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Evaluation of Method for Attributing Responsibilities due to Voltage Unbalance in Electrical Systems

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Abstract. Several voltage unbalance conditions produce different harmful effects to the proper functioning of the many electrical system equipments, such as three phase induction motors. Thus, it is essential to know those responsible for the unbalance, on the one hand the energy distributor having a duty to provide a supply in accordance with the regulations and, on the other hand, the consumer who wishes to receive energy with quality and is obliged to maintain its installation according to the norms. In this scenario, the present paper has as objective to evaluate the conforming and non-conforming current method in front of an electric system with the presence of unbalanced loads and a three-phase induction motor with regard to the attribution of responsibility due to voltage unbalance.

Key words

Power quality, attribution of responsibilities, voltage unbalance, conforming and non-conforming current method.

1. Introduction

The electric power distribution system is the most affected by the voltage unbalance when compared to the others. And since approximately 60% of the energy produced is used to power electric motors in industrial systems, it is of extreme importance to assess the responsibility for this voltage unbalance [1]. However, there are not many studies that present information regarding the identification of the origin of the voltage unbalance [2].

It is known that the presence of high levels of voltage unbalance provokes overheating, isolation request, excessive losses and reduction the life of motors and transformers, or even improper activation of their protection systems, leading to the halting of production processes. In addition, such operating conditions may cause non-characteristic harmonic currents to emerge in electronic motor drives devices, which further complicates the task of eliminating these effects [2], [3].

The Module 8 of the Electric Power Distribution Procedures in the National Electric System (PRODIST) of the Brazilian Electricity Regulatory Agency (ANEEL) determines the following limits for the voltage unbalance factor (VUF): 3.0% for nominal voltage (Vn) less than or equal to 1.0 kV; and 2.0% for Vn greater than 1 kV and less than 230 kV. It defines, for calculation of VUF, the method of symmetrical components or, alternatively, CIGRE method [4]. In addition, the method of symmetrical components is also adopted for determination of VUF in the IEC (International Electrotechnical Commission) and IEEE (Institute of Electrical and Electronics Engineers) norms.

Faced with these aspects, it becomes important to know the origin of the voltage unbalance so that it is plausible to define actions in order to mitigate their effects or propose corrective solutions. Furthermore, the identification of the responsibility portions related to the agents involved leads to the just establishment of possible sanctions, when the voltage unbalance factor exceeds the limits.

Within this context, the present paper proposes to contribute significantly with the studies for the identification of the responsibility for the voltage unbalance through the evaluation of the performance of the conforming and non-conforming current method in an electrical system with presence of non-static load.

2. Theoretical Framework

For an electrical system operates efficiently, both in transmission and distribution, it is essential to pay attention to the power quality (PQ). In this context, one of the factors that compromises this quality is the voltage unbalance, which occurs when the voltages in a three-phase electrical power system have different magnitudes and / or angular mismatch between the phases different of 120° electrical [5].

The unbalance of loads in the feeding phases is the main reason for the appearance of voltage unbalance, because for different impedances there are different currents. In this way, the main sources of voltage unbalance are generally found in distribution systems, where there are often monophasic loads inadequately distributed between the phases [5].

Among the principal methods used to calculate the voltage unbalance factor, it is possible to cite the method of symmetrical components and the CIGRE method.

The method of symmetrical components, proposed by Fortescue in 1918, is based on the principle that an unbalanced three-phase system can be decomposed into three symmetrical and balanced systems, which are: a positive or direct sequence system, which has phasors in the same sequence of phases of the original unbalanced system; a negative or inverse sequence system, which has phasors in inverse sequence to those of the original unbalanced system; and finally, a zero-sequence system, which has parallel phasors. Thus, in this method the VUF is defined by the ratio between the negative and positive sequence voltage. This method can be used for both line voltages and phase voltages [2].

The CIGRE method is a method proposed by *Conseil International des Grands Réseaux Electriques* (CIGRÉ) which is used in cases where the measuring instruments carry out only readings of the voltage modules [1]. This method, to determine the VUF, makes use of an expression based on a dimensionless quantity that correlates the line voltages. It is emphasized that the CIGRE method is considered equivalent to the method of symmetrical components, because both methods return the same value of VUF [2].

A. Methods for Attributing Responsibilities due to Voltage Unbalance

The main methods used for attributing responsibilities due to voltage unbalance are [6], [7]:

- *IEC method*: used only when it is possible to measure the level of unbalance of the system before and after the connection of an installation and thus to identify the level of emission of unbalance of this installation;
- *Three-phase power flow method*: associates the negative sequence active power with the voltage unbalance. This is done through the zero, positive and negative sequence power flows, according to the symmetrical components of the studied system;
- *Conforming and non-conforming current method*: makes use of the premise that the total current demanded by a load is the sum of two currents, one conforming and another one non-conforming to the imbalance presented in the supply voltage, which have indications of the level of degradation of the power quality. This is the method analysed in this paper, being better described below.

In [7], were evaluated such methods of assignment in an electrical system composed of static loads. The results obtained show that the latter method presented better performance in relation to the others. This was a relevant factor in the choice of this method to be investigated in the present paper involving, now, loads with dynamic behaviour.

B. Conforming and Non-conforming Current Method

The conforming and non-conforming current method, defined in [6], part of the proposition that the current absorbed by a load corresponds to the addition of two theoretical currents. It is denominated conforming current a portion of the current that has the same graphic patterns of the voltage. It is responsible for 100% of the positive sequence power steady fundamental frequency. The difference between the total and conforming currents is called non-conforming current, which is attributed to the load. In this way, both conforming and non-conforming current have all forms of deterioration of the power quality [6].

Thus, if the impedance of a load is balanced, it will only absorb conforming current. However, if a load changes the characteristics of the waveform of the supply voltages, it will absorb as much conforming current as non-conforming current [7]. It is noteworthy that, in [7], this method showed good results in systems containing only static loads.

From the method of symmetrical components, it is possible to obtain the zero ($\bar{V}_0$), positive ($\bar{V}_1$) and negative ($\bar{V}_2$) sequence voltages through the phase voltages $\bar{V}_A$, $\bar{V}_B$ e $\bar{V}_C$, according to (1) [8].

$$\begin{bmatrix}\bar{V}_0\\ \bar{V}_1\\ \bar{V}_2\end{bmatrix} = \frac{1}{3}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\cdot\begin{bmatrix}\bar{V}_A\\ \bar{V}_B\\ \bar{V}_C\end{bmatrix} \qquad (1)$$

The same principle is used to determine the zero ($\bar{I}_0$), positive ($\bar{I}_1$) and negative ($\bar{I}_2$) sequence currents through the phase currents $\bar{I}_A$, $\bar{I}_B$ e $\bar{I}_C$, as pointed out in (2).

$$\begin{bmatrix}\bar{I}_0\\ \bar{I}_1\\ \bar{I}_2\end{bmatrix} = \frac{1}{3}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\cdot\begin{bmatrix}\bar{I}_A\\ \bar{I}_B\\ \bar{I}_C\end{bmatrix} \qquad (2)$$

The conforming current is a portion of the current having the same level of unbalance of the voltage, being responsible for all active and reactive power of positive sequence. So, the positive sequence conforming current ($\bar{I}_{c1}$) is equal to the positive sequence current ($\bar{I}_1$). Already the zero ($\bar{I}_{c0}$) and negative ($\bar{I}_{c2}$) sequence conforming currents are proportional to their respective voltages $\bar{V}_0$ and $\bar{V}_2$. The equations (3), (4) and (5) express these concepts [6].

$$\bar{I}_{c1} = \bar{I}_1 \qquad (3)$$

$$\bar{I}_{c2} = \bar{I}_1\cdot\frac{\bar{V}_2}{\bar{V}_1} \qquad (4)$$

$$\bar{I}_{c0} = \bar{I}_1\cdot\frac{\bar{V}_0}{\bar{V}_1} \qquad (5)$$

The positive ($\bar{I}_{nc1}$), negative ($\bar{I}_{nc2}$) and zero ($\bar{I}_{nc0}$) sequence non-conforming currents are equal to the difference between the corresponding sequence currents and their respective conforming current, as shown in (6), (7) and (8) [6].

$$\bar{I}_{nc1} = 0 \qquad (6)$$

$$\bar{I}_{nc2} = \bar{I}_2 - \bar{I}_{c2} \qquad (7)$$

$$\bar{I}_{nc0} = \bar{I}_0 - \bar{I}_{c0} \quad (8)$$

The values of the non-conforming currents of each phase of the three-phase system ($\bar{I}_{ncA}$, $\bar{I}_{ncB}$ and $\bar{I}_{ncC}$) can be obtained through the symmetrical components of the non-conforming current, in other words, of the currents $\bar{I}_{nc1}$, $\bar{I}_{nc2}$ and $\bar{I}_{nc0}$, according to (9). These are the unbalanced currents assigned to the load [6].

$$\begin{bmatrix} \bar{I}_{ncA} \\ \bar{I}_{ncB} \\ \bar{I}_{ncC} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} \bar{I}_{nc0} \\ \bar{I}_{nc1} \\ \bar{I}_{nc2} \end{bmatrix} \quad (9)$$

It should be noted that, in an unbalanced system, the negative sequence component will be present. In this way, the unbalance factor given by the method of symmetrical components is related to the currents $\bar{I}_{c2}$ and/or $\bar{I}_{nc2}$ [7].

C. Conforming and Non-conforming Current Method Application Methodology

As previously discussed, the conforming current, for being responsible for 100% of the positive sequence power steady fundamental frequency, is attributed to the source. Already the non-conforming current is attributed to the load. It is also known that in a balanced system only the positive sequence component will be present, in other words, the negative sequence current is related to the unbalance of the system.

Thus, for the attribution of the contribution percentage with the voltage unbalance of the system, relative to each part (source and load), made use of negative sequence current and of negative sequence conforming and non-conforming currents.

Fig. 1 illustrates these current phasors and the projection of the negative sequence conforming and non-conforming currents over the total negative sequence current, based on (7).

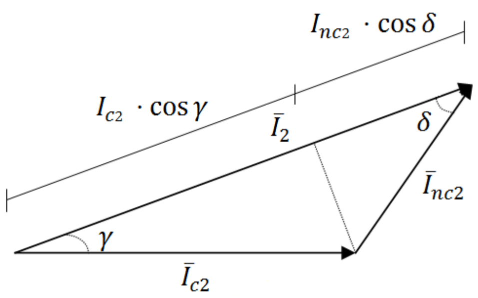

Fig. 1. Representation of negative sequence current phasor, negative sequence conforming and non-conforming current phasors and their projections.

Then, based on Fig. 1, the contribution percentages to the voltage unbalance of the system, referring to the source and the load, which denote the share of responsibility of each part, are calculated according to (10) and (11).

$$pcI_{c2Source} = \frac{|\bar{I}_{c2}| \cdot \cos\gamma}{|\bar{I}_2|} \times 100 \quad (10)$$

$$pcI_{nc2Load} = \frac{|\bar{I}_{nc2}| \cdot \cos\delta}{|\bar{I}_2|} \times 100 \quad (11)$$

Where: $pcI_{c2Source}$ and $pcI_{nc2Load}$ represent, respectively, the percentages of the projection of the negative sequence conforming and non-conforming currents over the negative sequence current of the system, which correspond to the share of responsibility of each party, and γ and δ are the angles of these projections.

Therefore, in this paper, the application of the conforming and non-conforming current method for attributing responsibility for the voltage unbalance was established through the use of (10) and (11). So, this method was implemented in MATLAB software.

3. Simulated Electrical Power System

The hypothetical electrical power system used as test in the simulations aggregates the main attributes that make up a real system, in which the industrial installations are electrically supplied by utility companies.

In the used electrical system, the utility is represented by a voltage source in series with an impedance, which represents the short-circuit level of the busbar. In addition, there is a representation of a distribution substation consisting of two transformers in parallel and a capacitor bank. Lastly, there are four distribution feeders, which supply electric power to four commercial and industrial installations, consisting of resistive and inductive linear loads, and a three-phase induction motor.

The ATP (*Alternative Transients Program*) software was used for the modelling and simulation of this electrical power system. Fig. 2 presents the modelled system. An electrical power system similar to this has already been employed in a study of sharing the harmonic voltage distortion responsibility [9].

The simulations were basically divided into three operating conditions, which are described below.

1) Operating Condition I:

In the first operating condition, a voltage unbalance of 1.91% is applied to the power system supply. Table I shows the values of the supply voltages for this case.

Table I - RMS voltages of the supply system for a voltage unbalance of 1,91%

Voltages at the input busbar of utility substation				
Voltage [V]	**Phase A**	**Phase B**	**Phase C**	**VUF**
Magnitude [V]	81210	78910	78920	1.91%
Angle [Degree]	-0.2527	-121.2	120.7	

2) Operating Condition II:

In this second operating condition, an unbalance is established in the system loads. The supply voltages is symmetrical while some of the commercial and industrial installations have different loading in the phases. The following case has been applied: loads 2 and 3 are unbalanced.

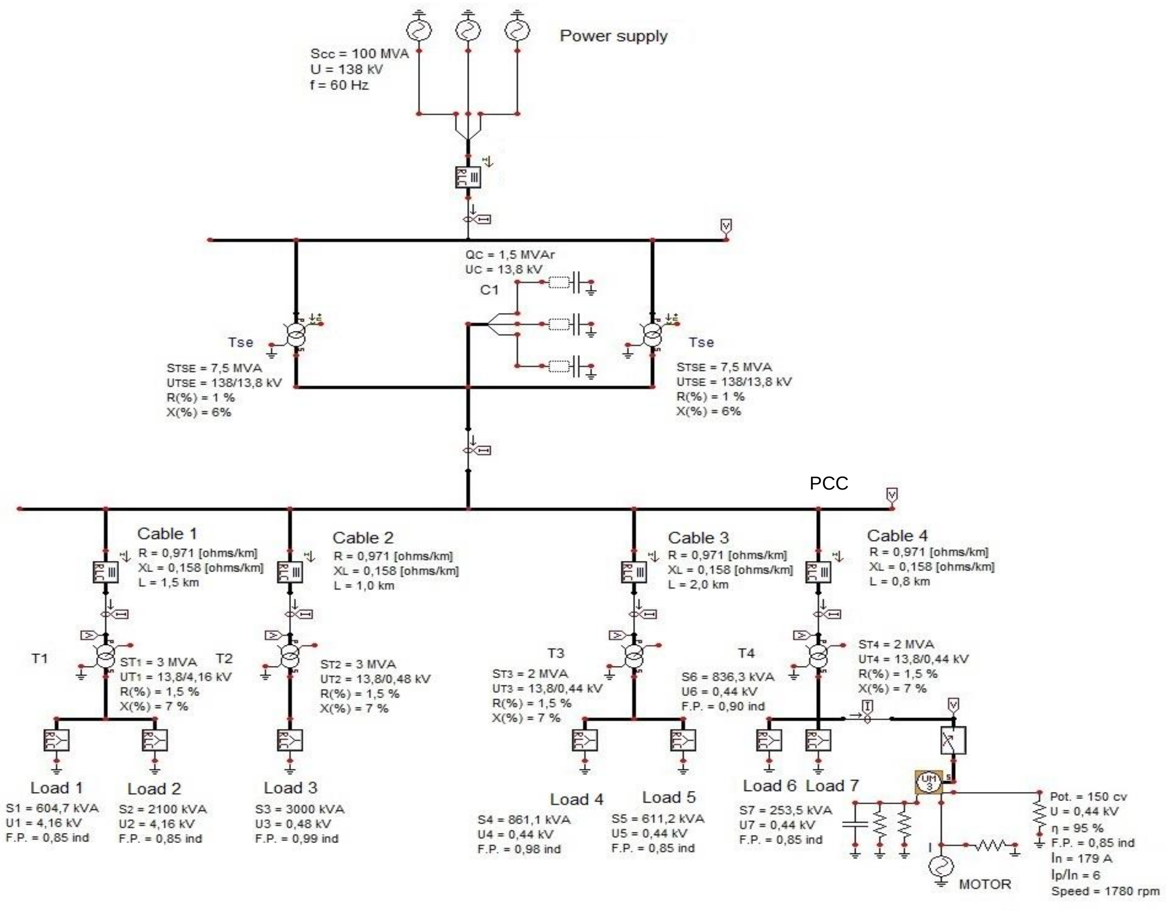

Fig. 2. Diagram of the electrical power system implemented in the ATP software.

The unbalance applied to the loads is performed by dividing the power of each load in different percentages over each phase. Tables II and III show how the unbalance was produced in load 2 and load 3, respectively.

Table II - Power distribution of the load 2 between the phases

Load 2	
Nominal Power (kVA)	2100
Percentage of power in phase A	9.53%
Percentage of power in phase B	33.33%
Percentage of power in phase C	57.14%

Table III - Power distribution of the load 3 between the phases

Load 3	
Nominal Power (kVA)	3000
Percentage of power in phase A	6.67%
Percentage of power in phase B	33.33%
Percentage of power in phase C	60.00%

3) Operating Condition III:

In this last operating condition, there is an unbalance in both the power supply and the system loads. The operation condition I is used in combination with the operation condition II.

Fig. 3 shows the phase voltage waveforms measured at the point of common coupling (PCC) for this operating condition of the electrical system.

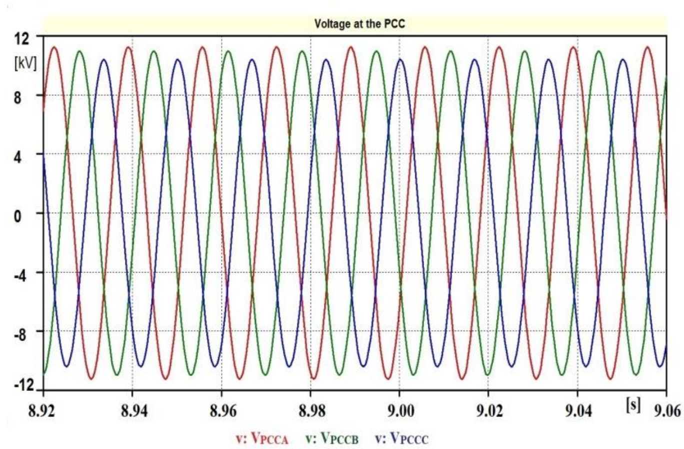

Fig. 3: Voltage waveform at the PCC in the operating condition III.

4. Results

The results of the application of the conforming and non-conforming current method and the analyses regarding the identification of the responsibilities related to the voltage unbalance are presented in this part. It should be emphasized that was used the method of symmetrical components for the calculation of VUF.

- *Results for the Operating Condition I*

Table IV shows the results for this operating condition, where it is possible to observe that at each measurement point the voltage unbalance factor was around 1,9%. From this table, it is verified that the conforming and non-conforming current method effectively assigned the highest percentage of responsibility for the voltage unbalance to the power supply (utility). In the primary of the transformer 2, it is observed that the percentage attributed to the industry is negative, which would indicate that this consumer is operating in order to reduce the voltage unbalance at this point. However, this consumer unit is operating with balanced loads, rendering the compensation unfeasible observed by means of method.

In the primary of the transformer 4, where we have the induction motor connected in the secondary, it is possible to notice that the percentage attributed to the utility is smaller than in the other points, which may indicate the influence of the induction motor on the response of the method.

Table IV - Results for the operating condition I

Electrical System with unbalance in the source of 1.91%			
Measurement point	**VUF%**	**Responsibility Percentage**	
		Utility	*Industry*
1° Transformer 1	1.92%	96.63%	3.37%
1° Transformer 2	1.95%	101.30%	-1.30%
1° Transformer 3	1.93%	96.92%	3.08%
1° Transformer 4	1.94%	66.26%	33.74%

- *Results for the operating condition II*

Table V shows the results for this operating condition, in which it can be noted that the larger VUF are in the two feeders where are the unbalanced loads 2 and 3 (VUF of 2.87% e 3.07%, respectively). From this table, it is clear that the method correctly assigns the highest percentage of responsibility for the industries in these two points, and that in the primary of transformers 3 and 4 the highest percentage is attributed to the utility. These results are correct, because in fact the voltage unbalance has external origin, seen from these two measuring points, indicating to them that the utility or other loads have responsibility for the identified voltage unbalance. In turn, this indicates that the conforming and non-conforming current method was able to identify the major origins of these voltage unbalances.

Table V - Results for the operating condition II

Electrical System with unbalance in the loads 2 and 3			
Measurement point	**VUF%**	**Responsibility Percentage**	
		Utility	*Industry*
1° Transformer 1	2.87%	-5.47%	105.47%
1° Transformer 2	3.07%	-4.27%	104.27%
1° Transformer 3	2.71%	97.08%	2.92%
1° Transformer 4	2.72%	67.10%	32.90%
PCC	2.71%	-5.35%	105.35%

In Table V there is an additional measuring point, which is the PCC. At this measuring point, it can be observed that the method correctly indicated the origin of the voltage unbalance in the industries, assigning a higher percentage for these. It is also noted that the method indicates with negative percentages that the utility is acting in a way to reduce such voltage unbalance, this due to the elements that characterize the level of short-circuit of the utility.

And again, it is observed that in the feeder where the motor is present, just after the transformer 4, the percentages attributed to both the utility and the industry were very close to the values obtained in the operating condition I. This shows that the three-phase induction motor negatively influences the conforming and non-conforming current method, because it has negative sequence impedance different from the positive sequence impedance, since this difference between the impedances is not treated in the formulation of this method.

- *Results for the operating condition III*

In this last operating condition, whose results can be seen in Table VI, it is possible to observe a VUF of the order of 4.5% at all measurement points, except in the primary of transformer 2, where the VUF is slightly higher. In this operating condition, it is also shown the values obtained for the PCC.

It is noted that in the PCC the method attributed the highest percentage of responsibility to the industry, which would indicate that the voltage unbalance caused by the two unbalanced loads (loads 2 and 3) is greater than that caused by the utility. However, from Tables IV and V, it is possible to attest that the unbalance caused by each part individually does not present such a great difference, which does not justify the significant difference between the percentage of responsibility attributed to the utility and the industry in the PCC.

Still from Table VI, it is observed that in the two feeders where the unbalanced loads are present (transformers 1 and 2) the method correctly attributes the highest percentage of unbalance to the industries, thus identifying the presence of voltage unbalance sources at these two measurement points. But the attributed percentages do not show an adequate relation when considering the isolated presence of unbalance on the part of source or loads.

Table VI - Results for the operating condition III

Electrical System with unbalance on both sides: source with 1.91% and loads 2 and 3 unbalanced			
Measurement point	**VUF%**	**Responsibility Percentage**	
		Utility	*Industry*
1° Transformer 1	4.46%	-4.31%	104.31%
1° Transformer 2	4.67%	-3.49%	103.49%
1° Transformer 3	4.47%	98.11%	1.89%
1° Transformer 4	4.49%	67.28%	32.72%
PCC	4.48%	-3.15%	103.15%

However, in the feeder where the motor is present (transformer 4) again the percentage of responsibility attributed to the utility and to the industry presented values very close to those of the other conditions of operation.

Despite the higher percentage correctly attributed to the utility, since the origin of the unbalance is external to the consumer installation relative to this measuring point, the percentage attributed to the industry is very significant. This proves the negative influence of the three-phase induction motor on the conforming and non-conforming current method.

5. Conclusion

This paper presented an assessment of the conforming and non-conforming current method applied in an electrical power system with the presence of unbalanced loads and a three-phase induction motor. For such analysis, the ATP and MATLAB software were used as computational tools for the simulations and obtaining the results.

Based on the data and results, it is possible to conclude that the conforming and non-conforming current method obtained satisfactory results, correctly attributing responsibility for the voltage unbalance, in the feeders where static loads were present for the cases where there was only one source of unbalance. For the other cases and measurement points, the method was just able to define the predominant origin of the unbalance. Furthermore, the method has managed to identify, in some cases, the possibility of an agent acting in a way to compensate for the voltage unbalance.

However, in the feeder where the three-phase induction motor was present, it was observed that the parcels of responsibility remained practically the same values for all operating conditions analysed, with considerable percentages attributed to the consumer unit containing the motor and other balanced loads. But this should not have occurred, since the utility, representing the rest of the system, would have responsibility, as the three-phase induction motor presents itself as a balanced load. Therefore, the present study demonstrates that the induction motor has a negative influence on the conforming and non-conforming current method, and such influence derives from the fact that this motor has different positive and negative sequence impedance and this difference is not considered in the elaboration of the investigated method.

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