Using PLC Based HMI System to Teach Power System Analysis

M.M. A. Rahman, Member ASEE
Grand Valley State University
Grand Rapids, MI
rahmana@gvsu.edu

Abstract
This paper presents an application of a PLC based human machine interface (HMI) system of a model power plant, developed through a masters project, to teach topics on power system analysis. The analysis of power system voltage and current evolved from phasor methods, a mathematical method for solving linear sinusoidal steady-state circuits and time-varying electromagnetic fields, to synchrophasor methods. Synchrophasor is a widely used method in the monitoring and analysis of power systems that employs a way to synchronize real-time phasor measurements of voltage, current, and power. In this HMI system, synchrophasors are used to monitor and control the output parameters of a generator in a model power plant. In this method students can see the time-variation of voltage and current instead of a mathematical representation (phasor) of this variation. Making this HMI system the main center of interest when teaching power system analysis topics such as alternator (ac generator) voltage generation and regulation can, therefore, be highly advantageous. This paper describes a unique teaching experience using the HMI system along with the phasor, and simulation method for understanding such power system topics. It was noticed that this pedagogical scheme satisfies the students, helps them understand the effect of loading on generator voltage regulation and control, and promotes a wide variety of competences.

1. Introduction

Historically, Electrical Engineering started with power engineering that deals with the generation and distribution of electrical energy. According to the National Academy of Engineering[1], electricity and its accessibility are the greatest engineering achievements of the 20th century, ahead of computers and aeroplanes[2]. In power engineering curriculum around the world, the topics related to the generation, transmission, and distribution this electricity are taught in power system analysis course using theory, simulation, and experimental techniques. In 2014, Consumers Energy of Michigan decided that the experimental analysis of a commissioned generator can be expensive and creates safety risks due to high voltages and currents involved. Having a reduced scale model of the generator for experimental purposes can mitigate cost and safety concerns. As a result, they collaborated with Grand Valley State University to develop a PLC based HMI system for a model power plant as shown in Figure 1. Pedagogical motivation behind this development was the possibility of using this reduced scale model for educational purposes. Once the prototype was developed, this model plant was used to study the voltage generation and regulation of generators under different kind of loads. This paper presents the findings of this study. This paper is organized as follows: Section 1 provides background of this work followed by an outline of this paper. A theoretical analysis of the topic using phasor method is presented in Section 2. Section 3 presents the simulation verification of theoretical results. Results of the experimental analysis using the HMI model plant are given Section 4. Section 5 concludes this paper with some observations.

Proceedings of the 2016 ASEE North Central Section Conference

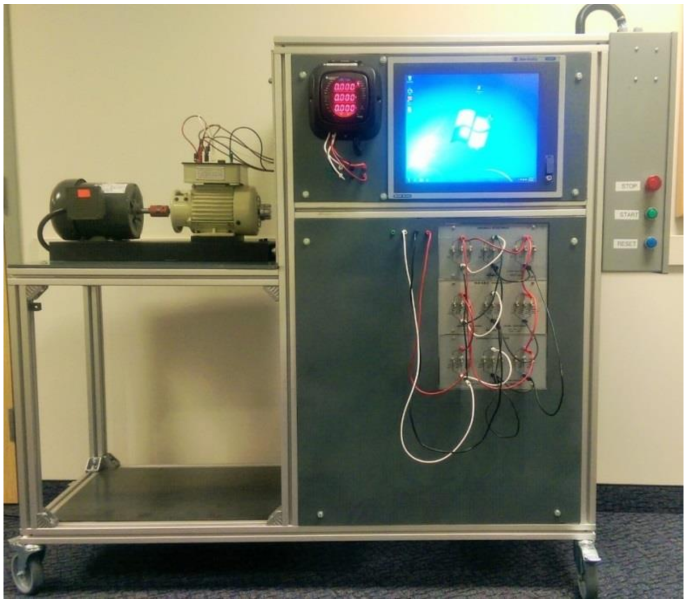

Figure 1: Picture of the prototyped model power plant[3]

2. Theoretical analysis using phasor method

Analysis of the induced voltage at the ac generator terminals is available in standard textbooks[4] and an equivalent circuit can be represented as shown in Figure 2 where E_A is induced voltage at the armature, X is synchronous impedance, and $V_\emptyset$ is the terminal voltage. A mathematical representation of this model is shown in (1). This model can be used to find the terminal voltage when a load is connected to the generator.

$$V_\emptyset = E_A - jXI_A \tag{1}$$

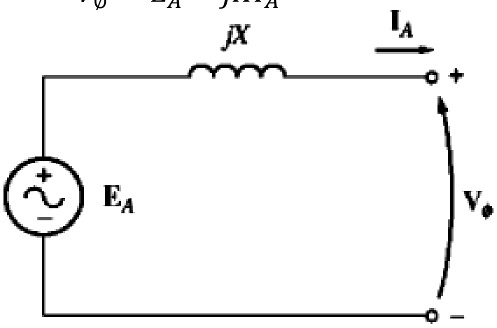

Figure 2: Single-phase equivalent circuit of a generator[4].

2.1 Resistive load

When a resistive load (unity power factor load) is connected to a generator the induced voltage $\boldsymbol{E_A}$ remains constant if excitation field current is constant. However, the load current $\boldsymbol{I_A}$ increases or decreases depending on the load resistance. Increasing current $\boldsymbol{I_A}$ causes the terminal voltage $\boldsymbol{V_\emptyset}$ to decrease, while decreasing the current causes the terminal voltage to increase. This is shown in the phasor diagram of Figure 3.

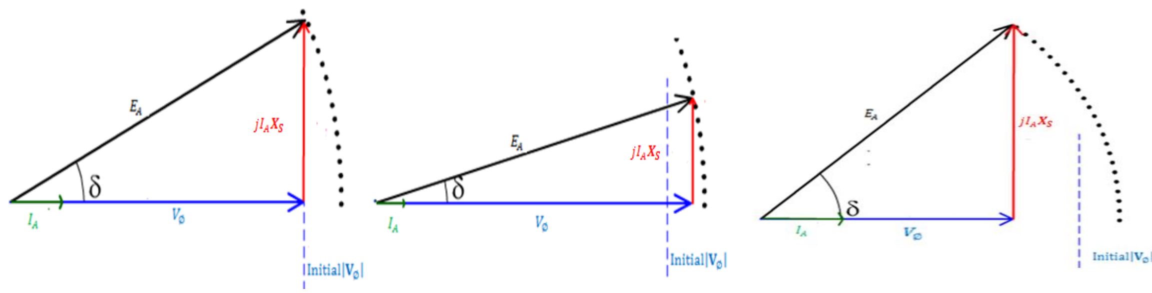

Figure 3: Effect of loading with resistive load. The initial condition (left), reducing the load current (center), and increasing load current (right)

2.2 Inductive load

When an inductive load (lagging power factor load) is connected to a generator with the excitation field current constant, increasing current $\boldsymbol{I_A}$ causes the terminal voltage $\boldsymbol{V_\emptyset}$ to decrease, while decreasing the current causes the terminal voltage to increase. This is shown in the phasor diagram of Figure 4.

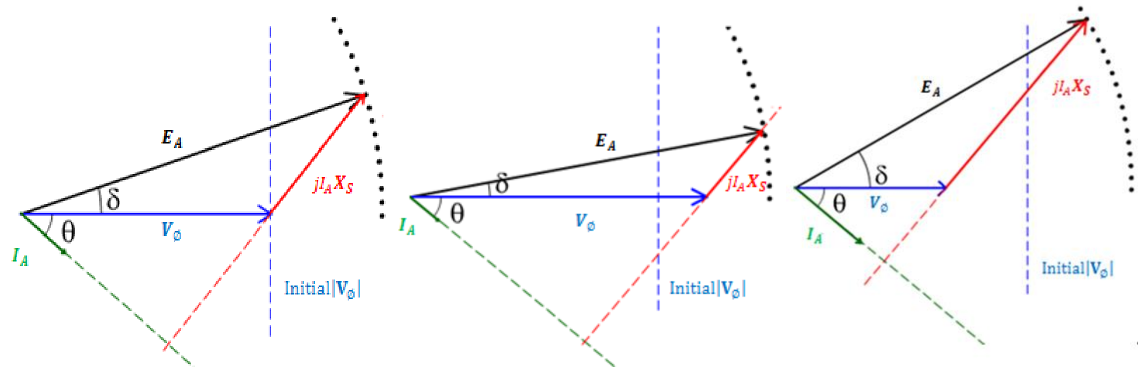

Figure 4: Effect of loading with inductive load. The initial condition (left), reducing the load current (center), and increasing load current (right)

2.3 Capacitive load

When a capacitive load (leading power factor load) is connected to a generator with the excitation field current constant, increasing current $\boldsymbol{I_A}$ causes the terminal voltage $\boldsymbol{V_\emptyset}$ to increase, while decreasing the current causes the terminal voltage to decrease. This is shown in the phasor diagram of Figure 5.

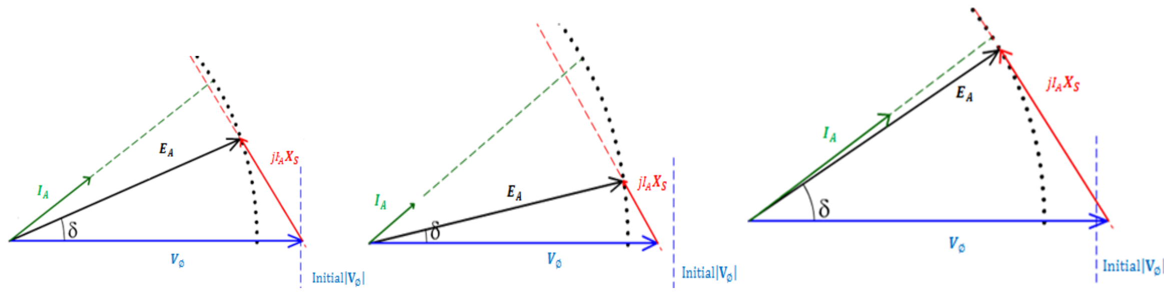

Figure 5: Effect of loading with capacitive load. The initial condition (left), reducing the load current (center), and increasing load current (right)

3. LTspice simulation results

The theoretical analysis using phasor method presented in Section 2 was verified by using LTspice circuit simulation program. For this purpose the equivalent circuit of Figure 2 with circuit parameter data for a 0.3 kW 60 Hz, 1800 RPM, three-phase salient pole synchronous generator was used. It should be noted that the same generator was used to implement the HMI model plant. A summary of the results is given in Table 1.

Table 1 LTspice simulation results

Load added	Initial terminal voltage (V)	Terminal voltage with new load (V)
R = 1200 Ω	220	176
L = 3.2 H	220	172
L = 3.2 H // 1.6 H	220	120
C = 2.2 µF	220	290

4. Experimental results using HMI model plant

The HMI model plant was used to study the effect of loading on generator terminal voltage under similar kind of loads as used in simulation analysis. Additionally, the effect of loading the generator with a combination of lagging, leading, and unity PF load was studied. Students were able to observe the real-time variation of terminal voltage in this study. Some of the scree-shots presented in Figures 6 to Figure 9 show how generator terminal voltage changes when a particular load is switched on or off. Results from this study are also summarized in Table 2.

Table 2 Experimental results from HMI model plant

Load added	Initial terminal voltage (V)	Terminal voltage with new load (V)
R = 1200 Ω	220	175
L = 3.2 H	220	170
L = 3.2 H // 1.6 H	220	110
C = 2.2 µF	220	255

Figure 6: Loading with a resistive load of 1200 Ω, voltage decreased from 220 V to 175 V

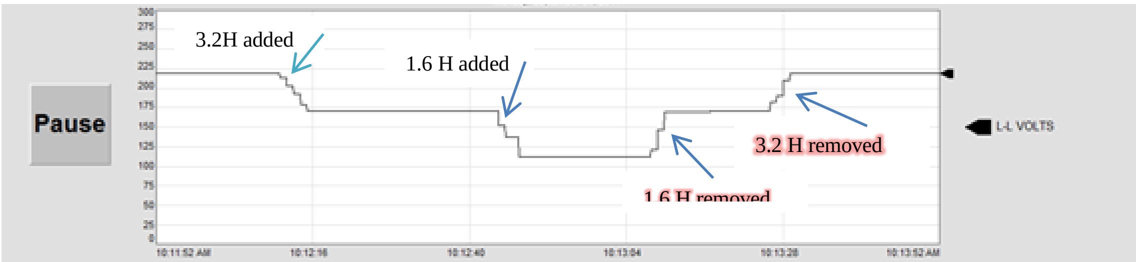

Figure 7: Adding inductive loads; voltage decreased from 220 V to 170 V to 110 V

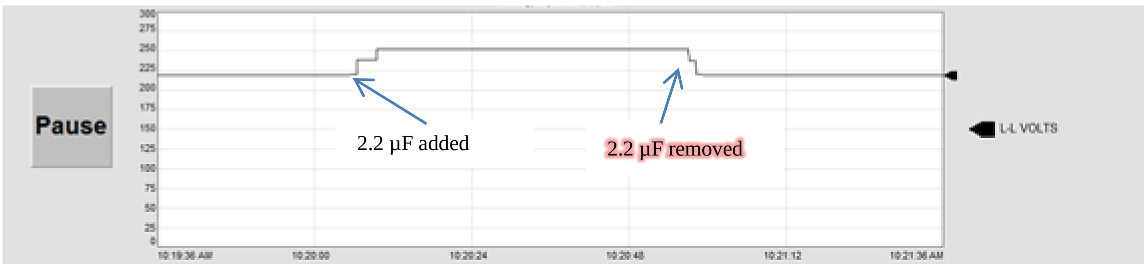

Figure 8: Loading with capacitive load; voltage increased from 220 V to 255 V

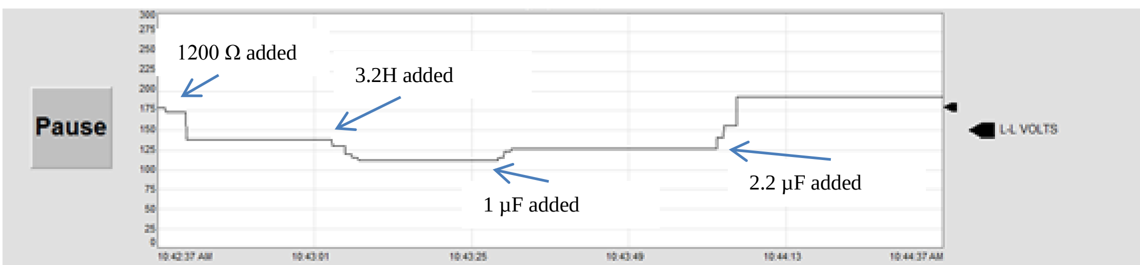

Figure 9: Loading with resistive → inductive →capacitive load in sequence; voltage changed from 180 V → 113 V → 190 V

5. Conclusions

This paper presented how a HMI power plant model can be useful in teaching topics in power system analysis. Effect of loading on generator terminal voltage can be taught using phasor method, simulation analysis, and traditional build & measure methods. Using HMI model power plant it was found that students can see the time-variation of voltage (and current) instead of a mathematical representation (phasor) of this variation. This pedagogical scheme to teach power systems analysis topics increased, as expressed by young engineers and students, their intuition and helped them understand the concepts more effectively. Thus, I believe that using HMI model plant fills an important gap in the understanding and educational development of our students.

Bibliography

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