Teaching Three-Phase Power ... A Low-Voltage Approach

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Abstract

Any electrical power systems course that includes demonstrations and/or laboratory exercises would benefit from a low-voltage three-phase power supply. Providing a low-voltage three-phase power supply allows classroom demonstrations and "hands-on" student participation in laboratory exercises without the danger associated with a 240 VAC system. Faculty and student surveys indicate that students would benefit from a "hands-on" approach and are more comfortable working with the safe low-voltage supply. Additionally, the flexibility and capabilities of the low-voltage three-phase power supply allow the instructor to implement demonstrations and laboratories that would not be possible on an energized 240 VAC system.

I. INTRODUCTION

The United States Air Force Academy (USAFA) teaches a first course in *Electrical Power Systems.* This course includes several labs and demonstrations designed to involve the student in the learning process. Three phase electrical power generation, distribution and use have been a particularly difficult group of concepts for most students to fully understand. A demonstration of three-phase alternating current circuits at 240 volts (VAC) was already provided; however, it was felt that a "hands-on" lab would provide a better learning opportunity for the students. Discussion with the faculty stressed that the need for "hands-on" lab experience must not compromise student safety. Additionally, it was felt that a student's concern for his/her own personal safety would hinder the learning experience offered by the lab if it were conducted at 240 VAC.

II. A STUDENT SURVEY

These faculty concerns appear to be shared by most students. In August of 1996, a survey consisting of three multiple choice questions was administered to the 42 students just starting the *Electrical Power Systems* course. *Electrical Power Systems* is a required course for all Electrical Engineering, Civil Engineering, Physics, and Computer Science majors. Of the 42 students starting the course only 2 were Electrical Engineering majors. A majority of the Electrical Engineering majors take this course during the Spring semester. The questions, a partial listing of the possible responses and the average numerical response to the questions are provided below.

1. How comfortable would you be working on an energized three-phase 240 VAC circuit?

    1. Very Comfortable
    2. Moderately Comfortable

3. Not Very Comfortable
Average - 2.45

2. How comfortable would you be working on an energized three-phase low-voltage circuit?

1. Very Comfortable
2. Moderately Comfortable
3. Not Very Comfortable
Average - 2.07

3. Would you rather conduct a "hands on" three-phase low-voltage lab or watch a three-phase high voltage demonstration? Both events will take the same amount of time.

1. Conduct The Lab
2. Watch The Demonstration
Average - 1.55

A similar survey was administered in August 1996 to 40 Electrical Engineering students who had previously completed the *Electrical Power Systems* course. Questions 1 and 2 were the same as above, so only the averages are provided for these questions.

1. Average - 2.00

2. Average - 1.68

3. How much benefit would a "hands on" three-phase low-voltage lab have been in helping you understand the three-phase circuit concepts? (As compared to the three-phase high voltage demonstration you received during the *Electrical Power Systems* course.)

1. Very Helpful
2. Moderately Helpful
3. Not Very Helpful
4. No Help At All
Average - 1.49

Both groups felt considerably more comfortable with the low-voltage system. The group starting the course (non-EE's) were about evenly divided as to their preference for a lab or a demonstration. The students that had already completed the course (EE's) felt more strongly about the benefits of a low-voltage three-phase lab.

III. THE THREE PHASE LOW-VOLTAGE SYSTEM

Historically, the three phase power supply used in an electrical engineering lab was of industrial voltage and amperage. For a first course in Electrical Power Systems, this supply was deemed inappropriate for anything other than closely supervised demonstrations.

One option is to use a standard function generator for lab work; however, the typical function generator can only create one waveform at a time. Teaching the concepts of three-phase electrical power requires the use of a power supply capable of generating three waveforms simultaneously. These three waveforms must be of the same frequency and voltage and be phase shifted relative to one another by 120 degrees. A three-phase, unit amplitude, 1 Hertz set of waveforms is shown in Figure 1. These waveforms are routinely designated phases A, B and C.[1] A standard function generator could drive a series of phase shift networks to create the required three waveforms; however, this system could only maintain the required 120 degree phase relationship at one frequency.

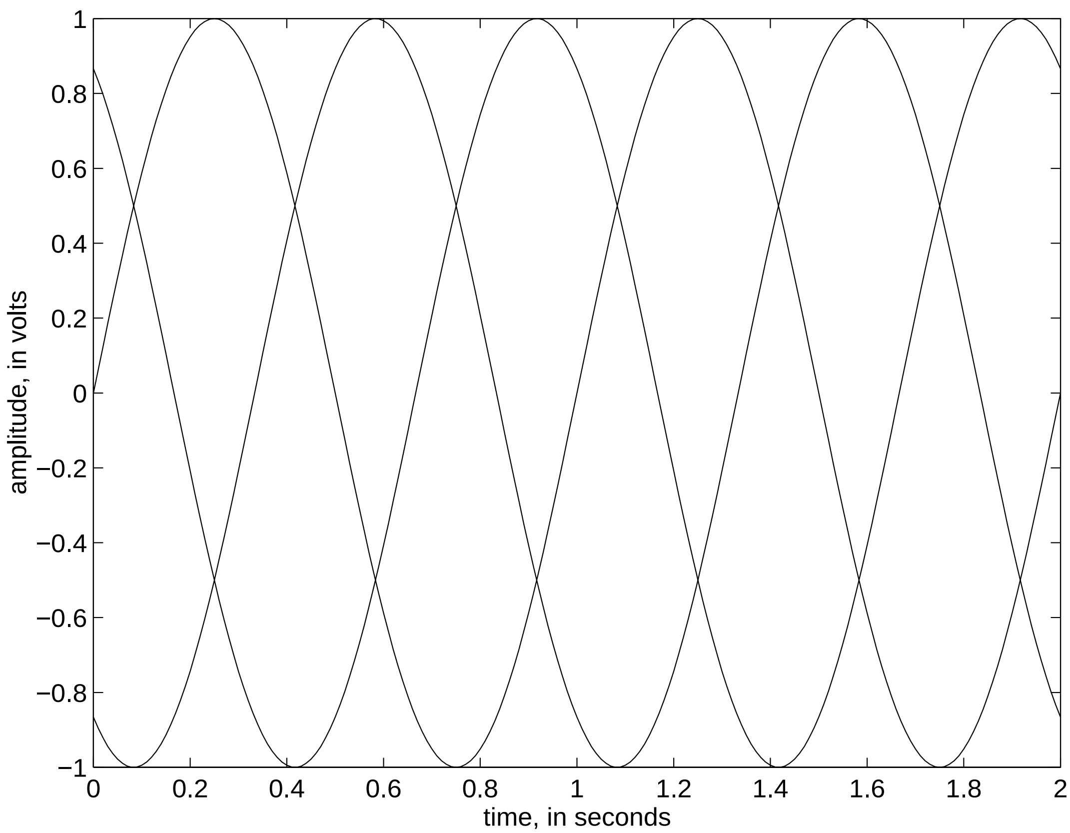

Figure. 1. An example of a three-phase unit amplitude set of waveforms.

A less traditional but very simple approach was taken when designing the three-phase low-voltage power supply.

A block diagram of the low-voltage three-phase power supply is shown in Figure 2. The system consists of three separate “channels” (driven from a common clock and counter) each of which produces one of the three phases of the three-phase power supply. Each channel contains a digital-to-analog converter (DAC) which is used to produce a signal from samples stored in an Erasable Programmable Read Only Memory (EPROM). The output of the DAC is smoothed and scaled by the amplifier/filter producing the desired waveform.

Each EPROM contains 255 samples that represent one cycle of the desired waveform. However, the samples are stored so that as they are read out, there is a 120 degree phase shift between any two channels. This phase shift is accomplished by a circular shift [2] of the samples stored in each EPROM. For 255 samples, shifts of 85 and 170 samples produce phase shifts of 120 and 240 degrees, respectively. The number 255 was chosen because it is divisible by three and provides an adequate number of samples per cycle to reproduce a smooth waveform utilizing a low order filter. Hence, all three channels are driven from the same eight-bit counter set up to count through 255 numbers. The counter is driven from a system clock with frequency f_{clock}. This produces a waveform on each channel with a frequency of $f_0 = \frac{f_{clock}}{255}$. Thus, a 15.3 kHz clock will produce a 60 Hz waveform. This approach produces sinusoids with less harmonic distortion than the three-phase 240 VAC power provided to our lab.

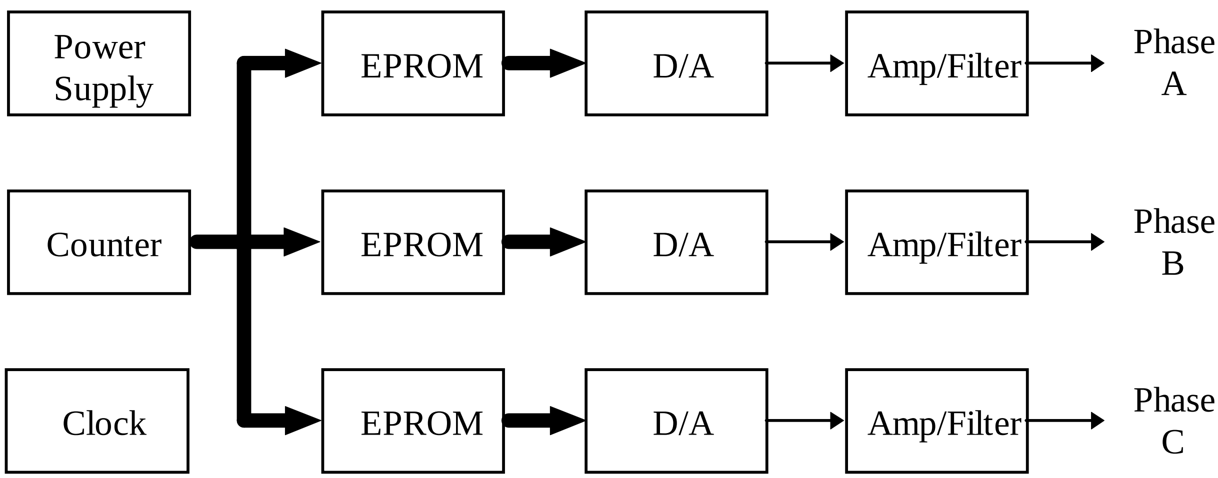

Figure. 2. System block diagram.

Each of the three channels is essentially a stand alone function generator. For this application, the EPROM's are programmed with the binary representation of sinusoids. Any waveform could be produced by storing the appropriate values in the EPROM. This will allow each channel to act as an arbitrary function generator. The EPROM values for the sinusoids were calculated using MATLAB®.[3]

Since voltages at 60 hertz, below 30 to 50 volts, are considered safe [4], the three-phase power supply output was designed so that it could not exceed 20 volts. This was accomplished by using an external DC power supply limited to 20 VDC. The final drive stages of this system are provided by three operational amplifiers (LM 741) which can only provide 25 milliamps of current each.[5]

IV. APPLICATIONS FOR AN UNDERGRADUATE POWER COURSE

Three phase sources, the relationships between Wye and Delta arrangements, the effect of phase imbalance, three-phase rectifiers and transmission lines were all investigated using this power supply. System loading must remain below the maximum drive current (25 milliamps) of each operational amplifier. Exceeding this limit will be immediately obvious, as the system output waveform will distort severely.

Two additional experiments or demonstrations were also conducted. The first involved slowing the system output frequency to below the one Hertz rate. Using a multi-channel oscilloscope attached to the system output has helped students understand the oscillatory relationship between the three phases.

The second demonstration is similar to the first, except the power supply drives one light bulb per phase. In this case the light bulbs represent the windings associated with a three-phase motor. The light bulbs light up simulating when the motor windings produce a magnetic field. Since magnetic fields can reverse polarity, and the voltages powering the light bulbs produce the same light intensity regardless of the polarity, each waveform is half-wave rectified to allow for the proper rotational display. This demonstration shows how the stator of a three-phase motor creates a rotating magnetic field. The system frequency can be started below 1 Hertz, then increased slowly until rotation is no longer visible. The flashing of a phase light becomes a constant glow as the frequency approaches 30 Hertz. Additional experiments and demonstrations are always possible!

V. POST USE SURVEY

In December of 1996 a final survey similar to the previous two surveys was administered to the 39 students who successfully completed the Fall 1996 *Electrical Power Systems* course. The questions, a partial listing of the possible responses and the average response to the questions are provided below.

1. How comfortable would you be working on an energized three-phase 240 VAC circuit?

    1. Very Comfortable
    2. Moderately Comfortable
    3. Not Very Comfortable

    Average - 1.95

2. How comfortable were you working on an energized three-phase low-voltage circuit?

    1. Very Comfortable
    2. Moderately Comfortable
    3. Not Very Comfortable

    Average - 1.43

3. How much did the “hands on” three-phase low-voltage lab help you understand the three-phase circuit concepts? (As compared to the three-phase high voltage demonstration).

    1. Very Helpful
    2. Moderately Helpful

3. Not Very Helpful
Average - 1.97

VI. CONCLUSIONS

After completing the *Electrical Power Systems* course both groups felt much more comfortable working on energized high and low-voltage circuits. The three-phase low-voltage power supply contributed to this positive result.

The three-phase low-voltage power supply is an inexpensive yet versatile addition to a lab and/or course teaching electrical power generation, distribution or utilization. The system's proven reliability and designed safety features make it an invaluable teaching tool!

Modifications to this system could allow for a portable standalone device that would not need the external clock or power supply. This would allow for increased flexibility for classroom use but with increased size, weight and cost.

Modifications could also increase the output drive power to allow for variable frequency motor control demonstrations.

VII. REFERENCES

[1] T. Wildi, *Electrical Machines, Drives, and Power Systems,* Simon & Schuster, Upper Saddle River, New Jersey, 1997

[2] A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, Prentice-Hall, New Jersey, 1989

[3] MATLAB®, The MathWorks, Inc., Natick, Massachusetts

[4] E.K. Greenwald (editor), *Electrical Hazards and Accidents - Their Cause and Prevention*, Van Nostrand Reinhold, New York, 1991

[5] Linear Databook 1, National Semiconductor Corporation, Santa Clara, California, 1988

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