Teaching Three-Phase Electrical Power Using a Low-Voltage Power Source

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Abstract

The United States Air Force Academy teaches a first course in Electrical Power Systems. While computer simulations and modeling techniques have become pervasive throughout most of the engineering curricula, and while the utilization of computers in the classroom and the laboratory represents a major pedagogical improvement, a hardware-based approach to teaching several electrical power distribution and usage topics can also be very effective. Our course includes several laboratory experiments and demonstrations designed to involve the student in the learning process. A locally designed and manufactured three-phase, low-voltage, variable-frequency power supply is used to teach parts of this Electrical Power Systems course. The three-phase low-voltage system enhances student safety while allowing for student involvement in the learning process. Additional laboratory time also leads to numerous other learning opportunities for the student. This paper discusses the utilization of the three-phase low-voltage power supply as a teaching tool. A discussion of several laboratory experiments and demonstrations is included. Some of these demonstrations, for example, slowing the power supply frequency to the point that phase rotation is visible without the use of electronic test equipment, cannot be accomplished using the more traditional high voltage “power bench” type equipment. Finally, the limitations of the three-phase low-voltage power supply are discussed.

I. INTRODUCTION

Electrical power systems are an essential part of the world’s infrastructure, economy, and way of life. Indeed, without a reliable source of power, many of the daily activities in a large part of the world would not be possible. The vast majority of the electrical power in the world is generated and distributed via three-phase power systems [1]. The basic concepts of three-phase power are taught to a wide variety of engineers in either a general circuits course or a class dedicated to energy conversion and power systems.

The systems used as examples when teaching power systems typically involve dangerously high voltages and currents. For obvious reasons of safety and logistics, it is not practical to have students work with actual power systems. Power demonstration stations that allow students to work with relatively low voltages (hundreds of volts) in a laboratory setting are available. With these stations, students can build and experiment with motors and other three-phase loads. However, these demonstration stations are usually large (the size of a lab bench), expensive (typically tens of thousands of dollars), potentially dangerous, and require that three-phase power be available in the laboratory. With a small, low-voltage (several volts), three-phase voltage source, powered by a DC supply, students can safely perform a wide variety of experiments involving three-phase power systems. In addition, the supply could be used as a portable demonstration unit, helping students visualize basic three-phase concepts in the classroom.

Such a low-voltage three-phase supply has been designed and built [2]. A first course in electrical power systems is taught at the United States Air Force Academy to students in the fields of electrical engineering, civil engineering, and computer science. The goal of the class is to give students a solid foundation in energy conversion and power systems. We have found that hardware-based demonstrations and laboratory exercises are an essential part of the educational process. This low-voltage three-phase source has proven itself as an inexpensive, reliable, safe, and effective learning tool [2]. This paper focuses on how we use our low-voltage three-phase supply in a laboratory and classroom setting.

II. DEMONSTRATIONS AND LABORATORY EXERCISES

The locally designed and built low-voltage supply is an ideal portable system for classroom demonstrations. The unit is a balanced, three-phase, wye-connected voltage source and is powered by a dual-voltage (nominally ± 15 V) DC supply. An oscilloscope is used to help students visualize the amplitude and phase relationship between the voltages in the system. By varying the sweep rate, it is possible to "zoom in" or "zoom out" on the voltages and clarify the relationships between the waveform parameters of the three phases. Furthermore, the output frequency of the unit can be varied, helping solidify the time, frequency, and phase relationships in AC systems.

Using built-in functions found in most analog and digital oscilloscopes, it is possible to subtract one phase voltage from another, thus showing the $\sqrt{3}$ difference in magnitudes and the 30° phase-shift relationship between phase and line voltages. In our case, we simply invert one channel and add it to another. This activity, useful in both a demonstration and laboratory environment, confirms and graphically illustrates more traditional teaching techniques such as phasor diagrams and algebraic manipulation.

The low-voltage unit, coupled with a power amplifier and a set of incandescent light bulbs, are used to dramatically show how power is sequentially delivered to the phases of a three-phase load. The demonstration equipment we built consists of light bulbs in a wye-connected configuration. However, both wye- and delta-loads can be illustrated using an appropriate face-plate. This demonstration shows how power is delivered to the phases of a load and the rotation of the magnetic field inside of a three-phase motor winding. If the sequence of the three-phase power is changed (i.e., from ABC to ACB), the direction of rotation is reversed. Student reaction to this demonstration has been overwhelmingly positive. Phasor diagrams or computer simulations have traditionally been used to show these relationships but we have observed that student understanding is increased by this classroom activity.

In the laboratory, students typically work in groups of two or three. Students connect three-phase loads to the supply, measure line and phase quantities, and experiment with system configurations as part of an assigned lab. Again, an oscilloscope is used to visualize the voltage and current waveforms. Both wye- and delta-connected loads can be examined in this way. However, because there is no neutral point in a delta-connected load, the internal ground found on most oscilloscopes limits the type of voltage measurements that can be made directly in these types of loads. As previously described, the line-to-line voltages can be measured by subtracting one waveform from another but a digital multimeter (DMM) is typically used for quantitative measurements. The use of the DMM not only avoids the grounding issues inherent with most oscilloscopes but also helps reinforce the idea of selecting the right laboratory instrument for a particular job.

Using an oscilloscope and a DMM, students confirm the relationships between line and phase parameters (voltages and currents) in the different types of loads. The magnitudes of currents are measured with the DMM and the phase is inferred from the oscilloscope waveforms. We currently use only purely resistive loads to simplify the phase relationship between currents and voltages. The concepts of lead and lag are explored in single-phase lab prior to the three-phase exercise.

Students measure the neutral currents in a wye-connected load to confirm the analysis carried out in the classroom. Students typically have difficulty visualizing that the neutral current is zero for a balanced load and source. This exercise shows that there is no or very little current flowing in our system and validates the phasor diagram usually used to show this relationship. Further, the effects of unbalancing the load can be demonstrated by removing a phase resistance or changing one resistor to a different value. The neutral wire from the source to the unbalanced load can then be removed to show the importance of this wire in practical three-phase systems.

Since the output of the unit is a set of three voltages with the same frequency but different relative phase angles, the phase measuring abilities of a modern oscilloscope are easily demonstrated. Students measure the phase angle difference between voltages. The lead and lag relationships between the phase voltages is somewhat confusing to most students until they see the waveforms on the oscilloscope’s screen and make the measurements for themselves.

III. ADVANTAGES AND LIMITATIONS OF THE SUPPLY

This three-phase supply can be built from readily available parts and has a material cost of around $1,000 for a set of six, including $800 for the initial fabrication of circuit boards. Subsequent runs of the board were less than $300 for a set of six. Assembly and testing time is estimated at approximately 5 hours per unit. One benefit of this modest cost is that an entire lab can be outfitted for a reasonable price. This allows small groups to have direct, hands-on experience with three-phase power systems. The output stages of the unit use the familiar 741 op amp and thus have built-in protection from direct shorts between phases or other misconnections. Since the output voltages are, at most, only tens of volts, the unit is safe [2]. When students misconnect the supply, no harm is done. This is in stark contrast to the consequences of a similar move in an actual power system or typical power demonstration unit. Students are not apprehensive about their personal safety and monitoring requirements are greatly reduced. The overall result is that students are more comfortable exploring various aspects of three-phase systems. Reliability has been outstanding. In three semesters of use, we have experienced only one failure. The problem was a faulty D/A converter. Because all major components are socketed, the units are easily maintained.

Aside from portability (a single supply measures just 6” W x 7.5” D x 3” H and weighs less than one-half pound) and low cost, another significant advantage is the frequency control of the output waveforms. The output frequency is controlled by a TTL-level clock signal. The useful output frequency range is from mHz to kHz. Studies with a spectrum analyzer show that the low-voltage three-phase source has a lower harmonic content than the high-voltage, three-phase power available via our commercial power bench [2].

One of the limitations of the device is its current drive capability. The op amps in the output are limited to approximately twenty-five milliamps [2]. The output voltage is limited to the DC power supply rails, typically 30 to 40 V peak-to-peak. These conditions imply that phase impedances must be on the order of a few thousand ohms to prevent current limiting in the output stage. Clipping and severe distortion are observed when the phase impedance is less than a few thousand ohms.

IV. OTHER POSSIBLE ACTIVITIES

The design of the low-voltage three-phase supply allows for many different configurations and experiments. For instance, the shape of the output waveform in the system is determined by the contents of an EPROM [2]. This means the unit is a simple, arbitrary waveform generator. In many inverter (DC to AC) systems, true sinusoids are not generated. Instead, a step-function approached is used to minimize hardware requirements and harmonics in the output. Waveforms with a similar shape can be synthesized, allowing students to measure their harmonic and power content.

Another use for the device would be as the power supply in a model of a three-phase distribution system. This has been done on a simple scale with a spool of wire but demonstration equipment that visually resembles an actual system could easily be constructed. This would allow students to fully explore the lumped-element transmission line model by measuring voltages and currents within the system. The concepts of voltage loss, efficiency, and power factor correction could be easily explored in such a system. Also, the effect on the system of losing one phase of the distribution network could be explicitly and easily shown.

One of the most important current topics in energy conversion is speed control of induction motors. Speed control of these motors can be accomplished by controlling the frequency of the applied power [3]. Such speed control units are found in applications ranging from elevators to new generation electric vehicles. Our variable-frequency three-phase supply could be used to control the gate voltages of SCR devices and thereby switch the relatively large, inductive currents required for motor control. This would allow students to conduct experiments on the load and speed characteristics of induction motors.

V. CONCLUSION

This paper has examined the advantages of a low-voltage three-phase supply in a teaching environment. The locally designed and constructed unit has proven to be a safe, reliable, robust, and inexpensive alternative to conventional, higher-voltage, expensive, and cumbersome demonstration stations. Learning is enhanced because students are able to have hands-on experience with a three-phase power system. Students are better able to visualize important phase and line quantities, phase rotation, and circuit connections. The unit can be used in a variety of classroom and laboratory situations to reinforce the fundamentals of power systems. In addition, there are many experiments and demonstrations, such as motor speed control, that could extend the present utility of the unit.

VI. ACKNOWLEDGMENTS

The authors would like to thank Mr Dick Speakman and Ms Susan Elmore for their invaluable assistance in the design and fabrication of the three-phase, low-voltage supply.

VII. REFERENCES

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