Synchronous Generator Simulation Using LabVIEW

(Student Paper)

M. Usama Sardar

Abstract**—**Computer-aided teaching tools have turned out to be an indispensable element of both classroom lectures and laboratory experiments. The application of market-ready mathematical and database programming software for teaching engineering course outline is well appreciated. This paper presents the utilization of *LabVIEW* (Laboratory Virtual Instrument Engineering Workbench) in introducing the features of electrical machine simulated at various possible control modes. The undergraduate students need minimal acquaintance of a programming language. The examples presented in the paper illustrate how LabVIEW software can be applied to simplify some of the steady-state characteristics of the three-phase synchronous generator operating alone. The result of introducing LabVIEW software as a teaching tool at the third-year level has been accepted and is now used as part of the practical sessions for the electrical machines course at Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, N.W.F.P. in Pakistan.

Keywords**—**Electric Machines, LabVIEW, simulation, synchronous generator.

I. INTRODUCTION

A. Need for a Change in Teaching Methodology

MODERN programming softwares are equipped with highly interactive displays, signal processing, prototyping, three–dimensional (3-D) plots, X–Y graphs, word processing and data layering to facilitate swift elucidation and presentation of results and trends. The direct application of this sort of software drastically simplifies simulation procedures for several practicing engineers in addition to undergraduate engineering students. The integration of the generator and electronics to adjust the inherent generator characteristics creates complications for the instructor to make things easier and present the subject matter to undergraduates without the assistance of some type of electronic simulation tools. A successful simulation tool necessitates time, energy, and proficiency in programming languages and general comprehension of the operational characteristics of the electrical machine and its performance.

It is indispensable to emphasize the engineering education curriculum with computer-aided teaching tools that are interactive as well as educational, in order to keep sustainable interest in the learning process for the students. For these reasons LabVIEW, a graphical programming language was introduced to initiate the modifications in teaching methodology at the Ghulam Ishaq Khan Institute of Engineering Sciences and Technology.

B. Core Technical Advantages of LabVIEW

The importance of LabVIEW can be realized by the following statement of the Associate Director of Penn State University:

"LabVIEW is a programming language, equivalent to C++, Visual Basic, or any other language. It is the *only* widely accepted graphical programming language. Graphical programming is a language of the future and carries with it many important programming concepts. I feel, it is the responsibility of universities (such as Penn State) to expose, at least, every computer science and engineering student to these new concepts."- Scott Deno, Associate Director Center for Electronic Design, Communications, and Computing Penn State University.

The visual representations bring programming closer to the human side of the human–machine interface, just as high-level languages tipped the accessibility scales relative to assembly languages. Moreover, LabVIEW has proven to be an invaluable tool in decreasing development time in research, design, validation, production test, and manufacturing. Besides this, the major advantages of LabVIEW include ease of learning, using and debugging, the simplicity of using the interface (front panel of a LabVIEW program) particularly for a user with a little or no knowledge of LabVIEW programming, modular development, complete functionality, available tools and resources, reliable performance and the capability of controlling equipment.

There are four critical elements of the LabVIEW development platform:

i) Intuitive graphical programming language
ii) High-level application-specific tools
iii) Integrated measurement and control-specific capabilities
iv) Multiple computing targets

II. LABVIEW SOFTWARE AS AN EDUCATIONAL TOOL FOR ELECTRIC MACHINE CASES

In 2006, the faculty of electronics engineering at Ghulam Ishaq Khan Institute of Engineering Sciences and Technology introduced LabVIEW software on a trial basis with the aim of enhancing interactive teaching and learning of the electric machines course. Synchronous generator simulation is straightforward once the fundamental features of LabVIEW software are mastered.

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Obviously, LabVIEW software is extensively used for several scientific and engineering applications and is not the only software available. It is easy to use and has numerous built-in functions that facilitate its use in many textbook applications. The next sections will reveal the versatility of adopting LabVIEW in evaluating the steady state characteristics of three-phase synchronous generator under variable input conditions. The multiple-choice electronic menu created by MS Access software as seen in Figs. 1 and 2 given to the student is used to navigate through LabVIEW programs according to the course outline.

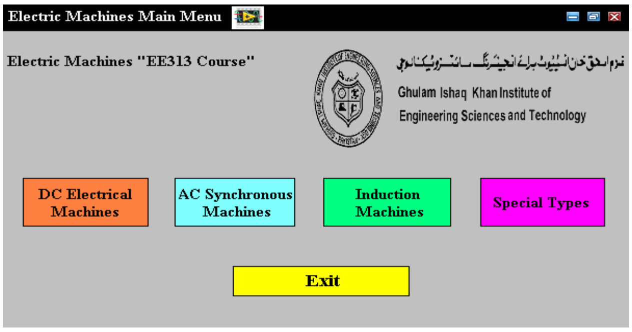

Fig. 1 The interactive electronic main menu

A. The Presentation of the Synchronous Generator Characteristics by LabVIEW

In electrical generator, the mechanical energy input and the electrical energy output can be presented in mathematical form, after presenting the physical operation of the generator with the equivalent electric circuit of the 3-ϕ synchronous generator shown in Fig. 3. The electric circuit is used to facilitate the calculation of the unknown quantity, for instance current or voltage, once the values of the resistive and inductive components are given. The values could be evaluated experimentally by conducting short-circuit and open-circuit tests on the generator if that is possible; otherwise, the manufacturer should be contacted for the information.

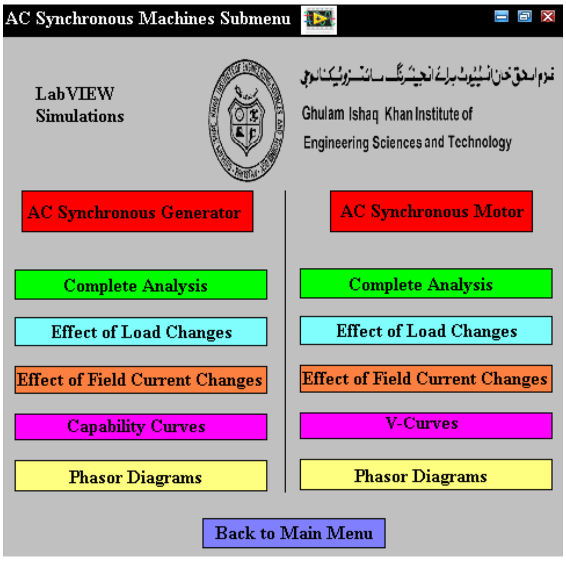

Fig. 2 The multiple-choice submenu for AC synchronous machines

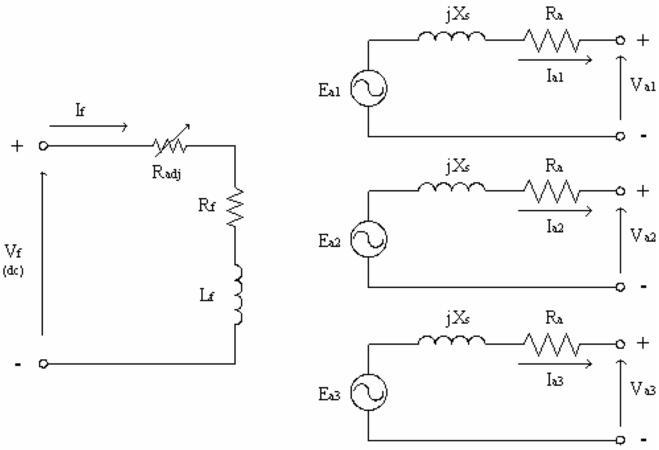

Fig. 3 The full equivalent circuit for a three-phase synchronous generator

The power flow, shown in Fig. 4, within the generator is tracked by balancing the input and the output taking into account the heat and magnetic power losses. The losses are quantified by performing several standard tests on the generator. The current flowing in the generator can be calculated using the equivalent circuit representing the generator physical elements. The steady-state developed torque and power are then evaluated and plotted to reveal the generator characteristics. The expected efficiency of those particular parameters can also be plotted. Almost every textbook presents the synchronous generator by it's per phase equivalent circuit, as shown in Fig. 5, and shows how steady-state current and power are estimated. In many cases, the armature resistance and copper losses are ignored to simplify the procedures.

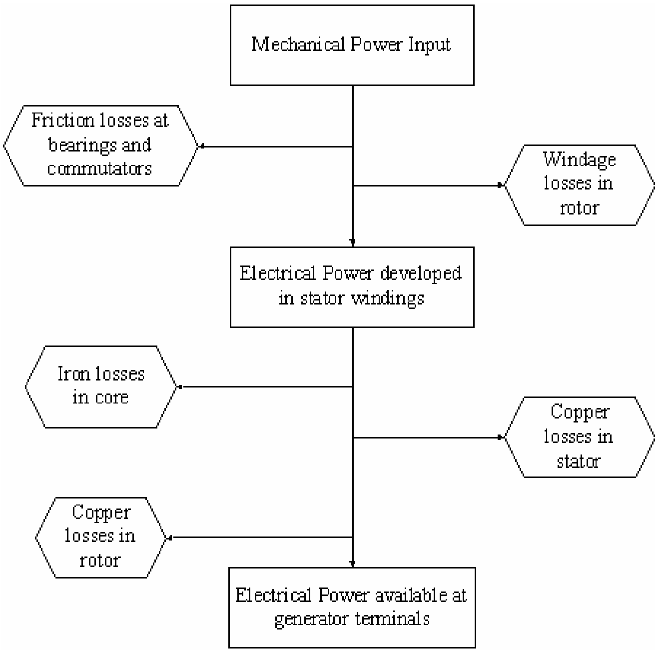

Fig. 4 The three-phase synchronous generator power flow diagram

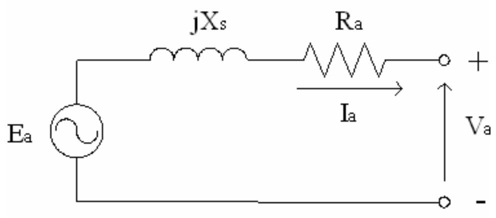

Fig. 5 The per-phase equivalent circuit of the synchronous generator

In many textbook examples, the synchronous generator current can be estimated with fairly acceptable accuracy using the above methodology. Example 1 (shown in the Appendix) presents the standard steps to determine the internal generated voltage using the equivalent circuit for the synchronous generator.

B. *The Student Interaction with the Software*

The practicality of using LabVIEW software for the student is that it will be possible to input various configurations of variables without any knowledge of text-based programming. The use of the built-in functions of the software in an interactive way to produce the complete generator characteristics over the entire variable range instead of just one operating point will be more informative for the student. This is one of the advantages over the numerical examples normally presented in the textbook. Therefore, the student can verify all the possible operating points along the generator characteristics. The LabVIEW simulations stored for the student in the electronic database of the course generate complete characteristics over the whole variable range allowing the student to examine the shape and verify different operating points.

Furthermore, the software can be used by the students for verifying laboratory experiments after entering the laboratory generator data and the operating conditions. The recorded test results for the laboratory machines could be compared for further verification between theory and practice.

III. Simulation Cases

To investigate the complete generator characteristics under varying conditions, the following cases are presented.

A. *Effect of Load Changes*

3 situations may arise depending upon the type of load added:

Case 1: If lagging loads are added to a generator, V_{phase} and V_t decrease significantly.

Case 2: If unity power factor loads are added to a generator, V_{phase} and V_t decrease slightly.

Case 3: If leading loads are added to a generator, V_{phase} and V_t increase.

But in many generator applications, we need to maintain V_t as constant. So in that case, E_a will vary. The LabVIEW phasor diagrams for the 3 cases that arise are given below:

Case 1: Effect of adding lagging loads (or inductive reactive power loads):

If lagging loads are added to a generator, E_a increases. Fig. 6 shows the phasor diagram generated in LabVIEW before adding loads and Fig. 7 shows the phasor diagram generated in LabVIEW after the lagging load is added.

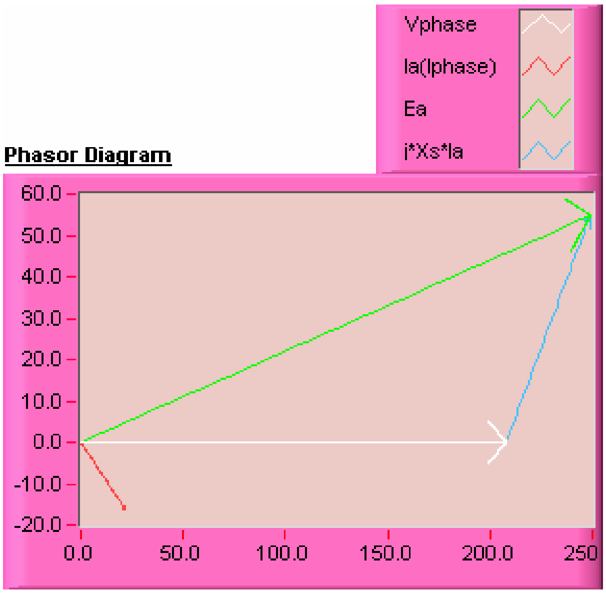

Fig. 6 Phasor diagram generated in LabVIEW before adding loads

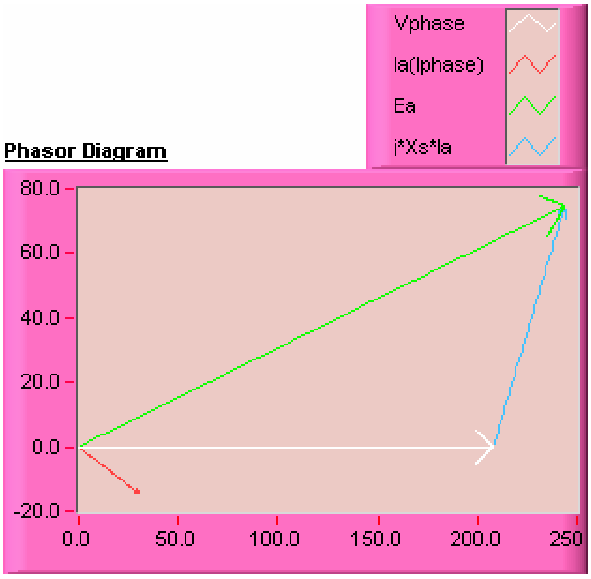

Fig. 7 Phasor diagram generated in LabVIEW after adding the lagging load

Case 2: Effect of adding unity power factor loads (no reactive power loads):

If unity power factor loads are added to a generator, E_a increases slightly. Fig. 8 shows the phasor diagram generated in LabVIEW before adding loads and Fig. 9 shows the phasor diagram generated in LabVIEW after the unity power factor load is added.

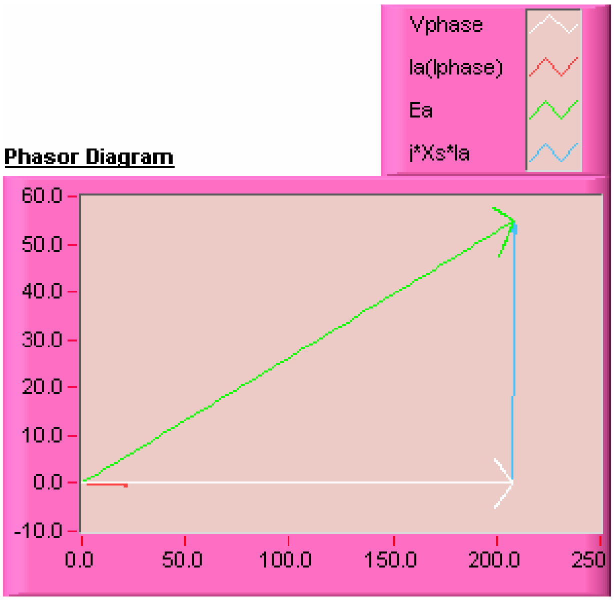

Fig. 8 Phasor diagram generated in LabVIEW before adding loads

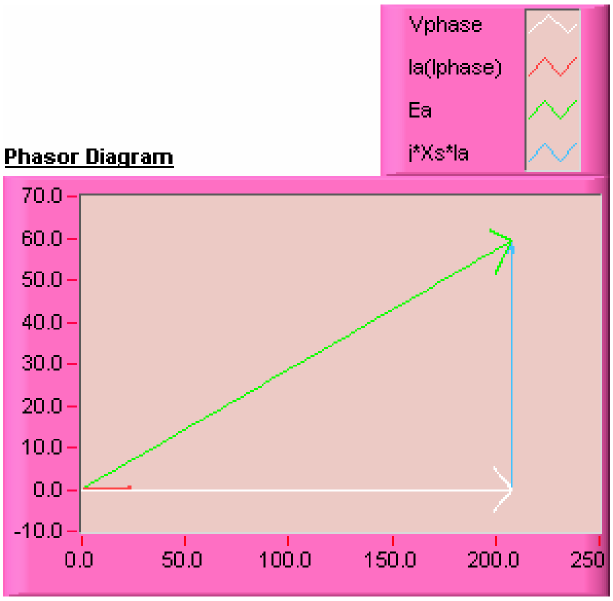

Fig. 9 Phasor diagram generated in LabVIEW after adding the unity power factor load

Case 3: Effect of adding leading loads (or capacitive reactive power loads):

If leading loads are added to a generator, E_a decreases. Fig. 10 shows the phasor diagram generated in LabVIEW before adding loads and Fig. 11 shows the phasor diagram generated in LabVIEW after the leading load is added.

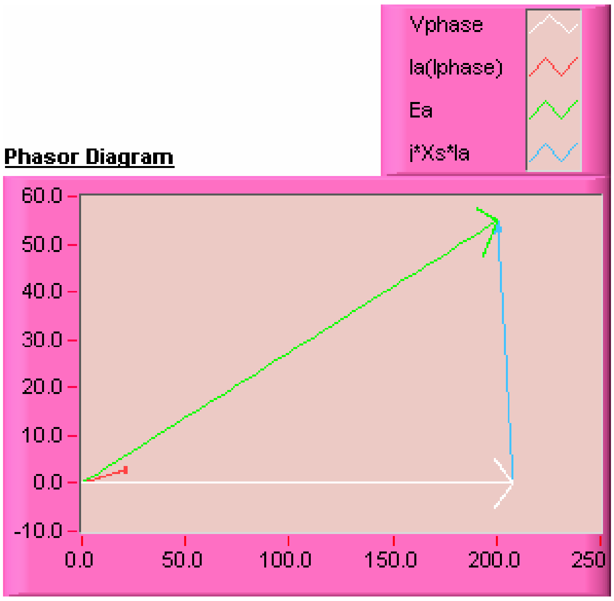

Fig. 10 Phasor diagram generated in LabVIEW before adding loads

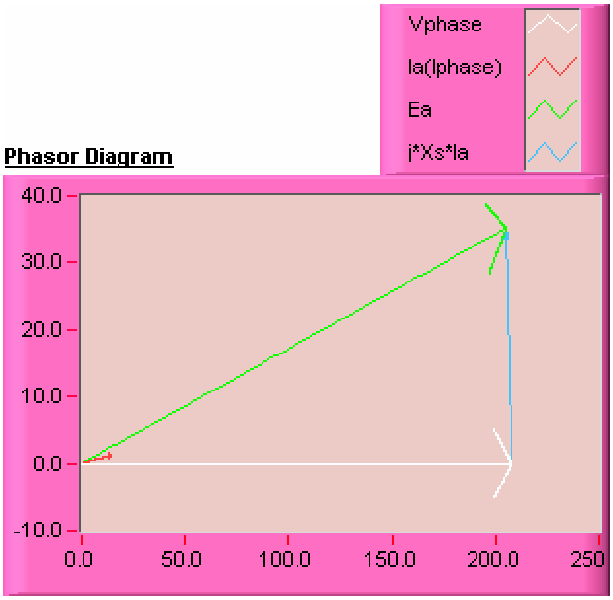

Fig. 11 Phasor diagram generated in LabVIEW after adding the lagging load

B. Output Power

Case 1: Effect of torque angle on output power:

Output power varies sinusoidally with the torque angle if the phase voltage and internal generated voltage are assumed constant. This is shown in Fig. 12.

Effect of Torque Angle on Output Power

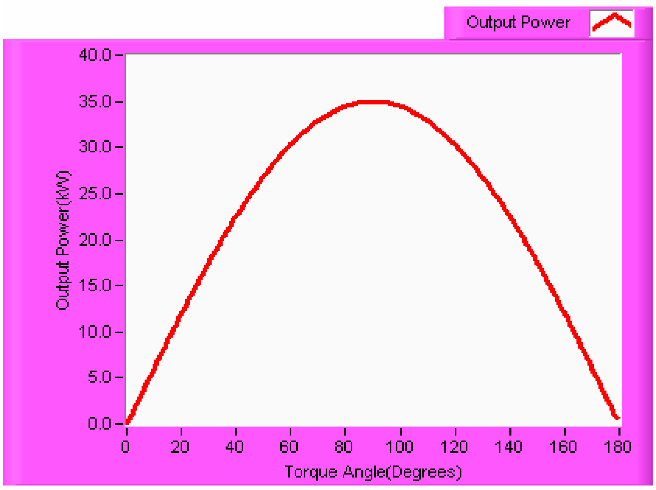

Fig. 12 Graph generated in LabVIEW showing the variation of output power with the torque angle

Case 2: Effect of phase voltage on output power:

Output power varies directly with the phase voltage if the internal generated voltage is assumed constant. This is shown in Fig. 13.

Effect of Phase Voltage on Output Power

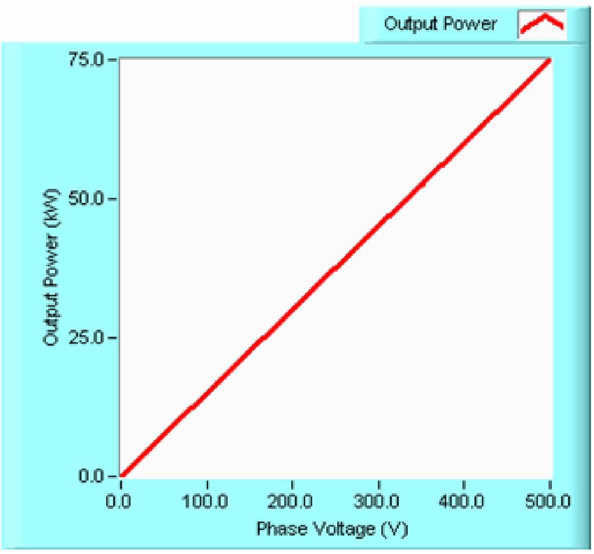

Fig. 13 Graph generated in LabVIEW showing the variation of output power with the phase voltage

Case 3: Effect of synchronous reactance on output power:

Output power varies inversely with the synchronous reactance if the internal generated voltage and phase voltage are assumed constant. This is shown in Fig. 14.

Effect of Synchronous Reactance on Output Power

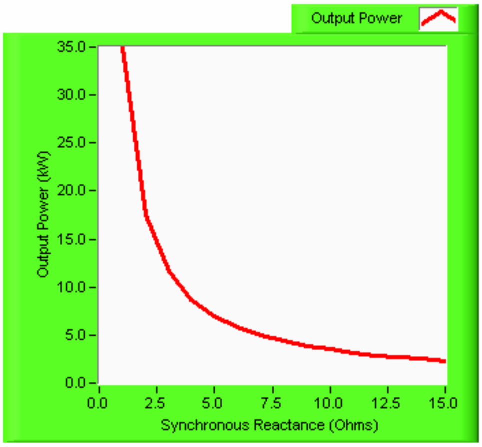

Fig. 14 Graph generated in LabVIEW showing the variation of output power with the synchronous reactance

Case 4: Effect of internal generated voltage on output power:

Output power varies directly with the internal generated voltage if the phase voltage is assumed constant. This is shown in Fig. 15.

Effect of Internal Generated Voltage on Output Power

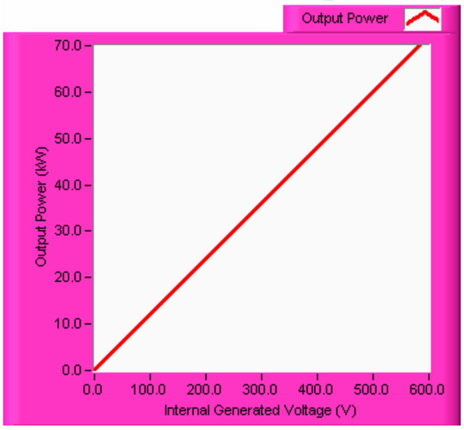

Fig. 15 Graph generated in LabVIEW showing the variation of output power with the internal generated voltage

C. Induced Torque

Case 1: Effect of torque angle on induced torque:

Induced torque varies sinusoidally with the torque angle if the phase voltage and internal generated voltage are assumed constant. This is shown in Fig. 16.

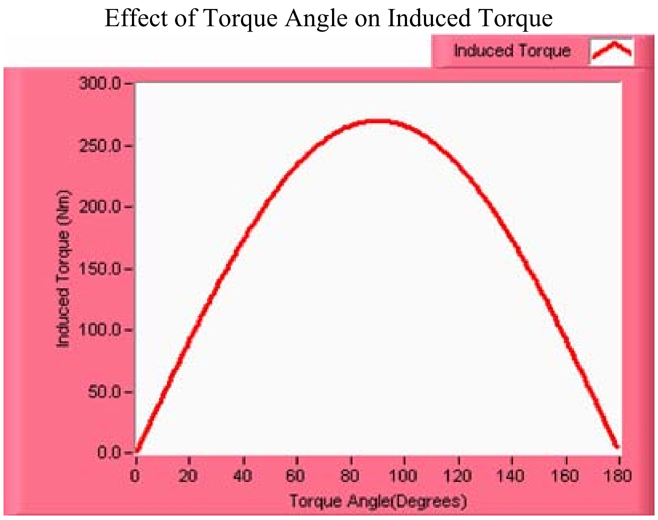

Fig. 16 Graph generated in LabVIEW showing the variation of induced torque with the torque angle

Case 2: Effect of phase voltage on induced torque:

Induced torque varies directly with the phase voltage if the internal generated voltage is assumed constant. This is shown in Fig. 17.

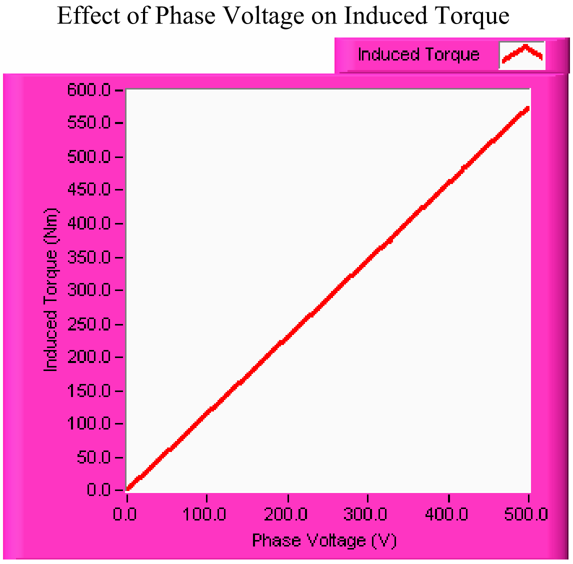

Fig. 17 Graph generated in LabVIEW showing the variation of induced torque with the phase voltage

Case 3: Effect of synchronous reactance on induced torque:

Induced torque varies inversely with the synchronous reactance if the internal generated voltage and phase voltage are assumed constant. This is shown in Fig. 18.

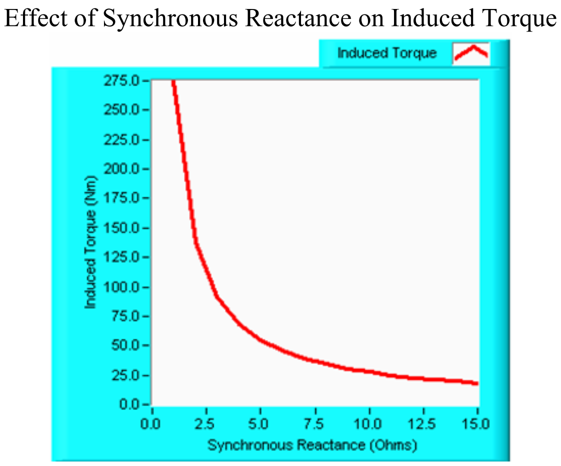

Fig. 18 Graph generated in LabVIEW showing the variation of induced torque with the synchronous reactance

Case 4: Effect of internal generated voltage on induced torque:

Induced torque varies directly with the internal generated voltage if the phase voltage is assumed constant. This is shown in Fig. 19.

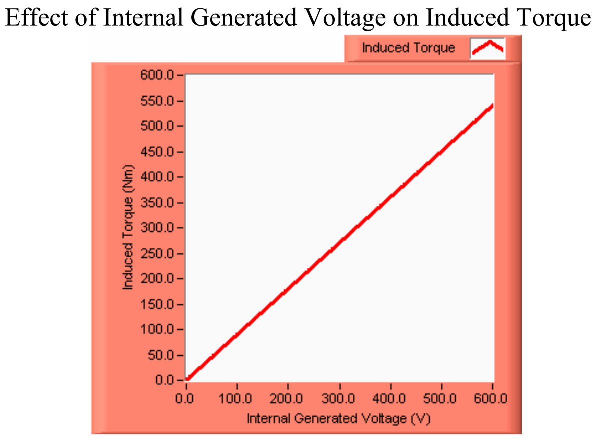

Fig. 19 Graph generated in LabVIEW showing the variation of induced torque with the internal generated voltage

Case 5: Effect of mechanical speed of rotation on induced torque:

Induced torque varies inversely with the mechanical speed if the internal generated voltage and phase voltage are assumed constant. This is shown in Fig. 20.

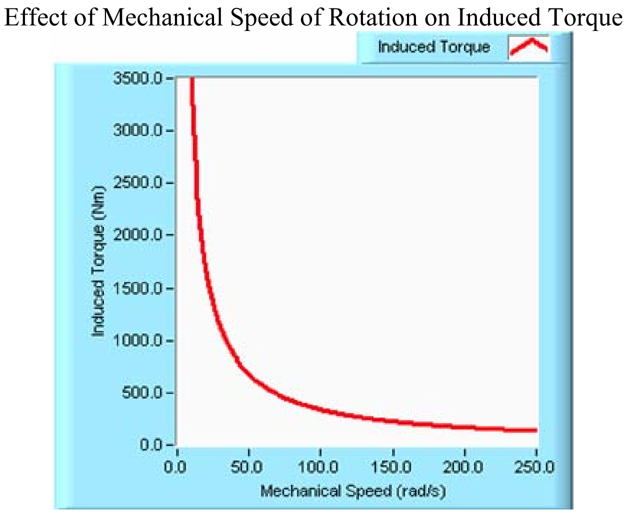

Fig. 20 Graph generated in LabVIEW showing the variation of induced torque with the mechanical speed of rotation

D. Voltage Regulation

Voltage regulation is a quantity that compares the terminal voltage of the generator at no load with the terminal voltage at full load. It is defined by (1):

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\% \qquad (1)$$

Case 1: Lagging power factor:

A generator operating at a lagging power factor has a positive voltage regulation.

Case 2: Unity power factor:

A generator operating at a unity power factor has a small positive voltage regulation.

Case 3: Leading power factor:

A generator operating at a leading power factor has a negative voltage regulation.

E. Synchronous Generator Capability Curves

Synchronous generator capability curves are used to determine the stability of the generator at various points of operation. A particular capability curve generated in LabVIEW for an apparent power of 50,000W is shown in Fig. 21. The maximum prime-mover power is also reflected in it.

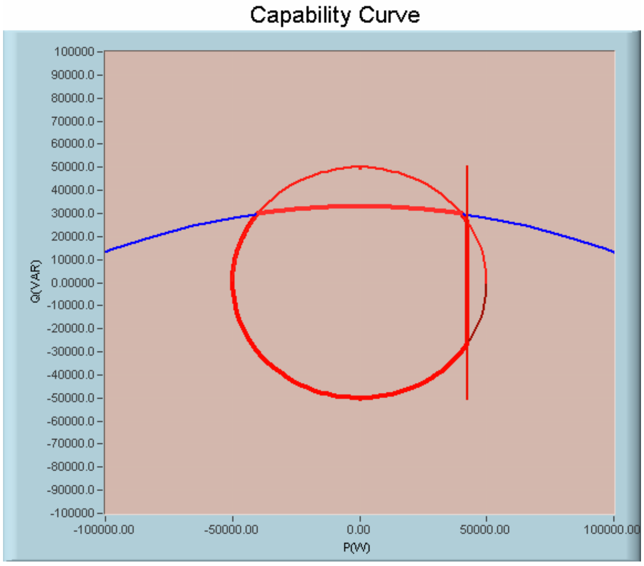

Fig. 21 Synchronous generator capability curve generated in LabVIEW also showing the maximum prime-mover power limit

IV. CONCLUSION

LabVIEW is a wonderful tool to initiate a simple approach to evaluate the steady-state characteristics of the synchronous generator. The software has a high potential for the analysis of system performance and can be used in simulation techniques effectively. The use of the built-in functions of LabVIEW in an interactive way to produce the complete generator characteristics over the entire variable range instead of just one operating point will be more informative for the student. This is one of the advantages over the numerical examples normally presented in the textbook. As computing languages are not essential, the undergraduate student can investigate the synchronous generator characteristics quickly and easily.

APPENDIX

The following numerical example shows the result of changing the loads on the generator. It can be observed from part (c) of example 1 that E_A increases when lagging power factor loads are added. Similarly, the fact that E_A decreases when leading power factor loads are added is shown with the help of part (f) of example 1. These results are in conformity with the section A of the simulations cases described above with the help of phasor diagrams generated in LabVIEW.

Example 1:

A 480-V, 60-Hz, Δ-connected, four-pole synchronous generator has a synchronous reactance of 0.1 Ω and an armature resistance of 0.015Ω. At full load, the machine supplies 1200A at 0.8 PF lagging. Under full-load conditions, the friction and windage losses are 40 kW, and the core losses are 30 kW. Ignore any field circuit losses.

(a) What is the speed of rotation of this generator?

(b) How much is the internal generated voltage of the generator in order to make the terminal voltage 480 V at no load?
(c) If the generator is now connected to a load, and the load draws 1200 A at 0.8 PF lagging, how much will the internal generated voltage be to keep the terminal voltage equal to 480 V?
(d) How much power is the generator now supplying? How much power is supplied to the generator by the prime mover? What is this machine's overall efficiency?
(e) If the generator's load were suddenly disconnected from the line, what would happen to its terminal voltage?
(f) Finally, suppose that the generator is connected to a load drawing 1200A at 0.8 PF leading. How much will the internal generated voltage be to keep V_t at 480V?

Solution:

This synchronous generator is Δ-connected, so its phase voltage is equal to its line voltage, while its phase current is related to its line current by the equation:

$$I_L = \sqrt{3} I_{\Phi}$$

(a) The relationship between the electrical frequency produced by a synchronous generator and the mechanical rate of shaft rotation is given by the following equation:

$$n_m = \frac{120 f_e}{P}$$

Substituting the given values:

$$n_m = \frac{120(60)}{4} = 1800 r/\min$$

(b) Since the generator is at no load, I_A=0, thus

$$E_A = V_{\Phi} = V_T = 480V$$

(c) If the generator is supplying 1200A, then the armature current in the machine is

$$|I_A| = \frac{I_L}{\sqrt{3}} = \frac{1200}{\sqrt{3}} = 692.8A$$

PF=0.8 lagging, so

$$I_A = 692.8\angle -36.8^o A$$

If the terminal voltage is adjusted to be 480V, the internal voltage is given by:

$$E_A = V_{\Phi} + R_A I_A + jX_S I_A$$

$$= 480\angle 0 + (0.015)(692.8\angle -36.8^o) + (j0.1)(692.8\angle -36.8^o)$$

$$= 532\angle 5.3^o V$$

Thus to keep V_T = 480V, E_A must be adjusted to 532V. This shows that E_A increases when lagging power factor loads are added because the value of E_A was 480V as shown in part (b).

(d) The power that the generator is now supplying can be found from the following equation:

$$P_{out} = \sqrt{3} V_T I_L \cos\theta$$

$$= \sqrt{3}(480)(1200)\cos(36.87) = 798kW$$

The mechanical input power is given by:

$$P_{in} = P_{out} + P_{elec-loss} + P_{core-loss} + P_{mech-loss} + P_{stray-loss}$$

Where it is given that:

$$P_{core} = 30\,kW$$

and

$$P_{windage} = 40kW$$

The stray losses were not specified here, so they will be ignored. In this generator, the electrical losses are:

$$P_{elec-loss} = 3I_A^2 R_A = 3(692.8)^2(.015) = 21.6kW$$

So the total input power to the generator is:

$$P_{in} = 798 + 21.6 + 30 + 40 = 889.6kW$$

Therefore, the machine's overall efficiency is:

$$\eta = P_{out} / P_{in} \times 100\% = 798/889.6 \times 100\% = 89.75\%$$

(e) If the generator's load were suddenly disconnected from the line, the current I_A would drop to zero. Since the field current has not changed, V_T and Vφ must rise to equal E_A. Therefore, if the load were suddenly dropped, the terminal voltage of the generator would rise to 532V. Thus

$$V_T = 532V$$

(f) If the generator were loaded down with 1200A at 0.8 PF leading while the terminal voltage was 480V, then the internal generated voltage would have to be:

$$E_A = V_{\Phi} + R_A I_A + jX_S I_A$$

$$= 480\angle 0 + (0.015)(692.8\angle 36.87^o) + (j0.1)(692.8\angle 36.87^o)$$

$$= 451\angle 7.1^o V$$

Therefore, the internal generated voltage E_A must be adjusted to 451V if V_T is to remain at 480V. This shows that E_A decreases when leading power factor loads are added because the value of E_A was 480V as shown in part (b).

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First of all, I am very thankful to God, who made me able to work hard and complete my research paper. Specially, I would like to express my sincere thanks to my supervisor ***Dr. Laiq Khan*** who enlightened me with the concepts of electric machines in detail and broadened my vision regarding the subject. His help was indispensable in mastering the vast subject of electric machines, in particular synchronous generators. He was generous enough to give me much of his precious time and his encouragement in writing the paper was vital for me. He not only reviewed the paper but also suggested the necessary corrections in it. I am really grateful to him for all his help and time.

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