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Two-Wire Distribution System for Supplying Three-Phase Rural Loads

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Abstract Currently, the supply of electricity to rural districts is realized, in almost all cases, through single-phase medium-voltage overhead distribution lines. However, some of these installations will eventually demand the use of more expressive electrical loads, which makes the use of three-phase distribution systems a necessity, thus bringing about the substitution of the existing single-phase network. Some of the more usual techniques, based on power electronics, make the supply of three-phase loads possible from converters especially developed for single- to three-phase transformation. In this context, this article presents a new and innovative low-cost methodology, based on electromagnetic arrangements, without the use of power electronics, for attending to rural three-phase supply needs through the use of a new overhead two-wire distribution system.

Keywords Rural distribution systems · Single-three-phase conversion · Rural three-phase loads

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1 Introduction

The characteristics of electric energy consumers, along with financial limitations for investments in rural electrification programmes, have pushed electric energy companies to rely on the use of single-phase energy distribution systems. Some of the features associated with such systems are low monthly consumption, low consumer density and few simultaneous maximum demands.

The development of new techniques for irrigated agriculture, as well as the benefit of locally produced products, has placed upon the rural producers the need to increase their energy consumption, particularly when dealing with maximum demand. However, the use of the single-phase system currently available forces the rural agricultural producer to take on the limitations and peculiarities inherent to the system.

As it currently stands, a significant load increase to any rural consumer would depend upon the substitution of the existing medium-voltage overhead network, for a new three-phase network, thus burdening the consumer to the extent that investments earmarked for the increased production become unfeasible. However, the limitation associated with the load increase of rural consumers, lies solely upon the single-phase transformer and not the single-phase medium-voltage branch itself, once the minimal size conductors standardized by the various distribution utilities are sufficient to support load levels several times greater than the nominal current of the standardized single-phase transformers. In almost all rural facilities, single-phase transformers of 5 or 10 kVA are usually found.

The earliest methodologies available for single- to three-phase conversion were based on passive elements such as capacitors and reactors with autotransformer converters (Maggs 1946). However, this kind of system presents well-

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known disadvantages and limitations (Dewan and Showleh 1981).

Power electronics was first started to be used on single- to three-phase conversion systems in the 1960's (Hisano et al. 1966; Elliott and Elliott 1970) and remained the most commonly used solution during the following decades (Dewan and Showleh 1981; Enjeti and Choudhury 1992; Zhang et al. 1995). It is still the most widely used solution for solving the problem of converting the number of phases in an electrical system, presenting different technologies for specific applications (Santos et al. 2011; Machado et al. 2006; Bellar et al. 2004a,b). Some modern techniques (Machado et al. 2009; Jinn-Chang and Yao-hui 2011; Jacobina et al. 2010), based on power electronics, make the supply of three-phase loads possible from especially developed converters.

After the evaluation of various configurations used in power electronic converters for single- to three-phase conversion, an observation was made by Bellar et al. (2004a,b) that none of them could satisfactorily attend those quality requisites for acceptable operation, design requirements and costs. In fact, the use of power electronic-based converters, in general, allows only a punctual service for particular three-phase loads as, for example, electric motors. In most cases, the number of converters required is equal to the number of electric motors that need to be supplied (Busarello et al. 2009; Dias et al. 2010). In addition, the use of these converters does not promote an expansion in the local electric energy market, as the available power supply becomes limited to the existing single-phase consumer transformers.

The technique proposed in this article is based simply on specific electromagnetic arrangements, without any need for embedded electronics, capacitors or reactors, making not only the use of three-phase loads possible from the available single-phase networks, but also the increase in the local electricity market, without the need of large investments for the project's implementation. This therefore, becomes an innovative solution not seen in the electricity sector as of now.

2 Theoretical Fundamentals

The underlying goal behind this proposal is the three-phase supply from two conductors, which is based on the availability of two energized conductors with angular displacement of 60° between its correspondent voltages. In addition, the two voltages displaced by 60° must supply the delta connection on primary side of a three-phase transformer, and the remaining phase on the transformer's primary terminals must be solidly grounded.

Therefore, if the existence of the single-phase medium-voltage, two-conductor branch line (phase and neutral) is confirmed, then the first part of the proposal's goal (availability of two energized conductors) can be reached with the

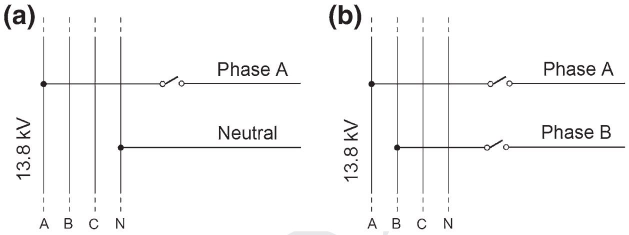

Fig. 1 **a** Original derivation of the single-phase branch line and **b** derivation proposed for the new two-phase branch line.

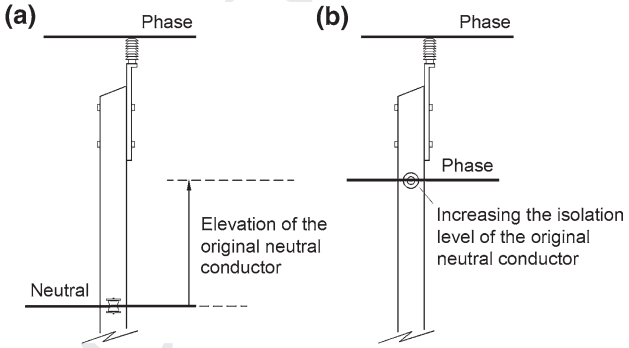

Fig. 2 Adaptation of the original existing neutral-conductor support structures of the new single-phase branch.

transference of the neutral conductor connection to another energized conductor from the same three-phase feeder. Figure 1 illustrates the necessary procedures.

In addition to the procedure indicated in Fig. 1, it will be necessary to promote the substitution of the isolators of the original neutral conductor, which will now have a medium-voltage level, and also to promote the elevation of the conductor support structure, as indicated in Fig. 2. Given the above, the suggestion is that three-phase supply to rural consumer facilities can be achieved through the use of the existing single-phase branch line (phase and neutral), only making its adaptation to a new two-wire configuration. All the available conductors will be used, and the only disbursement necessary will be the adaptation of the original neutral-conductor support structure, including the changing of the isolators. Compared to the costs associated to a new three-phase branch line, the costs associated with the new supply proposal are of little significance.

The second part of the underlying goal is relative to the angular displacement by 60° between the two phase voltages, which can be achieved through transformer polarity resources. Figure 3 shows that the polarity of a single-phase transformer depends primarily on how the turns are wound, which can result in additive or subtractive polarity. In the subtractive polarity, angular displacement does not exist between the primary and secondary voltages, resulting in an angular displacement of 0°. On the other hand, in the case of additive polarity, the angular displacement between the primary

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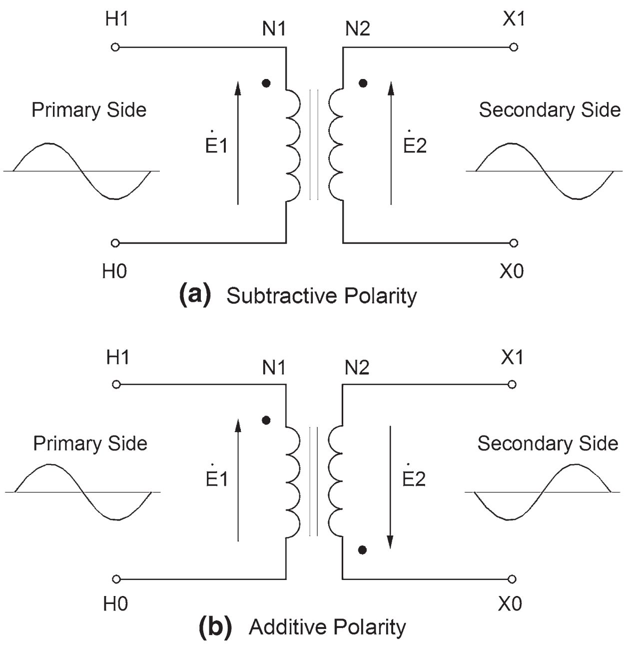

Fig. 3 Indication of polarities in a single-phase transformer and corresponding waveforms for input and output side.

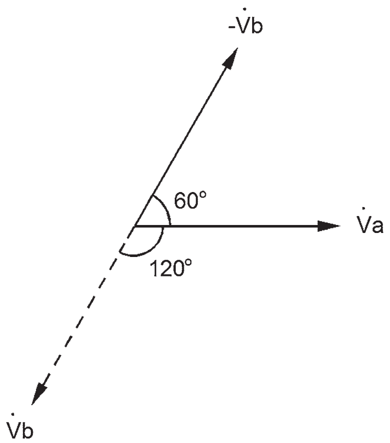

Fig. 4 Phasor diagram illustrating the resulting voltages on phases A and B for the single-phase branch line.

and secondary voltages, for the same phase, will be 180°. Figure 3 illustrates this situation.

Therefore, if one considers the addition of a single-phase transformer, in one of the phases which has an additive polarity, the input and output voltages for this referred phase would have an angular displacement of 180°. Taking therefore, the phase voltage A as a reference and taking into consideration the installation of a single-phase transformer (additive polarity) in phase B, one will finally arrive at an angular displacement of 60° between the resulting phase voltages A and B, as shown in the phasor diagram indicated in Fig. 4.

The need for an angular displacement of 60° between the resulting phase voltages A and B (for the single-phase branch line) can be understood by taking into account the basic premise of the proposal, i.e., the balanced three-phase voltages on the secondary side of a *DYg* transformer. Thus, considering the phase voltages (V_{an}, V_{bn} and V_{cn}) on the secondary side of the transformer being equal to

$$\begin{bmatrix} \dot{V}_{\mathrm{an}} \\ \dot{V}_{\mathrm{bn}} \\ \dot{V}_{\mathrm{cn}} \end{bmatrix} = \begin{bmatrix} V \angle \alpha \\ V \angle \alpha - 120^\circ \\ V \angle \alpha + 120^\circ \end{bmatrix} \quad (1)$$

and also considering the turns ratio of the transformer $V_{(\mathrm{p})}/V_{(\mathrm{s})} = n$, it follows that the line voltages on the primary side of the *DYg* transformer (V_{AB}, V_{BC} and V_{CA}) will be given by

$$\begin{bmatrix} \dot{V}_{\mathrm{AB}} \\ \dot{V}_{\mathrm{BC}} \\ \dot{V}_{\mathrm{CA}} \end{bmatrix} = \begin{bmatrix} n.V \angle \alpha \\ n.V \angle \alpha - 120^\circ \\ n.V \angle \alpha + 120^\circ \end{bmatrix} \quad (2)$$

or,

$$\begin{bmatrix} \dot{V}_{\mathrm{AB}} \\ \dot{V}_{\mathrm{BC}} \\ \dot{V}_{\mathrm{CA}} \end{bmatrix} = \begin{bmatrix} \dot{V}_{\mathrm{AN}} - \dot{V}_{\mathrm{BN}} \\ \dot{V}_{\mathrm{BN}} - \dot{V}_{\mathrm{CN}} \\ \dot{V}_{\mathrm{CN}} - \dot{V}_{\mathrm{AN}} \end{bmatrix} = \begin{bmatrix} n.V \angle \alpha \\ n.V \angle \alpha - 120^\circ \\ n.V \angle \alpha + 120^\circ \end{bmatrix} \quad (3)$$

From (3), and considering $V_{\mathrm{CN}} = 0$, once the phase C conductor is no longer present on the branch line, the phase voltages on the primary side of the consumer's three-phase transfomer are the following:

$$-\dot{V}_{\mathrm{AN}} = n.V \angle \alpha + 120^\circ \text{ or } \dot{V}_{\mathrm{AN}} = n.V \angle \alpha + 120^\circ - 180^\circ$$
$$= n.V \angle \alpha - 60^\circ$$

and

$$\dot{V}_{\mathrm{BN}} = n.V \angle \alpha - 120^\circ$$

Thus,

$$\dot{V}_{\mathrm{AN}} = n.V \angle \alpha - 60^\circ \quad (4)$$
$$\dot{V}_{\mathrm{BN}} = n.V \angle \alpha - 120^\circ \quad (5)$$

Finally resulting in

$$\Delta\theta = \theta_{\mathrm{A}} - \theta_{\mathrm{B}} = (\alpha - 60^\circ) - (\alpha - 120^\circ) = 60^\circ \quad (6)$$

Thus, taking into consideration the underlying goal of the proposal, the phase voltages available on the primary side of the consumer's three-phase transformer will be given by

$$\dot{V}_{\mathrm{AN}} = 1.0 \angle 0^\circ \text{ pu}, \quad \dot{V}_{\mathrm{BN}} = 1.0 \angle 60^\circ \text{ pu and } \dot{V}_{\mathrm{CN}} = 0.0 \text{ pu} \quad (7)$$

It is emphasized here that the phase C conductor is not physically available in the new two-phase branch line. Therefore, the positive, negative and zero sequence voltages, on the primary side of a conventional three-phase transformer, with a grounded delta–star-type connection and supplied by the voltages indicated in (7), will be given by:

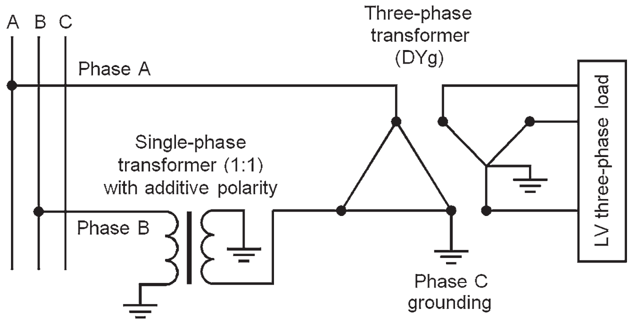

Fig. 5 Diagram of the proposed system for supplying rural three-phase loads.

$$\begin{bmatrix} \dot{V}_0 \\ \dot{V}_1 \\ \dot{V}_2 \end{bmatrix} = \frac{1}{3} \times \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} 1\angle 0^\circ \\ 1\angle 60^\circ \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0.577\angle 30^\circ \\ 0 \\ 0.577\angle -30^\circ \end{bmatrix} \text{pu} \quad (8)$$

The calculation for the resulting voltages on the secondary side of the conventional three-phase transformer should take into consideration the angular displacement of +30° for the positive sequence voltage, and −30° for the negative sequence voltage, provided by the grounded delta–star connection of the three-phase transformer. Therefore, the resulting voltages on the secondary side of the three-phase transformer are

$$\begin{bmatrix} \dot{V}_{\text{an}} \\ \dot{V}_{\text{bn}} \\ \dot{V}_{\text{cn}} \end{bmatrix} = n \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} 0\angle 0^\circ \\ 0\angle (0^{0\circ} + 30^\circ) \\ 0.577\angle (-30^\circ - 30^\circ) \end{bmatrix}$$

$$= n \cdot \begin{bmatrix} 0.577\angle -60^\circ \\ 0.577\angle 60^\circ \\ 0.577\angle 180^\circ \end{bmatrix} \text{pu} \quad (9)$$

where V_{an}, V_{bn} and V_{cn} are the phase voltages on the secondary side of the conventional three-phase transformer, with a grounded delta–star-type connection.

Through the verification of (9), the resulting phase voltages on the secondary side of the conventional three-phase transformer make up a perfectly balanced three-phase system. The only caveat intrinsic to the process concerns the phase voltage amplitudes on the low-voltage side of the three-phase distribution transformer, which are equal to 0.577 pu or likewise to $1/\sqrt{3}$ pu. Therefore, to obtain line voltages equal to 220 V on the secondary side of the consumer's transformer, it will be necessary to use a transformer with a nominal secondary voltage equal to 380 V, which is already of a standardized set by the electrical distribution utilities.

The complete structure necessary for supporting the new supply service of rural three-phase loads, through a new two-conductor distribution network, is presented in Fig. 5.

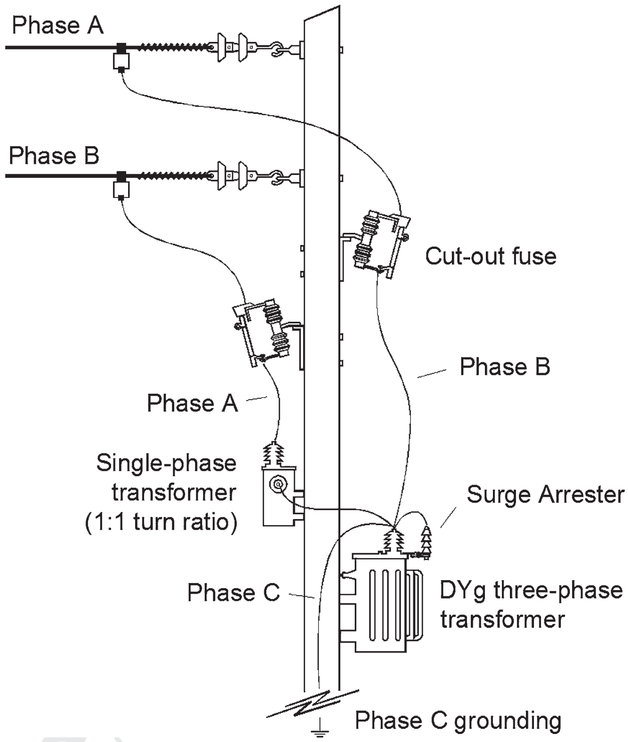

Fig. 6 Schematic drawing of the network topology for the proposed system for supplying rural three-phase loads.

One observes in Fig. 5 that there exists a need to use a single-phase transformer with a turns ratio of 1:1 for the voltage adaptation of one of the phases of the new two-phase branch line, as well as for the grounding of phase C in the primary side of the distribution transformer. Figure 6 shows the same structure in a more detailed form.

Once the algebraic developments relative to the new proposal for a two-conductor distribution network are concluded, it becomes necessary to prove its effectiveness by means of computational simulations and also laboratory testing, which will be presented in the following topics.

3 Computational Evaluation of the Proposed Methodology

For performing the computational evaluation of the proposed methodology for providing a two-conductor three-phase system, the circuit in Fig. 7 should be used, which represents a two-phase medium-voltage branch line, set aside for supplying a three-phase load. All the computational simulations were carried out in the time domain by using the Matlab-Simulink© software. The transformers were modelled taking into account their saturation curves.

The parameters used for modelling the single-phase and three-phase transformers are shown in Fig. 8.

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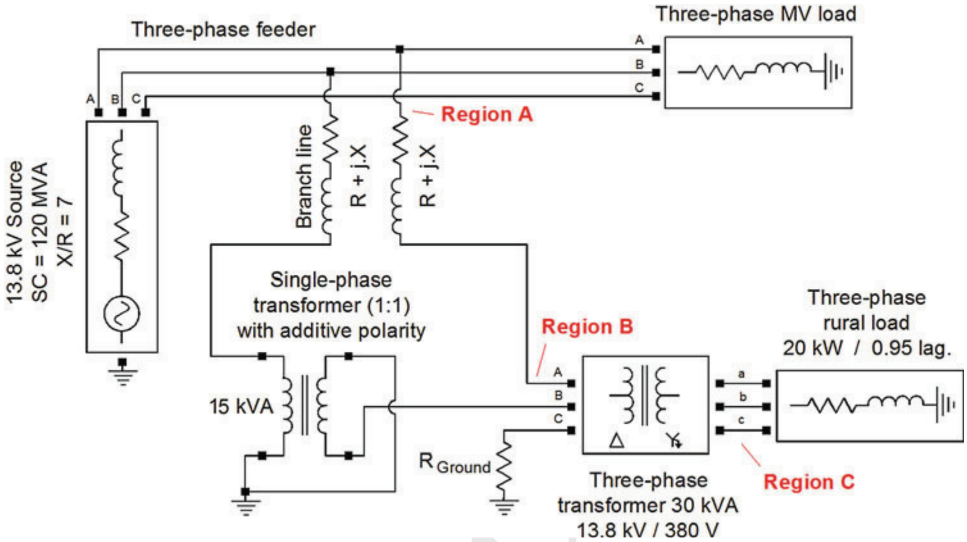
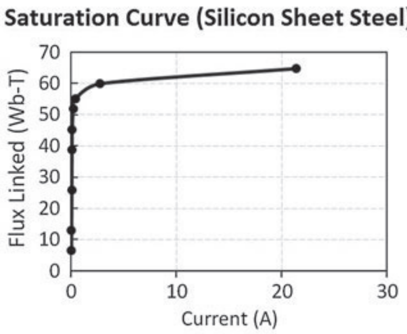


Fig. 7 Three-line diagram of the electric distribution system being studied (note: *SC* short-circuit power).



Three-phase transformer	
Rating	30 kVA
Voltages	13.8 kV / 380 V
Z%	3.5 %
Turn ratio	1 : 0.027
Single-phase transformer	
Rating	15 kVA
Voltages	7.96 kV / 7.96 kV
Z%	1.5 %
Turn ratio	1 : 1

Fig. 8 Model parameters for the transformer simulation.

The ground resistance in the circuit in Fig. 7 should be highlighted, which will be analysed more specifically later. Based on the regions indicated in Figs. 7 and 9 are shown the voltages on the connection point of the two-phase branch line (Region A) and on the primary side of the three-phase transformer (Region B). The amplitudes of the voltages are given in pu based on the rated voltage.

As shown in Fig. 9a, the voltages for phases A and B for the original three-phase feeder (from which the two-phase branch line is derived) have an angular displacement of 120°. On the other hand, as an effect from the single-phase transformer installation (1:1 turn ratio) on phase B, and as already predicted in the analytical developments carried out during the previous section, the voltages of the phases A and B have an angular displacement of 60° in the primary side of the three-phase transformer of the consumer facility (Fig. 9b).

The current waveforms on the medium-voltage side of the two-phase branch line, as with the return through the ground, are indicated in Fig. 10. All currents are indicated in pu on the basis of the nominal current load.

As already expected, the instantaneous currents on the medium-voltage side of two-phase branch line are unbalanced. However, the amplitudes associated with unbalance are much smaller than those given by the single-wire earth return (SWER) systems, which are widely spread throughout some distribution utilities. Another important aspect to be observed is that the phases A and B are sharing the total load power. Thus, the power rating of the single-phase transformer must be equal to 50 % of the consumer's three-phase transformer.

Finally, Figs. 11 and 12 present the voltage and current waveforms on the secondary side of the three-phase consumer transformer, respectively. The amplitudes of the voltages are given in pu based on the rated voltage.

As can be seen in Fig. 11, in accordance with the analytical development carried out in the previous section, the voltage on the secondary side of the three-phase transformer of the consumer facility is perfectly balanced, considering the low-voltage loads as also balanced.

In the same manner, the instantaneous currents registered in low voltage load are perfectly balanced, as shown in Fig. 12. All the currents are indicated in pu on the basis of a nominal current on the load.

In the event of unbalanced low-voltage loads, the resulting voltage unbalance will be exactly the same as those obtained when considering conventional three-phase circuits.

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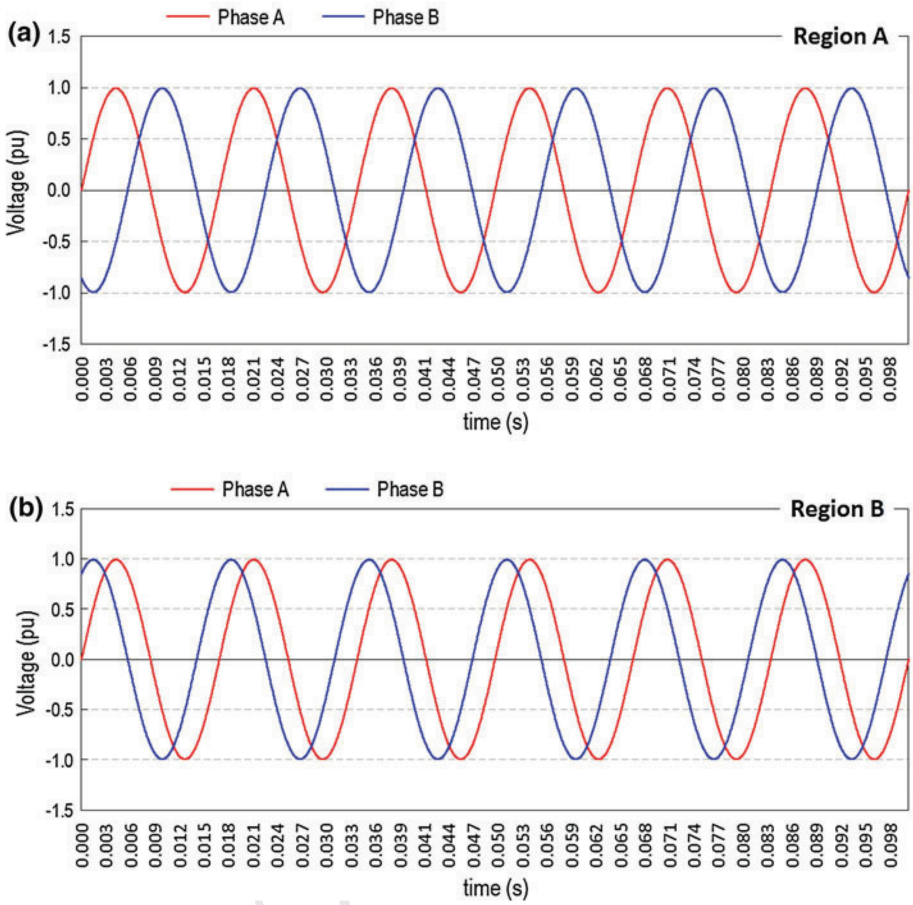
Fig. 9 **a** Voltage waveforms on the two-phase branch line derivation point, and **b** voltage waveforms on the primary side of the three-phase consumer transformer.



The only caveat of importance and relevance at this point concerns the impact of ground resistance (R_{Ground}) on the voltage unbalance, checked at the secondary side of the consumer three-phase transformer. Therefore, by carrying out new simulations for different values of ground resistance, the graph in Fig. 13 was obtained, which shows amplitude of the voltage unbalance as a function of different values of ground resistance.

As indicated in Fig. 13, in practical aspects, the ground resistance value is of little significance in terms of the voltage unbalance amplitude checked at the secondary side of the three-phase transformer. Voltage unbalance levels with amplitudes of up to 2.0 % are perfectly acceptable at medium-voltage levels (ANEEL 2008). The explanation for this result is extremely simple, once that the impedance of the three-phase transformer at the consumer facility is much greater than the system's impedance equivalent seen from the medium-voltage view point, and thus, the variations of ground resistance, when compared with the magnitude of the transformer's impedance, exert little influence on the voltage unbalance amplitudes.

In the eventuality of ground conductor break-down (phase C), the voltage unbalance verified on the low-voltage side of the consumer's transformer has the same amplitude as seen with three-phase transformers with DYg connection supplied by conventional three-phase systems. That is, considering the lack of phase C on the medium-voltage side, the phase voltages in phases A, B and C noted on the low-voltage side of the transformer will have amplitudes of 1.0, 0.58 and 0.58 pu, respectively (Aung and Milanovic 2006). Figure 14 shows the simulation results considering the lack of the phase C grounding conductor on the medium-voltage side.

In the next section, the results for the various laboratory tests will be shown, which aim at providing definite proof for the proposed methodology, regarding a new two-wire distribution system for supplying rural three-phase loads.

4 Experimental Evaluation of the Proposed Methodology

In order to carry out the evaluation of the proposal for providing three-phase supply from a two-wire distribution system, the circuit indicated in Fig. 15 was used, which considered a three-phase induction motor of the squirrel cage type, with 1/4 hp rating and a nominal voltage of 220 V. Both the single-phase and the three-phase transformers used have the same 1:1 turn ratio.

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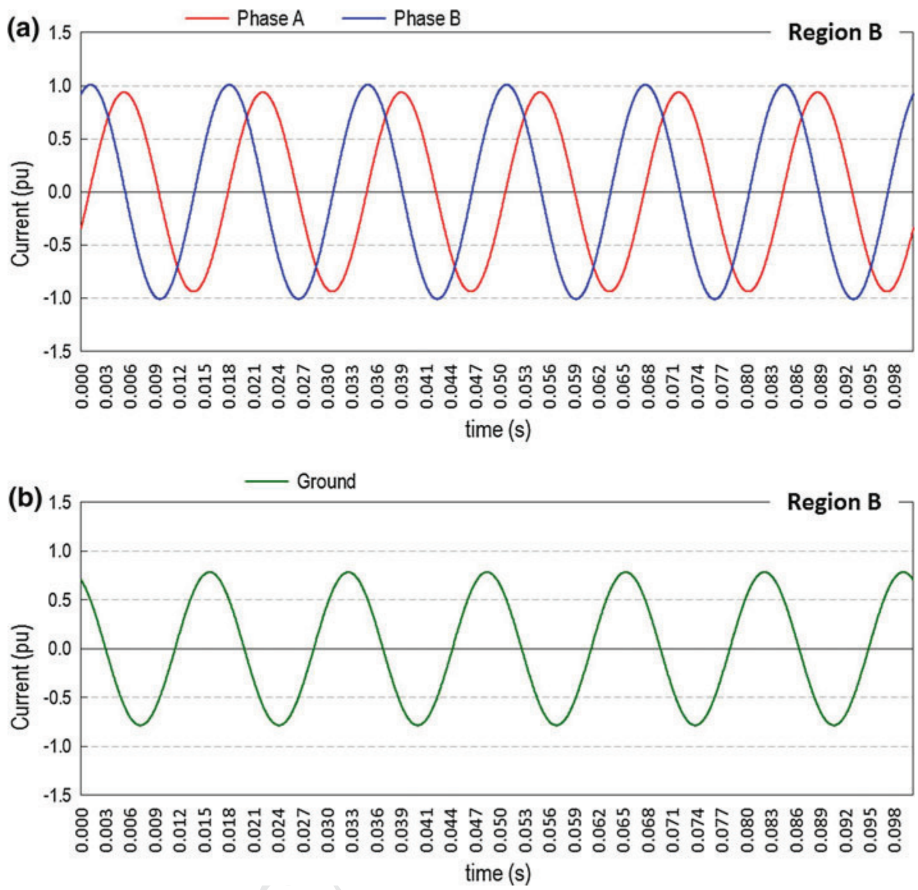

Fig. 10 **a** Current waveforms on the primary side of the two-phase branch line, and **b** current waveform on grounding path.

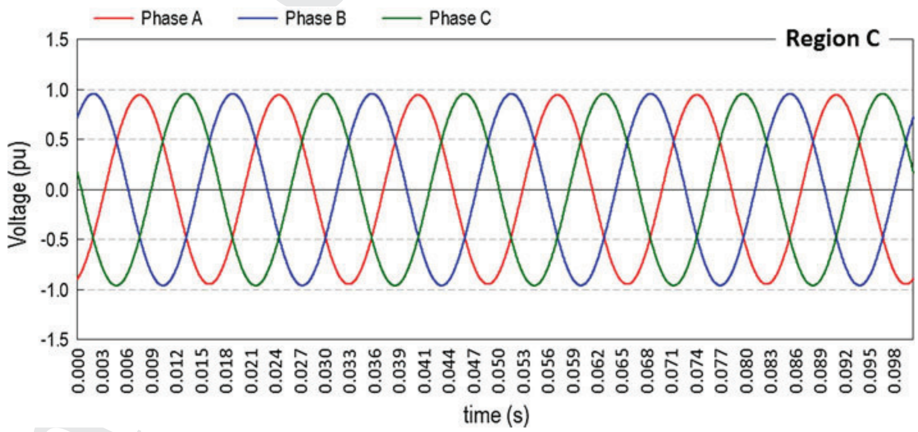

Fig. 11 Voltages waveforms on the secondary side of the consumer three-phase transformer.

The instantaneous voltages obtained in the primary side of the three-phase transformer, with a grounded delta–star-type connection, are shown in Fig. 16. The results there indicated, considering the steady state condition on the induction motor, show themselves to be strongly coherent with those obtained by means of computational simulation (see Fig. 9b). To help in the comparison of the results obtained through practical experimentation in relation to those obtained by means of computational simulation, all results are expressed in pu. The current amplitudes will also be expressed in pu on the basis of nominal load current.

The currents obtained on the primary side of the three-phase transformer are indicated in Figs. 17 (phases A and B) and 18 (ground path).

Again, the currents obtained on the primary side of the three-phase consumer transformer are extremely coherent with the currents obtained by means of computational simulation (see Fig. 10a, b).

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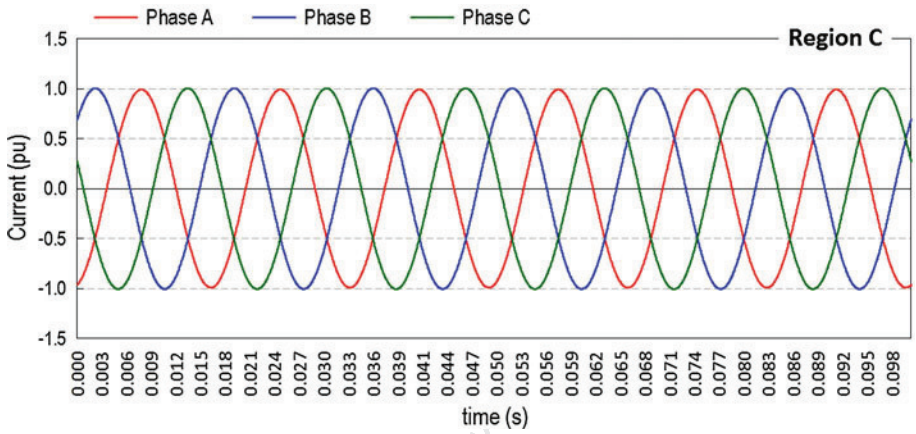

Fig. 12 Current waveforms on the secondary side of the consumer three-phase transformer.

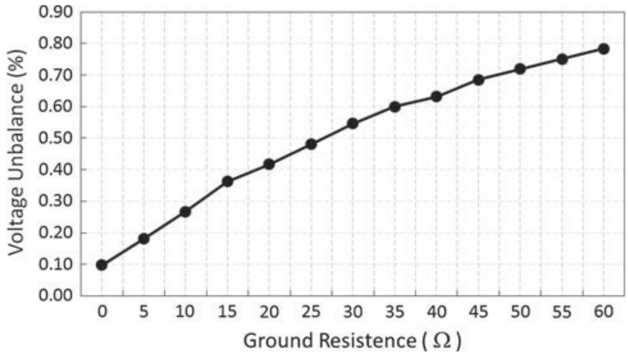

Fig. 13 Voltage unbalance amplitudes on the low-voltage side as a function of ground resistance magnitudes.

Finally, Fig. 19 presents the voltage waveforms on the secondary side of the three-phase consumer transformer, respectively. The amplitudes of the voltages are given in pu based on the rated voltage (220 V phase–phase).

As obtained in the computational simulations (see Fig. 11), the resulting voltages on the low-voltage side of the three-phase transformer, which service the induction motor, make up a three-phase balanced system as shown in Fig. 19.

Likewise, in accordance with Fig. 20, the steady-state currents registered on the secondary side of the three-phase transformer (induction motor) are equally of three-phase and balanced. It is worth highlighting again that the currents are indicated in pu on the basis of nominal load current.

Lastly, the performance of the proposed system was evaluated when a sudden and transient solicitation is made (underload induction motor starting). The voltages and the currents on the secondary side of the three-phase transformer are indicated in Fig. 21.

As can be seen in Fig. 21, despite the two-wire supply system, the three-phase motor starting operated without anomalies, the machine remaining in normal operation until the end of the experiment. In summary, therefore, the results

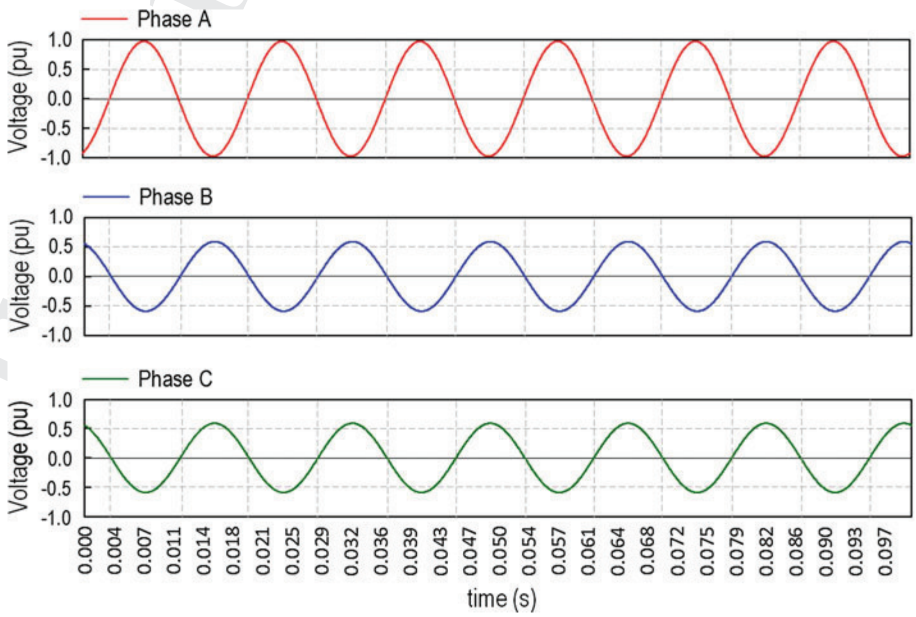

Fig. 14 Voltage waveforms on the secondary side of the consumer three-phase transformer with no grounding conductor.

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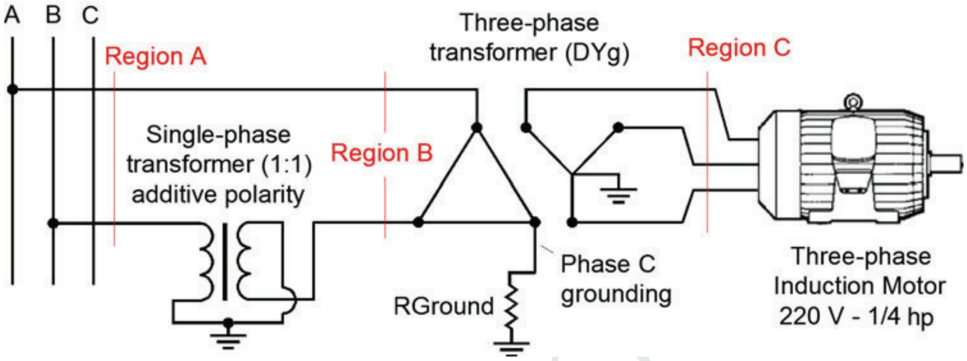

Fig. 15 Experimental arrangement used for performance analyses of the proposed methodology.

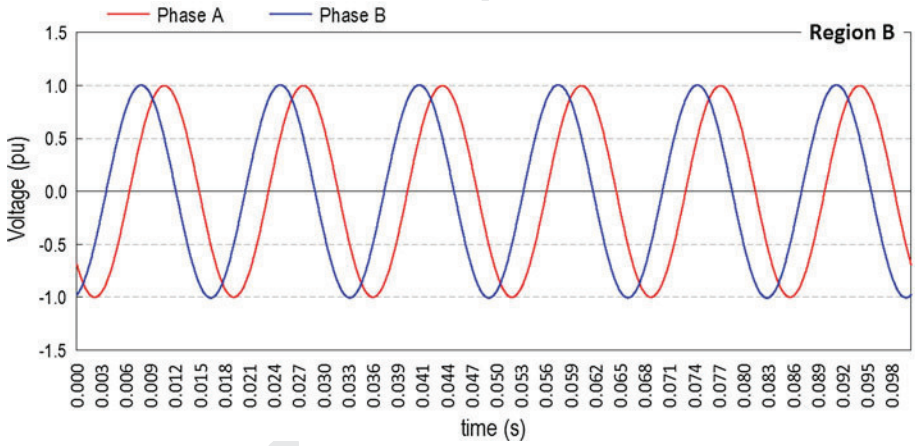

Fig. 16 Voltage waveforms on the primary side of the three-phase transformer.

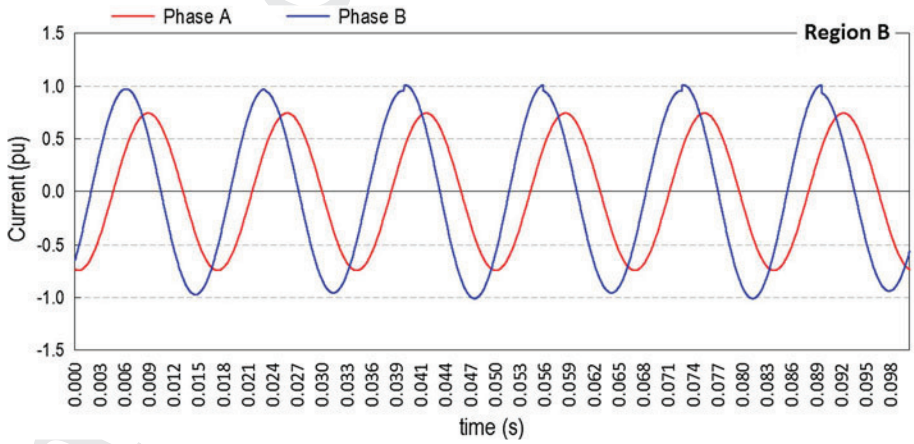

Fig. 17 Current waveforms on the primary side of the three-phase transformer.

obtained through the experimental procedures were found to be totally aligned to the results obtained in analytical and computational methods.

5 Economic Analysis

Once the performance for the proposed new distribution system has been proven satisfactory, compared with the conventional systems, it is worth highlighting also the economic benefits which come with the new proposal. Table 1 presents the costs of adaptation of an existing single-phase branch line (with phase–neutral topology and 10 miles long) into the new two-wire system and costs of those for the construction of a new conventional three-phase branch circuit.

It should be verified that the new medium-voltage branch line arrangement for supplying three-phase rural loads represents approximately 12 % of the construction costs

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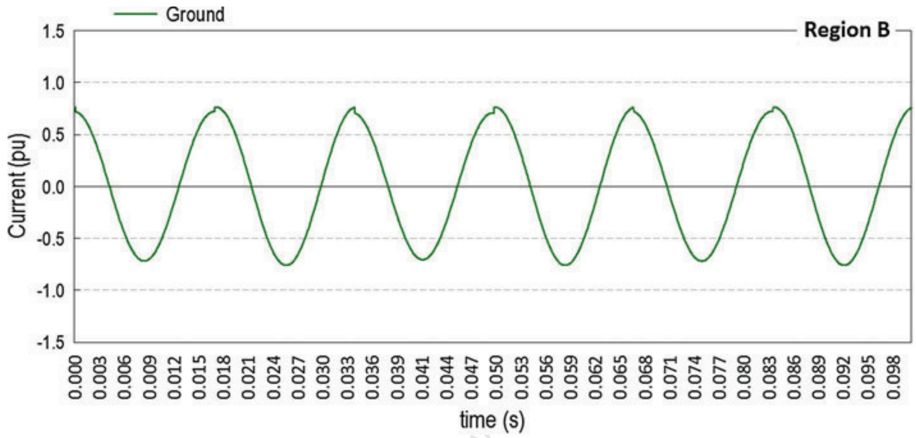

Fig. 18 Current waveform on grounding path.

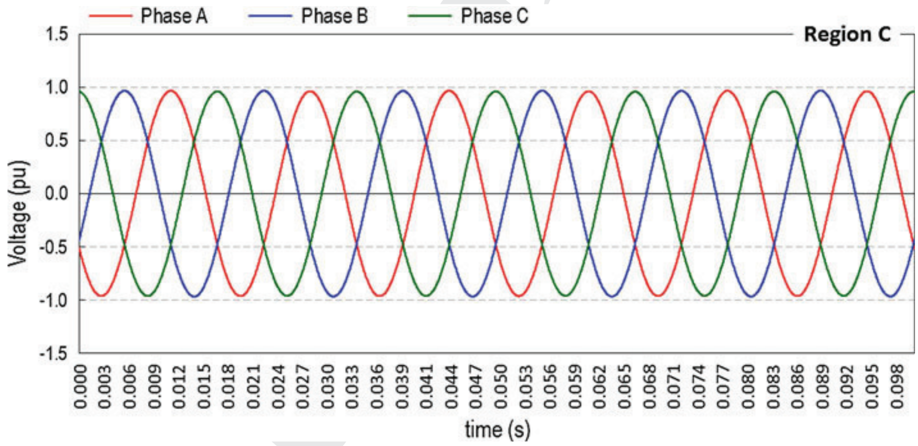

Fig. 19 Voltage waveforms on the secondary side of the three-phase transformer.

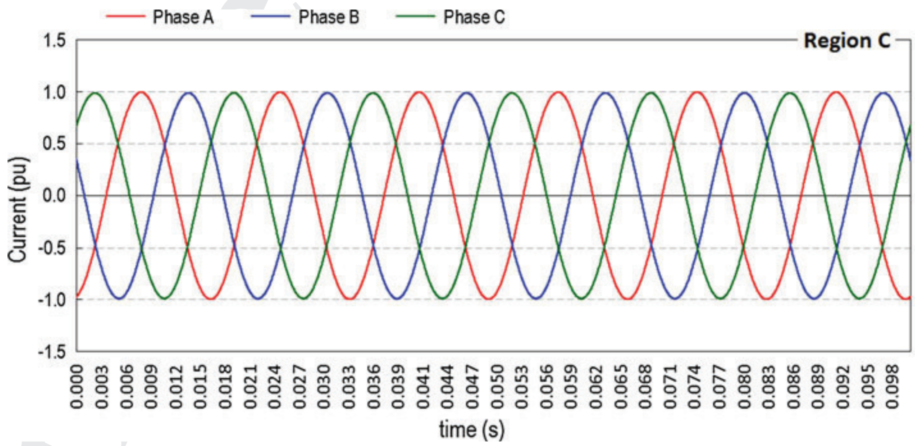

Fig. 20 Current waveforms on the secondary side of the three-phase transformer.

of a conventional three-phase branch line, once the proposed topology uses the existing conventional single-phase structure.

The difference in cost indicated would be of tangible benefit to the consumer as well as electrical utility, once the 12 % of costs, compared with the conventional three-phase network, is segregated independently from any type of apportionment between distribution utility and consumer in relation to the investment to be made. In addition, in the specific case concerning the distribution utility, one has to still consider the load increase to be accounted for on an adapted single-phase branch line. In other words, taking into account the current single-phase branch line (phase and neutral) in use, the power restriction is found to be associated quite simply to the single-phase transformer and not to the single-phase branch circuit, because the distribution utilities use conductors with a current rating much greater than the transformer rating.

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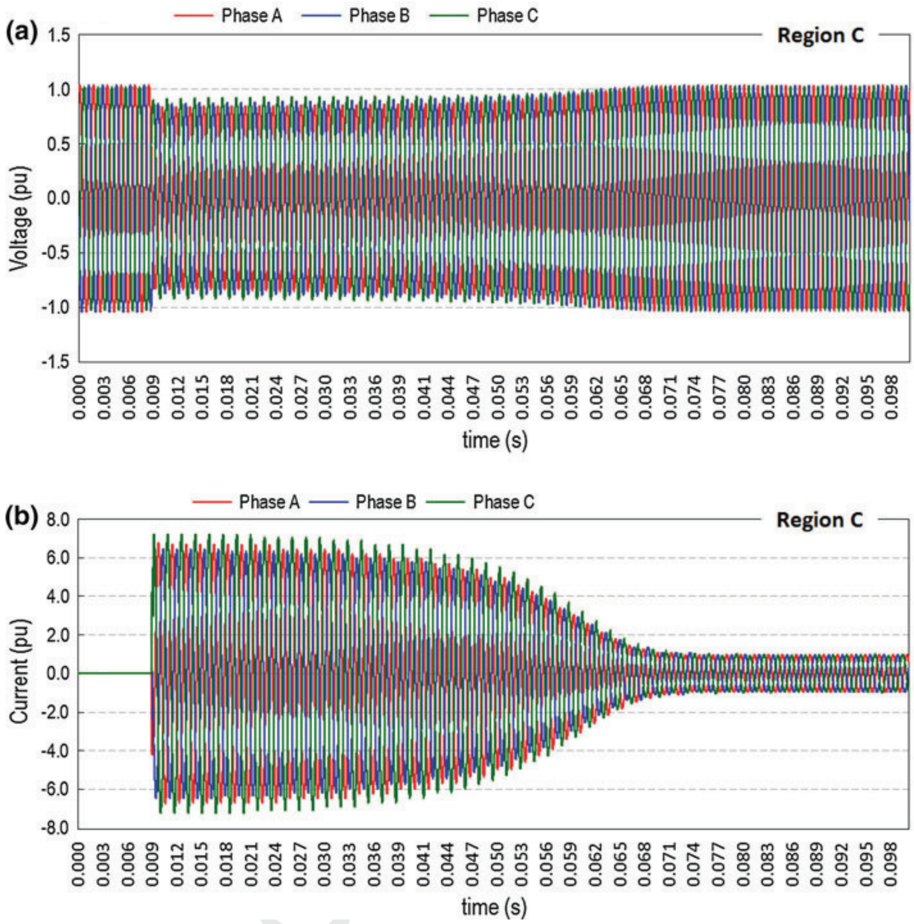

Fig. 21 **a** Voltage waveforms and **b** current waveforms on the secondary side of the three-phase transformer–induction motor starting conditions.

Table 1 Construction costs for medium-voltage (13.8 kV) distribution network used for local distribution utility

Option 1: new three-phase lateral line	Price (USD)
Construction of a new MV three-phase branch line (13.8 kV)	135,644.04
Purchase of a new three-phase transformer (30 kVA–13.8 kV/380 V)	2,871.52
Total: option 1	138,515.56
Option 2: proposed solution	Price (USD)
Adptation of the existing MV single-phase branch line	12,997.83
Purchase of a new three-phase transformer (30 kVA–13.8 kV/380 V)	2,871.52
Purchase of a new single-phase transformer (turn ratio 1:1)	1,013.46
Total: option 2	16,882.81

6 Conclusions

This article presented a methodology for the energy supply of three-phase rural consumer facilities from a new two-wire medium-voltage system based on electromagnetic arrangements which are simple and practical in nature. To meet this proposal, the single-phase branch lines currently used by electrical utilities can be easily converted over to two-phase branch lines, at a relatively low cost, to promote one of the basic goals behind the proposed methodology. The performance of the proposed methodology, which visualizes the use of a new two-wire distribution system, for the supply of rural three-phase loads, was proven to be sound through the use of analytical, computational and experimental developments. Therefore, in scientific terms, the proposal presented favourable practical results, which are extremely promising. Nonetheless, further study is in progress aimed at analysing the impacts of the proposed methodology with respect to power quality. Accordingly, it is expected that the results achieved will be similar to those presently observed

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for SWER systems existing around the world. In addition, it is believed that the construction of a commercial-scale prototype project should be the next step with the aim of validating the above proposal.

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