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Escuela Académico Profesional de Ingeniería Eléctrica

Tesis

Analysis Of The Power Curve And Development Of A Graphic Interface For The Operation Of The Synchronous Generator In The Machu Hydroelectric Plant

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Para optar el Título Profesional de
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ANALYSIS OF THE POWER CURVE AND DEVELOPMENT OF A GRAPHIC INTERFACE FOR THE OPERATION OF THE SYNCHRONOUS GENERATOR IN THE MACHU HYDROELECTRIC PLANT

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Abstract: The objective of the research was to develop a computational interface that allows the automatic drawing of the power chart and is compatible with current automation process equipment such as the HMI and SCADA for the H.C. Machu. The research approach is quantitative, the method is deductive-descriptive, the type of research carried out is applied, a descriptive level of research and the design was non-experimental and longitudinal. Obtaining as a result from the mathematical review of the construction of the power curves of the synchronous generators for both smooth poles and salient poles, the operating restrictions in operability limits, conditions of maximum exciter current, maximum stator current, maximum primary motor power, minimum starting power, were absorbed into Cartesian and polar expressions, in such a way that this allowed the delivery of the algorithms to be processed computationally. Concluding that it was possible to develop a graphical interface in the MATLAB software, which traces the power curve of the synchronous generators, the location of the operating points and control of the operability limits through the current of the excitation field applicable to the Machu Hydroelectric Power Plant.

Keywords: Synchronous generator, graphical interface, algorithms, MATLAB, excitation current.

I. INTRODUCTION

Regarding the type of power plants in Peruvian territory, they can be classified according to their contribution to the total energy production to the National Interconnected Electrical System of Peru (SEIN). Figure 1 shows the total energy production from December 2022 to January. From 2023, it is understood that hydraulic, wind, and thermal power plants use electric generators by motion, unlike photovoltaic power plants that are based on the photoelectric effect. It is also appreciated that the participation of power plants by motion, such as hydraulic and thermal It is 95% of the total energy production.

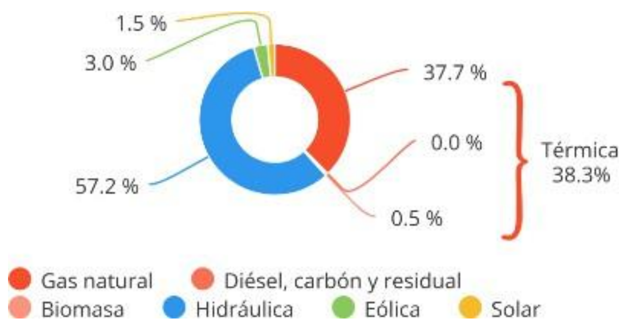

Figure 1. Monthly Electricity Statistical Bulletin 2023. It was extracted from the National Society of Mining, Oil and Energy website. prepared by the same institution with information from the COES.[1]

It is important to indicate that during the year 2022, failures have been recorded that occur in the elements that constitute SEIN, with the generating plants and transmission lines occupying the largest number of failures as shown in Figure 2.

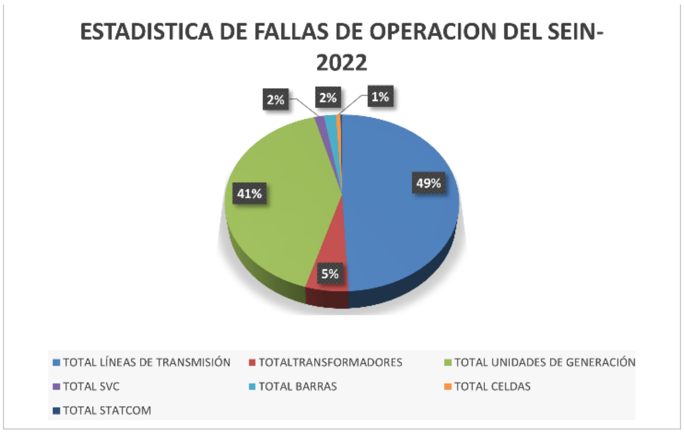

Figure 2: Representation of the number of failures in the SEIN-2022 Source: Own elaboration, data taken from COES.

The Economic Operation Committee of the National Interconnected System (COES) also reports the origin of these failures in Figure 3, describing the causes and the percentage occupied by human and operation failures.

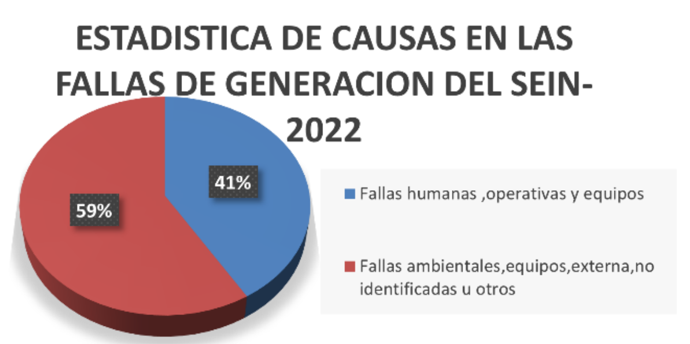

Figure 3: Representation of the causes of failures in the SEIN -2022 generation plants Source: Own elaboration, data taken from COES.

The causes of man-machine origin are of special alert since they represent almost half of them, considering in this article that failures of human origin cause chain failures in equipment, neglecting unavailability due to predictive and corrective maintenance.

Currently, large, medium and small power plants have implemented the modern SCADA system, Artificial Intelligence, cybersecurity, internal and external protection, to maintain stable normalized voltages, frequency, reactive powers and operating points within the limits. limits of each type of synchronous generator, as well as speed regulation in wind turbines and turbogenerators.

Taking into account the recommendations of the IEE421.5-2016 standard.[2] in the control and excitation limit, using the type 7 model, which is the use of the stator current with a rotating rectifier, which is the case of the two synchronous generators of the Huasicancha plant.

The isolated micro plants interconnected to the SEIN, which are few but increasing, do not have the resources to be able to implement sophisticated control systems for the graphic visualization of the operating points of the synchronous generators as the large plants have, due to that the profitability of the power produced is lower than the cost of implementing these technologies already described, including a return of more than 10 years or a return on profitability of 10 to 20 years. This is the case of the Machu Hydroelectric Plant (Huasicancha-Junín) which presents problems in its man-machine operation, due to the lack of equipment that displays the power charts constantly and immediately. Therefore, there is a need to have visualization equipment for the operating points of synchronous generators and for its implementation cost to be economically viable.

Therefore, the objective is develop a computer interface that allows the automatic drawing of the power chart and is compatible with current automation process equipment such as HMI and SCADA for the mini hydroelectric plant Machu.

II. MATERIALS AND METHODS

The research carried out is better suited to the type of applied research [3], because the first step that has to be carried out is the collection of information in this case from the C.H MACHU, either from reports, manuals, and reports, as well as the power and frequency data of each generating unit of the plant.

The theoretical revision is necessary for the construction of power curves for both the generators of smooth poles and protruding poles for this purpose were used bibliographic material of Chapman [4] Gómez[5], Fraile [6], Mojammed et al [7] and Vrazic et al [8].

Condensation of equations in both types of generators

A. Equations -smooth poles:

$$P^2 + \left(Q + \frac{3*{V_0}^2}{X_s}\right)^2 \leq \left(\frac{3*E_{a,max}*V_0}{X_s}\right)^2 \;.... (1)$$

Cartesian equation for the development of the circumference maximum excitation current limits.

$$\left(\frac{3*E_{a,min}*V_0}{X_s}\right)^2 \leq P^2 + \left(Q + \frac{3*{V_0}^2}{X_s}\right)^2 \;.... (2)$$

Cartesian equation for the development of the circumference limits of minimum excitation current.

$$S \leq \sqrt{P^2 + Q^2} \text{.........} (3)$$

Cartesian equation for the development of the circle for stator current.

$$P \leq \text{Pmec} .... (4)$$

Mechanical power delivery to the rotor shaft of the synchronous generator

$$P \leq \frac{3*{V_0}^2}{X_s} * \tan\delta .... (5)$$

It is necessary to indicate that to graph the region of this equation is dependent $0 \leq \delta \leq 70º$ on being known technical information in the operation.

The stroke of the power curves can be seen in figure 4 with the operating limits.

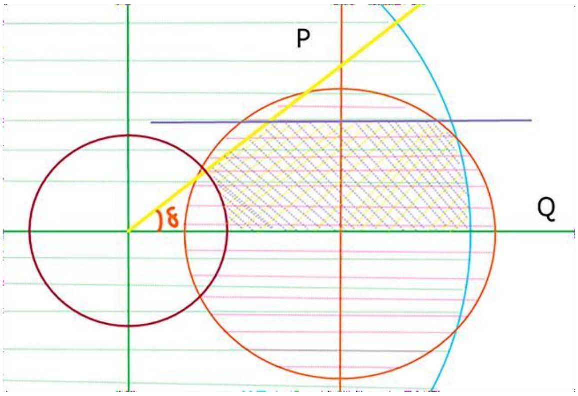

Figure 4: Power diagram P and Q with operating limits. Source of own authorship.1

B. Equations -outgoing poles:

$$P = \frac{3*V_0*E_0*sen(\delta)}{X_d} + \frac{3*(X_d - X_g)*{V_0}^2 * sen(2\delta)}{2*X_d*X_g} \;.... (6)$$

$$Q = \frac{3*V_0*E_0*\cos(\delta)}{X_d} - \frac{3*{V_0}^2}{2}\left(\frac{1}{X_g} - \frac{1}{X_d}\right) - \frac{3*{V_0}^2}{2}\left(\frac{1}{X_g} + \frac{1}{X_d}\right)\cos(2\delta) .... (7)$$

In figure 5 the power curvature points are located to mathematical development.

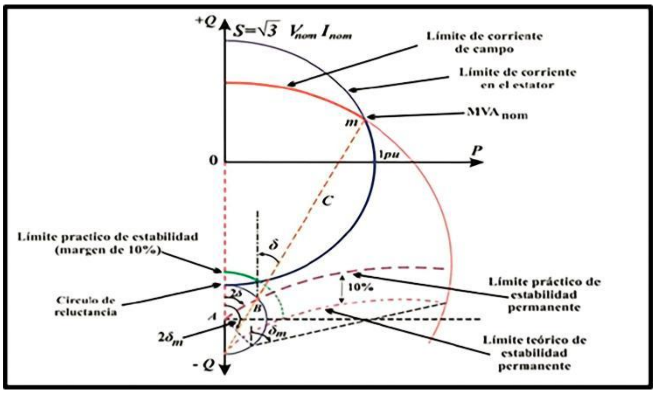

Figure 5: Power curve according to mathematical development. Taken "Modeling of the synchronous generator and capacity curve" by Gómez [5]

The equations can be plotted in Matlab software, considering the "x" axis as Q and the "y" axis as P, in MATLAB accepts the equations in polar form that is can express the Cartesian equations presented in polar form as shown in figure 6.

$$X = X1 + R * \cos(\theta) \qquad (8)$$

$$Y = Y1 + R * \mathrm{sen}(\theta) \qquad (9)$$

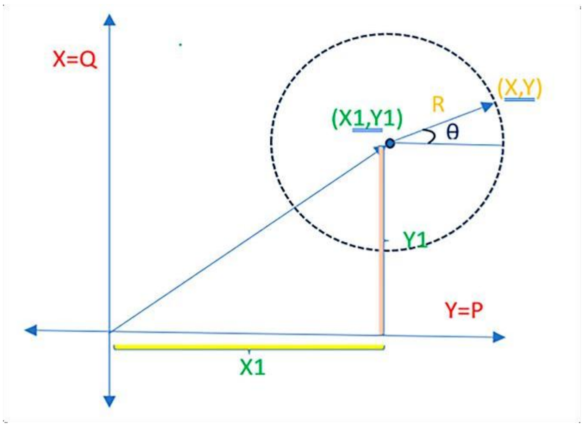

Figure 6: Polar expression for the circle equation.2

You can see the similarity of Cartesian equations to be absolved as polar equations regardless of the degree of complexity as is the case with synchronous generators of protruding poles.

Construction of the graphical interface

Final conditions for the development of power curves, use the system per unit ,this is because the MATLAB software has a compatibility in using units , is therefore to make the graphics on the system per unit, and this is convenient by selecting only two fundamental parameters which are the nominal apparent power of the synchronous generator and the output voltage in the generator terminals, these will be equal to the plate of characteristics of the synchronous generators.

You select the elements that will count the graphical interface for it was made use of the APPDESIGNER command that is the developer of MATLAB applications, figure 7 shows the final development followed by (Table 1) which contains the characteristics of the elements with their type and Tag.

Figure 7: Completed graphical interface for both smooth pole generators and protruding poles.3

N.º	ELEMENT	APP.GENERAL	APP OF INDEPENDENT ELEMENTS	STRING	TYPE
1	Input text	-	APP.ELECTRICAL GENERATOR POWER CURVE	ELECTRICAL GENERATOR POWER CURVE	TEXT
2	Designer logo	-	App. IMAGE	ENERKEN SAC	IMAGE
3	Text and numeric type input	-	App.S	Apparent power (S- kVA)	EDIT FIELD (Numeric)
4	Text and numeric type input	-	App. VL	Nominal voltage (VL- kV)	EDIT FIELD (CNumeric)
5	Text and numeric type input	-	App.XS	Synchronous reactance (CXs. Ohm)	EDIT FIELD (Numeric)
6	Text and numeric type input	-	App. fp	Power factor Fp	EDIT FIELD CNumeric)
7	Text and numeric type input	-	App. PM	Primary motor power	EDIT FIELD (Numeric)
8	Text and numeric type input	-	App.KVAR	Reactive Power (kVAR)	EDIT FIELD (Numeric)
9	Selection buttons	App TYPE OF POLES	App.SMOOTH	SMOOTH	Radio button Group
			App. OUTGOING	OUTGOING	

10	Calculation button	-	App. CALCULATE	Calculate	Button
11	Regulation button	-	App. FIELD CURRENT	POTENTIOMETER IF	Button
12	Regulation knob and text		App.IF	IF	Knob

Table 1: Recording elements in the graphical interface developed in the APPDESIGNER command. Each element created in the graphical interface is created as the application's own application.

III. Results

The graphical interface performs the automatic tracing of the power curves by means of three interactions for the case of the hydroelectric power plant this is a power plant that has synchronous generators of the type protruding poles , which will be treated as generators of the smooth type , this decision is not determinant in errors of this is because the direct axis reactances and quadrature are similar , in (Table 2) we can see the plate of characteristics of the synchronous generator of C.H . Machu-Huasicancha.

HYDROELECTRIC POWER MACHU -HUASICANCHA JUNIN	
INSTALLED POWER	0.9MVA
POWER FACTOR	0.85
TURBINES	
TYPE	FRANCIS
AXLE	VERTICAL
AMOUNT	2
NOMINAL POWER	0.5OMW
MANUFACTURER	Browing & co
GENERATORS	
TYPE	Polos Salientes
NOMINAL POWER	0.45MW
OUTPUT VOLTAGE	0.44KV
REACTANCE QUADRATURE Xd	1.2
REACTANCE QUADRATURE Xq	1.05
AMOUNT	2
MANUFACTURER	SIEMENS

Table 2: Nominal bale of the generators being both of the same characteristics.

Explanation of the 03 interactions:

1. First Interaction: Input of data from the first stroke characteristic plate for power curves, as shown in the figure 8.

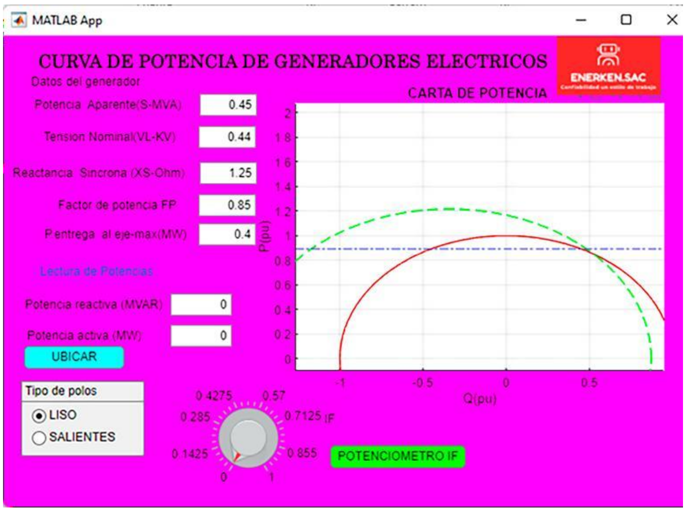

Figure 8: The first interaction is performed, where power curves are presented.4

2. Second Interaction: Input the information of the measuring instruments such as the meter and the meter to determine the point of operation, as shown in the figure 9.

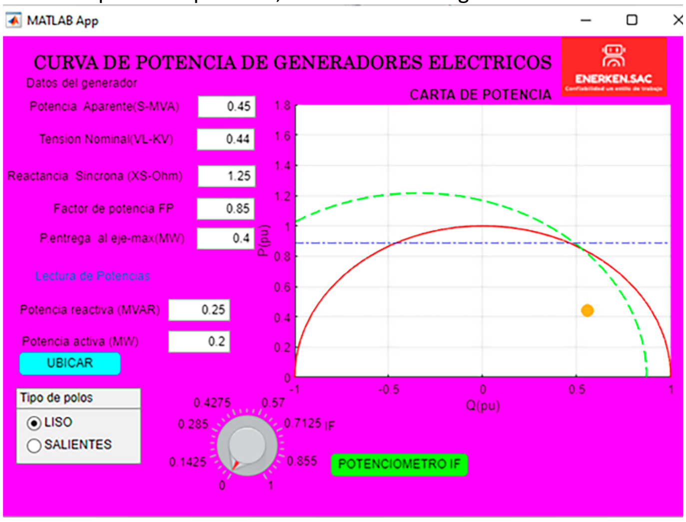

Figure 9: Location of the synchronous generator operating point.5

3. Third Interaction: Delimitation of the power curves avoiding over-generation by means of the potentiometer knob, as shown in the figure 10.

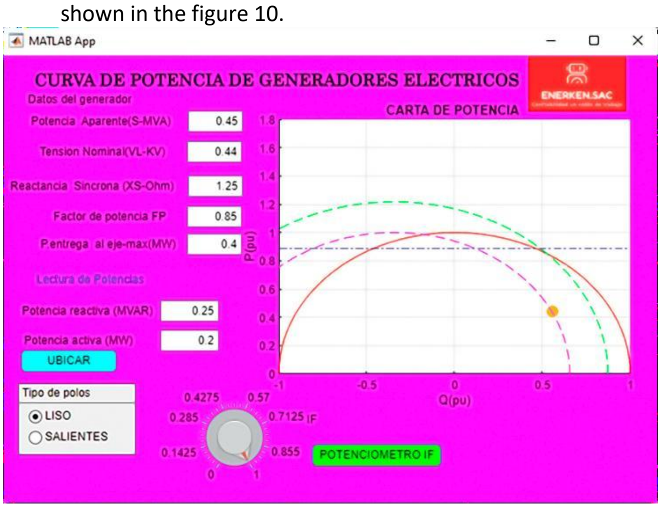

Figure 10: The operability region of the synchronous generator is defined6 by the excitation field if current, which avoids over-generation.

With the implementation of the graphical interface, the hours of availability of C.H. MACHU electric generators will be exceptionally improved, this improvement can be seen in the following Tables 3 and 4.

Before

GRUPO 4GE-005-007				
YEAR	Scheduled unavailability	Unscheduled unavailability	Corrective maintenance	Availability
2018	225	6	6	97.26%
2019	365	9	20	95.44%
2020	415	8	12	94.97%
2021	325	15	48	95.51%
2022	290	8	16	96.37%

Table 3: *Table of failures per hour of unavailability in the generation groups C.H. Machu -Huasicancha, 2018-2022.*

After

	GRUPO 4GE-005-007			
YEAR	Scheduled unavailability	Unscheduled unavailability	Corrective maintenance	Availability
2018	*225*	*6*	*6*	*97.29%*
2019	*365*	*9*	*20*	*95.49%*
2020	*415*	*8*	*12*	*95.01%*
2021	*325*	*15*	*48*	*95.59%*
2022	*290*	*8*	*12*	*96.45%*

Table 4: *Table of unavailability corrected by nullifying the operative human factors in the availability improvement generation groups, C.H. Machu - Huasicancha, in both generators.*

This shows the increase in the percentage of available hours of C.H. MACHU synchronous generators. Implementing the graphical interface to instruments such as HMI and SCADA language compatible to these equipment and instruments.

IV. DISCUSSION OF RESULTS

In this research was proposed as a general hypothesis "Through the theoretical-mathematical review of the construction of power curves and operating limits of synchronous generators, the algorithms necessary for insertion in a computational application can be posed.

The result of the mathematical review of the construction of the power curves of the synchronous generators for both smooth poles and for protruding poles, the restrictions of operation on operability limits, conditions of maximum excitatrix current, maximum stator current, maximum primary motor power, minimum starting power, were absorbed in Cartesian and polar expressions. It took such a form that this allowed the delivery of the algorithms to be processed computationally.

These results are supported by the mathematical analysis given by Moraga [9] , in which he also makes a mathematical analysis in Cartesian coordinates, which is similar to the processing of this research except that the polar coordinates are added for computational processing.

In agreement with the comparison of both results, it is confirmed that to know the necessary parameters of the plate of the synchronous generators and by means of the cartesian-analysis polar, allow to develop the methodology for the construction of the power chart of synchronous generators.

In this research the specific hypothesis1 is proposed that "Developing a computer application within the MATLAB software will allow the visualization of the power curves of the generators of the C.H. MACHU"

The power curve of the synchronous generators of the Huasicancha hydroelectric plant was developed using MATLAB software and with its new submenu APPDESIGNER MACHU -JUNIN ,and this by means of the construction methodology recorded in chapter 3.The incorporation of the algorithms and programming of each of the elements of this, were performed the tests and the automatic strokes of the Machu Hydroelectric Power Plant -Huasicancha, achieving the location of the operation points of the generation groups as well as the manipulation of the operability limits by manipulating the excitatrix current .

These results are similar to the research carried out by Moraga [9] , who in his research thesis successfully developed a computational tool for the Colbum hydroelectric plantChile ,designed in Microsoft Excel and with the programming language Visual Basic, allow the power curve tracing and data collection in a graphical interface , except that it has to be mentioned that such programming language are not compatible with the current equipment of automation, likewise it is only in static form, the present investigation has the versatility of being able to manipulate the field current of excitatriz (if) dynamically.

In this research the specific hypothesis 2 that mentions:"The location of the operating points of the synchronous generators of the C.H. MACHU in real time and the manipulation of the excitatrix current will allow a better operation of the generators increasing the hours of availability"

The result was to obtain an increase in the hours of availability because it cancels an important part that are the failures by human factors - operational that are related to the visualization of the power charts, For this, an inference was made if the computer application had been available in the years 2018 -2022, reducing by almost 100% the operational human factor, increased availability hours.

These results are supported by Rojas [10] , who in his research came to conclude that the graphical visualization by means of a computational tool, allows the annulment of almost 90% of the failures of human operation, increasing the number of hours of availability.

In this way it is asserted that the graphical visualization and the dynamic manipulation of the excitatrix current allow a better operability and reliability of decisions in the generation in stable terms of course, give this way the output is avoided by machine operation faults - man.[11]

V. CONCLUSIONS

1. A computer graphical interface was developed, first the theoretical mathematical analysis was carried out that allowed to better understand the Cartesian equations with the interpretation of them in the polar coordinates for the stroke of the power curves of the synchronous generators of smooth poles and projections, since the power angle δ can be modeled between [0;360°]. With this information through the MATLAB software and with the APDESIGNER graphic application development command having the programming codes and the graphic display command, it was possible to create the computational graphical interface this is developed through three interactions, first with the entry of the fundamental electrical parameters, then the active and reactive power obtained by the measuring instruments and the third by manipulating the excitation current for the rotor of the synchronous generator and this development language is compatible with development languages for HMIs leaving the evidence of its development and the achievement of the objectives set.
2. Visualization of the power chart was performed in real time by taking data from the watimeter (active energy meter) and varmeter (reactive energy meter) in the computer software developed, this observation can be made as many times as required in the CH-Machu power chart. In this way also see the limits of operability and adjust the points of operability within the limits of permanent operability.
3. It was evaluated that the output voltage and the output power of the synchronous generators can be manipulated with the stator field current of the synchronous generators and in this way maintain them in the limits of operability efficiently, This was demonstrated in the final development of the graphical interface in the third interaction by manipulating the field effect current without exceeding the magnetic saturation values.
4. The use of computational tools such as MATLAB allows the development of applications that allow the improvement of industrial processes and this article is evidence of this.

VI. RECOMMENDATIONS

1. Continue the analysis of the power curve of synchronous generators, although it is true the approach and analysis of the power chart was developed in the Cartesian system this can be developed in other systems so that graphic expressions and algorithms are given in a more practical way, one of them may be the complex system or polar system.
2. Within the theoretical approach that was developed was in a permanent state, that is to say without counting the short-circuit failures in symmetrical and asymmetrical form, neither were the effects of distortion by harmonics, it is therefore necessary that in future investigations the incorporation of this

type of failures be considered in its effect on the locations of the operability in power curves.

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