive response and is named the capacitive coupling source supply (CCS).

The system analysed in this paper is quite robust and provides energy with the quality and reliability observed in the transmission system, which means that the CCS quality is much higher than that found in regular rural distribution systems. However, during some specific switching, the ferroresonance (FRR) phenomenon [12] was observed, namely, in the energizing and load rejection. The eventual load variation can lead to transformer saturation.

The ferroresonance phenomenon can provoke different effects on the system, especially if it is not promptly removed. Some of these problems are the occurrence of overvoltages, overcurrents, transformer overheating, and its eventual explosion, meaning that FRR can cause severe damage to the assets [13].

It is essential that this phenomenon is prevented or promptly removed. Currently, there are some proposals in the literature that are normally applied in potential transformers (PTs), among which the following stand out:

- Shunt resistors on the transformer's low voltage side, [14].

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- Permanent damping resistors, [15].
- Air core shunt reactor on the transformer's high voltage side, [16].
- Air core reactor connected in the tertiary winding of the power transformer, [1].
- Air core neutral reactor on the transformer's high voltage side, [17].
- Activation of the surge arrester protections on the transformer's high voltage side when ferroresonance is detected, [18].

All these possible solutions can solve the ferroresonance phenomenon, but none of them have been considered for unconventional distribution substations. CCS is a new system with particular characteristics, and it is necessary to evaluate how it can promptly remove the FRR.

This paper can be divided into two parts. First, the phenomenon is identified, and second, the mitigation method is proposed. The mitigation solution consists of inserting shunt resistors on the low voltage side of the step-down transformer based on energy quality indices. Additionally, the surge arrester located at the substation outgoing circuit with adequate specification further improves the CCS performance.

The paper contributions are summarized below:

- Innovative ferroresonance mitigation method applied to CCS.
- Identification of the minimum load for safe energization switching and load shedding.
- Identification of the control method to insert a shunt resistor.
- Identification of optimal shunt resistance values.

2. Test system description

The unconventional rural electrification system described in [10] is summarized below. The PSCAD/EMTDC was used to implement the study.

2.1. Host transmission line and collector line

The host transmission line (HTL) from which energy is extracted to feed the rural load is a 200 km long 230 kV line and transposition cycles of 1/6, 1/3, 1/3 and 1/6. The soil resistivity adopted was 4000 Ω.m. The transmission line was represented with the phase domain frequency-dependent model and has a surge impedance loading (SIL) of 200 MVA. Additionally, the short-circuit level of the generation equivalent system is 6 kA and that of the reception is 4.8 kA. The equivalents have X/R ratios of 35 and 12 at the sending and receiving terminals, respectively. In addition, the HTL has a 20 Mvar shunt reactive compensation at each terminal, with a quality factor set to 400, and a neutral reactor with $\frac{X_h}{X_d} = 1.5$ with a quality factor of 40.

A collector line (CL) composed of a bundle of two isolated steel cables is located within the right of way (ROW) of the HTL. The simulated model was represented as a four (04) phase line with the shielding wires implicitly represented in the section where the CL exists. The CL bundle was considered the fourth phase. Fig. 1 shows the characteristics of the tower, conductors, shielding wires, and collector wires.

As the CL is immersed in the electric field of the HTL, the voltage induced in the CL corresponds to a natural capacitive divider that depends on the voltage on the HTL and the spatial coordinates [11]. Spark gaps (SG) are installed to mitigate overvoltages on the collector line. They are represented as a voltage-controlled switch with a 5 Ω resistor. Three SGs are arranged, one at each end of the CL and another at its centre, and they operate when $|v_{LC}(t)| > 80\text{kV}$ [10]. Additionally, if the SG is activated and $|i_{SG}(t)| > 20$ A, the gap current continues flowing until $|i_{SG}(t)| \leq 5$ A.

When the CL voltage varies with the rural load level, meaning that when the CL is not connected to the substation (no-load condition), the induced voltage is 40 kV. This value is the same as when supplying 100% of the rural load for the analysed system. The CL length is 20 km, leading to an equivalent capacitance of 0.2195 μF.

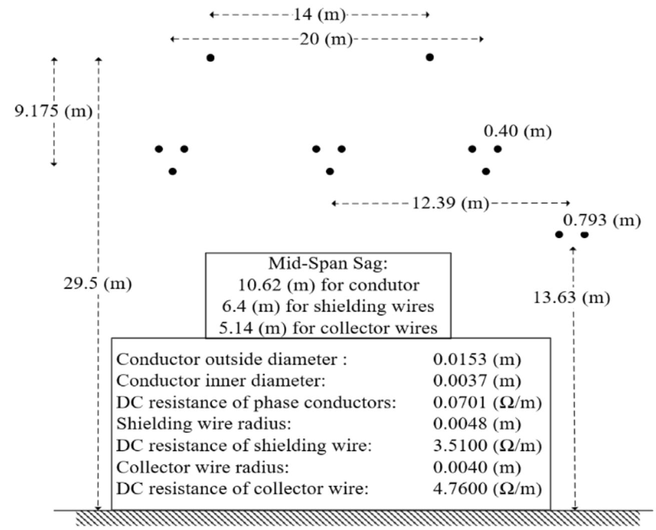

Fig. 1. Characteristics for HTL and CL towers, based on [11].

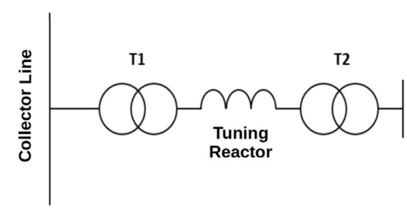

Fig. 2. Distribution substation, based on [9].

2.2. Unconventional distribution substation

To ensure voltage regulation at the rural load, an unconventional distribution substation (SS) was designed. It is composed of a tuning reactor of 1.0371 H and two single-phase 120 kVA transformers (T_1 and T_2), with both windings grounded. The characteristics of the transformers are as follows: leakage reactance 0.09 pu (quality factor of 100), magnetizing reactance 0.2 pu, magnetizing voltage 1.15 pu, magnetizing current 1%, winding losses of 0.001 pu and transformation ratio of 40/8 kV and 7.9/20 kV, respectively. In Fig. 2, the SS equivalent circuit is shown.

2.3. Rural feeder and the load

A single-phase feeder with metallic return was proposed in [10] to attend the load, with a length of 50 km, nominal voltage of 20 kV, and conductor type 4/0 AWG. The conductor parameters are as follows: resistance of 0.1612 Ω/ km, reactance of 0.4503 Ω/ km and susceptance of 3.6663 μS/km. The SS was located at 110 km of the HTL, and the point of common coupling (PCC) is the middle of the CL.

The rural load is connected to the feeder through a distribution transformer (T_3), with parameters similar to those presented of transformers T_1 and T_2 and a transformation ratio of 20/0.11 kV. The target load is 0.1 MW, which is similar to the HTL loss. This load was modelled as constant impedance with a unitary power factor, considering that the final consumers were residential users. Fig. 3 presents the single-line diagram of the system.

2.4. Normal operating condition

To illustrate a normal operating condition, Fig. 4 shows the case where the BRK breaker closes, energizing the substation together with the full load. It can be observed that the voltage at the load reaches normal conditions smoothly, and no overvoltage is observed.

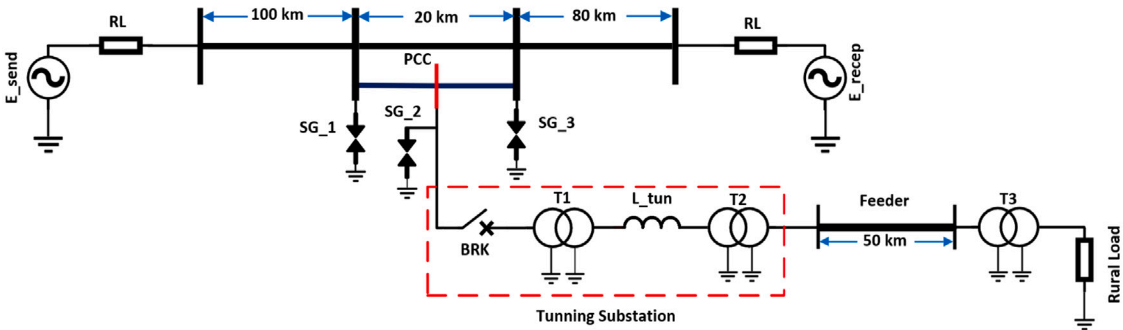

Fig. 3. CCS single-line diagram.

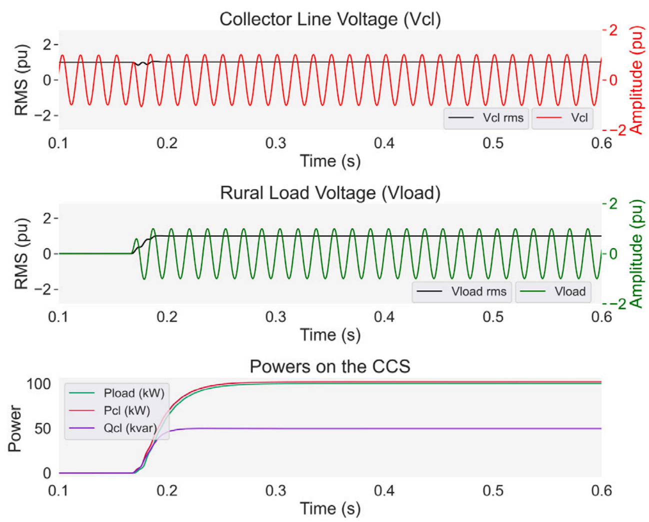

Fig. 4. CCS response for 100% load energization.

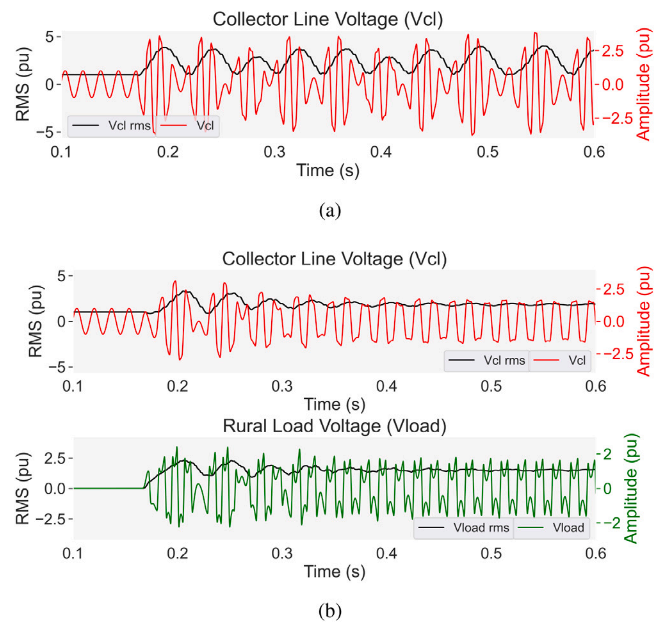

Fig. 5. Substation energizing in no-load condition (a) and with a 20 kW load (b).

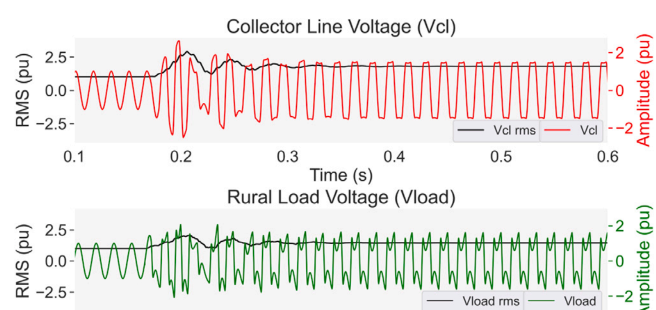

Fig. 6. Load shedding event. Initial load: 100 kW; final load 40 kW.

3. Critical operating conditions

Due to the topology of the unconventional distribution substation, some operating conditions can jeopardize the capacitive coupling source system. As a fundamental frequency resonant circuit was designed to strengthen the source, abrupt load supply changes can lead to the ferroresonance phenomenon when the system is under light-loading conditions. Specifically, two conditions must be carefully studied:

- Substation energization (at no load condition or with light load).
- Load shedding (partial or full load).

To allow a clear view of the phenomenon, the CL spark gaps were removed; otherwise, they would clip the overvoltages.

In Fig. 5, two substation energization cases are presented, namely, the no-load condition and energization with a 20 kW load, both with the circuit-breaker closing at $t = 160$ ms. For the no-load case (Fig. 5.a), it is possible to observe a sustained subsynchronous ferroresonance phenomenon with very high overvoltage (3.8 pu). For the 20 kW case (Fig. 5.b), the response is slightly different. The subsynchronous ferroresonance phenomenon appears, but it is a transient phenomenon that changes towards a fundamental ferroresonance response severely distorted due to transformer saturation. Very high overvoltages are observed, specifically 2.0 pu at the CL and above 1.8 pu at the load.

As we have seen that no FRR phenomenon occurs when the SS is energized with full load, it is expected that there is a minimum load that will prevent or remove the FRR phenomenon. This will be properly analysed in the following section.

Another important operating condition is load shedding. For example, consider the system operating at full load, and at $t = 160$ ms there is a change to 40 kW. Fig. 6 shows the voltage waveforms at the CL and at the load. It can be observed that this response is similar to the 20 kW energization case, with the main difference being the duration of the subsynchronous ferroresonance phenomenon, which in this case does not last as long.

Therefore, when the CCS system is driven to a light load operating condition, the FRR phenomenon appears. It is necessary to identify the load range for both energization and load rejection that guarantees the normal operation of the rural electrification system.

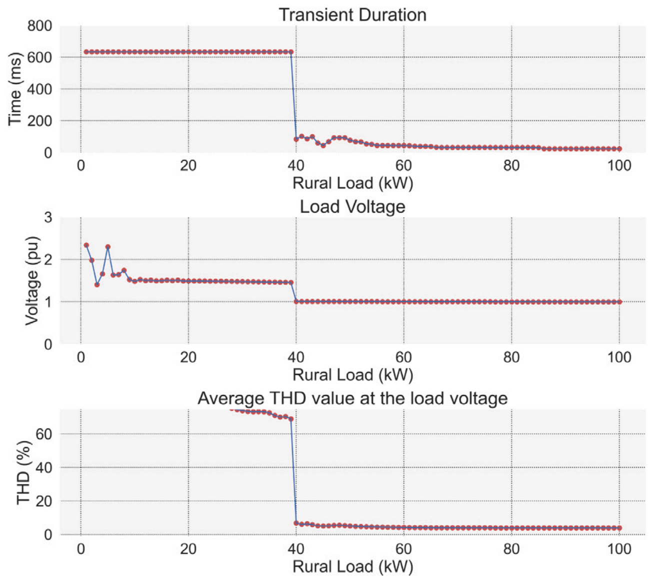

Fig. 7. Substation energization varying load values. No mitigation method. Observing quality parameters.

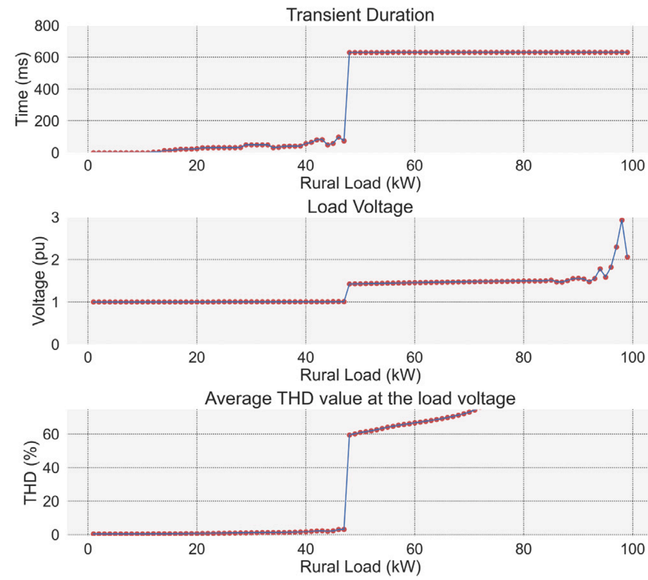

Fig. 8. Load shedding varying load values. No mitigation method. Observing quality parameters.

3.1. Substation energization switching - load characterization

To study the interaction between the load level and the FRR phenomenon during substation energization switching, the load was varied in the range of [1:100] kW in steps of 1 kW. Some data were analysed, such as the transient duration, the rms load voltage, and the THD (total harmonic distortion) at the load voltage. As can be verified in Fig. 7, these parameters allow a clear identification of the minimum load that ensures a stable operating condition. Furthermore, these data can be used to identify when it is necessary to implement a mitigation procedure.

Specifically, for loads below 40 kW, the system is unstable, resulting in deteriorating variables as the load decreases. The transient duration is limited to the simulation time, and the FRR will not vanish by itself. Similarly, the THD is very small when the system is in a stable condition (3.9%), and it changes abruptly to over 60% when the load is below the safe minimum value. An important finding is that the transient duration is below 200 ms for the stable cases, and this value is adherent to distribution quality standards [19].

3.2. Load shedding - load characterization

Similarly, the CCS performance was studied for the load shedding condition, starting with the system operating at full load, and eventually the load was reduced in the range of [99:1] kW in steps of 1 kW. In this case, the critical value of load that can be disconnected while maintaining the normal operating condition of the rural system is 47 kW. Fig. 8 shows the response of the same parameters analysed in the previous section: the transient duration, the rms load voltage, and the load voltage THD. They allow a proper identification of the safe load shedding range.

Again, the transient duration is limited by the simulation time, as the FRR will not vanish if no mitigation procedure is implemented. The THD data are very robust and can definitely be used to trigger the mitigation method.

3.3. Main results

In summary, Table 1 is considered for the characterization of the substation energization switching and load shedding conditions.

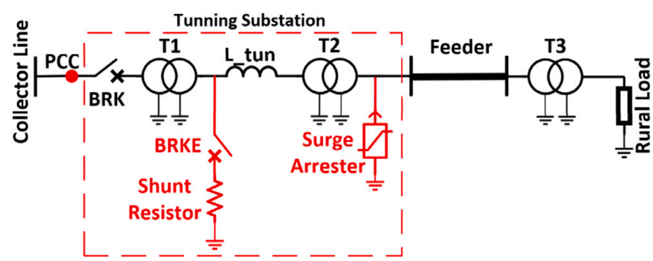

Fig. 9. CCS single-line diagram — Surge arrester and shunt resistor positions.

Table 1
Load limits for the substation energization and load shedding.

Condition	Load range (kW)	Is stable?
Energization switching	[1–39] [40–100]	No Yes
Load shedding	[99–48] [47–1]	No Yes

An important remark is that the obtained values of load limits are adequate for the proposed system. They cannot be generalized. However, the proposed methodology can be applied to new unconventional rural distribution systems.

4. Proposed mitigation procedure

Several methods were considered to mitigate the ferroresonance phenomenon, and the use of shunt resistors (SR), based on [14], was the most effective. A surge arrester (SA) [18] was installed at the outgoing circuit of the substation. This device was not considered in the above analysis because it would prevent a clear view. Different locations were analysed for the SR, and the selected one was positioned at the low voltage side of the T_1 transformer, specifically between T_1 and the tuning reactor. The new CCS configuration is shown in Fig. 9.

The proper specification of the shunt resistor and the surge arrester data are of major importance. The SA is very important to further reduce the transient FRR phenomenon, and its parameters are shown in Table 2 [20,21], and [22]. The reference voltage is 24 kV and its energy capability is 5 kJ/kV, totalling 120 kJ.

Table 2
Surge arrester V-I curve.

V (pu)	I (kA)
1.1	0.0000001
1.28	0.000001
1.33	0.00001
1.37	0.0001
1.39	0.001
1.42	0.01
1.52	0.1
1.65	1
1.75	3.816
1.9	10
3.8	100

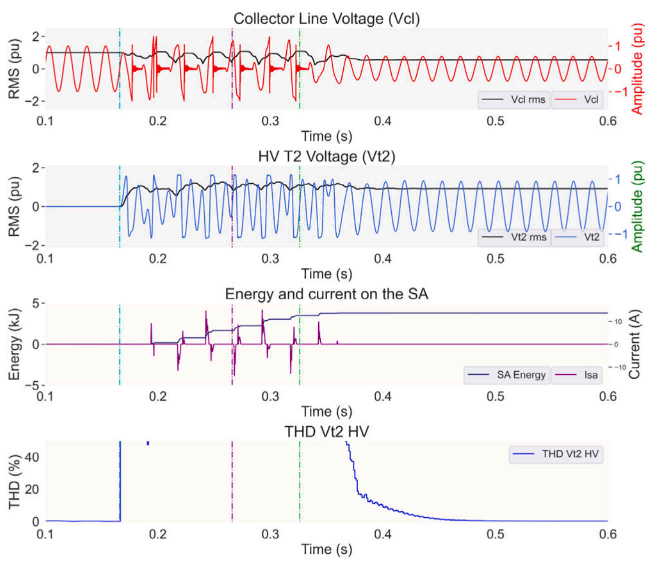

Fig. 10. Substation energization with 7 kW and SR = 700 Ω mitigation method.

The collector line spark gaps were represented in the system to obtain the real response of the rural system. They actually contribute to removing the transient FRR, but only when the adequate SR method is applied.

As observed in the previous section, the voltage THD can be used to initiate the mitigation method, namely, to close the shunt resistor. As the stable condition has a very low voltage THD value, it was specified that the shunt resistor will be energized after a delay of 100 ms of the circuit-breaker (BRK) closing operation (SS energization switching) or when there is a load rejection (outgoing power changes abruptly), and the voltage distortion at the outgoing circuit goes above a threshold ($THD_{V_{T2}} > 5\%$). When the digital closing signal increased, an additional 60 ms closing delay was issued to represent the mechanical response of the circuit breaker.

4.1. Energization case

The minimum load to be energized to maintain the CCS normal operation is 40 kW, which represents a resistance of 1600 Ω on the T_1 low voltage side. Taking this value as a reference, an SR variation range of [500–1600] Ω in steps of 100 Ω was considered. The load was varied as [1–39] kW in steps of 2 kW.

Similar to the characterization cases, the following premises are considered:

- Transient duration ≤ 500 ms.
- 0.9 pu ≤ $V_{T2_{rms}}$ ≤ 1.1 pu.
- $THD_{V_{T2}} \leq 5$ %.

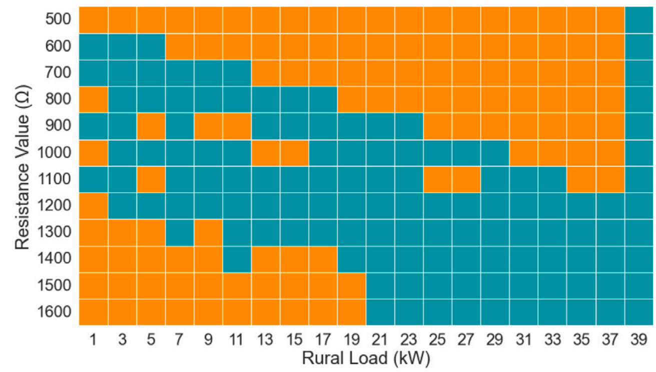

Fig. 11. Success matrix for SRs values — SS energization cases.

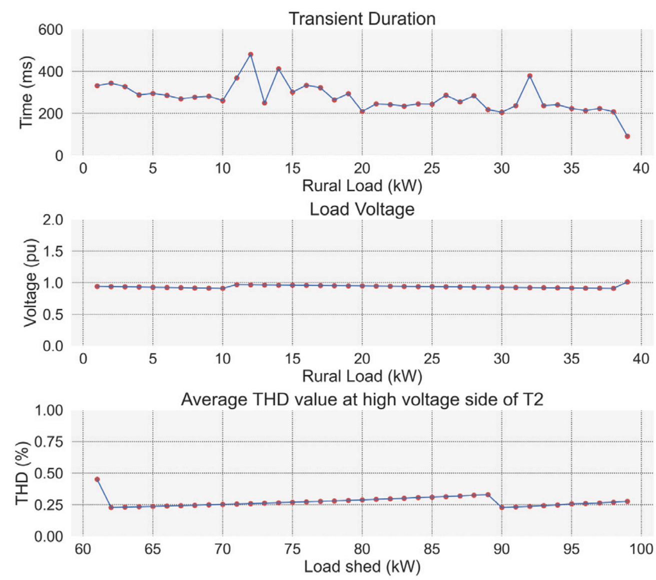

Fig. 12. Substation energization varying load values — With mitigation procedure.

To illustrate the control performance, Fig. 10 shows a 7 kW energization with SR = 700 Ω.

System energization occurs when $v_{CL}(t) = 0$ V at t= 166 ms (turquoise vertical line), presenting transient instability, which causes SG operation. The FRR control is activated after 100 ms (purple vertical line). At approximately t = 320 ms (green vertical line), the BRKE switch closes energizing the SR. When the FRR phenomenon is suppressed, the SGs stop conducting, and the system becomes stable. The SS output voltage waveform presents a quasiperiodic FRR phenomenon caused by the gap operation. The maximum observed voltage is 1.25 pu, and the maximum energy absorbed by the SA for this case is 3.78 kJ. The THD graphic shows that after the transient period, $THD_{V_{T2}} \leq 1\%$.

Fig. 11 summarizes the obtained results, with the orange cells being failed results (did not respect all the objectives) and the green cells being successful results. Thus, a 700 Ω value for loads smaller than 11 kW and a 1300 Ω SR for the remainder range were adopted.

The simulation process was refined for load steps of 1 kW (results in Fig. 12) considering the proposed solution. Most of the cases have transient durations lower than 400 ms; however, for some scenarios (12 kW and 14 kW), the transient time is above 400 ms. These cases are on the verge of normal operating conditions.

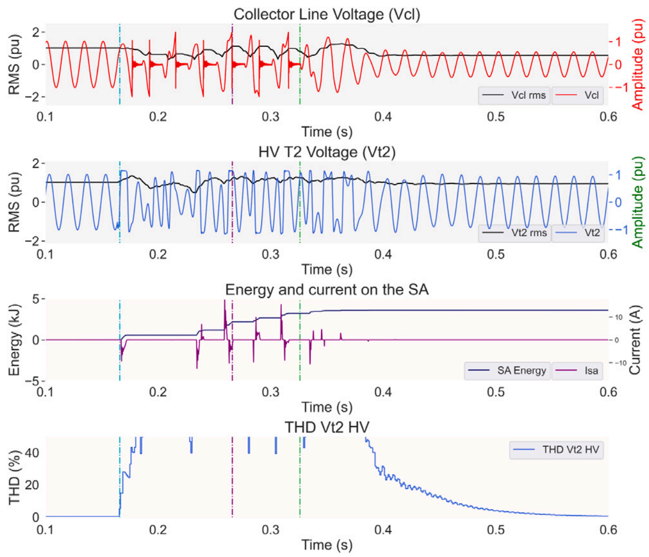

Fig. 13. Load shedding event. Initial load: 100 kW; final load 1 kW and 700 Ω SR mitigation method.

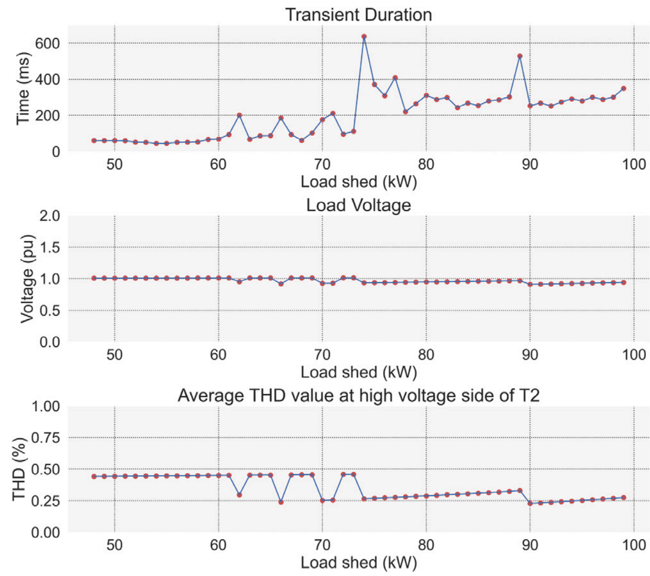

Fig. 14. Load shedding varying load values — With mitigation procedure.

Table 3
Critical operating conditions and specified shunt resistors.

Condition	Load range (kW)	SR value (Ω)
Energization switching	[0–11]	700
	[12–39]	1300
	[40–100]	Not required
Load shedding	[100–91]	700
	[90–66]	1300
	[65–48]	2200
	[47–1]	Not required

4.2. Load shedding case

Similar to the energization condition, the load shedding was varied as [48:99] kW in steps of 3 kW. The SR range considered is [500-2200] Ω in steps of 100 Ω.

Fig. 13 shows a successful case for 99 kW load shedding with SR = 700 Ω. The load shedding occurs at t = 166 ms with a maximum voltage peak of 1.69 pu. The SGs operate, which results in a maximum v_{CL} value of 1.41 pu. At 326 ms, the circuit-breaker BRKE energizes the 700 Ω SR. From this point on, the system tends towards a stable response that is reached after t = 400 ms. The maximum energy absorbed by the SA for this case was 3.6 kJ.

After simulating all possible combinations of load shedding and SR values, and taking into account the above criteria, the mitigation method was set to a 700 Ω SR for load rejected values greater than 90 kW, SR = 1300 Ω for a load shedding range of [66:90] kW, and 2200 Ω SR for load shedding at [48:65] kW. Fig. 14 shows the CCS response for the proposed load shedding mitigation method.

There are two cases where the SR value objectives are not completely adherent, specifically for 74 kW and 89 kW load rejections. However, this inconsistency is only for the strictly specified transient duration that can be adjusted accordingly with the local distribution standard.

5. Discussions

The results obtained in this research are adequate for the power system studied. The appropriate shunt resistor values for each FRR condition are shown in Table 3.

The shunt resistor insertion and removal procedure is triggered by the outgoing circuit voltage and THD.

The ferroresonance phenomenon was removed for substation energization with light load or no-load conditions and for important load shedding events with the use of an appropriate shunt resistor and surge arrester. The results obtained validate the proposed mitigation method that brings robustness and reliability to the unconventional capacitive coupling rural electrification system.

The objectives established to identify the most adequate values of SRs can be refined based on the local distribution regulations where the rural system is installed. As an example, the Brazilian distribution system standard [19] is copied below. Accordingly, the previous objectives could be more flexible.

- Transient duration $\leq$ 3 s.
- 0.93 pu$\leq V_{T2_{rms}} \leq$1.05 pu.
- $\mathrm{THD}_{V_{T2}} \leq 10\%$.

If new objectives were adopted, different SRs could be installed. This must be carefully considered when designing the SR mitigation method.

6. Conclusions

The unconventional rural electrification system proposed in [10] is a robust solution to provide energy to remote villages in the vicinity of an extra high voltage transmission line corridor. As it is basically a capacitive source connected to a substation composed of transformers and a series reactor, the system is prone to the ferroresonance phenomenon under light-loading conditions.

To remove the undesired FRR phenomenon, a shunt resistor located at the low voltage side of transformer T1 is connected when the outgoing circuit voltage distortion goes above a defined level. A group of shunt resistor values were identified for each operating condition, which provides robustness to the system promptly. A surge arrester located at the substation outgoing circuit further enhances the system performance.

The values presented in this manuscript are adequate for the studied system. Specific values should be identified for other power systems and rural distribution loads, including the distribution feeder.

The methodology presented can be applied to any new system, and the following steps should be followed:

- Characterization of the minimum load for substation energization switching and load shedding.

- Characterization of shunt resistor values and surge arrester data.

It is expected that a substation outgoing circuit voltage THD threshold of 5% should be adequate for all systems.

Shunt resistor control is being enhanced, and new results will be presented in the near future.

CRediT authorship contribution statement

R.E. Rojas: Conceptualization, Methodology, Investigation, Writing – original draft. **J.S. Chaves:** Conceptualization, Methodology, Supervision, Writing – review & editing. **M.C. Tavares:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Raul Enrique Rojas Varela reports financial support was provided by Natonal Council for Scientfc and Technological Development. Maria Cristna Dias Tavares reports financial support was provided by Coordinaton of Higher Educaton ersonnel Improvement. Maria Cristna Dias Tavares reports financial support was provided by State of Sao Paulo Research Foundaton.

Data availability

Data will be made available on request.

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