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Errors in the measurement systems with the inclusion of single-phase loads at 220V in three-phase distribution networks

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***Abstract*—This research analyzes the problems presented by the measurement systems in one Phase three wires electrical distribution networks when single-phase loads are connected to 220V and proposes to replace the equation to eliminate the error that occurs in the energy meter. This case of study was given in Ecuador due to the massive inclusion of induction cookers through the change of the energy matrix promoted by the state since this account with more than 90 of hydroelectric energy to meet their electric demand.**

It is important to explain that this research does not include in the state of the art the problem and the solutions, because this novelty was presented promptly in Ecuador due to the technical conditions of the energy distribution system, at the voltage level versus the construction voltage of the single-phase loads that in the case of induction cookers were imported from countries that handle 220V single-phase voltages. This consequence does not present a choice, it is ethical for those responsible for the measurement systems of the Utility, to present a solution to the inconvenience of how it is developed in this investigation.

***keywords*—Error in Measurement System, Single Phase Loads, Three Phase Networks, ED's, RSND.**

I. NOMENCLATURE

ED's: Distribution Utility
kWh: kilowatts hour – Energy
VE: Electric Vehicles
KW: Kilowatts - Electric Power
COMEX: Foreign Trade
GLP: Petroleum Liquid Gas
RSND: Reinforcement of the National Distribution System

II. INTRODUCTION

This research focuses its analysis on determining the error in the measurement of the electrical energy that certain single-phase loads at 220 V introduce in the measurement when they are connected in three-phase systems, this research is based in the magnitudes of active, reactive power and power factor, registered by different specialized equipment, installed in different monophasic users designed to work at 220V in single-phase or three-phase distribution systems, in addition, also should be studying behaviour of the load that prevails in the user, to determine vectorially as influence of this in the change the phase shift between voltage and current.

Given the high incidence that the electric load of the induction cookers has on the electrical system of the utility, the present work study the problem of the measurement of this type of loads; in addition, it will be demonstrated later, other single-phase users to 220 V that do not produce problems in the measurement of the consumed energy.

Once the variable and the parameter that generates the error in the measurement system is determined, it will be calculated and modeled mathematically, in order to point out the possible solutions from the side of the load and/or the measurement for which it is necessary to make adjustments in the energy meter integration algorithm. Finally, according to the existing regulations, a comparison will be made between what is described in the RTE INEN 101 Standard and the parameters measured and calculated in the induction cookers, with the purpose of issuing technical recommendations to the utility.

III. REGULATORY ANALYSIS IN ECUADOR FOR INDUCTION COOKERS

The National Development Plan through the program for the change of the energy and production matrix promotes industrial development, so, the Committee on Foreign Trade (COMEX) in spanish, resolved the elimination of tariffs for the importation of induction cookers and its elements for assembly in the country. In addition, the Ministry of Industries and Productivity through the Undersecretary of Quality approved the Ecuadorian Technical Regulation PRTE INEN 101 "Applied appliances for induction cooking", whose objective establishes the minimum requirements that must be met by household appliances for induction cooking. Among the most relevant considerations are: [1] [2]

- Operating voltage level between 180V and 250V.
- Suspended status (form to turn off), when the status selector indicates "disconnected" or "OFF", without generating an electromagnetic heating field.
- Active power consumption in standby mode $\leq$ 1W.
- Total Harmonic Distortion (THD) for voltage $\leq 3\%$ and $\leq 5\%$ for the current in normal operation.
- The Power Factor must be equal to or greater than 0.98 in normal equipment operation

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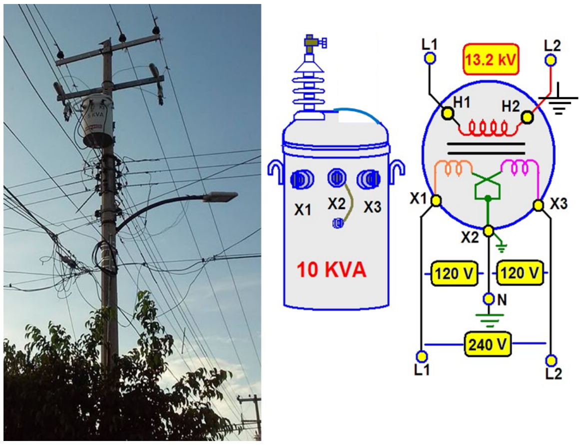

Fig. 1. Connection Single Phase Transformer

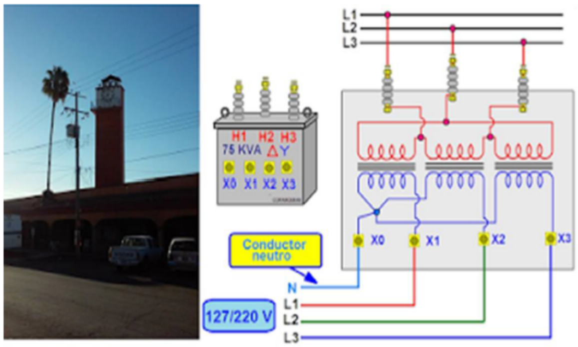

Fig. 2. Connection Three-Phase Transformer

Among other incentives, the Electricity Regulation and Control Agency -ARCONEL, modified the tariff schedule, incorporating an incentive of 80 kWh/month for users using the induction cooker and 20 kWh/month in the low voltage residential tariff for heating sanitary water. [1]

IV. LOW VOLTAGE DISTRIBUTION NETWORKS AND MEASUREMENT SYSTEMS

The ED's in Ecuador are technologically divided into two regions: the coast region, which mostly uses 1P3W single-phase distribution systems and three-phase systems connected in open delta 3P4W and the sierra region that uses 1P3W single-phase distribution systems in isolated areas of the centers villages and three-phase systems in population centers or those with the greatest demand for electricity. [3]

A. Transformers and Distribution Networks

The single-phase transformers are fed in half voltage by a phase-earth, obtaining 240V (low voltage), this voltage comes from the sole coil of the secondary of the transformer and 120V is obtained from the intermediate tap. [4] [5]

The three-phase transformers are built with three primary and three secondary windings, the most used connection is DYN5, as shown in Fig. 2. The 220V voltage is obtained from two phases of a transformer. [6] [7]

In three-phase networks the normalized voltage is 3x127/220V or similar, which for the purposes of this analysis will have no effect. [4] [5]

B. Measurement Systems Used

According to the topology of electrical networks in Ecuador, the most commonly used measurement systems are the following: [4] [5]

1) Single-phase two-conductor, for small businesses.
2) Single-phase three-conductor, widely used in the coastal region for all types of service, due to the predominant topology of the networks and the type of electric charge in the residential sector.
3) Biphasic three-conductor, is the most used today by the ED's, according to the current regulations for civil constructions.
4) Three-phase four-conductor: Used for residential services with higher electrical load, workshops and shops.

In order to reduce the level of non-technical losses in the country, the governing body, ordered that all energy meters have an energy calculation system based on the sum of the absolute values of the energy measured in each phase $[E_T = [E1] + [E2] + [E3]]$. With this formula, the value of the total energy is always incremental, despite the fact that one of the phases produces a negative energy value, preventing the ED's from affecting their income. [8]

Although this artifice was profitable for the reduction of non-technical losses, The utility "CENTROSUR" determined that this equation for calculating the energy consumed in some types of users, produced errors in the recording of the meters when certain types of loads were connected to them. This conclusion was reached after a thorough analysis of the abnormal behavior of some energy meters when recording the consumption of an induction cooker; The results of this analysis are the ones that we expose in this investigation.

In this investigation, the method used is the error test, since the tests are carried out in the Laboratory of Meters of the ED's, contrasting the values obtained with those of standard equipment of class of precision 0.02 Cl, is Therefore, the state of the art does not present a comparison between different methods, moreover, in specialized literature these errors have not been presented anywhere in the world, so the solution becomes innovative for the scientific community.

V. MEASUREMENT TESTS IN 220V SINGLE PHASE USERS INSTALLED IN THREE PHASE NETWORKS

Measurements were made to different types of induction cookers connected to three-phase networks, in which it was determined that, when they work with a power factor less than or equal to 0.5, measurement errors occur of energy; the error increases as the power factor decreases. It should be noted that in an induction cooker the power factor is capacitive and in the standby mode it is similar to zero.

For the test, whose results are shown in the Table I, two types of energy meters were used: the first, programmed with the algorithm of incremental integration of the sum of the absolute values of energy per phase $[E_T = |E1| + |E2|]$ and

TABLE I
VERIFICATION OF ERRORS IN THE MEASUREMENT.

Position cooking	KW	kVAR Q1	kVAR Q4	FP real	Meter 1	e %	Meter 2	e %
9	1.53	0	0.23	0.99	1.58	2.94	1.54	0.39
8	1.52	0	0.23	0.99	1.52	0.26	1.52	0.13
7	1.19	0	0.23	0.98	1.19	0.08	1.19	0.25
6	0.90	0	0.23	0.97	0.92	1.67	0.91	1.11
5	0.72	0	0.23	0.95	0.73	1.53	0.73	0.97
4	0.35	0	0.18	0.89	0.41	18.26	0.34	-0.29
3	0.24	0	0.17	0.82	0.39	62.92	0.24	-0.83
2	0.23	0	0.17	0.81	0.38	68.89	0.22	-0.44
1	0.09	0	0.17	0.48	0.18	95.56	0.09	-1.11
standby	0.02	0	0.14	0.11	0.08	460.00	0.01	-1.33

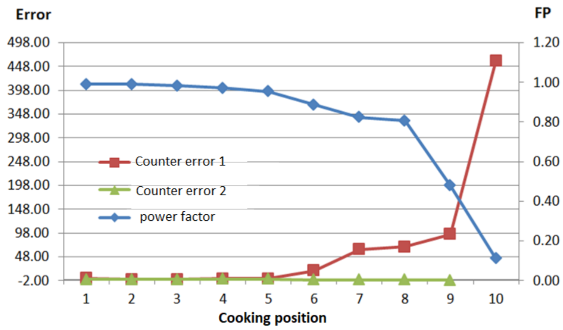

Fig. 3. Error Curves and Power Factor of the Loads

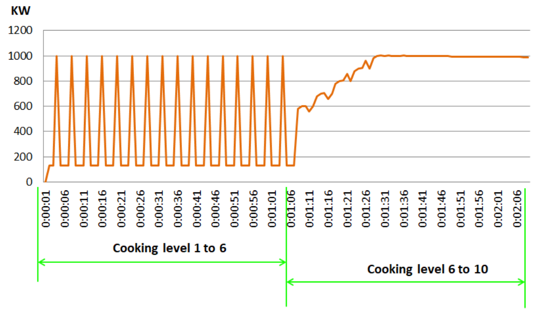

Fig. 4. Load Profile of the Induction Cooker

the second, programmed with the algebraic integration of the energies per phase $[E_T = E1 + E2]$. As shown in Table I, the first meter produces a high error from the standby power of the cooker to the cooking position 4, in which the power of the cooker is stabilized . The second meter keeps the correct energy record during the entire work regime of the cooker, including the standby mode.

To support the above, it is necessary to explain the electrical behavior of the induction cooker. In Fig. 4 it is observed that the active power level of an induction cooker, from cooking position 1 to position 6 is intermittent, registering peaks and valleys, while from position 7 to the 10 the power is incremental, until reaching its maximum value, as shown in Fig. 4. Based on the tests carried out, it was determined that the induction cooker from the standby mode to position 6 works with a low average power factor of less than 0.6, the load being always capacitive.

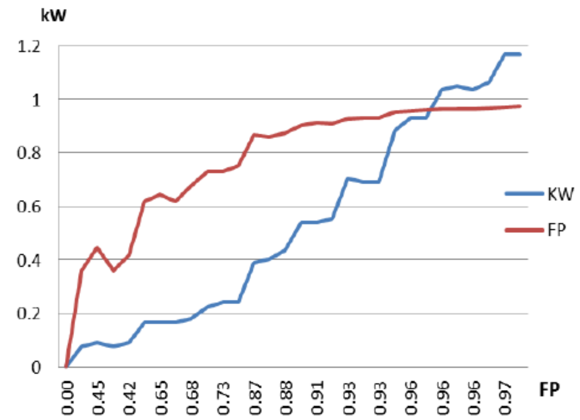

Fig. 5. Power Factor vs Power of the Cooker (Load)

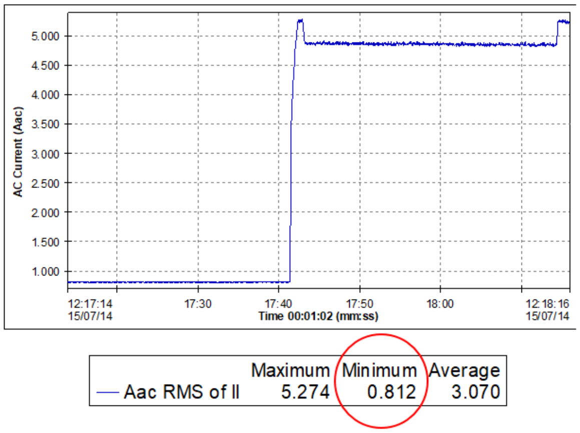

Fig. 6. Induction Cooker Current Profile

While, the cookers in standby mode keeps some of its components energized, so it registers a permanent current with a phase angle close to 90°$[FP = 0]$. Fig. 6 shows a current profile of an induction cooker, which in standby mode reaches 0.812 A.

VI. ANALYSIS OF THE LOAD FROM THE SIDE OF THE MEASUREMENT

As described in Fig. 10, from the side of the energy counter the resulting voltage [220V] has a phase shift of 30° with respect to each phase, so the phase shift produced between the

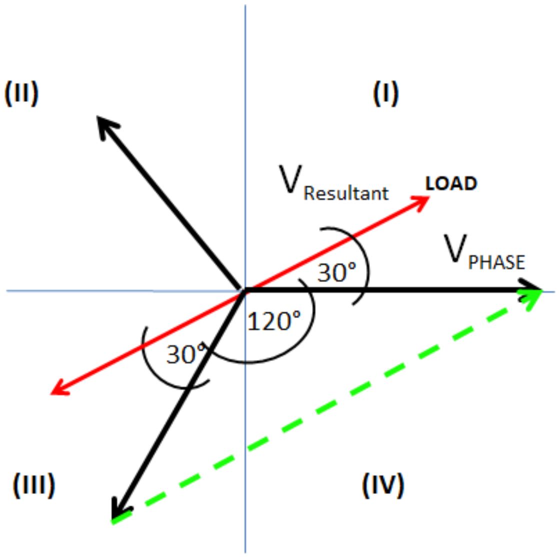

Fig. 7. Fasorial Diagram of the Resulting Voltage Seen from the Accountant

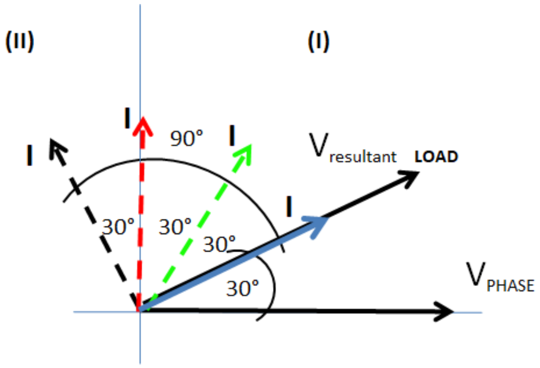

Fig. 8. Phasorial Diagram of Current in Loads of one of the Elements of Measurement

The resulting voltage and current of the load will be "seen" by each measurement element with 30° difference. From the load side there is a single voltage and a single current, while from the side of the meter there are two voltages and two currents because the meter is two-phase to three wires.

The phasor diagram in Fig. 11, shows different load currents seen from one of the measurement elements. In the case of a resistive load its current will be seen by the energy meter with a phase shift of 30°. A charge current with an offset of 60° will be seen by the counter with a phase shift of 90°, that is, the consumed energy would not be recorded $[FP = 0]$. In the case of a current produced by a fully capacitive load, it will be seen by the meter with a phase shift of 120°, which will produce an energy record in quadrant II [Negative power], simulating that it is delivered to the distribution system, a situation that is not real. Any load whose power factor is less than $0.5[60°]$ will produce erroneous values in the measurement, which will increase as the power factor decreases.

The energy meter whose algorithm for the consumption record is based on the sum of absolute values $[E_T = |E1| + |E2|]$ will convert a negative energy value into positive, so double energy registration is introduced . If the counter has the algorithm of algebraic summation $[E_T = E1 + E2]$, the value of the energy of each of the measurement elements will cancel each other, since they are of opposite signs, as long as their magnitudes are equal, in the working period of the kitchen in standby mode. In this sense, the resistive loads $[FP = 1]$ and inductive $[FP > 0.5]$ do not produce errors in the measurement.

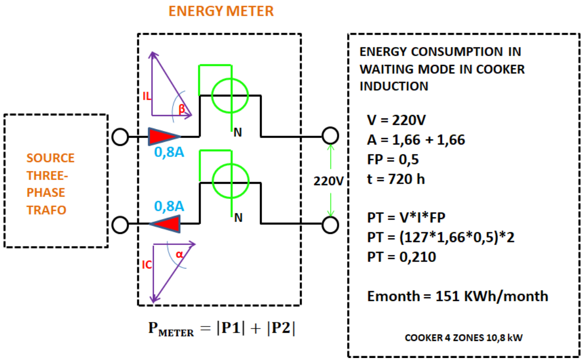

Fig. 9. Energy Record Generated by the Error in the Measurement

VII. Incidence of the Determined Error in Energy Consumption

After the analysis, it was determined that the induction cookers, by construction and operation principle, permanently energized the standby mode, so that their power factor in these conditions is close to zero, causing a considerable error in the measurement record , as indicated in point 7. Fig. 9 represents the most critical case in the measurement of energy that occurs when the kitchen is in standby mode.

VIII. Analysis of the Load from the Side of the Measurement

As described in Figure 10, from the side of the energy counter the resulting voltage [220V] has a phase shift of 30° with respect to each phase, so the phase shift produced between the The resulting voltage and current of the load will be "seen" by each measurement element with 30° difference. From the load side there is a single voltage and a single current, while from the side of the meter there are two voltages and two currents because the meter is two-phase to three wires.

The phasor diagram in Fig. 11, shows different load currents seen from one of the measurement elements. In the case of a resistive load its current will be seen by the energy meter with a phase shift of 30°. A charge current with an offset of 60° will be seen by the counter with a phase shift of 90°, that is, the consumed energy would not be recorded $[FP = 0]$. In the case of a current produced by a fully capacitive load, it will be seen by the counter with a phase shift of 120°, which will produce an energy record in quadrant II [Negative power], simulating that it is delivered to the distribution system, a situation that is not real. Any load whose power factor is less than 0.5 60°, will produce erroneous values in the measurement, which will increase as the power factor decreases.

The energy meter whose algorithm for the consumption record is based on the sum of absolute values $[E_T = |E1| +$

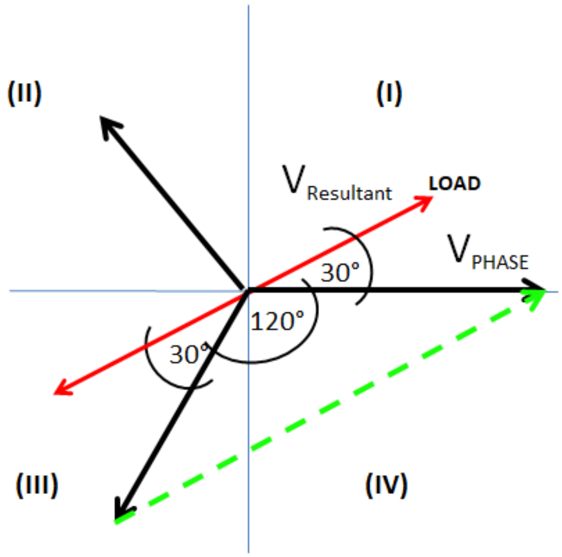

Fig. 10. Phasorial Diagram of the Resulting Voltage Seen from the Accountant

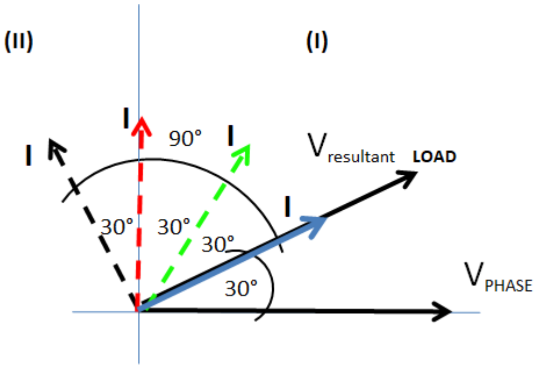

Fig. 11. Phasorial Diagram of Current in Loads of one of the Elements of Measurement

$|E2|]$ will convert a negative energy value into positive, so double energy registration is introduced . If the counter has the algorithm of algebraic summation $[E_T = E1 + E2]$, the value of the energy of each of the measurement elements will cancel each other, since they are of opposite signs, as long as their magnitudes are equal, in the working period of the kitchen in standby mode. In this sense, the resistive loads $[FP = 1]$ and inductive $[FP > 0.5]$ do not produce errors in the measurement.

IX. INCIDENCE OF THE DETERMINED ERROR IN ENERGY CONSUMPTION

After the analysis, it was determined that the induction cookers, by construction and operation principle, permanently energized the standby mode, so that their power factor in these conditions is close to zero, causing a considerable error in the measurement record , as indicated in point 8. Fig. 9 represents the most critical case in the measurement of energy that occurs when the kitchen is in standby mode.

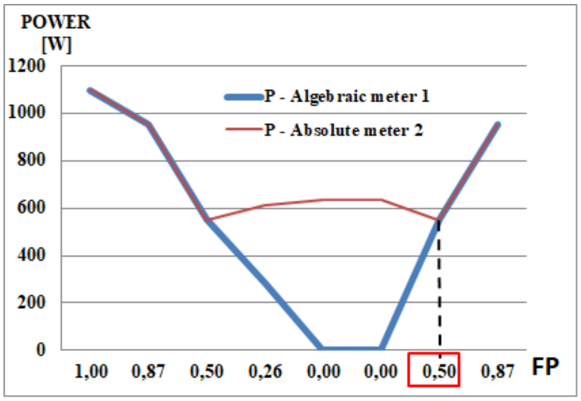

Fig. 12. Measurement Errors in Accountants According to the Programming Algorithm

X. MATHEMATICAL SIMULATION OF THE MEASUREMENT OF A 220V SINGLE PHASE LOAD CONNECTED TO A THREE PHASE NETWORK

Below is the mathematical modeling performed with two energy meters through different integration algorithms representing the measurement of a single-phase load at 220 V connected to a three-phase circuit: the first with the energy integration equation based on the summation algebraic of the partial energies $[E_T = E1 + E2]$ and the second with the equation based on the sum of absolute values of the same partial energies $[E_T = |E1| + |E2|]$.

If the voltage of 220V and the current in 5A are kept constant and only the angle of phase shift produced by the load varies, the two meters will register the same energy while said angle does not exceed 60° in advance or delay, after this angle, while the first counter records the real energy of the load, the second registers unreal values, product of adding the absolute values of the partial energies, as shown in the Table II and the Fig. 12.

Mathematical modeling allows us to reinforce the conclusion that the resistive loads $[FP = 0]$ and real inductive loads $[FP > 0.5]$ do not produce errors in the measurement, while the capacitive loads that produce phase shifts greater than 60° between voltage and current, introduce errors in the measurement of energy, only in counters whose equation of integration of the total energy is based on the sum of absolute values of the same partial energies $[E_T = |E1| + |E2|]$. This last condition simulates the actual behavior of an induction cooker, in operating mode from the standby mode to a certain cooking position. Similarly, from the values. Shown in the Table II it is found that the error in the measurement occurs when an induction cooker is in standby mode, because in this position the load is capacitive pure $[FP = 0]$.

Fig. 12 shows that the error area is in the values of the power factor less than 0.5, this condition in the measurement system that uses the algorithm of integration of absolute values will generate a considerable error, increasing the total energy for billing.

TABLE II
MATHEMATICAL REPRESENTATION OF DIFFERENT LOADS OF TWO TYPES OF METERS.

Charge	**Phi Charge**	**FP Charge**	Power	**FP-1**	**FP-2**	**P-F1**	**P-F2**	**P - Med 1 Algebraic**	**P - Med 2 Absolute**	**Phi Elem - Med**	**e% Med 1**	**e% Med 2**
R	0	1.00	1,100	0.87	0.87	549.91	549.91	1100	1100	$30^\circ y - 30^\circ$	0%	0%
R	0	1.00	1,100	0.87	0.87	549.91	549.91	1100	1100	$30^\circ y - 30^\circ$	0%	0%
R-C	30	0.87	953	0.50	1.00	317.50	635.00	953	953	$60^\circ y 0^\circ$	0%	0%
R-C	60	0.50	550	0.00	0.87	0.00	550.55	551	551	$90^\circ y 30^\circ$	0%	0%
R-C	75	0.26	285	-0.26	0.71	-164.47	448.95	284	613	$105^\circ y 45^\circ$	0%	115%
C	90	0.00	0	-0.50	0.50	-317.50	317.50	0	635	$120^\circ y - 60^\circ$	0%	Infinite
R-L	270	0.00	0	0.50	-0.50	317.50	-317.50	0	635	-60$^\circ y 120^\circ$	0%	Infinite
R-L	300	0.50	550	0.87	0.00	549.91	0.00	550	550	-30$^\circ y 0^\circ$	0%	0%
L	330	0.87	953	1.00	0.50	635.00	317.50	953	953	$0^\circ y 30^\circ$	0%	0%

XI. Possible Solutions to Error in Measurement

Once it has been demonstrated that effectively the counters that have the integration equation with absolute values $[E_T = |E1| + |E2|]$ produce errors in the energy register whenever there are 220V single-phase loads connected in three-phase systems such as induction cookers, this research analyzed the following solutions:

1) Use single-phase, two-wire measuring systems connected to 220V between phase and neutral, eliminating the phase shift between the fundamental and resulting voltages.
2) Remove the neutral reference of the two-phase meters, so that the resulting voltage would be seen by the meter as a single value.
3) The solution is to reprogram the energy counters by replacing the firmware with the energy integration equation with algebraic values, totally eliminating the problem.

The two initial solutions are not practical.

XII. Mathematical Model in Matlab

To reinforce the research, a model was developed in Simulink-Matlab® that compares the energy register made by two types of electric meters: the first with the algorithm $[E_T = |E1| + |E2| + |E3|]$ and the second with the algorithm $[E_T = E1 + E2]$, when single-phase loads are connected to 220V in three-phase networks. The developed scheme is shown in Fig. A.

The load data (Induction cooker without load) correspond to: $P = 15W$, $Q = -372VAR$. Meter with absolute value summation algorithm

TABLE III
NOT LOAD CONSUMPTION - MATHEMATICAL REPRESENTATION OF MODEL RESULTS.

	Parameters of the Induction Cooker	**Meter with Algebraic Summation Algorithm**	**Meter with Absolute Value Summation Algorithm**
P	15 W	15 W	30 W
Q	-372 VAR	372 VAR	372.1 VAR

XIII. Conclusions

This research presented the problems generated by the connected single-phase loads in three-phase systems, as well as their solutions, the most relevant findings are detailed below.

1) When single-phase loads at 220V are connected to single-phase networks, the measurement will not be affected.
2) Resistive charges $[FP = 1]$ and inductive $[FPreal > 0.5]$ do not produce errors in the measurement.
3) When the induction cooker is connected to the mains without any of its inductors operating (standby mode), the greatest error occurs in the measurement, since the angle of phase shift between voltage and current is close to 90°.
4) The algorithm $[E_T = |E1| + |E2|]$ of calculation of energy in the meters is the one that introduces errors in the measurement, due to the integration of the absolute values.
5) The only load that causes these errors in the measurement is the capacitive one, provided that the angle of phase shift between voltage and current exceeds 60°.
6) The Utility ”CENTROSUR” has proceeded to change the configuration of the meters acquired from the homologation, in such a way that the algorithm calculates the total energy with the algebraic sum of the partial energies $[E_T = E1 + E2]$, with which eliminated the error in the measurement.

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APPENDIX

Measurement Errors in Accountants of Energy According to the Programming Algorithm