



AUTOMATIC V-CURVE ANALYZER FOR SYNCHRONOUS GENERATORS

ARTÍCULO CIENTÍFICO

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ABSTRACT

Synchronous machines are components of the electrical system that carry characteristics that make their modeling complex, such as excitation system, magnetic saturation where their physical construction involves mechanical and electromagnetic components. A correct modeling of synchronous machines is fundamental for studies that focus on quality and stability of the electrical power system. One of the main characteristics of synchronous machine the ability to work with different power factors for the same load driven be it mechanical in the case of motors or electric in the case of generators. This capability is translated through the v-curve that shows the capacity of the synchronous machine to vary the power angle by absorbing or providing reactive energy to the network by varying the excitation electric current when the machine is subjected to constant power.

The analysis from v-curve of the synchronous generator occurs through the performance of tests where multiple steps are required, besides requiring conditions that remain constant when performing these steps, such as constant rotation speed of the system and power provided, which can cause errors in the measurements by the user. When considering the difficulties in performing the tests manually, real-time system concepts were used to devise a system that simulates automation in the tests and measurements necessary to obtain the v curve of a synchronous generator, applying Simulink software that provides a platform to model and simulate systems in conjunction with LabVIEW software that provides a graphical programming environment and provides data acquisition and control tools for testing.

KEYWORDS: Synchronous machines, v-curve, real-time systems, data acquisition, LabVIEW, Simulink.

1. INTRODUCTION

Behind the evolution of contemporary human life pattern, it is unthinkable to discard synchronous machines that have a great contribution in the area of energy generation (SOUSA, 2011). The availability of coherent models of the elements that make up the electrical system is of great importance for the analysis and simulations in stages of expansions and real-time control of the electrical power system (POSSATTI, 2013).

Synchronous machines carry characteristics that make their modeling complex, such as excitation system, magnetic saturation and their physical construction that involves mechanical and electromagnetic components. A correct modeling of synchronous machines is fundamental for studies that focus on the quality and stability of the electrical power system (POSSATTI, 2013).

Being one of the characteristics of synchronous machine the ability to work different power factors for the same load driven be it mechanical in the case of motors or electrical in the case of generators (KOSOW, 1982). This capability is translated through the v-curve that demonstrates the ability of the synchronous machine to vary its power angle, absorbing or providing reactive energy to the network, by varying its excitation current (RAGNEV, 2005).

The development of the v curve of the synchronous generator requires testing where external components are needed to perform measurements of the quantities involved, in addition to conditions such as constant rotation speed that hinder the tests, besides being subject to errors in the measurements.

The main objective of this work was to develop a system that uses concepts of systems in real time, to perform simulation of the test of a synchronous generator applying the Simulink software that provides a platform to model and simulate systems in conjunction with LabVIEW software that provides a graphical programming environment and provides data acquisition and control tools for performing the software tests.

2. METHOD

2.1 STATE OF THE ART

2.1.1 SYNCHRONOUS GENERATOR

The synchronous generator is an indispensable device in electric power generation and is universally used by utilities to supply power to consumers (TORO, 2016). However, to realize this supply, synchronous generators depend on magnetic fields for energy conversion, fields that are produced from two windings, a fixed called stator, and a rotating winding defined as the rotor. (LIPO, 2012).

According to Chapman (2013), in a synchronous generator, a magnetic field is produced in the rotor, and for this it is necessary a permanent magnet or an electromagnet, and the alternating current flows through the stator.

When a synchronous generator is mechanically excited and goes into a permanent regime, its characteristic is to work as a voltage source that has electrical frequency (1) determined by the speed of its mechanical drive (UMANS, 2014).

$$f_e = \left(\frac{pole}{2} \right) \frac{n}{60}$$

1

Where:

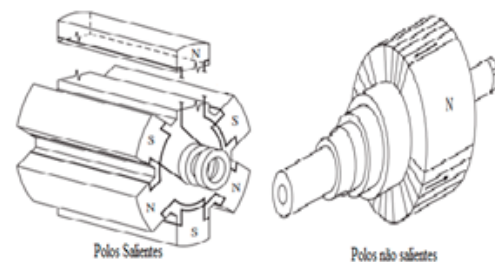
f_e = electric frequency of the generator;

n = speed in RPM of the mechanical drive

$pole$ = generator pole numbers

Synchronous machines can be divided into two categories, machines with salient poles where the magnetic pole protrudes radially from the rotor, and machines with non-salient poles, where windings are leveled with the rotor surface (SEN, 2013). Because synchronous machine rotors are subject to varying magnetic fields, they are constructed from slender blades to reduce losses by parasitic currents (CHAPMAN, 2013). Figure 1 shows the construction of the two different rotor shapes.

Figure 1 - Salient pole and non salient pole rotor



Source: Chapman, 2013.

When applying a direct electric current to a rotor without permanent magnet, and mechanically excite through its axis, a rotating magnetic field inside the machine will be produced in order to induce a set of three-phase stresses to the synchronous generator stator, in a given stator phase the induced voltage, depends on the flow of the machine, frequency of the driving excitation and construction of the machine (CHAPMAN, 2013). The voltage(EA) is defined by equation 2

$$EA = K\phi\omega$$

2

Where:

E_A = internally induced voltage in the generator;

ω = speed in radians of mechanical drive;

K = constant depends on the construction aspects of the machine;

In a real machine, the internally generated voltage (EA), will not be the voltage obtained in the generator output terminals, the voltages will be equal only when there is no circulation of armature current, this condition allows the development of an equivalent circuit model of the synchronous generator (CHAPMAN, 2013).

When a current circulates in the stator of a synchronous machine, around the windings is produced a magnetic field, transversal that has the tendency to distort the main flow, causing effective total flow to degenerate, this effect and called reinforcement reaction, which is dependent on the intensity of the current and its lag in relation to the induced electromotive force, this reaction is one of the main factors for the difference between the voltage in the terminal and the voltage generated internally (JORDAO, 1980).

In addition to the armature reaction, the stator coils have resistance and self-inductance value, which assigns even more to the differentiation between the value of the induced voltage and the de facto voltage in the generator terminals (UMANS, 2014). Taking into account the effects of reinforcement reaction and the physical properties of stator coils, the terminal voltage is described (in a given phase of the generator (CHAPMAN, 2013).

$$V\phi = E_A - jX_s I_A - R_A I_A$$

3

Where:

$V\phi$ = Generator output terminal voltage;

E_A = internally induced voltage in the generator;

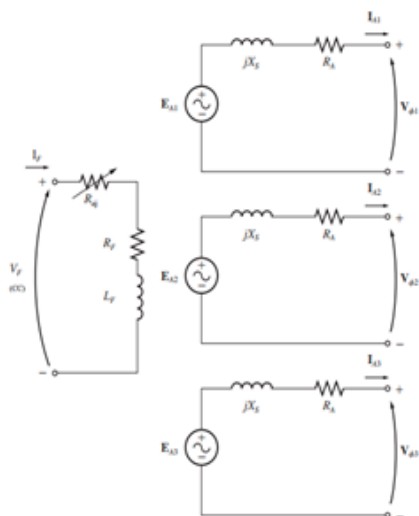
jX_s = reinforcement reaction in conjunction with stator self-inductance called synchronous reactance;

R_A = stator resistance;

I_A = armor chain;

From equation 3, the equivalent circuit of a synchronous machine that can be seen in Figure 2 is characterized, where we have the rotor and its direct current excitation and its reactances and the right, the induced stresses, its three respective phases and their reactances, such as the terminal voltage in each of the phases.

Figure 2 - Equivalent circuit of a three-phase synchronous machine.



Source: Chapman, 2013.

In a synchronous machine under operating conditions where terminal voltage and armature current are constant, an apparent output power value can be defined by the voltage product by current ($UMANS, 2014$). The apparent power being defined as: ($V\phi)(I_A)$)

$$S = \sqrt{P^2 + Q^2}$$

Where:

S = apparent power;

P = active power;

Q = reactive power;

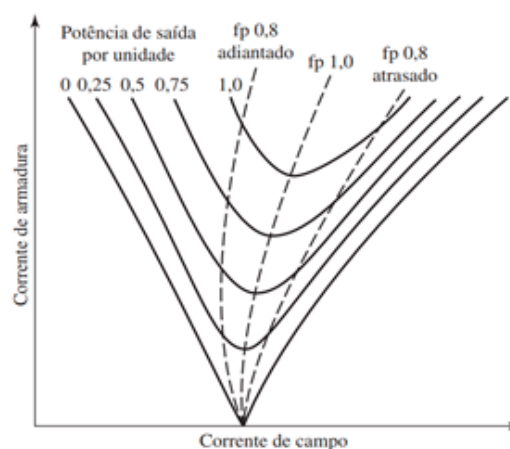
For a constant load, the induced voltage is dependent on the magnetic flow of the machine as shown in equation 4, where the flow is related to the excitation current of the rotor, if the current is controlled in order to make induced voltage lower than the terminal voltage, the generator is under excited. Similarly, it can change the current value, producing a terminal voltage greater than the induced voltage the generator is over-excited (NASAR, 1984).

In a synchronous generator, sub excitation means absorbing reactive power presenting an early power factor, over-excitation occurs when the generator provides reactive power and presents delayed power factor (UMANS, 2014).

According Umans (2014), for a given active power load and terminal voltage, the operating power factor of synchronous machine and its armature current can be controlled by varying the field current. This feature is very important in synchronous machines that makes one of its applications be the correction of power factor (NASAR, 1984).

By varying the field current, you obtain distinct current values of reinforcement), assuming a constant power, you can plot a characteristic curve for the generator, this curve is called the V curve of the synchronous machine (NASAR, 1984). Figure 3 exemplifies a V curve of a synchronous generator, where it presents five curves for different operating powers. (I_f)(I_A)

Figure 3. Asynchronous machine v - curve.



Source: Umans ,2014.

The present work aims to automatically test the v-curve of a synchronous generator, to perform it is necessary the mechanical excitation of the generator shaft, one of the choices for this is a direct current motor.

2.1.2 DIRECT CURRENT MOTOR

For Carvalho (2011), direct current motors are composed of two main parts, stator and rotor. The stator is where field windings are found in each pole individually, and has the function of producing the static magnetic field, this set are known as polar shoe. The stator in turn is composed of reinforcement windings, which are characterized by the production of the rotating field. The components of a direct current machine are described below.

- **Switch:** It is a mechanical converter that ensures that the direction of current circulating in the reinforcement windings is always the same.
- **Brushes:** are responsible for the electrical contact between the stator and the rotating part of the motor.
- **Interpoles or Compensation Poles:** are made available between the poles and the polar shoe, connected in series with the armor, in order to reduce effects from the reinforcement reaction.

In the direct current motor, there are distinct ways of excitation of its windings, which can be form (TORO, 2016). Individual where each of its windings has a current source remains its own, in this type of connection, and possible to perform the speed control, through the variation of the reinforcement tension if maintained the constant flow called reinforcement control. You can also control the velocity by varying the flow by maintaining the static reinforcement stress, called field control (FUENTES, 2005).

The type of excitation in derivation or shunt to which windings are distributed in parallel, in order to use only one energy source, and present constant velocity, even being subjected to load variations (FUENTES, 2005).

Engines with winding in series where, the armature current and the field current are the same, making it possible to change the speed through the variation of terminal voltage in the engine, but there is the empty start (CHAPMAN, 2013).

The connection of the windings in a composite form presents the junction of the series and parallel characteristics, the serial part of the field winding assists or opposes the parallel part of the winding (FUENTES, 2005), in the same way that the shunt connection presents constant speed when it opposes, and little variability when the series winding assists (ORNELAS, 2000).

A direct current motor can be modeled mathematically through electrical, mechanical, and electromechanical quantities, by defining the voltage applied in its reinforcement winding as input variable, angular velocity and position are quantities that are interested in controlling are the system output variables.

The transfer function of a continuous current motor $G(s)$ is:

$$G(s) = \frac{\omega(s)}{Va(s)} = \frac{Km}{(Ra + L_a s)(Js + f) + KmKg} \quad 5$$

Where:

$\omega(s)$ = angular motor speed

$Va(s)$ = armor voltage

Km = torque constant

Ra = armor resistance

L_a = armor inductance

J = moment of inertia of the load

f = viscous coefficient of friction

Kg = Constant force against electromotive

When the direct current motor is in operation, its speed may undergo changes, either through mechanical variations in load or changes in the supply voltage, Through the function of direct current motor transfer relating angular speed and reinforcement voltage, it can vary its speed where there are several control methods which PID control method (proportional, integral and derivative) stands out for this application (PATANÉ, 2008).

2.1.3 PID CONTROL

The transfer function is defined as the algebraic relationship between the output of any system with its respective input (NISE, 2017). The control techniques are based on the feedback principle, where the measurement of the output signals is through these, you can change the input of the system in order to control the output of the system, since the system is previously characterized by its transfer function as can be demonstrated in equation 5 (BAYER; ARAÚJO, 2011).

The type of control algorithm with the highest industrial application is the PID method, even though it is one of the oldest, when compared to new techniques using first-rate digital technology (GARCIA, 2003). Where PID stands out for being a robust controller due to its simple functionality, for the sizing of a controller of this type it is necessary to determine three parameters, proportional gain, integral gain and derivative gain (DORF; BISHOP, 2001).

The transfer function of a PID controller is:

$$Gc(S) = K1 + K2/s + K3s \quad 6$$

Where:

$K1$ = is characterized by the proportional part of control

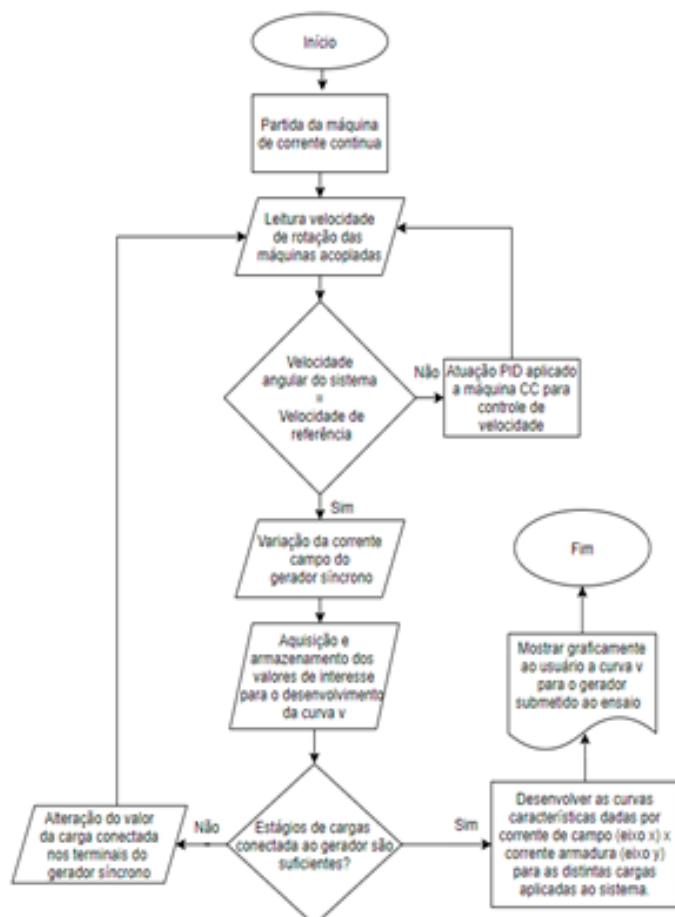
$K2/s$ = is characterized by the integrative part of control

$K3s$ = is characterized by by control derivative Through the control methods it is possible to perform the speed variation of the direct current motor, by comparing the angular velocity and its reinforcement voltage.

2.2 METHODOLOGY

This project aimed to simulate the development of an automated test system in a synchronous generator in order to obtain its v-curve, through measurements and controls mediated by the LabVIEW graphical programming language in conjunction with Simulink software that provides an interface for modeling and analysis of dynamic systems. Image 4 demonstrates the flowchart of the method applied in the simulation to obtain the v-curve.

Figure 4 - Flowchart method applied to carry out the project.



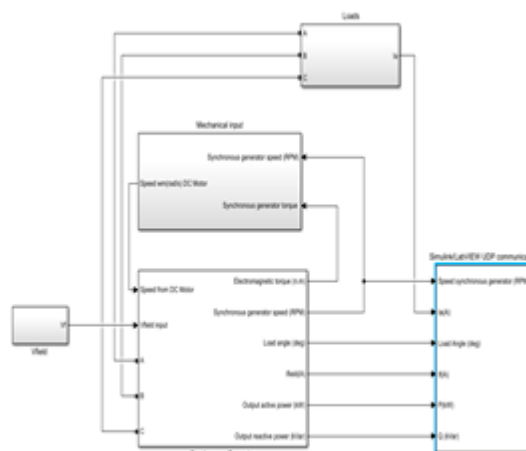
Source: The Author. 2020

3. RESULTS

3.1 ASPECTS OF THE SYSTEM MODEL IN SIMULINK SOFTWARE

The simulation of the system consists of the modeling via Simulink presented in image 5, then the interest values for analysis and development of the v curve are sent to LabVIEW through the UDP communication protocol after receiving these data will be processed and finally the v curve is traced, the results presented are divided into the following sections.

Figure 5 - Physical system model for simulation

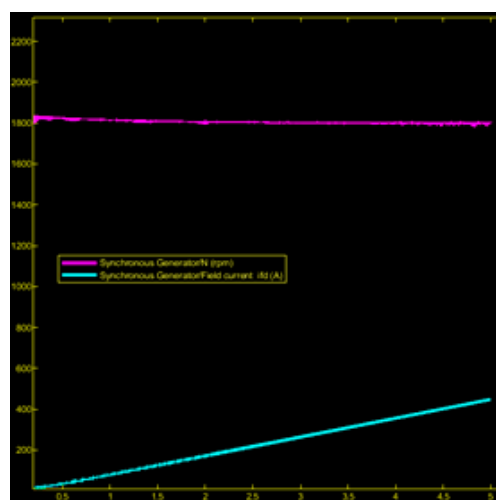


Source: The Author. 2020

3.1.1 MECHANICAL POWER SUPPLY SYSTEM FOR SYNCHRONOUS GENERATOR

The project aimed to test a synchronous generator, which for the generation of electricity requires a mechanical energy source that will be converted into electric, for a synchronous generator to work at constant frequency as defined in equation 2, a constant rotation speed independent of the load variations is required, for this purpose a direct current motor with regulated speed was used through pid control algorithm where its speed is measured is used as a setpoint generating a variation of the armature voltage of the engine through an H-bridge system that receives a PWM signal generated from the output of the PID controller in conjunction with a PWM generator controlling the pulse width of the signal.. For greater veracity of the system the speed of the direct current motor is dependent on the electromagnetic torque of the synchronous generator. Figure 6 brings the behavior of synchronous generator speed before field current variation to a constant load connected to the terminals with the speed feedback system of the direct current machine.

Figure 6 - System response synchronous machine rotation speed under field current variation.

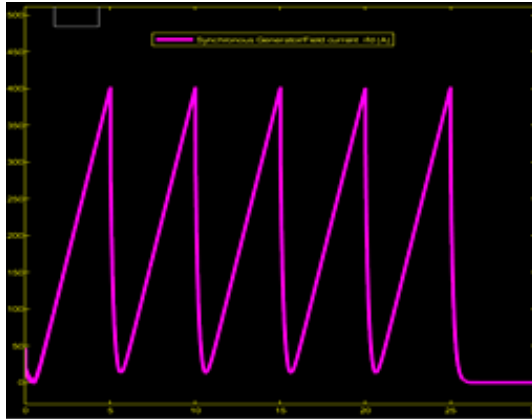


Source: The Author. 2020

3.1.2 SYNCHRONOUS GENERATOR FIELD EXCITATION AND LOAD BANK

The variation of the field current and made by means of timed swsows in Simulink itself, through the use of ramp signals. Figure 06 demonstrates the field current variation of the synchronous machine during the simulation, for a v-curve test in 5 distinct power stages.

Figure 7 - Demonstration of the variation of the field current applied in a generic model of a synchronous generator for different stages.



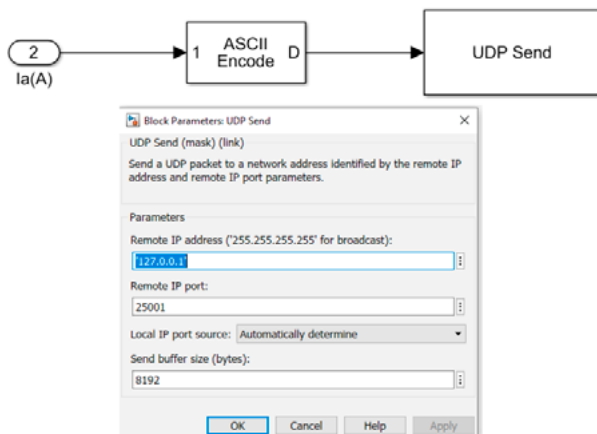
Source: The Author. 2020

The system works in a timed manner, for the variation of the electrical load applied to the generator

3.1.3 DATA TRANSFER BETWEEN SIMULINK AND LABVIEW

There are different ways to perform communication between Simulink and labVIEW, can occur through serial communication, by drivers that implement virtual instrumentation or even by communication protocols such as udp that was adopted in the present work, due to the practicality of application of the same. image 8 shows the blocks responsible for up communication between the software, we notice the presence of a block that encodes the signal sent according to the ascii table.

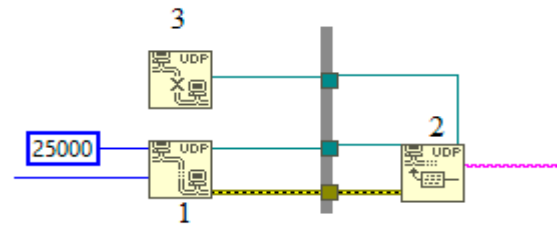
Figure 8 - Sending signals by Simulink.



Source: The Author. 2020

In the LabVIEW data received through UDP communication through native blocks of your library, Figure 9 demonstrates the three fundamental blocks for the reading application performed.

Figure 9 - Receiving signals by LabVIEW.



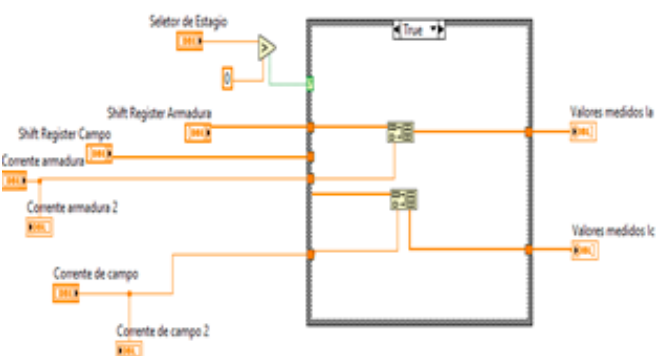
Source: The Author. 2020

Where:

1. UDP Open: opens a socket on the port defined by a constant numeral value;
2. UDP Read: read the socket defined in block 1;
3. UDP Close: Closes the previously defined socket.

When the data is received by LabVIEW, in text format which makes it necessary to convert these to numeric variables that is made from a subVI that performs this conversion. After the conversion of the data, the separation of the data obtained in each of the measurement stages for different powers applied to the generator is carried out by means of a second subVI used in series for the different measurement stages, the separation of each step is done by means of signals that are sent by the model in Simulink when the value of the load connected to the generator terminals occurs, this signal is used as a condition for a case structure in LabVIEW, while that signal is present the subVI will store the measured values. Image 8 demonstrates the subVI mentioned earlier for the acquisition of the field current and armature values of the synchronous generator where the storage of the same is done through shift registers according to the loop interactions of the main VI where arrays are formed containing the obtained values.

Figure 10 - Selection of power stage provided and storage of the field current and reinforcement of the synchronous generator



Source: The Author. 2020

After the acquisition and storage process, the v-curves of the synchronous generator are developed, soon after the field current x current reinforcement graphs are developed that characterize the v curves of the generator according to the different powers provided by the generator. Table 1 shows the constructive characteristics of a synchronous generator.

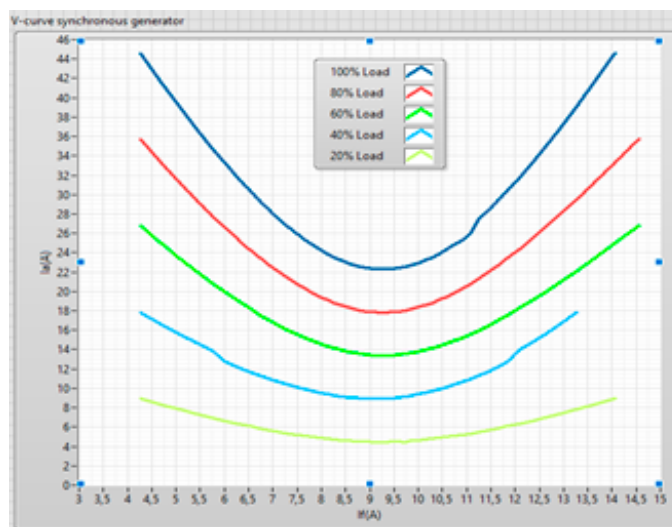
Table 1. Constructive characteristics of a synchronous generator.

	Valor
Tensão nominal (V)	220
Potência nominal (kVA)	10
Frequência (Hz)	60
Velocidade nominal (RPM)	1800
Reatância síncrona (Ω)	4,84
Reatância de armadura (Ω)	0,484
Fator de Potência da Carga	0,85 l
Número de polos	4

Source: The Author. 2020

As curvas v obtidas para o gerador descrito acima, podem ser observadas na figura 11, onde trabalhou-se com cinco valores de carga distintos.

Figure 11 – V-curve analysis of the synchronous machine described in table 1



Source: The Author. 2020

4. DISCUSSION AND CONCLUSIONS

The process for the simulation of an automatic analyzer for v-curve of synchronous generators has fulfilled the desired requirements, presenting a model that represents the actual operation of a mechanical coupling between a direct current motor and a synchronous generator, from the system of supply of mechanical torque by the direct current motor as of the responses of the synchronous machine submitted to the test.

In future works, it is recommended to apply the test method in a real synchronous machine, where both software used in this project can be used to interfacing sensor data acquisition, application of control methods among other activities that will be necessary.



REFERENCIAS



- Bayer, F.M.; Araújo, O.C.B. Controle Automático de Processos. 3. ed. Santa Maria: Universidade Federal Santa Maria, 2011. 91 p. Disponível em: <http://estudio01.proj.ufsm.br/cadernos_automacao/quinta_etapa/controle_automatizado_processos_2012.pdf>. Acesso em: 10 maio 2020.
- Castro, C. A. Geradores Síncronos. Notas de aula. Faculdade de Engenharia Elétrica, UNICAMP. Disponível em: <<http://www0.fee.unicamp.br/cursos/ET720/>>. Acesso em: 19 fev. 2020.
- Chapman, S. J. Fundamentos de Máquinas Elétricas. 5. ed. New York: McGraw-Hill, 2013.
- Dorf, R. C.; Bishop, R. H. Sistemas de controle modernos. 8. ed. Rio de Janeiro: Ltc, 2001.
- Fuentes, R.C. Apostila de Automação Industrial. Colégio Técnico Industrial de Santa Maria, 2005. Disponível em: <http://w3.ufsm.br/fuentes/index_arquivos/CA05.pdf>. Acesso em: 20 abr. 2020.
- Garcia, C. Controle de Processos Industriais, Apostila do curso de pós graduação em Instrumentação, Automação e Controle, IMT – Instituto Mauá de Tecnologia, Escola de Engenharia Mauá, 2003.
- Jordao, R, G. Máquinas Síncronas. Rio de Janeiro: Editora da Universidade de São Paulo, 1980.
- Kosow, I. L. Máquinas Elétricas e Transformadores. Porto Alegre: Editora Globo, 1982.
- Mamede Filho, J. Manual de equipamentos elétricos. 4 ed. Rio de Janeiro: LTC, 2013.
- Monticelli, A.J, A. Introdução a Sistemas de Energia Elétrica. São Paulo: Editora Unicamp, 2003.
- Nasar, S. A. Máquinas Elétricas. São Paulo: Editora McGraw-Hill do Brasil, 1984.
- National Instruments.” O que é aquisição de dados?” 2009. Disponível em: <<https://www.ni.com/data-acquisition/what-is/pt/>>. Acesso em: 21 fev. 2020.
- Nise, N. S. Engenharia de Sistemas de Controle. 7. ed. Rio de Janeiro: LTC, 2017.
- Ornelas, P. “Motores Elétricos de Corrente Contínua Universidade Federal da Bahia” – Escola Politécnica – DEM, 2000.
- Possatti, L. H. F. “Identificação de Parâmetros de Máquinas Síncronas Utilizando Dados Operacionais”. 2013. 167 f. Dissertação (Mestrado) - Programa de Engenharia Elétrica, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 2013.
- Souza, M. H. “Determinação de Parâmetros de Máquinas Síncronas Pelo Ensaio de Resposta em Frequência: Proposta de Metodologia com Inversor de Frequência”. 2011. 93 f. Dissertação (Mestrado em Engenharia) - Escola Politécnica da Universidade de São Paulo, São Paulo, 2011.
- Toro, V. Del. Fundamentos de máquinas elétricas. Rio de Janeiro: LTC, 2016.
- Umans, S. D. Máquinas elétricas: de Fitzgerald e Kingsley. 7. ed. Porto Alegre: AMGH, 2014.