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Repowering rural single-phase distribution network: A non-conventional proposal using two overhead wires and the ground as the third phase

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ABSTRACT

This work proposes an innovative concept for repowering the installed single-phase distribution system, which is widely used in rural areas. It is well known that the single-phase distribution network delivers less power than a traditional three-phase electrical system. In this sense, in order to attend rural three-phase loads, such as three-phase induction motors, thus taking advantage of the existing single-phase rural distribution systems, a non-conventional three-phase system with two overhead wires and the ground as the third phase is proposed. The distribution system is modeled and the simulation results performed using the ATPDraw software. Finally, while field tests were performed on a reduced low voltage (380 V) prototype. This paper aims to show that it is possible to transform a single-phase rural distribution system into a three-phase, reusing as much as possible, all of the existing single-phase rural structure.

1. Introduction

Generally speaking, single-phase transmission systems are used in rural areas [1]. Several countries use the SWER (single wire earth return) which is less expensive than the single phase system with a physical wire return. However, both grids have a reduced power transmission capacity and this limits the rural area development as well as the growth of agribusiness.

Some countries have developed technologies which aim to supply electricity to remote rural communities. In the USA, for example, a phase-neutral system was proposed. This is a single-phase, two-wire system derived from one phase and the neutral of a 3-phase, 4 wire medium voltage system, with the star point permanently earthed [2].

The single wire earth return (SWER) in New Zealand was first proposed by Lloyd Mandeno [3]. This technique has been used in New Zealand since the 1930s and is still actively used in rural areas of, New Zealand, Australia, South Africa as well as parts of South East Asia and Brazil [4].

In order to supply three-phase loads, the first alternative available for conversion from single-phase to a three-phase system, at the load side, were based on passive elements, such as capacitors and reactors with autotransformer converters [5]. Most of these converters remain balanced at only one specified load.

An alternative example is presented in [6,7]. It is noticed that there are several power electronic devices used to convert single to polyphasic systems. New topologies in the conversion system for use with three-phase loads have been developed in order to mitigate the harmonic distortion and reduce the converter losses [8].

Yet another technique for three-phase and single-phase power distribution along HV (115–330 kV) transmission lines is via insulated shield wires, energized at MV (20–34.5 kV) from the main HV/MV transformer stations, using the earth as an MV phase conductor [9].

In [10] a three-phase system method for rural areas, with two wires is proposed this system has performance, no presenting unbalances for 0 Ω grounding impedance. However, the power transmission line capacity is limited to twice of the single phase.

This work aims to present a new concept for rural distribution systems. This idea has come about in order to attend the electrical power needs of rural areas located in the Western Amazon Region

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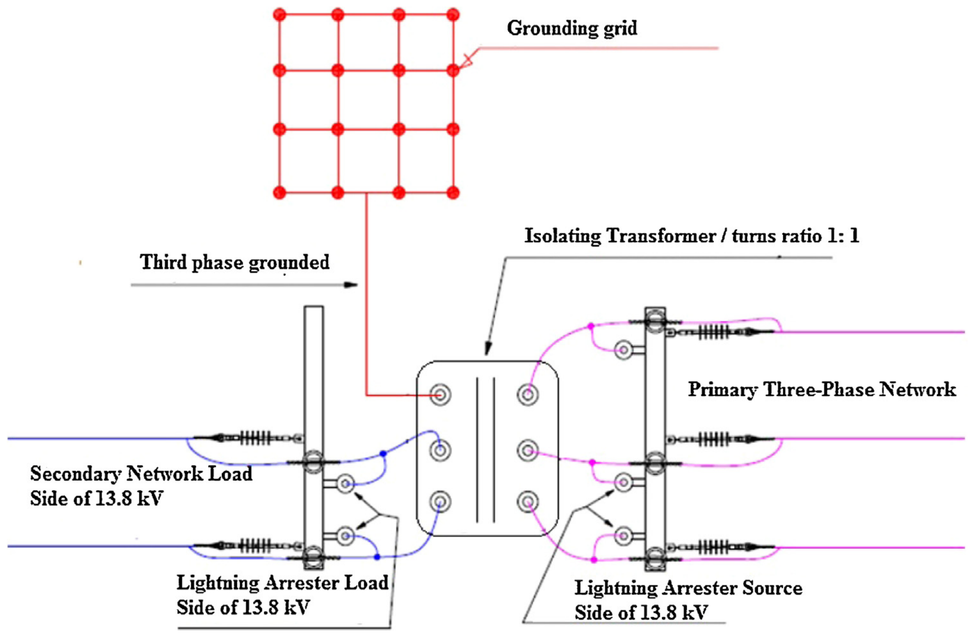

Fig. 1. The proposed system of the simplified scheme: the IT has one phase grounded.

of Brazil, which is fed by single wire earth return (SWER) system. This technique is based on a three-phase system with two overhead wires where the earth is the third phase. With a few adaptations to the SWER system, it is possible to increase, by threefold, its transmission capacity. In order to validate this proposal, several ATPDraw simulations are carried out and field tests are accomplished on an LV (380 V) prototype.

2. Proposed system explanation

The circuit presented in Fig. 1, shows an overview of the proposed system with the isolation transformer (IT) used to feed the two overhead wires and the earth as the third phase.

This non-conventional distribution system is energized by a regular three-phase voltage through a conventional IT which is located between the source and the non-conventional distribution line. This transformer must fulfill the steady state operation with one phase of the secondary grounded and the other with voltage to ground as the phase to phase. The single-phase transformer bank or three-phase with one of the primary terminals, connected to ground can also be installed along the medium voltage, non-conventional distribution line. Therefore, the single-phase transformer will need to have two high voltage bushings, as this is a double-phase system since the ground is one of the phases.

Three-phase loads can be fed without any restrictions [9]. As ground resistance is much lower than any physical conductor [11] and ground reactance is also slightly lower than the conductor [12], the system is, consequently, not compensated. Therefore, it is expected that the negative sequence is present in the non-conventional circuit, because of the impedance difference between the ground phase and the two overhead cables.

2.1. Repowering of the existent single-phase circuit

An important characteristic of the proposed system is that it can be applied using the pre-existent SWER or single-phase metallic-return systems structures. The medium voltage single-phase line is adapted to a three-phase configuration. Thus, the present single-phase consumer transformer is replaced by a three-phase one, in order to receive the feeder that reuses the pre-installed single-phase system (SWER) and only one overhead wire is added. The third phase is solidly connected to the ground, as shown in Fig. 2. The SWER poles may, either, need or not be replaced, depending on the case.

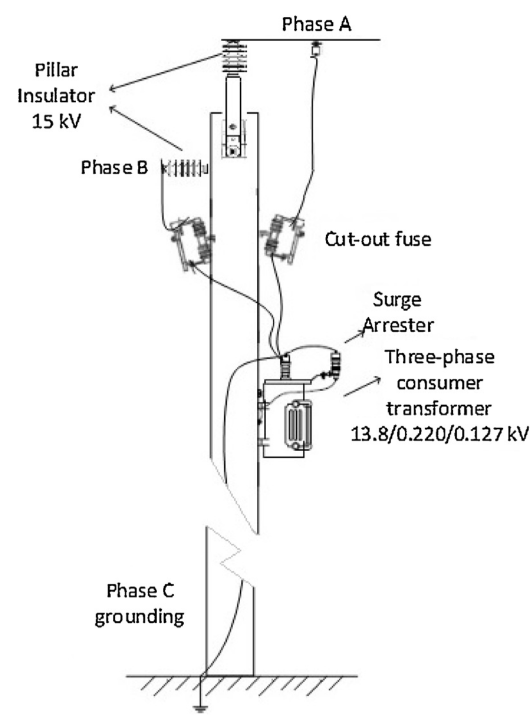

Fig. 2. Three-phase consumer transformer fed by two overhead conductors using the already existing SWER conductor (earth as third phase).

Considering the requirements to use this system, it is noticed that, in the practice, almost all the ancillary resource is used. Therefore, an increase in electric power capacity is proposed with minimal environmental impact using the existing distribution feeders.

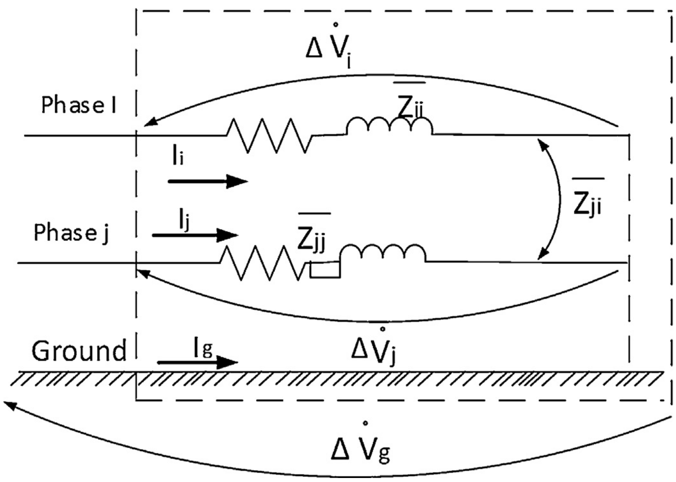

Fig. 3. Proposed system simplified circuit.

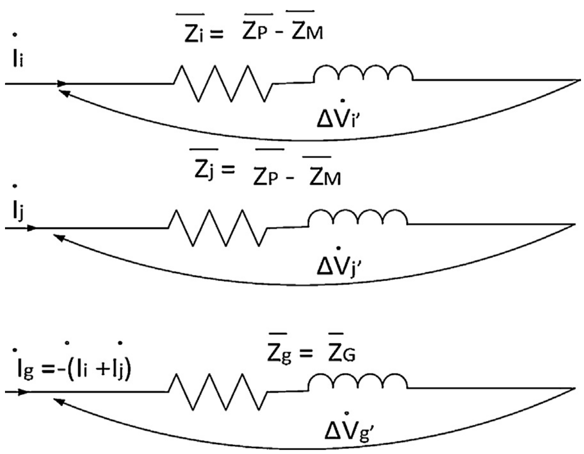

Fig. 4. Proposed three-phase equivalent circuit system with the overhead wires and ground impedances.

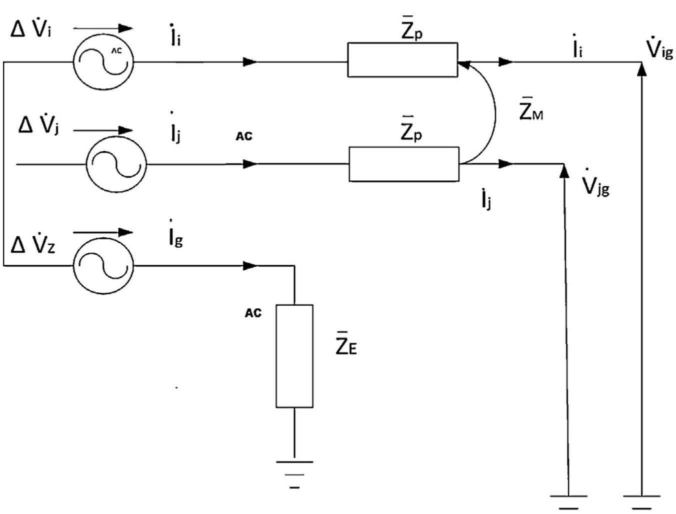

Fig. 5. Proposed system equivalent circuit.

2.2. Line parameters of the proposed system

Consider two-phase circuit of Fig. 3. Its bus impedance matrix is represented by Eq. (1), which is a symmetrical 2×2 matrix where its elements $\bar{Z}_{ii}$ and $\bar{Z}_{jj}$ are the self-equivalent impedance, and $\bar{Z}_{ji}$ is

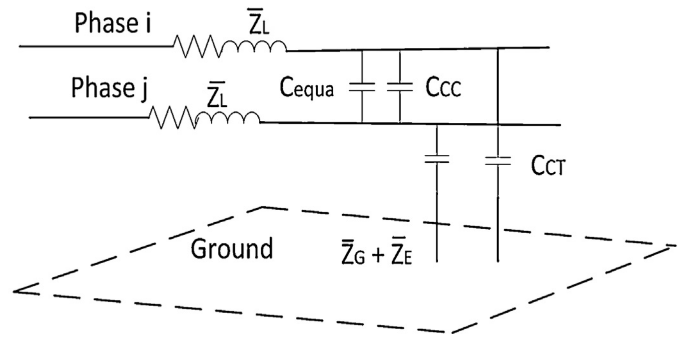

Fig. 6. Equivalent circuit per km formed by overhead conductors and earth.

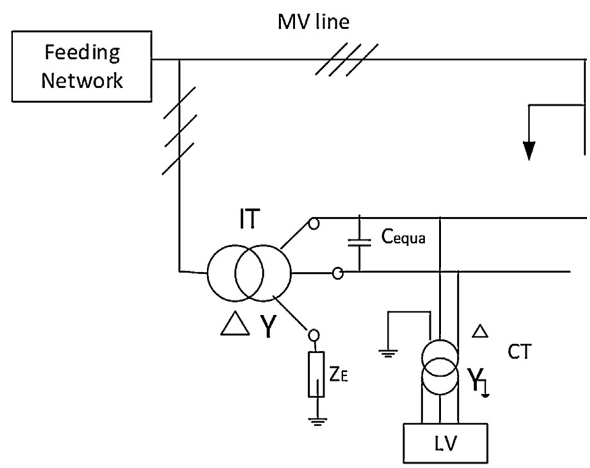

Fig. 7. Single line diagram of the "3-phase" proposed system.

the mutual equivalent impedance. It includes Carson's correction due to the effect of the soil [13]. Note that it is a two-phase circuit with its return through the ground, where $\dot{I}_g = -(\dot{I}_i + \dot{I}_j)$. Considering that the self-equivalent impedance $\bar{Z}_{ii} = \bar{Z}_{jj} = \bar{Z}_P$ and $\bar{Z}_{ji} = \bar{Z}_M$ Eq. (1) can be replaced as Eq. (2) [13]:

$$[\bar{Z}] = \begin{bmatrix} \bar{Z}_{ii} & \bar{Z}_{ji} \\ \bar{Z}_{ji} & \bar{Z}_{jj} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \Delta\dot{V}_i \\ \Delta\dot{V}_j \end{bmatrix} = \begin{bmatrix} \bar{Z}_P & \bar{Z}_M \\ \bar{Z}_M & \bar{Z}_P \end{bmatrix} \begin{bmatrix} \dot{I}_i \\ \dot{I}_j \end{bmatrix} \tag{2}$$

Fig. 3 shows the phases coupling. This model needs to be decoupled in order to obtain another system where the phases do not affect each other. To do this, it is necessary to transform the two-phase circuit into an isolated three-phase circuit, considering the third phase is the grounded [14], as shown in Fig. 4. This figure shows the equivalent circuit behavior considering the superpositioning effect of the common equivalent mode and the differential mode. The impedance of the overhead part takes into account the impedance of the differential mode and the impedance $\bar{Z}_G$ influences only in the common mode.

The voltage drop is represented by $\bar{Z}_G$ due to common mode excitation. So $\dot{I}_i = \dot{I}_j = \dot{I}$ (common mode) as is shown in Eqs. (3)–(8).

$$\Delta\dot{V}_i = \Delta\dot{V}_i' - \Delta\dot{V}_g' \tag{3}$$

$$(\bar{Z}_P + \bar{Z}_M)\dot{I} = (\bar{Z}_P - \bar{Z}_M) + 2\bar{Z}_G\dot{I} \tag{4}$$

Solving Eq. (4)

$$\bar{Z}_G = \bar{Z}_M \tag{5}$$

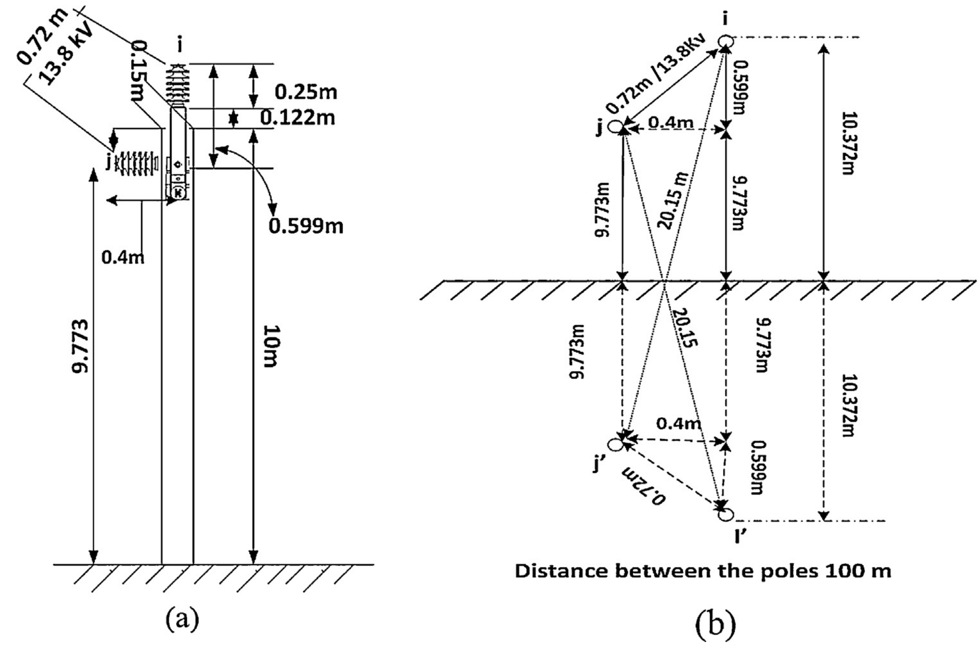

Fig. 8. (a) Pole front view that supports both metal conductors of the non-conventional distribution system. (b) Shows the overhead conductors and distances for its images.

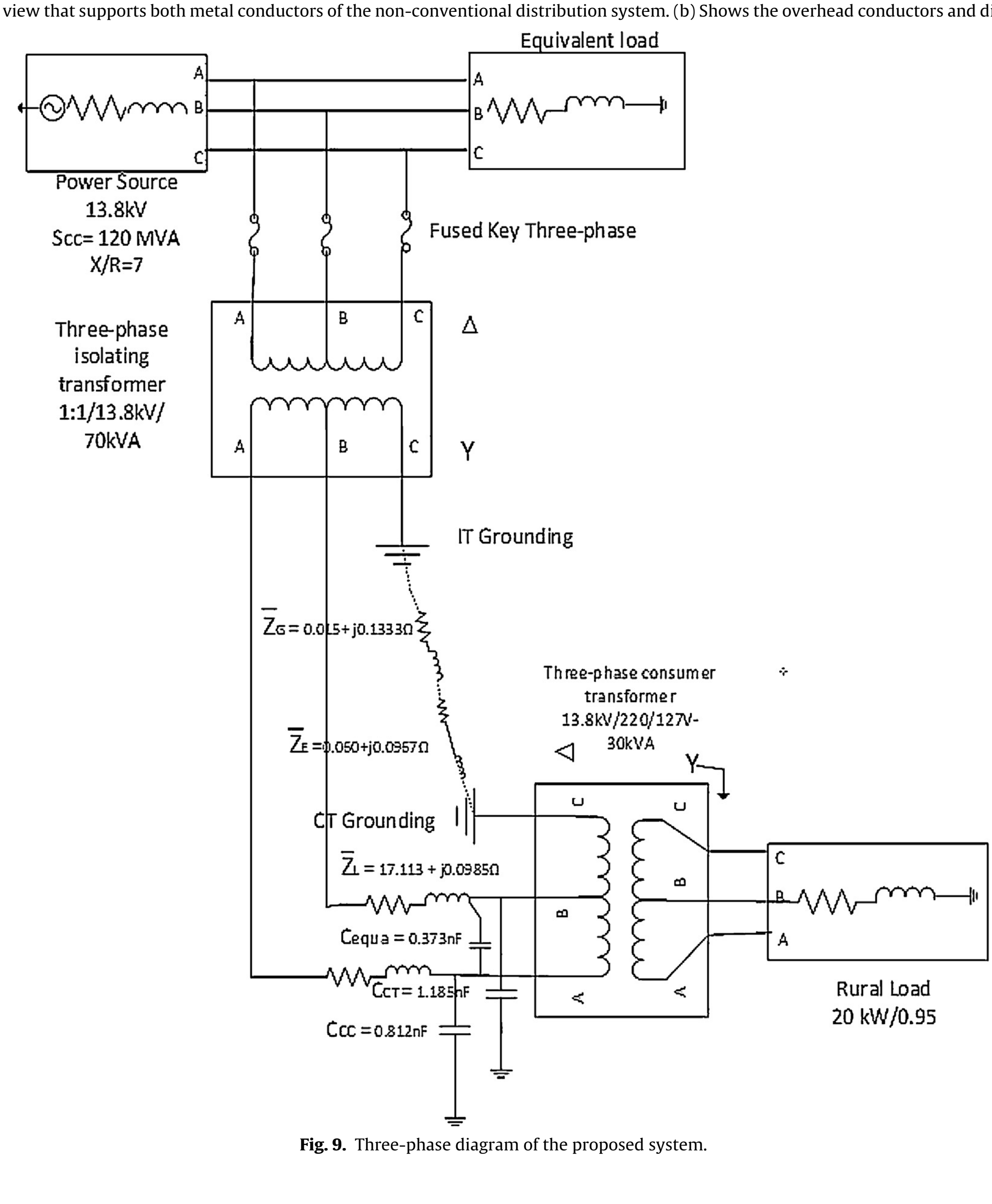

Fig. 9. Three-phase diagram of the proposed system.

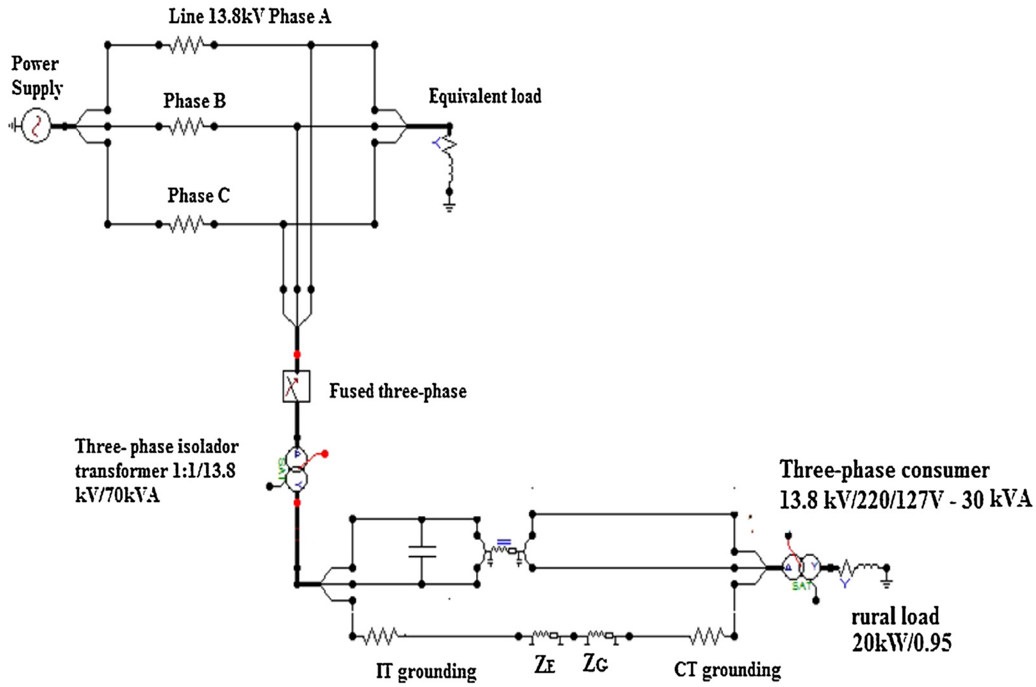

Fig. 10. Three-phase ATPDraw diagram of the proposed system.

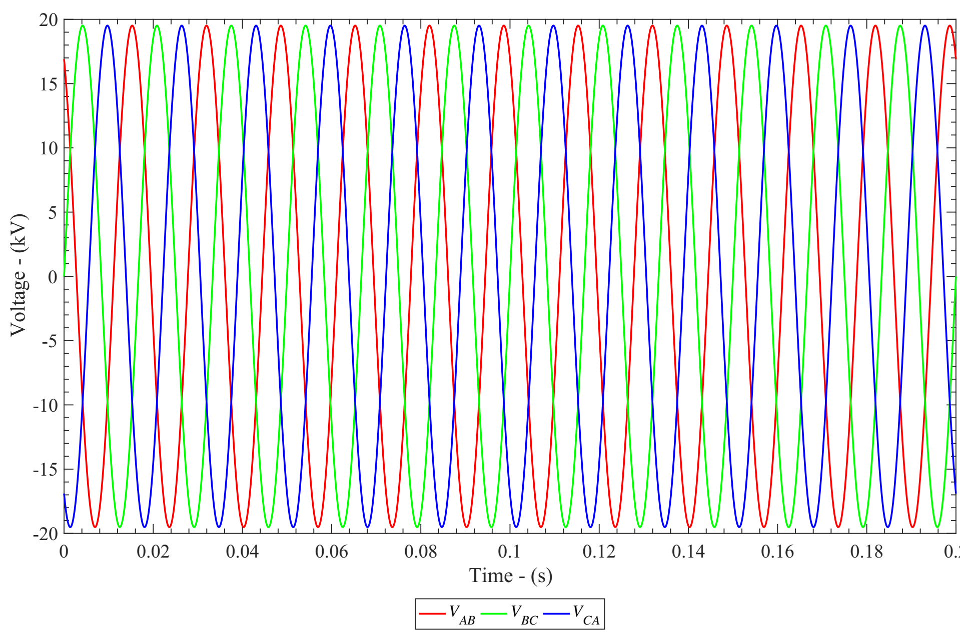

Fig. 11. Instantaneous line voltages at the IT primary side: peak phase-to-phase voltage V_{AB} = 19.514 kV, V_{BC} = 19.516 kV and V_{CA} = 19.515 kV.

$$\bar{Z}_L = \bar{Z}_P - \bar{Z}_M \tag{6}$$

$\bar{Z}_P$ and $\bar{Z}_M$ may be calculated by a Carson modified equations [13], resulting in Eqs. (7) and (8). Therefore:

$$\bar{Z}_P = r_i + r_d + j0.12134\left[\ln\left(\frac{1}{GMR_i}\right) + 7.93402\right] \tag{7}$$

$$\bar{Z}_M = r_d + j0.12134\left[\ln\left(\frac{1}{D_{ij}}\right) + 7.93402\right] \tag{8}$$

where r_i = conductor's resistance i (Ω/mile); $r_d = \pi^2 \times f \times 10^{-4} = 0.09530$ Ω/mile – ground resistance [11]; GMR_i = geometric mean radius of the conductor i in (feet); D_{ij} = the distance between the conductors i and j.

Eqs. (5) and (6) show that the circuit is asymmetrical since the overhead line impedance $\bar{Z}_L$ is different from the impedance of the phase which uses the earth as a conductor.

In [9] it can be seen that the capacitance between the overhead wires is smaller than that between the conductors and the ground. Consequently, the whole system is naturally unbalanced. In this way, balancing impedances should be added.

2.2.1. Longitudinal balancing

In order to make the three-phase circuit formed by two overhead cables and the ground return path symmetrical, the simplest

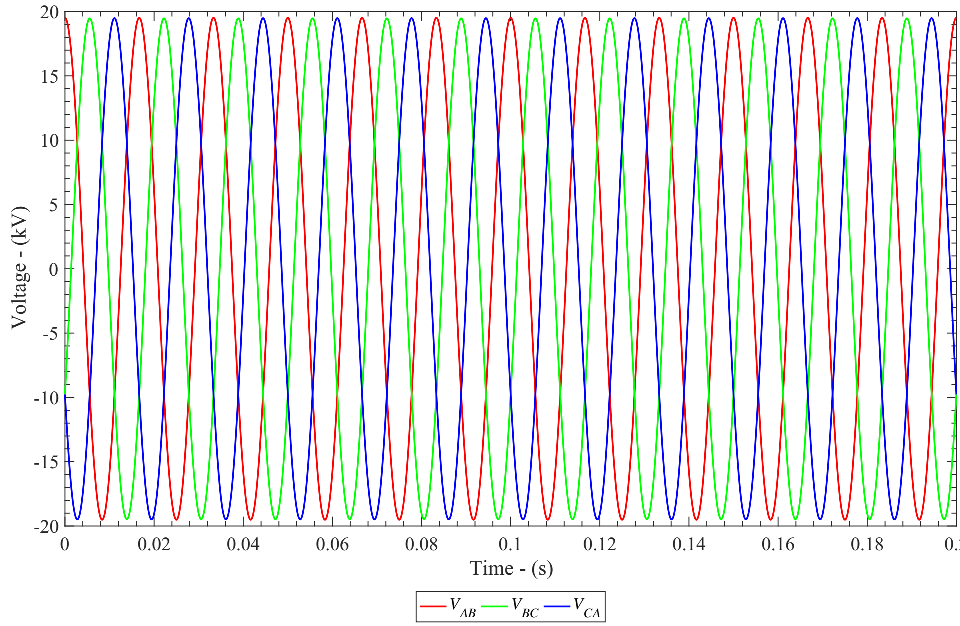

Fig. 12. Instantaneous line voltages at the IT secondary side: V_{AB} = 19.511 kV, V_{BC} = 19.470 kV and V_{CA} = 19.471 kV.

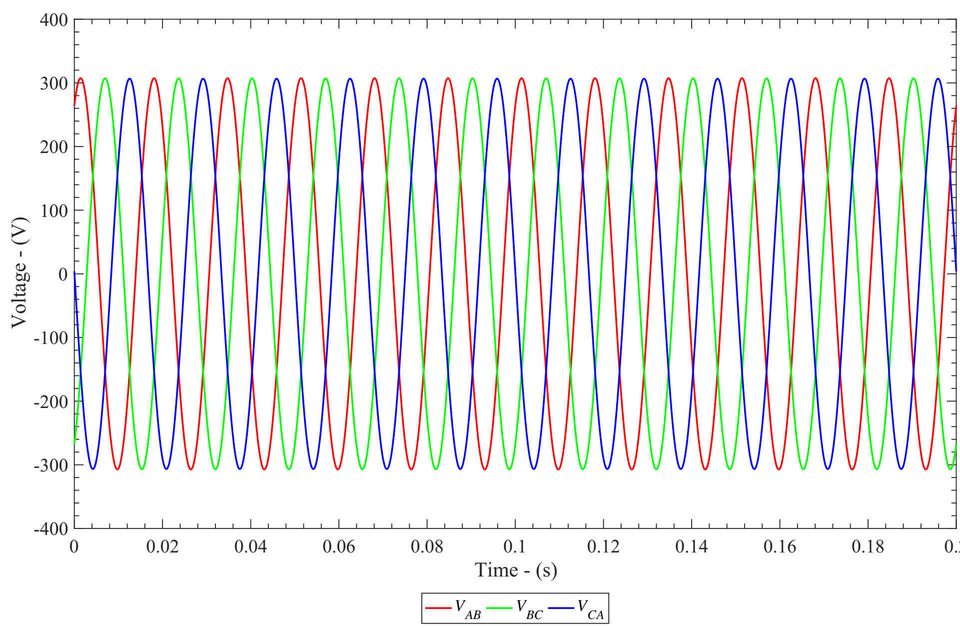

Fig. 13. Instantaneous line voltages at the low consumer(tm)s transformer LV side: V_{AB} = 307.32 V, V_{BC} = 307.84 V and V_{CA} = 306.64 V.

solution is to apply complementary asymmetries adapted to cancel or reduce practically the inherent asymmetries of the proposed system. The proposed method to reduce asymmetry is to add a series compensation impedance $\bar{Z}_E$ as defined in Eq. (9), in and it is added to $\bar{Z}_G$ (Fig. 5).

$$\bar{Z}_E = r_i - \pi^2 f 10^{-4} + j0.12134 \left[\ln\left(\frac{D_{ij}^2}{GMR_i} \right) \right] - 0.962713 \quad (9)$$

2.2.2. Transverse balancing

Fig. 6 shows the proposed system capacitances, calculated according to Eqs. (10)–(12).

$$C_{CT} = \Sigma_{j=1}^{2} C_{ij}\,[\text{nF/km}] \quad (10)$$

where i = 1 or 2,

Capacitance to ground

$$C_{CT} = C_{11} + C_{21} \quad (11)$$

Conductors capacitance

$$C_{CC} = -C_{21}\,[\text{nF/km}] \quad (12)$$

As the capacitance (Fig. 6) between phases is smaller than between phase and earth, it is necessary to add a capacitance between phases, according to Eq. (13)

$$C_{equa} = C_{CT} - C_{CC} \quad (13)$$

With longitudinal and transverse balancing the proposed system is balanced.

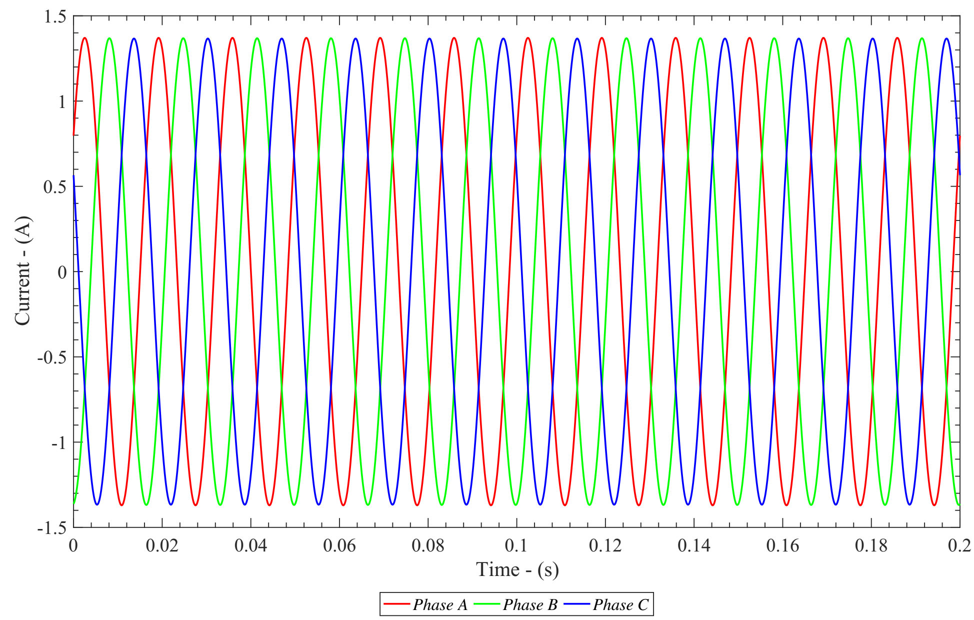

Fig. 14. Instantaneous currents at IT secondary side: peak currents, phase A – 1.363 A, phase B – 1.363 A, phase C – 1.366 A.

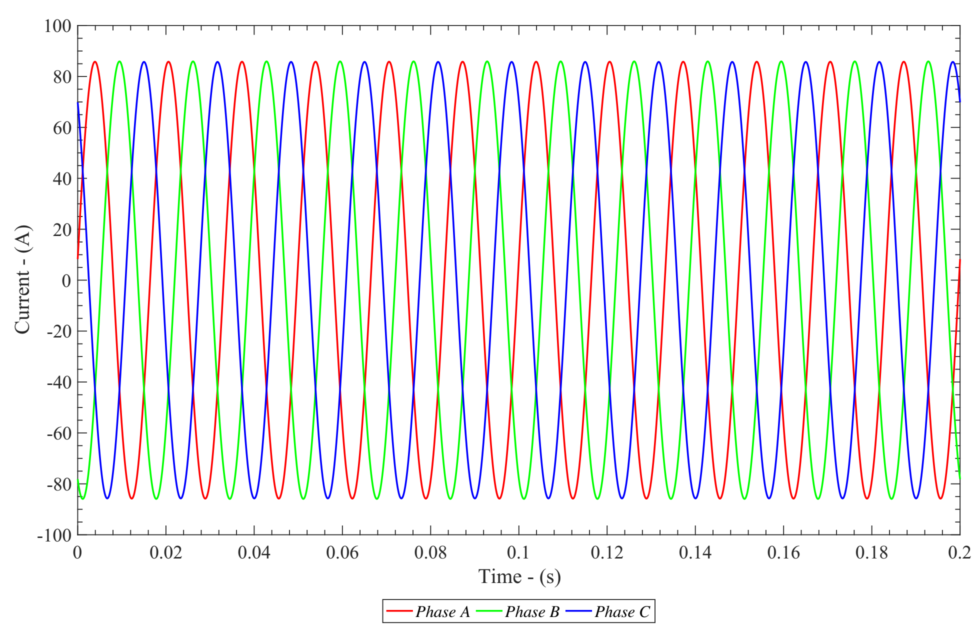

Fig. 15. Instantaneous current at the consumer transformer LV side: peak currents, phase A – 85.81 A, phase B – 85.91 A, phase C – 85.70 A.

3. Case study

Fig. 7 shows a single line diagram of the proposed system. As has already been observed in this work, and considering the characteristics of the structures used in SWER systems according to Fig. 8(a), the superior insulator can be reused. A second insulator is installed at the lateral pole, resulting in the three-phase circuit with the ground as one phase. Fig. 8(b) shows the distances between poles and overhead wires to the earth and their images.

3.1. Circuit's parameter and conductor's data

The $\bar{Z}_P$ (self) and $\bar{Z}_M$ (mutual) impedances are calculated by Carson modified equations [13]. Tables 1 and 2 presents the

Table 1
Circuit's parameter.

Circuit's parameter	Value
Frequency (f)	60 Hz
Resistivity (ρ)	100 Ω/m
Ground resistance (r_d) $r_d = \pi^2 f 10^{(-4)}$ [11]	0.09530 Ω/mile

Table 2
Conductor's data.

Conductor's data	Value
Two conductors i and j, Fig. 8(a) and (b)	1/0 AWG
Resistance (r_i)	0.7090 Ω/km or 1.1410 Ω/mile
GMR_i	0.00388 m or 0.01273 feet
Distance between the conductors i and j	0.72 m or 2.3622 feet

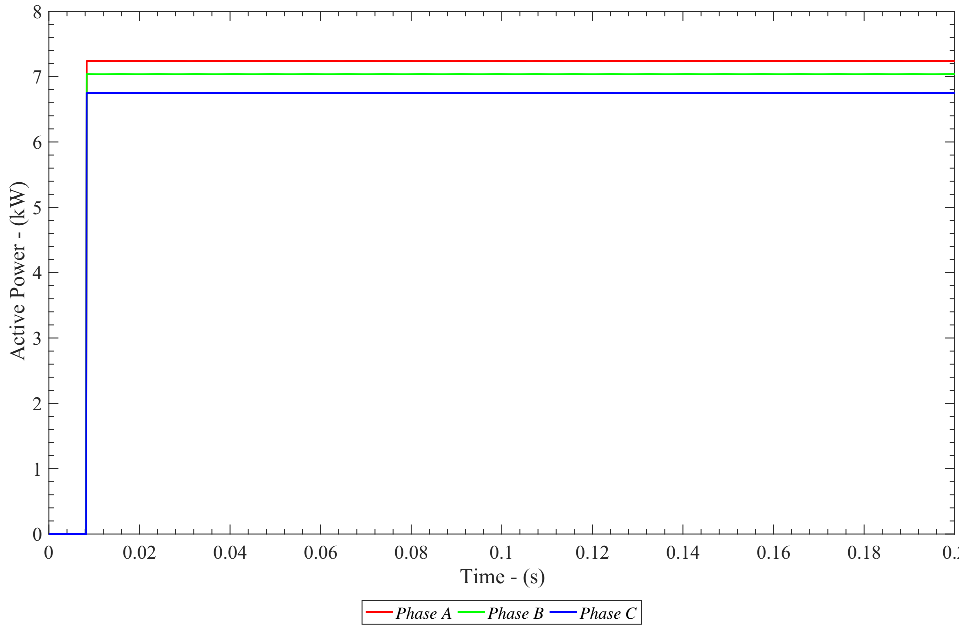

Fig. 16. Active power at the high voltage consumer transformer windings: phase A – 7.237 kW, phase B – 7.037 kW, phase C – 6.747 kW.

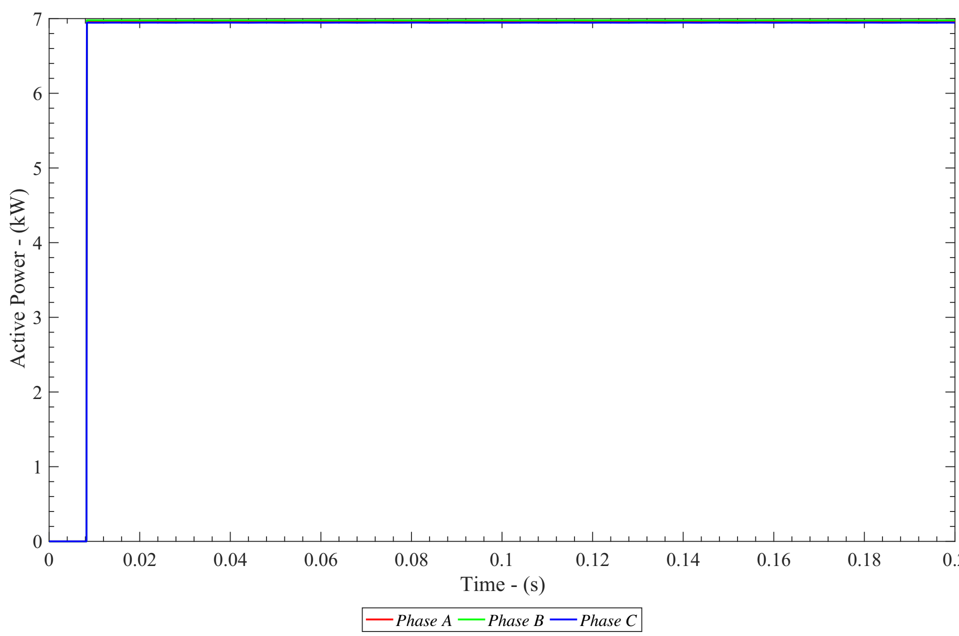

Fig. 17. Active power at the low voltage consumer transformer windings: phase A – 6.958 kW, phase B – 6.677 kW, phase C – 6.622 kW.

parameters and the impedances calculated using Eqs. (7) and (8).

Calculate the self and mutual impedance Eqs. (7) and (8).

$\bar{Z}_P = 1.2363 + j1.4922\ \Omega$/mile or $0.768 + j0.9272\ \Omega$/km

$\bar{Z}_M = 0.0953 + j0.8584\ \Omega$/mile or $0.05922 + j0.53334\ \Omega$/km

3.2. Series impedance calculation

Calculate the series impedance, Eqs. (5) and (6):

$\bar{Z}_L = \bar{Z}_P - \bar{Z}_M = \bar{Z}_{ii} - \bar{Z}_{jj} = 0.2738 + j0.3939\ \Omega$/km

$\bar{Z}_G = \bar{Z}_M = \bar{Z}_{ii} = 0.05922 + j0.53334\ \Omega$/km

Calculate compensation impedance, Eq. (9):

$\bar{Z}_E = 1.0457 + j0.62129\ \Omega$/km or $0.6498 + j0.3861\ \Omega$/km

3.3. Shunt capacitance calculation

The conductor's ray R_i and R_j = 5.055 mm or 0.016585 feet; distance between the conductors i and j = 0.72 m or 2.3622 feet.

The distance between the conductors and its images are:

$S_{ii'} = 20.744$ m; $S_{jj'} = 19.55$ m; $S_{ij'} = 20.15$ m; $S_{ji'} = 20.15$ m.

The transverse balancing capacitances are given by Eqs. (11), (12) and (13), respectively:

$C_{CT} = C_{11} + C_{21} = 4.74$ nF/km;

$C_{CC} = - C_{21} = 3.247$ nF/km;

$C_{equa} = C_{CT} - C_{CC} = 1.4930$ nF/km.

Fig. 8(a) shows that the conductors are not parallel. However, the defined capacitance is simplified, due to the low influence between the geometric conductor's arrangements in this voltage class system.

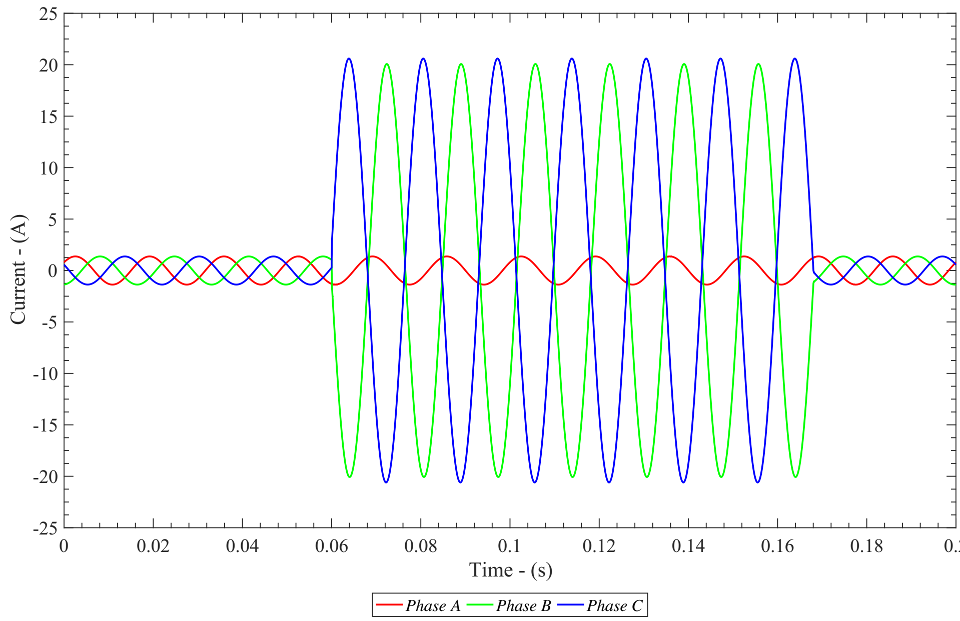

Fig. 18. Instantaneous phase currents at the IT secondary side for a short circuit between phase-B and ground.

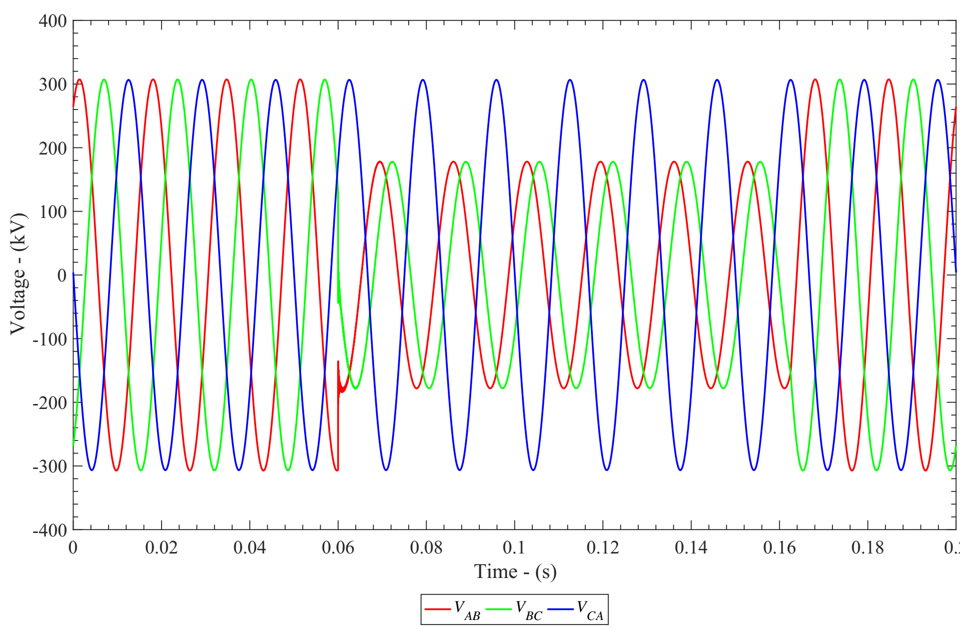

Fig. 19. Instantaneous phase voltages at the consumer transformer LV side for a single phase short circuit at IT source side.

4. Proposed system performance analysis

4.1. Computational simulation

To compare the proposed system technique with that presented in [10], the data related to the rural load is the same as 20 kW (PF = 0.95) and the distance of the IT up to the consumer transformer (CT) is 250 m. The line parameters and the equipment data and load are shown in Fig. 9.

The simulations are performed in ATPDraw as shown in Fig. 10, the circuit being used.

Fig. 11 shows the instant phase-to-phase voltage at the primary (IT) side (source side).

Fig. 12 shows at the IT secondary line voltage.

Fig. 13 shows that the consumer transformer instantaneous voltages at the load side are balanced

The IT secondary side instant electric currents are balanced and shown in Fig. 14. The CT instant currents at the LV side, are presented in Fig. 15. As can be observed, these are also balanced.

As can be seen in Figs. 13 and 15, the voltage consumer's transformer secondary side are balanced, considering balanced loads.

Figs. 16 and 17 respectively represent the active and instantaneous powers at the primary and secondary sides of the consumer transformer. Due to the asymmetric structure of the transmission line where a phase is the ground, the proposed system became unbalanced, with one of the phases overloaded. However, with the installation of compensating impedance $\bar{Z}_E$ added to the ground impedance $\bar{Z}_G$, and with the equalization of capacitances, there is a

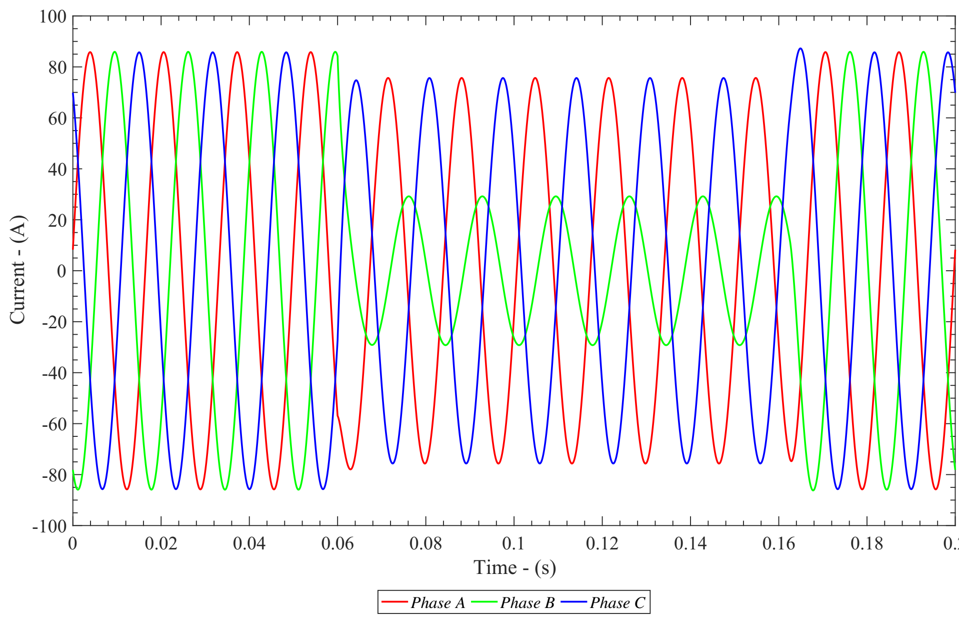

Fig. 20. Instantaneous currents at the consumer transformer LV side for a single phase short circuit at the IT primary side.

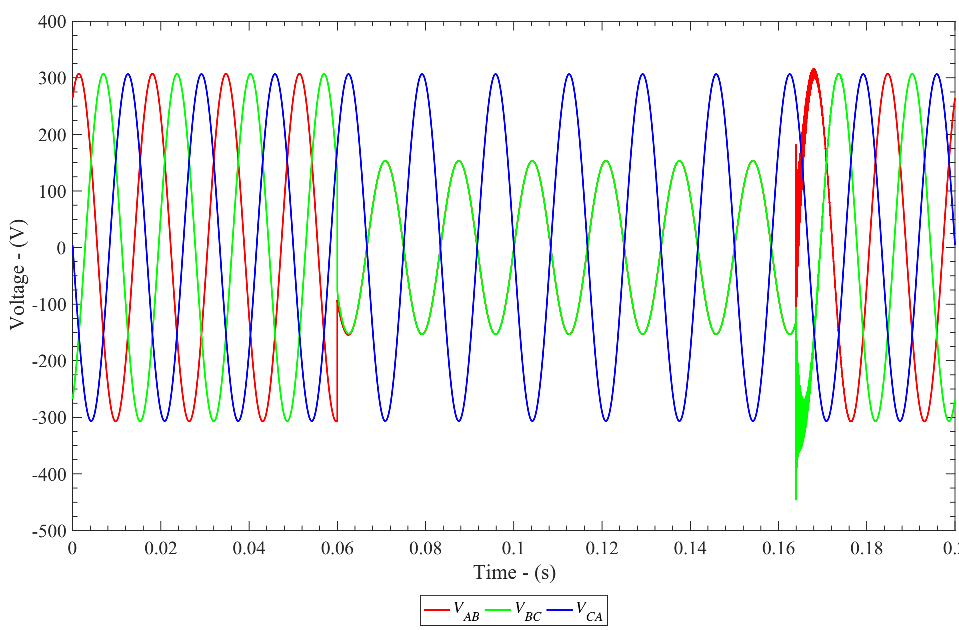

Fig. 21. Instantaneous phase voltage at the load side of the consumer transformer, for a AB short circuit at the HV consumer's transformer side (non-conventional distribution system).

balance between the overhead cables and the ground which is the third phase.

As shown in the figures cited, the active power in the primary is balanced. Under these conditions the proposed system presents a solution equivalent to conventional systems, without limitations to feed the loads used in the rural area.

4.2. Shunt faults

Fig. 18 shows, the behavior of a short-circuit fault that between the IT and the CT occurred with the aerial phase B and the ground. The 10-cycle time-fault current has an approximate value of 19 A.

A solid single phase fault in the conventional main three-phase line (primary side of the IT) results in a momentary decrease of 50% in V_{AB} and V_{BC} voltages, for about 10 cycles at 60 Hz (short circuit duration time). The voltages at the consumer's transformer secondary side are shown in Fig. 19.

Fig. 20 shows the instant current at the consumer LV side. It is noticed a 20 A peak current in the phase B, while its maximum current in steady state is about 85 A. The consumer's three-phase load is balanced, Y-connected and modeled as a constant impedance, with $Z_A = Z_B = Z_C = 1.89 + j0.833\,\Omega$. This load is used to allow the effects analysis provided by the disturbance without unbalanced interferences produced by the load.

Once single-phase faults do not occur on the non-conventional side, only phase faults are noticeable. Figs. 21 and 22 show the instantaneous voltage and current at the consumer's transformer secondary side for a solid phase-to-phase short circuit on the non-

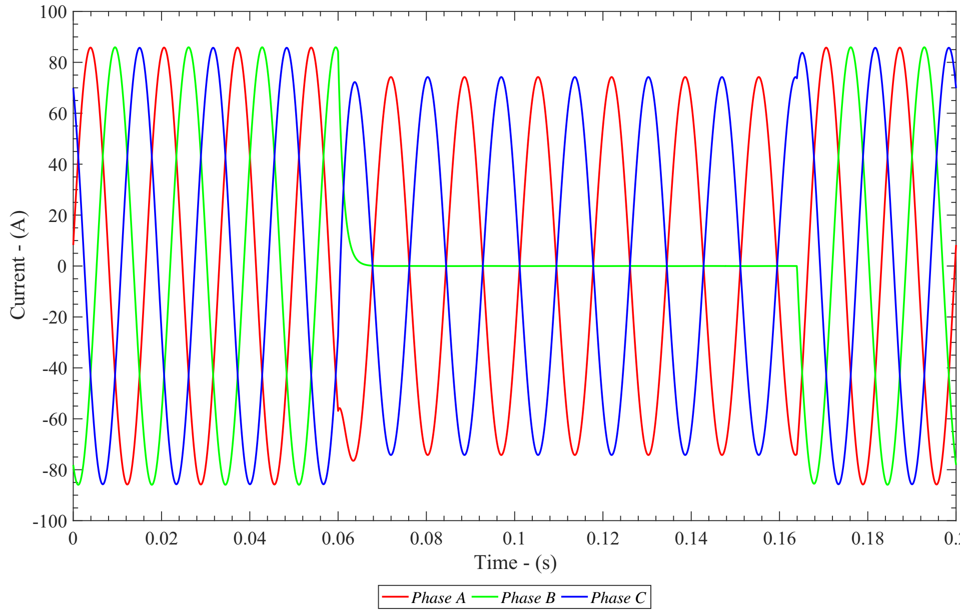

Fig. 22. Instantaneous phase voltage at the load side of the consumer transformer, for a AB short circuit at the HV consumer's transformer side (non-conventional distribution system).

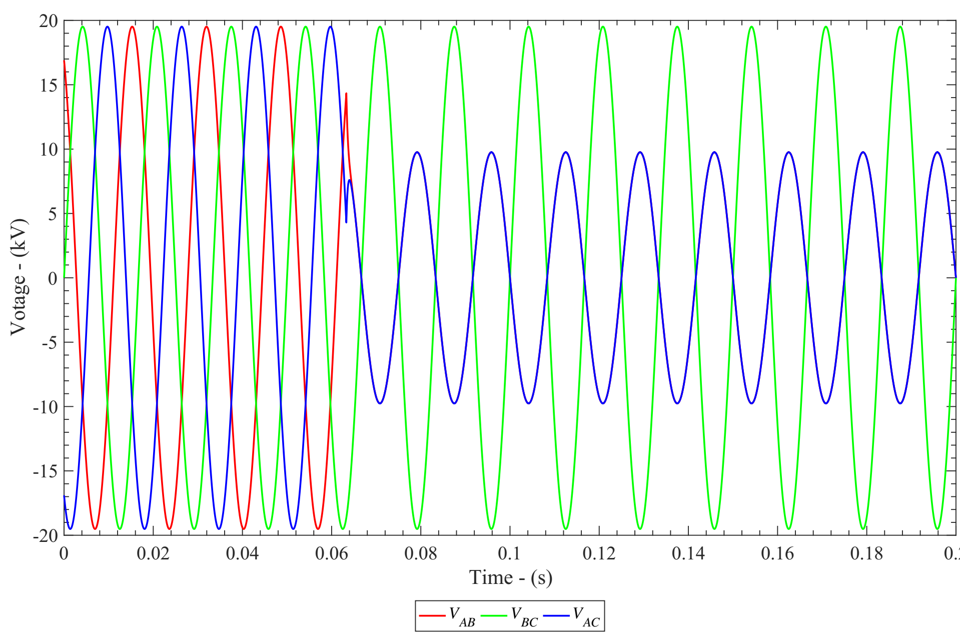

Fig. 23. Instantaneous line voltage at the IT secondary side for a one line open fault (phase A).

conventional distribution system side (between IT and consumer transformer), involving phases A and B. This temporary disturbance remains for 10 cycles after that, the system is restored. It is noted in Fig. 21 that, during the fault, the *A* and *B* line voltages, have the same phase angle and have 50% of phase C amplitude value. Fig. 22 shows that the A and B phases instant current have the same amplitude and are displaced 180°, whereas phase C is zero.

4.2.1. *Series faults*

Fig. 23 shows the voltages in the IT secondary side. Here, the phase A line is open. The disturbance begins at 0.06 s. The phase V_{AB} and V_{CA} line voltages are 50% smaller than V_{BC}. The load supplied under these conditions may not work as expected.

4.3. *Experimental evaluation*

A scaled field test is carried out. A LV (380 V) prototype is developed. Fig. 24 shows the electrical circuit used to supply a three-phase 1.5 cv induction motor, 60 Hz, 1725 rpm, 220 V, rated current of 4.2 A. The IT and CT distance is 39 m. The distance between the two overhead phase conductors and the plane soil surface is 0.80 m. Fig. 25 shows the prototype.

Figs. 26 and 27 show the steady estate instant voltages in the consumer's transformer LV side. The engine runs at 10% and 80% of its rated load, respectively. Although no longitudinal and transversal balancing impedances are used, the unbalanced level is lower than 2%. The motor operates properly.

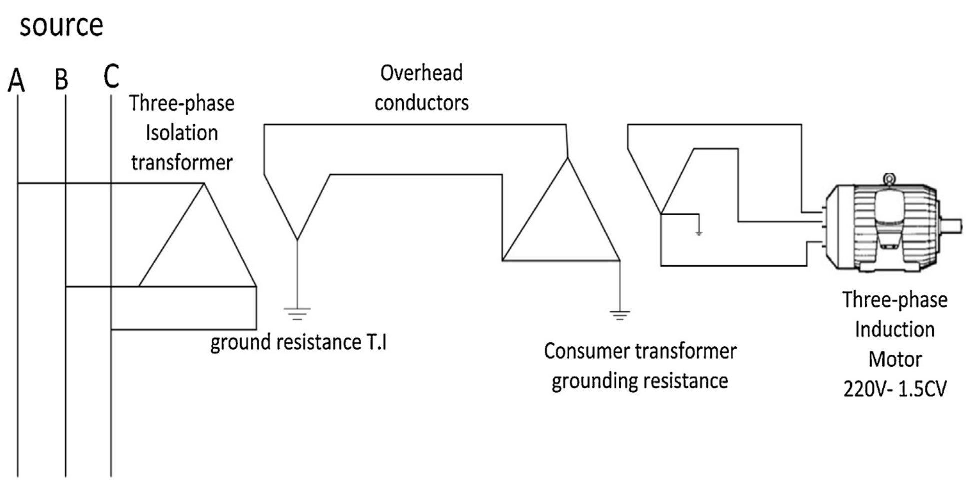

Fig. 24. Proposed system reduced LV prototype.

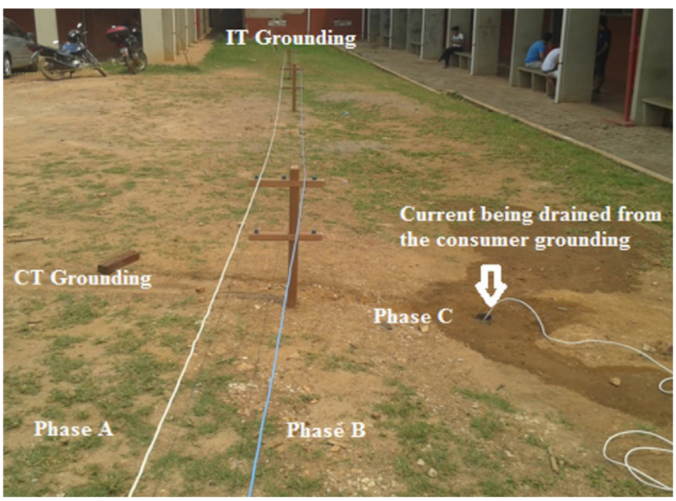

Fig. 25. Prototype circuit.

5. Conclusion

This article proposes a new rural distribution system that uses two overhead conductors and the earth as the third phase. The technique allows converting the already installed SWER, in use by the utilities, into three-phase systems. Computational simulation and experimental developments show that the technique is promising. It is observed that the proposal is feasible in terms of:

- The possibility to connect to the phase directly to the ground, has transformed it into a conductor;
- The behavior similar to a conventional three-phase system, when submitted to a disturbance (open phase or short circuit);
- The system security of the proposed system is inherent in electrical engineering and can be compared to systems "shield wire scheme" (SWS) [9] and the SWER dangers studied [15];
- The confinement of the currents flowing through the ground between the isolation transformer and consumer transformer, isolating rural systems of urban systems, and consequently establishing both the field and urban areas, increased reliability;
- The possibility of installing in series with ground impedance a reactor, qualifies the system to distribute active power between the three phases equally. This allows a suitable supply for rural three-phase loads. Under the same conditions as a conventional three-phase system.

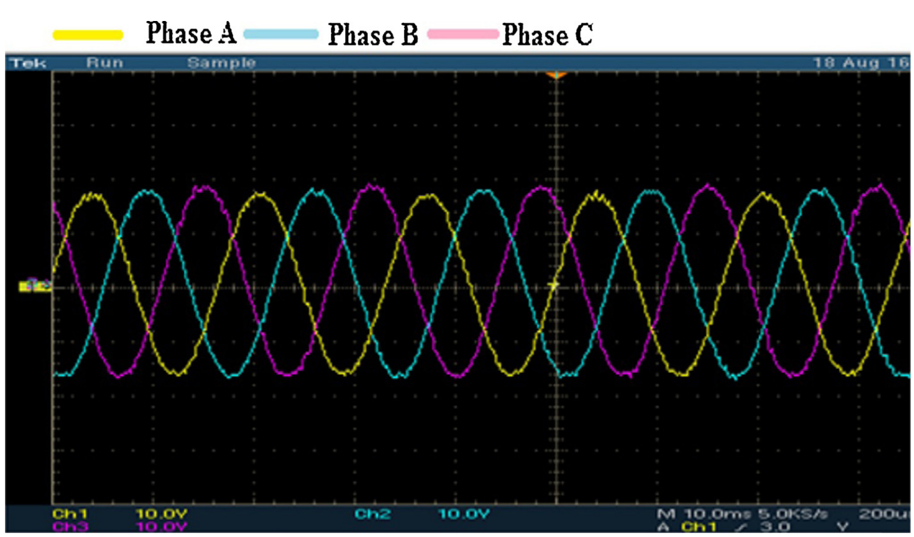

Fig. 26. Phase voltages on the consumer's transformer LV side (load side). Non-conventional distribution system feeding a three phase induction motor rated at 10% rated load: Peak phase-to-phase voltages, V_{AB} = 296.98 V, V_{BC} = 294.16 V and V_{CA} = 306.88 V.

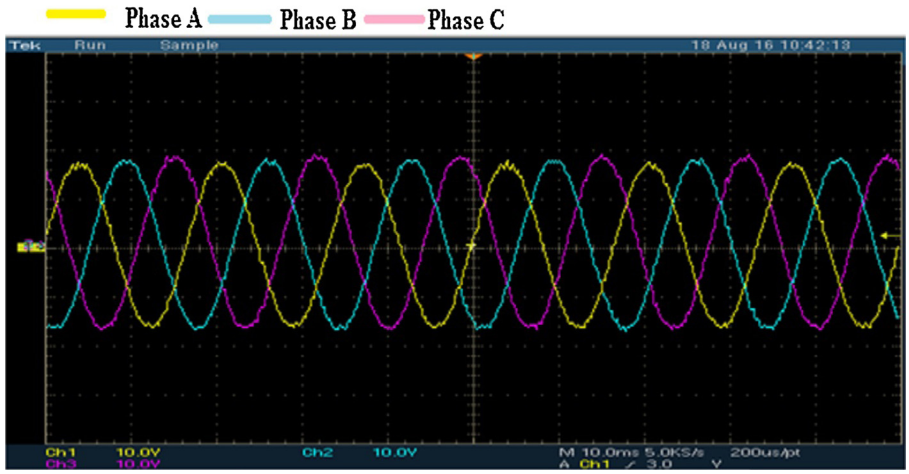

Fig. 27. Phase voltages on the consumer's transformer LV side (load side). Non-conventional distribution system feeding a three phase induction motor rated at 80% rated load: peak phase-to-phase voltages, V_{AB} = 285.67 V, V_{BC} = 270 V and V_{CA} = 288.50 V.

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