A Variable Frequency Drive Trainer for use in a University Agricultural Electricity Course

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Abstract

This article describes the construction and evaluation of a relatively inexpensive (< $600.00) variable frequency drive (VFD) trainer for use in an undergraduate agricultural electricity course. The trainer met the design criteria of safety, cost, availability of both keypad and remote operation, and programmability through the keypad. We developed a student laboratory activity for use with the trainer and students (n = 21) in an undergraduate agricultural electricity course used the activity and trainer in spring 2018. We assessed students’ prior familiarity and experience with VFDs and their perceptions of the effectiveness of the trainer and activity as a way to learn about VFDs. Prior to classroom instruction and the laboratory activity, students indicated they had little if any exposure to VFDs. After completion of the laboratory activity, 100% of students agreed the activity was effective in helping them learn to program and operate a VFD. Based on the trainer’s effectiveness in this pilot test, we intend to construct additional trainers for use in the undergraduate agricultural electricity course.

Keywords: lab activity; trainers; variable frequency drive
Introduction

The synchronous speed \( (N_s, \text{ in rev/min}) \) of an alternating current (AC) induction motor is determined by the number of poles in the stator windings and the frequency (cycles per second, in Hz) of the applied AC voltage (Gustafson & Morgan, 2004). Equation 1 describes this relationship.

\[
N_s = \frac{(Hz \times 60 \text{ sec/min})}{(\text{number of poles} / 2)} \tag{1}
\]

Thus, when operating on standard 60 Hz AC electricity, a two-pole motor has a synchronous speed of 3600 rev/min (RPM), a four-pole motor has a synchronous speed of 1800 RPM, and so on. Under no-load conditions, a motor will operate at approximately 99.5% of synchronous speed due to “slip” between the rotor and stator magnetic fields. Under full-load, slip increases and the rotor turns at approximately 96% of synchronous speed (Gustafson & Morgan, 2004). Therefore, the full-load speed listed on the motor nameplate is typically 3450 RPM for two-pole motors, 1725 RPM for four-pole motors, and so on.

The previous discussion indicates there are three methods of changing the speed of an AC induction motor - change the slip percentage, change the number of stator poles, or change the frequency of the applied voltage (Gustafson & Morgan, 2004). While the first two methods are used in certain speed control applications, the variable frequency drive (VFD) is the most practical and efficient method of controlling motor speed.

VFDs are available for either single- or three-phase electrical input, but generally deliver three-phase electrical output for powering and controlling three-phase motors. Single-phase input VFDs also serve as phase-converters and are sometimes used to drive three-phase motors even when speed control is not the primary objective.

A VFD consists of three functional groups: an AC to direct current (DC) converter, a DC filter, and an output inverter (Fig. 1). A Lenze AC Tech (2017) publication describes the operation of each functional group. The AC to DC converter consists of diodes arranged as a bridge rectifier; these diodes allow current to flow in only one direction, producing a pulsating, half-wave DC output. The DC filter consists of an inductor and one or more parallel-connected capacitors. The inductor and capacitor(s) filter out any AC voltage wave resulting in a relatively pure DC signal to the output inverter. The output inverter consists of two insulated-gate bipolar transistors (IGBTs) per output phase. These IGBTs act as solid-state switches and are controlled by the VFD’s programmable microprocessor. The microprocessor is capable of switching the IGBTs thousands of times per second and at specific intervals, resulting in a three-phase AC variable voltage and a pulse-width modulated (PMW) frequency output (Fig. 2). The duration of the on pulse determines the output voltage while the interval between on pulses determines the output frequency and thus the motor speed (Fig. 2).

Variable frequency drives (VFDs) are widely used in agriculture and other industries. On farms, VFDs are used to control ventilation fans in greenhouses and livestock facilities (Tietel et al., 2008), irrigation pumps (Henry et al., 2014), materials handling systems, and milking pumps (Roșca et al., 2015). In industry, VFDs are used on a wide range of applications, for example, machine tools (Wang et al, 2012) and pellet mills (Jackson, Turner, Mark, & Montross, 2015). Thus, Agricultural Systems Management students should be familiar with VFDs and be prepared to select, install, operate, and service these devices (Schumacher, Ess, Strickland, & King, 2002).

Figure 1. Simplified schematic and functional components of a 120 VAC single-phase to 240 VAC three-phase VFD (adapted from Lenze AC Tech, 2017).

Figure 2. VFD pulse-width modulated (PMW) output showing lower (left) and higher (right) voltages and frequencies for one output phase (adapted from Cowie, 2001).

Research has supported the efficacy of hands-on activities and models for teaching principles of tractor ballasting (Stringham and Swan, 2012), programmable logic controllers (Dickinson and Johnson, 2006), tractor stability (Koc and Liu, 2013), and electrical safety (Miller & Beard, 2004), among other technical concepts and skills. According to Stringham and Swan (2012),

> "Models are less expensive, more convenient, provide a safer lab environment for students, and . . . can be used as a program recruiting tool" (p. 3).

The cost of commercially-available VFD trainers such as the LearningLab (Dugger, IN) VFD trainer range from $2,595 to $2,861, depending on the vendor, making it difficult for agricultural systems management programs to provide class quantity trainers for student laboratory use. Thus, a need existed to develop and evaluate a low-cost VFD trainer that would allow programs with limited budgets to provide multiple units for instruction and hands-on laboratory use.
Purpose and Objectives

The purpose of this project was to develop and evaluate a low-cost VFD trainer for use in an undergraduate agricultural electricity course, AGME 3173 - Electricity in Agriculture. Specific objectives were to:

1) Develop a safe, functional VFD trainer at a cost of less than $600 per unit;
2) Determine students’ previous experience with VFDs; and
3) Determine students’ perceptions of the educational effectiveness of the VFD trainer and associated laboratory activity.

Methods

Trainer Design Criteria

We established the following criteria to guide development of the VFD trainer:

- The trainer must be safe for students to use
- The trainer must cost less than $600 per unit to build
- The trainer must allow for both local (keypad) and remote operation by external controls (switches, potentiometers, etc.)
- The trainer must be programmable through a keypad

Once criteria were established, we selected components and materials and constructed the VFD trainer.

Student Laboratory Activity

We developed a written laboratory activity for use with the VFD trainer. The activity required students to make basic calculations and program the correct minimum and maximum frequencies (Hz) for a minimum motor speed of 600 RPM and a maximum speed of 1000 RPM. As shown in Equation 2, the frequency required for a two-pole motor to operate at 600 RPM is 10 Hz. The frequency required for operation at 1000 RPM (16.7 Hz) would be calculated using the same equation.

\[ \text{Hz} = \frac{\text{Desired RPM}}{\text{Synchronous RPM}} \times 60 = \frac{600}{3600} \times 60 = 10 \text{ Hz} \]  

(2)

Students then programmed the VFD to set 5-second motor acceleration and deceleration times. Next, students calculated and programmed the maximum current output percentage so the VFD provided overload protection for the motor. Based on the motor’s nameplate current rating of 1.4 A and the VFD’s maximum current output of 1.7 A, the proper setting was 82.4% (Eq. 3).

\[ \text{Maximum VFD Output \%} = \frac{\text{Motor Nameplate Amps}}{\text{VFD Output Amps}} \times 100 = \frac{1.4 \text{ A}}{1.7 \text{ A}} \times 100 = 82.4\% \]  

(3)

Finally, students operated the motor, recorded the VFD output frequency, measured motor RPM with a digital tachometer, and calculated and set the display frequency multiplier so the VFD display indicated motor RPM, instead of the default (VFD output frequency). Assuming a measured shaft speed of 1791 RPM at 30 Hz, the display frequency multiplier would be set at 59.7 (Eq. 4).
Once students had completed all VFD programming tasks, they demonstrated its successful operation to the instructor. The instructor restored the VFD to the default settings between groups. Because only one VFD trainer was available in spring 2018, we designed the laboratory activity for student teams of two or three to rotate through the VFD trainer station and, by studying the VFD operator’s manual and making necessary calculations beforehand, complete the activity in approximately 15-minutes. This allowed all 23 students to complete the lab activity in a single two-hour lab period.

**Evaluation of Educational Effectiveness**

Students ($N = 23$) enrolled in a junior-level agricultural electricity course (AGME 3173) in spring 2018 received approximately 30-minutes of classroom instruction on basic VFD operating principles and then completed the VFD lab activity. Immediately following completion of the activity, students ($n = 21$) completed a voluntary, seven item Likert-type survey (1 = strongly disagree and 4 = strongly agree) designed to assess their previous experience with VFDs (two items) and their perceptions of the effectiveness of the VFD trainer and associated laboratory activity as a learning experience (five items). A panel of three experts in educational research and technical education examined the survey and deemed it to possess face and content validity. *Post hoc* analyses determined coefficient alpha reliabilities of .85 and .87 for the summated scales measuring students’ prior experiences and perceptions of educational effectiveness, respectively.

**Results**

**Trainer Construction**

Development of the trainer began with the selection of the VFD and motor combination. After evaluating various manufacturers, we selected the Lenze (Uxbridge, MA) SMVector ESV371-1S model VFD. This VFD accepts 120/240 VAC single-phase input and outputs 240 VAC three-phase at a maximum rated output of 1.7 A with a variable frequency of 0 - 500 Hz. The VFD has a NEMA Type-1 enclosure and is rated for control of three-phase motors of 0.5 HP (0.37 kW) or less. The cost for the VFD was $251 per unit.

We selected a Leeson (Grafton, WI) model C4T34FB5B 208-230 VAC three-phase motor for use on the trainer. The motor’s rated power (0.33 HP or 0.25 kW) and current draw (1.4A @ 230 V) were within the capacity of the Lenze VFD. The totally enclosed, fan-cooled (TEFC), two-pole motor had a rated full-load speed of 3450 RPM at 60 Hz and cost $184 per unit.

In addition to the VFD and motor, we purchased several other items to construct the trainer (Table 1). These included a 120 VAC power cord (AWG #12); a SPST switch, box, and cover; a 15-ampere cube fuse with a DIN-rail mounted finger-safe fuse holder; one 15 VDC-rated rotary on-off switch; one 15 VDC-rated SPDT toggle switch; and one linear-taper 5K ohm potentiometer. The total cost for constructing the trainer was $534.70 per unit.
Table 1. Materials and costs for constructing VFD trainer.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Item</th>
<th>Unit Price ($)</th>
<th>Total ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lenze SMVector ESV371-1S VFD</td>
<td>251.00</td>
<td>251.00</td>
</tr>
<tr>
<td>1</td>
<td>Leeson 0.33-HP three-phase electric motor</td>
<td>184.00</td>
<td>184.00</td>
</tr>
<tr>
<td>1</td>
<td>2&quot; x 4&quot; x 2&quot; plastic switch box</td>
<td>3.87</td>
<td>3.87</td>
</tr>
<tr>
<td>2</td>
<td>4&quot; x 4&quot; x 2&quot; plastic junction boxes</td>
<td>4.50</td>
<td>9.00</td>
</tr>
<tr>
<td>1</td>
<td>15 A fuse</td>
<td>15.50</td>
<td>15.50</td>
</tr>
<tr>
<td>1</td>
<td>15 A finger-safe fuse holder</td>
<td>6.53</td>
<td>6.53</td>
</tr>
<tr>
<td>1</td>
<td>Rotary motor on-off switch</td>
<td>3.50</td>
<td>3.50</td>
</tr>
<tr>
<td>1</td>
<td>SPST toggle power switch</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>1</td>
<td>1 5K ohm linear-taper potentiometer</td>
<td>35.00</td>
<td>35.00</td>
</tr>
<tr>
<td>1</td>
<td>3-prong power cord</td>
<td>3.05</td>
<td>3.05</td>
</tr>
<tr>
<td>na</td>
<td>Miscellaneous wire, conduit, and hardware</td>
<td>na</td>
<td>5.75</td>
</tr>
<tr>
<td>1</td>
<td>2' x 4' x ¾&quot; glued board</td>
<td>na</td>
<td>14.25</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>$534.70</td>
</tr>
</tbody>
</table>

We surface-mounted these components on a 24-in x 48-in x ¾-in display board and wired the DC control devices with AWG-16 THHW conductors and wired from the VFD to the motor using AWG-12 THHHW conductors in flexible plastic conduit. Following the manufacturer’s wiring diagram (Lenze, 2006), we wired the ungrounded conductor of the 120 VAC power cord through a 15 A finger-safe fuse holder and connected it to the VFD’s L1 terminal, the grounded conductor was connected to terminal L2, and the equipment grounding conductor was connected to the PE terminal. The three-phase motor was wired to the VFD’s U (A-phase), V (B-phase), and W (C-phase) terminals and the equipment grounding conductor to the motor was wired to the VFD’s PE terminal. The SPST motor on-off switch was wired between control terminals 1 and 4. The 5-k motor speed control potentiometer was wired to control terminals 2, 5, and 6. The common of the SPDT switch used to reverse motor rotation was wired to control terminal 4, with the outputs connected to 13A (standard rotation) and 13B (reverse rotation). The wiring connections at the VFD are shown in Fig. 3. (Safety note: Readers should consult and follow the VFD and motor manufacturers’ wiring diagrams and instructions to ensure correct and safe installation and operation.)

Safety
For safety, we supplied 120 VAC electrical input to the VFD trainer through a GFCI-protected outlet. We electrically grounded both the single-phase input and the three-phase output in accordance with electrical code (National Fire Prevention Association, 2017) requirements and manufacturer recommendations (Lenze, 2006). In addition, we attached a clear, acrylic mechanical guard to the shaft end of the motor to prevent student contact with the output shaft and pulley. Fig. 4 shows the completed VFD trainer.
Figure 3. VFD wiring diagram showing power in, power out, and control device connections. Readers should consult and follow the VFD and motor manufacturers’ wiring diagrams and instructions to ensure correct and safe installation and operation.

Figure 4. The completed VFD trainer in use. Students are verifying motor RPM with digital tachometer.

**Evaluation of Trainer and Student Laboratory Activity**

The survey results showed that students enrolled in AGME 3173 in spring 2018 reported little exposure to VFDs prior to classroom study and completion of the trainer-based laboratory
activity. The mean score on the two survey statements measuring previous experience was 1.67 (SD = 0.97) with the median and modal score both being 1.0. These results indicated students generally did not have prior experience with VFDs before completing the lab activity.

Students agreed the VFD trainer and laboratory activity were effective in helping them learn about VFDs. The mean score on the five survey statements measuring perceived educational effectiveness was 3.51 (SD = 0.58) with a median score of 3.60 and a modal score of 4.0. These results indicated students strongly agreed that the trainer and laboratory activity were effective in helping them learn about VFD operation and programming. Table 2 summarizes student responses for both previous exposure to VFDs and perceptions of the learning activity by scale and item.

Table 2. Student (n = 21) perceptions of previous exposure to VFDs and effectiveness of trainer-based laboratory activity.

<table>
<thead>
<tr>
<th>Summated Scale</th>
<th>M</th>
<th>SD</th>
<th>Mdn</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Previous Experience</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I was familiar with VFDs prior to this class.</td>
<td>1.67</td>
<td>0.97</td>
<td>1.0</td>
</tr>
<tr>
<td>I had hands-on experience with VFDs prior to this lab activity.</td>
<td>1.76</td>
<td>1.04</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Educational Effectiveness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The hands-on experience with the VFD trainer increased my understanding of this technology.</td>
<td>3.51</td>
<td>0.58</td>
<td>3.6</td>
</tr>
<tr>
<td>I know more about VFDs as a result of this laboratory activity.</td>
<td>3.62</td>
<td>0.50</td>
<td>4.0</td>
</tr>
<tr>
<td>Using the VFD trainer helped me learn about this technology.</td>
<td>3.62</td>
<td>0.59</td>
<td>4.0</td>
</tr>
<tr>
<td>I feel confident that I have a basic understanding of VFD theory.</td>
<td>3.33</td>
<td>0.87</td>
<td>4.0</td>
</tr>
<tr>
<td>I feel confident I understand how to operate a VFD.</td>
<td>3.48</td>
<td>0.75</td>
<td>4.0</td>
</tr>
</tbody>
</table>

*Note.* Based on a scale where 1 = strongly disagree and 4 = strongly agree.

**Summary and Conclusions**

We constructed a safe, functional VFD trainer at a unit cost of $534.70. The trainer was constructed at a materials cost of approximately 20% of the retail price of commercially available VFD trainers. The trainer met all specified design criteria related to safety, cost, local and remote operation, and programmability through the keypad.

Survey results indicated students enrolled in a junior-level agricultural electricity course at a four-year university had little if any prior knowledge of or experience with VFDs. Given the importance of VFD applications in agricultural industry, this finding reinforced our original perception that it was important to provide students in AGME 3173 and similar courses with hands-on experiences programming and operating VFDs. The survey results also indicated that AGME 3173 students agreed the VFD trainer-based laboratory activity was an effective learning experience.

Overall, we concluded the VFD trainer and lab activity were economical and educationally effective additions to our undergraduate agricultural electricity course. We intend to construct additional trainers for use in future semesters. This will allow us to significantly expand the scope of the laboratory activity and still allow students to complete the activity in one lab period. In addition, we plan to add a programmable logic control (PLC) interface to each trainer so students can learn more advanced motor speed control applications.
References


