THESIS

BENEFITS OF USING VARIABLE FREQENCY DRIVES ON GREENHOUSE EXHAUST SYSTEMS

Submitted by

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ABSTRACT

BENEFITS OF USING VARIABLE FREQENCY DRIVES ON GREENHOUSE EXHAUST SYSTEMS

Greenhouses provide many benefits to a plant producer by allowing for a tightly controlled environment best suited for the crop. Since sunlight is allowed almost free access to the inside of a greenhouse, removing heat buildup becomes a large obstacle to deal with. Energy needed to meet a typical cooling requirement can be costly and lowering overhead will be helpful to a sustainable greenhouse business. Variable frequency drive (VFD) technology has the potential to not only save electricity and reduce monthly operating costs, but can offer the grower climactic and water use benefits as well. Two greenhouses were compared for this study, one having a typical On/Off style fan system and the other has a VFD system installed. The parameters looked at were short cycling, total energy use, temperature, crop growth, and water use. The results of the research indicate that VFDs do offer significant reduction in electricity usage, showing only half of what the On/Off fans used. A reduction in water use was also seen with slightly greater crop growth in the VFD greenhouse. VFDs on exhaust fans show benefits that any greenhouse grower would like to have in their operation.

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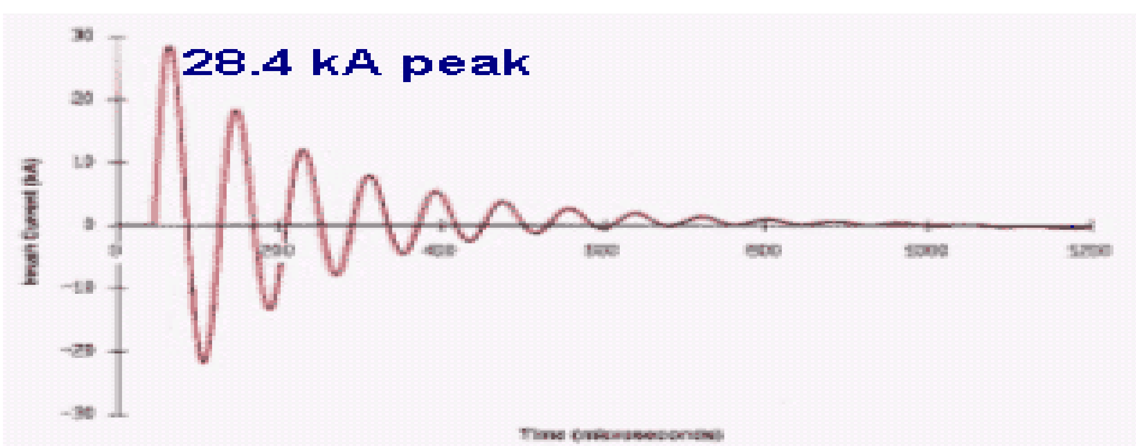
INTRODUCTION

Variable frequency drives (VFDs) have been in use to control the RPM of electric motors for over a decade and little attention has been paid to their application in a greenhouse environment. Greenhouses can be considerably difficult to cool, especially in summer months when solar radiation is highest (Nelson, 2003, Boodley and Newman, 2009). Large fans usually around 1 meter in diameter, coupled with an evaporative mechanism are a common method to remove heat and can consume considerably high amounts of electricity (Sanford, 2012). Fans need to be sized in such a way that maximum air flow will be high enough to meet the maximum cooling requirement; however, this causes the fan to short cycle when cooling requirement is lower. Short cycling is when a fan turns on at full power at the high temperature set point and then shuts completely off when the desired temperature returns, repeatedly only running for a short duration throughout the day. This becomes increasingly inefficient because when a fan is started, much energy is required to get it up to full speed, a time when the motor can consume several times its normal full-load (fig. 1).



http://www.sandc.com/webzine/2002/032502_2.asp

Fig. 1: In-rush current. Zero on y-axis represents normal full-load. In-rush can last 200-400 milliseconds

In-rush current can be a major detriment to equipment life, creating unnecessary heat and stress each time the fans are turned on (McGranaghan, 2006). It is easy to see the benefits of implementing a fan system that adapts to changing conditions and this is why it's surprising that so few greenhouse owners are even looking into a variable frequency drive install.

The primary objectives of this study were to determine the energy efficiency, climate control capacity, and water use characteristics of VFDs on exhaust fans in a greenhouse environment. The study demonstrated how a simple installation of a VFD system on already in-place exhaust fans can reduce overhead of water and electricity while increasing crop growth. Crop scheduling is a major concern with any greenhouse grower and VFDs have the capability to reduce variable microclimates throughout the greenhouse. A greenhouse that is homogenous in temperature and humidity will allow the grower to be more precise with timing and increase crop uniformity. Overall, the research showed that there are improvements that can be made to greenhouse exhaust systems and variable frequency drives can provide many of these in one package.

LITERATURE REVIEW

Greenhouse Cooling

One of the benefits of growing crops in a greenhouse is a controlled environment that is decoupled from outdoor extremes. This helps the grower produce plants that are higher in quality and faster maturing than outdoor production (Nelson, 2003, Boodley and Newman, 2009). There are many obstacles, however, that a greenhouse owner must contend with to maintain the desired environment; perhaps the most difficult obstacle to overcome is the intense solar energy that gets trapped inside the greenhouse and converted to heat (Nelson, 2003). Cooling a greenhouse can be a challenge during times of high solar energy, even when outdoor temperatures are low (Nelson, 2003). Plants are very susceptible to high heat and even a moderate degree of heat stress significantly slows whole plant growth (Taiz and Zeiger, 2006; Kamp and Timmerman, 2002). Thus, greenhouse cooling is an area of constant energy and water use, in which improvements are desirable to reduce the overhead costs of the greenhouse grower (Boodley and Newman, 2009).

There are two basic types of cooling used in the greenhouse: active and passive. Passive cooling is accomplished simply by opening a vent and allowing natural air flow to cool the greenhouse (Kamp and Timmerman, 2002). This type of cooling does indeed help reduce air temperatures inside, but is very limited by wind speed and cannot cool lower than outdoor air temperatures (Boodley and Newman, 2009). In fact, due to solar energy being trapped under the greenhouse covering, temperatures of about 17^{o} C higher than ambient can be observed (Nelson, 2003). To solve this problem, active ventilation was invented and coupled to an evaporative mechanism. A cooling system that has forced ventilation while adding moisture to the air has the capability of cooling a greenhouse down to about 10^{o} C below outside temperatures, or 80% of the difference between the dry bulb and wet bulb temperatures (Bucklin, 2004; Boodley and Newman, 2009). These systems are common in today's horticulture industry and can be a large chunk of the operational costs of a greenhouse. Creating new and improved practices that can increase cooling efficiency will be beneficial to the horticulture industry as a whole.

Greenhouse cooling needs can change dramatically throughout the day and growing season (Kamp and Timmerman, 2002). During morning and afternoon hours, when outside temperatures are low but the sun is still shining, solar gain can still cause the indoor environment to heat up enough that some cooling is required. Exhaust fans that are designed to cool a greenhouse when sun light and temperatures are at their most extreme, are turned on at full power during these mild conditions and ran for a short time, quickly cooling back down to the set point when they shut back off. This does work as the fans are able to maintain greenhouse temperatures, but can be very energy inefficient. Converting a single speed exhaust fan system to one that is dynamic and adjusts to changes in outdoor conditions would be advantageous to a greenhouse system (Tietel, 2004).

Alternating Current Induction Motors

Throughout many different industries, far and away the most common type of motor used in any motion system is the alternating current (AC) induction motor (Parekh, 2003). A motion system can include anything that is moving, be it an object, liquid or air and the force needed for motion can be provided electrically with the use of motors. Electric motors have a wide variety of applications and can be very adaptable while maintaining a rugged and durable mechanism of movement. Motors that run on electricity also come in a diversity of styles, each being suitable for differing applications. Motors fit into the broad categories of direct current (DC) and alternating (AC) types, with each containing a multitude of power outputs and control abilities. AC induction motors are easier to design and engineer, however, DC motors are actually easier to control torque and speed. Since AC electricity is the most accessible and widely used, we must gain a greater understanding of the workings of AC induction motors such that we can realize precise control of its characteristics (Parekh, 2003).

The AC induction motor has 2 main parts, the stator and the rotor, and the spinning force comes from the magnetic interaction between these parts when hooked up to an AC power supply (Parekh, 2003). Electricity generated at the power plant alternates between positive and negative voltages in a sinusoidal form. This alternation creates a rotating magnetic field in the stator and induces a voltage (how induction motors get their name) in the rotor. The induced voltage then creates its own magnetic field in the rotor and it is the interaction between these two fields that provides a force and turns the load.

An interesting aspect of AC induction motors is that the magnetic field created from the stator rotates at a speed that is a function of the power supply frequency (equation 1) and number of poles in the stator. A motor requires a minimum of two poles, and the more poles it has, the slower it will rotate at a certain frequency. Also, more poles can mean more torque; since the distance between poles is shorter, the force between them is stronger (Melfi, 1992).

Equation 1:

$$\mathbf{RPM_{stator} = 120 \times (frequency_{hz} / \#\ of\ Poles)}$$

Since the rate of rotation, RPM, is a function of the frequency supply, controlling the RPM can be achieved by controlling the input frequency. This is a major characteristic that a variable frequency drive takes advantage of in many aspects, from precise speed control to the in-rush eliminating soft starting technology.

There are 2 main types of AC induction motors which are characterized by the number of stator windings, the single phase and three phase variants. Single phase is the most common and there are likely more of these types of motors used today than all of the other types of motors combined (Parekh, 2003). These motors have the lowest maintenance requirements and usually a lower installation cost, while still being versatile. A major drawback of single phase, however, is that these motors are not self-starting and need a kick to get the motor rotating initially. Due to the high initial force needed to get heavy loads moving, the single phase motors are not good when more than 1 horse power is required. Three phase motors, on the other hand, are self-starting and need no additional circuits to get the motor turning from a stop. These types of induction motors can actually generate a high degree of starting torque and have an extremely wide range of power outputs, from 0.5 HP up to 100,000 HP or more (General Electric, 2012). The downfall is that they are more expensive for initial installation; however, this can be offset with power savings over the course of the motor's life. Three phase motors run at higher voltages and the phases of the electricity are offset by 120 degrees, so 3-phase motors run more efficiently than single phase motors. In general, single phase motors are better for small applications that have low initial power needs, while three phase motors are better for larger applications in industry (Parekh, 2003).

The exhaust fan cooling systems that are common in the greenhouse industry can be run using either single or three phase motors and each type can be run using a variable frequency drive. It becomes important for the owner to decide which is right for their particular application and future outlook, while having knowledge of the power supply availability in their area. Three phase systems will be significantly more expensive on initial install, but can save money in the long run. Many times, motors are installed that generate more torque than is needed, which can waste energy (Ferriera, 2006), unless a VFD is installed and used properly. The VFD technology can bring high efficiency to any exhaust system setup with AC induction motors.

Variable Frequency Drive Technology

Semi-conductor technology has come a long way in the last ten years, with microprocessors getting less expensive and amassing capabilities rapidly. The greenhouse industry has recently started to take advantage of improved computer technology with automated equipment and environmental controllers. Variable frequency drive technology has been improving steadily along with semi-conductor advances and could bring major improvement to greenhouse operation (Burt, 2008; Easton Consultants, 2000). Since it is industry standard to use AC induction motors for multiple applications, VFDs can be applied easily with minimal extra equipment purchases (Parekh, 2003). Also, greenhouse controllers with built in programming to control VFDs are becoming more common place, while new VFD technology allows connection with older controllers. Many options are now available for compatibility with a multitude of set ups (Carrier Corporation, 2005).

Variable frequency drives can be used to control the rate of rotation of an AC induction motor by varying the frequency of electricity supplied. The way in which a VFD actually varies the frequency is through a number of steps, but the main idea is that it converts an analog (AC) supply to a digital, DC supply, which then allows the unit to supply the motor with any frequency programmable. The up and down (positive to negative, fig. 2) sine wave of a typical AC supply is first converted to a DC current using a series of diodes arranged in an electrical bridge. The diode bridge actually re-constructs the negative half of the AC onto the positive half (fig. 3), and then a DC bus smoothes out the signal such that any AC component is filtered out (fig. 3). Now that the VFD has complete "control" of the signal, it actually re-creates a synthesized AC signal that is then supplied to the motor. The synthesized AC signal doesn't provide an exact replica of an AC sine wave; instead, it provides voltage pulses that are at a constant magnitude, each consecutive pulse differs in voltage and duration, simulating an actual alternating current (fig.4). The duration of each pulse and the length of time between pulses, as well as each pulse's voltage, determine the frequency that the motor "sees." The VFD can be set up so that it varies the output frequency based on an input signal voltage. This

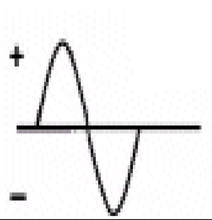


Fig. 2
Sinusoidal AC electrical signal

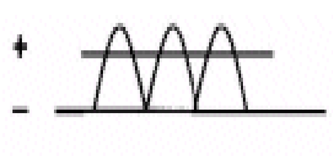


Fig. 3
Diode Bridge converts AC to DC and the Bus then smoothes signal

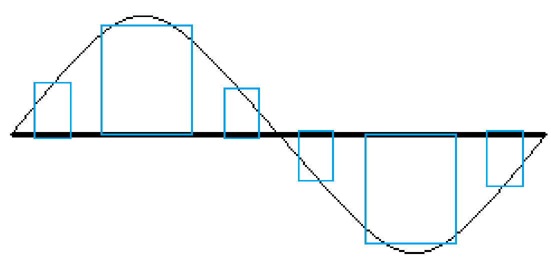


Fig. 4 Blue boxes represent the DC pulses that mimic an AC signal which is provided to the motor from the VFD.

voltage is the control signal and can be managed by many types of greenhouse controllers based on cooling needs (Easton Consultants, 2000; Carrier Corporation, 2005).

There are many possible benefits of using VFDs in a greenhouse; energy savings and climate control are probably the biggest (Teitel, 2004). Using a VFD will allow the greenhouse controller to ramp up or down fan speed as cooling requirement increases and decreases. This allows the fan to run for longer periods of time which limits costly in-rush current and increases mixing. Recent upgrades in semi-conductor technology has allowed for a new feature, called soft-starting, to be built into VFDs. Soft starting involves slowly bringing up the fan speed to the desired RMP over a period of about 5 seconds (this time can be programed into the VFD unit), nullifying the in-rush current effect. Eliminating in-rush reduces two costly things: energy use and equipment stress (McGranaghan, 2006).

A key energy saving attribute of VFDs comes from something termed an affinity law. The affinity law states that the change in power is proportional to the cube of the change in speed, thus running a fan at 50% max speed can save around 75% of the energy (a fan running at 50% max rpm only uses 12.5% horsepower, Fig. 5). Using VFDs allows the fan speed to be slowed all the way down to 20% of full speed. Running a fan for a longer period of time at a slower RPM not only saves energy due to affinity characteristics, it reduces short cycling and increases greenhouse air mixing. Climate homogeneity is something that a research greenhouse must be able to maintain and using VFDs can really help with this (Teitel, 2004). A significant reduction in energy usage and microclimate unevenness can be seen in a greenhouse environment with correct application of VFDs.

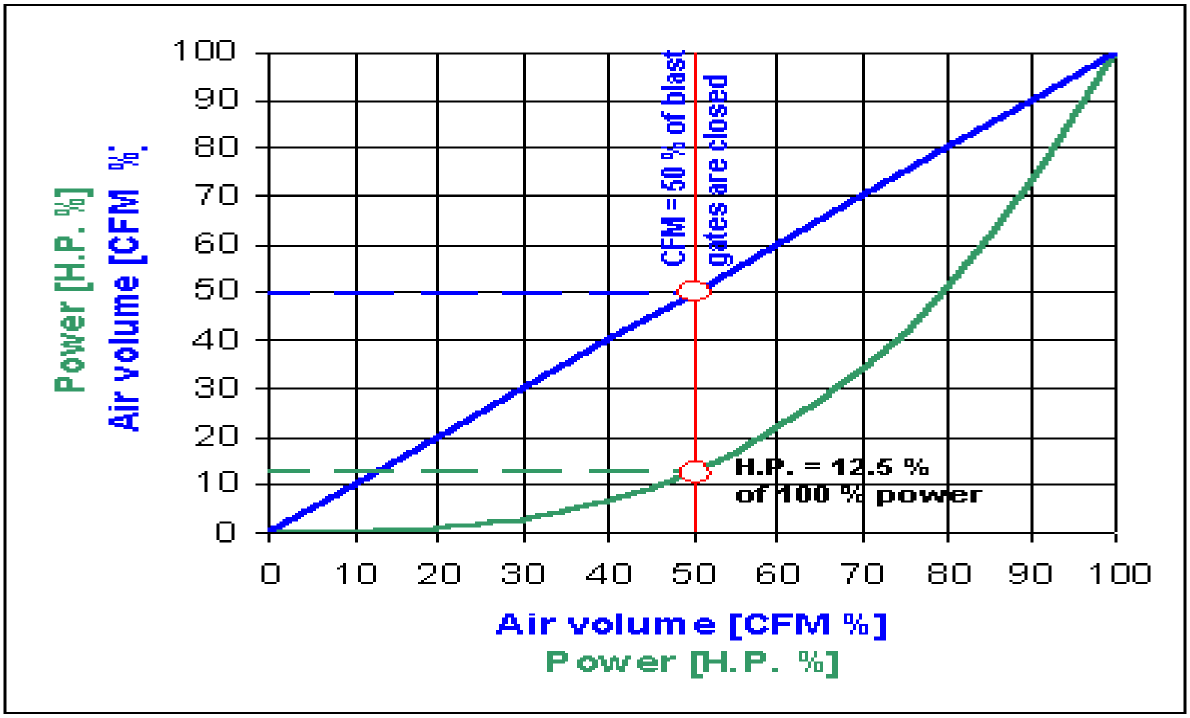


Fig. 5: Affinity law characteristics of motors where it can be seen than at 50% RPM the motor uses only 12.5% of max horse power, a major characteristic usable for reducing energy consumption.
http://www.ecogate.com/industrial/industrial.htm

Water Loss

Water use in a greenhouse comes from many places; the largest quantities are from evapotranspiration, greenhouse cooling, and evaporation off soil surface (Sabeh, 2006; Shibata, 1995, Boodley and Newman, 2009). Water can be costly, thus it is of great interest to the horticulture industry to find new ways of reducing total water use. Each of the three listed processes that contribute to water loss are affected by ventilation air speeds through the greenhouse. The higher the ventilation speeds, the faster water will be lost out of the greenhouse (Sabeh, 2006).

Evapotranspiration rates through plant leaves are inhibited by the boundary layer; the thicker the boundary dead air layer the slower the evapotranspiration (Monteith, 1965). Boundary layer thickness is altered by wind speed, for example, faster moving ventilation air will reduce the boundary layer thickness (Zhang, 1992). This in turn increases transpiration rates of plants in the greenhouse (Monteith, 1965). Another major factor affecting transpiration rate is vapor pressure deficient, or the difference between the humidity in the atmosphere and the inside of the leaf. As the vapor pressure deficit rises, the water potential of the air becomes greater, thus water evaporates out of leaves faster (Monteith, 1965). It was found in tomato plants, that transpiration rates increased linearly with ventilation rates (Sase, 2006). Stomatal pores provide a low resistance pathway for diffusional water vapor movement out of the plant, and during higher temperatures, stomata can be fully open allowing almost free movement of water vapor (Taiz and Zeiger, 2006).

Water used by an evaporative mechanism for cooling purposes can consume large amounts of water when high solar energies are prevalent (Boodley and Newman, 2009). Therefore, evaporative cooling systems that use water more efficiently are important for reducing total water use in a greenhouse system. This becomes even more important in areas where water resources are limited and high daily average temperatures exist. Sabeh 2006 found that the rate of water use increased linearly with ventilation speed, while also noting that the cooling efficiency of a pad wall decreased with increasing ventilation rates. Thus, it is of interest to look at reducing air flow rates to reduce water loss from evaporative cooling.

A major source of water loss in a greenhouse is evaporation off the soil media surface in potted plants. Evaporation from soil is a distinctly different process than transpiration, but is affected very similarly by temperature, relative humidity, and air flow rates through the greenhouse (Harp, 2007 and Smits 2010). Increases in temperature, ventilation rates and decreased relative humidity will undoubtedly increase evaporation rates from soil surface. Limiting evaporation from soil will not only reduce total water use by greenhouse, but also may positively affect plant growth by maintaining higher soil moistures for longer periods of time. It is an objective of this study to look at the evaporation and evapotranspiration differences between differing ventilation strategies.

Climate Homogeneity

Variation of multiple parameters is common throughout any greenhouse. Temperature, humidity, and light intensity can be significantly different from one side of the greenhouse to the other and outdoor environmental factors can influence microclimate variation as well (Tietel, 2004, Greenhouse Systems International Conference, 1994). Dissimilarities can be great enough to cause plants to grow unevenly and of a reduced quality. In flowering plant production, the grower is highly concerned with crop uniformity, thus, a homogenous greenhouse environment is desired (Boodley and Newman, 2009).

Temperature is something that can change dramatically throughout a greenhouse, especially when an evaporative pad wall and forced ventilation are used together (Bucklin, 2004; Nelson, 2003). The pad wall is located opposite of the exhaust fans and uses water vapor to drop the air temperature as it moves across the greenhouse, creating much cooler temperatures nearest the pad wall (Bucklin, 2004; Greenhouse Systems International Conference, 1994). Structure can also affect the movement of air, causing eddies in the ventilation current and subsequent microclimate differences. One method to combat this is to increase air mixing by running ventilation equipment longer, such that air is flowing more often, even if it is at a reduced rate. Microclimate homogeneity is of utmost importance in a research greenhouse setting as researchers need to reduce as many variables as possible. There is significant interest in constructing better climate control systems that increase microclimate homogeneity.

MATERIALS AND METHODS

Overview of the greenhouses used in this research

The aim of this research was to gain an understanding of the possible benefits that can be realized using VFDs in a greenhouse setting. The benefits examined were energy use efficiency, microclimate uniformity (related to crop uniformity), and water use. A comparison was made between two identical greenhouses with one key difference; one was setup with typical on/off controlled fans and the other had a VFD controlling the fan speed. The greenhouses are at W.D. Holly Plant Environmental Research Center at Colorado State University and are directly next to each other. Both greenhouses are the same size (9.14m x 15.24m) with the same covering material (double wall poly carbonate), shade cloth system, passive ventilation, evaporative pad wall, fan/motor size, each having 2 exhaust fans.

In the greenhouse with the VFD (VFD GH), one VFD is hooked up to both exhaust fans, controlling their speed based on the programming parameters setup in a greenhouse climate control module (Wadsworth Envirostep). The control module contains the set points, which also determine how fast the exhaust fans run. This process has two basic aspects: first is the difference between the air temperature and set points determines the fan speed and the second is a modulated voltage output from the control module used as the signal to control what frequency is sent to the motor from the VFD unit. Motor RPM is a function of the frequency of the synthesized alternating signal which is created using pulse width modulation (discussed previously). The further from the set point the faster the fan will spin until speed reaches 100%. The fans will remain on at full speed until the temperature begins to drop. Once the temperature begins to get closer to the low set point, the fan speed will ramp down and then shut off once the low set point is reached. The difference between the low set point and high set point determines the percent RPM the fan will spin at each temperature increment. In this system, the difference between the high and low set points is 4^o F (Degrees were reported in Fahrenheit here because the programming in the control module is set using Fahrenheit and converting to Celsius would not allow for an effective description of how the program works as the module uses the difference between the set point and temperature sensor reading to determine how fast the motor should run. Converting to Celsius would cause confusion in the numbers.), meaning that the fan speed steps up and down by 25% for each increment. So, at 73^o F the fan turns on at 25% of its max speed, at 74^o F it goes up to 50%, then at 75^o F it turns up to 75%, and then goes to full speed at 76^o F until the temp begins to drop. The process is reversed until the fans have cooled the greenhouse to below the low set point, then the fans will shut off completely.

The greenhouse used to make a comparison (NON VFD GH) has the same size fans and motors, but is set up differently. Here, one fan is controlled by an on/off relay switch, with the other fan having an individual VFD. Since this is the comparison greenhouse, the VFD control programming in the Envirostep is setup such that it acts tantamount to an on/off style fan. Thus, the parameters here will be very similar if not identical to a typical greenhouse setting where the fans come on at full power and run that way until they shut off. All measurements were taken from the on/off fan side. The set points were set the same in both the VFD GH and the NON VFD GH.

Energy use

Two factors that allow VFDs to reduce energy usage are the absence of an in-rush current and the affinity law that tells us that a fan running at 50% RPM only uses about 12.5%

of its full power (see figure 2, page 13). In-rush current is removed by limiting short cycling and the soft starting technology used by the VFD unit. As the fans are allowed to run at lower RPMs for longer periods of time, many on and off cycles are taken away; in-rush current happens at startup. When the VFD fans do start from a stop, the fan is ramped up to its desired speed over a period of about 5 seconds, severely decreasing the initial load needed to overcome inertia and friction.

To quantify these concepts, two systems of electricity monitoring were used. The first is an amp event logger which takes instantaneous amperage readings every 30 seconds. These data show when the fan is turned on and off and how long it remains at each state, while also showing the ramping up and slowing down of the VFD system. Two individual data loggers (HOBO U12) were connected to amp clamps (HOBO UV-B) that were then attached around a power wire going to the fan motor, one logger for each greenhouse yielding simultaneous data between the VFD GH and the NON VFD GH. The data set was then analyzed by first converting the amperages to values of 1 or 0, 1 signifying the fan in an on state and 0 signifying the fan in an off state (any amp value greater than 0.06 amps was converted to a 1 and all other values were converted to 0). Each value (1 or 0) was then subtracted from the previous value, which yielded data that represented change of state events (change of state means turning on or off). When the fan turned on, a 1 is given. When the fan turned off, a -1 was given. 0 signifies no change, meaning the fan remained on or off in between recordings. These values were then converted to absolute values, all the 1's were summed and the total was then divided by 2 (see fig. 9 for a visual sample of this process). This quantified the on/off cycles for the duration of the recording period (9/9/11-10/14/11). The percent difference of on/off cycles between the VFD and NON VFD fans was calculated and plotted (fig. 9)

The second monitoring system is a total energy usage logger (Current Cost systems, EnviR). This unit monitors and logs the complete real time electricity usage, then converts it to KWh units and a cost estimate. Total electricity use was monitored for a period of 33 days, from 1/2/12-2/3/12; the total usages for each fan were then summed at 7 and 33 days. This logger monitored the energy usage simultaneously between both greenhouses eliminating outdoor environmental variables between different time frames.

Water Use

It is hypothesized that the more even and stable climate provided in the VFD GH will cause a reduction in water use. As water leaves the pot either through the plants stomata or evaporation off the soil surface, the pot will lose weight. Thus, to monitor water loss, a hanging lysimeter was used. This system was composed of a data logger (Campbell CR-1000) with a relay multiplexer used to read voltages of 6 load displacement sensors from which 6 pots, each containing a *Syngonium podiphylum,* were hung. A calibration regression was done using water at 5 gram increments up to 55 grams and the equation of this line was used to convert from volts to grams (fig. 6). The program for the data logger was written in Short Cut, a program created by Campbell Scientific for easy data logger programming, and set to record data every 5 minutes continuously. This set up was replicated in both the VFD and NON VFD greenhouses using identical equipment and programming parameters. Due to a single load displacement sensor failure, however, in the VFD greenhouse only 5 pots were hung and weighed. Data was monitored for 6 watering cycles, or about 4 weeks, and a comparison of the slopes of water loss was analyzed for each plant, the greater the slope the faster the water loss. The average water loss rate for all plants during each watering cycle in each greenhouse was then taken and used to determine which fan system caused then most water loss. A water cycle is defined as the time from soil saturation with water to wilting point.

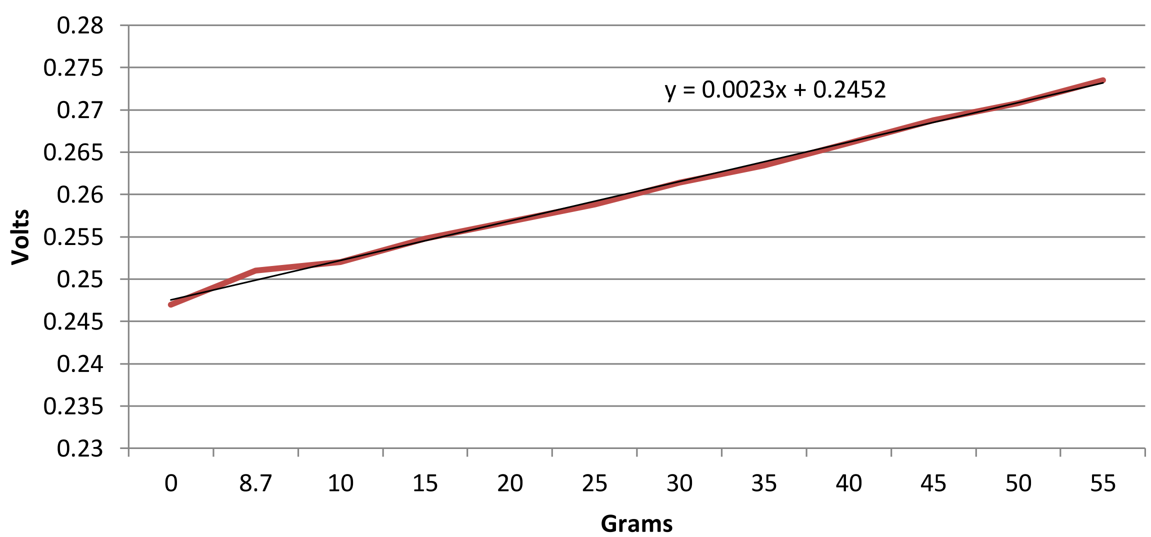


Figure 6: Calibration regression used to convert from volts to grams to analyze water loss characteristics from hanging lysimeter data logger setup.

Crop Growth

A common greenhouse crop, *Syngonium podiphylum,* was grown in both greenhouses for 5 months (11/3/11 to 3/2/12) to look at growth uniformity and production between the two systems. In each greenhouse, 62 plugs of *Syngonium podiphylum* that were equal age and roughly equal size were potted (11/3/11) in 4 inch square plastic pots using Pro-Mix media, making a total of 124 plants. They were always watered and fertilized at the same time, using 100ppm of 15-5-15 fertilizer (CalMag) nutrient for the first 2.5 months. After 2.5 months, the ppm was increased to 150 due to increased plant size and growth. Leaf counts of each plant were taken at transplanting and again at 5 months. These data were used to see if the VFDs have an effect on uniform growth around each greenhouse as well as differences in total growth between the VFD GH and NON VFD GH. Two separate applications of the pesticide imidacloprid (Marathon, Olympic Horticultural Products Company) were applied to the soil surface for systemic uptake to limit a possible confounding pest pressure difference between both greenhouses.

Climate Variability

An important aspect of any successful greenhouse operation is maintaining a uniform environment such that there are no differences with crop size or quality at harvest time. Using VFD systems should create a much more even and uniform climate as the fans will be running more consistently at lower RPMs, limiting dead or hot spots while maintaining a temperature closer to the set points with smaller variation. Temperature data loggers were placed in each greenhouse. The loggers were then set to record temperature every five minutes to produce data showing temperature change characteristics around the greenhouses. The average change was calculated by subtracting each data entry from the previous one, yielding the change in temperature from one reading to the next. These differences were then averaged to get an average change data set and plotted.

Five loggers were used in each greenhouse and were placed in the center of 5 benches. There are 6 benches along the length of the greenhouse; the bench closest to the evaporative pad wall did not have a logger placed on it due to logger availability. The benches are 2.44 meters wide, thus this is the distance between each logger.

RESULTS

Short Cycling and In-Rush Current

The two data loggers with amp clamps were set to read instantaneous amperage readings every 30 seconds. The results of these data show that the fans with the VFD do run more steadily and cycle less than the NON VFD fans. This amperage data (figures 7, 8) also shows that the VFD is indeed changing speeds throughout the day, running continuously for much longer before shutting off completely. With the fans on and off cycles reduced significantly in the VFD GH, in-rush current is eliminated due to previously cited in-rush characteristics of electric motors. From the data shown in fig. 8, large spikes in current can be seen at various readings in the On/Off fan data. These spikes, some being 10 amps (9/10/11 at 8:45 and 9/11/11 at 8:00am), are in-rush current events that the data logger was able to capture due to it taking a reading at exactly the time when the fan turned on. As in-rush usually only lasts about 500 milliseconds, the spike is not seen each time the fan is turned on in the data, but it is definitely there (McGranaghan, 2006). In figure 8, some of the in-rush spikes that were observed were 5 times the normal full amp load. It's hard to really observe the full in-rush current without special equipment, but in-rush is definitely occurring, and although we can't always see it in the data, in-rush current comes every time the On/Off fan is started (McGranaghan, 2006). Not one in-rush spike was observed in the VFD fan data through the entirety of amp clamp data collection.

The quantification of on/off cycles reveals just how much more the NON VFD fan is cycling. Over the course of all the recoding periods (9/9/11-9/14/11, 9/14/11-9/23/11, 9/23/11-9/30/11, 9/30/11-10/7/11), the NON VFD fan cycled an average of 23.32% more than the VFD fan. Figure 10 shows the percent difference in on/off cycles for each recording period. The NON VFD fan always cycled more, thus the percent difference is actually the percent more cycles the NON VFD fan exhibited. Figure 11 shows the actual numbers of on/off cycles from each recording period for each fan. An average of 172 more cycles was seen in the NON VFD fan.

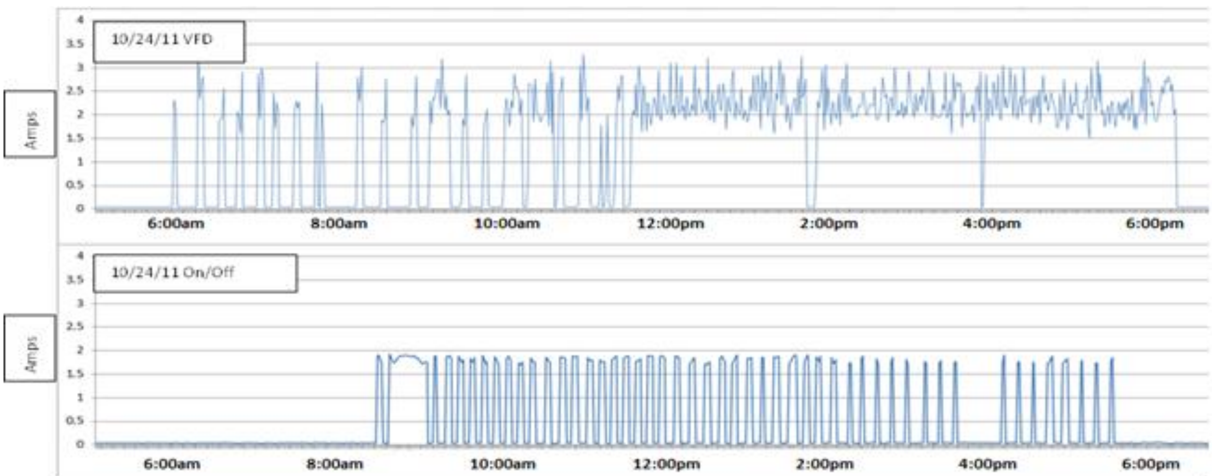


Fig. 7 : Instantaneous amperage data using amp clamps and HOBO U12 data loggers for the day of 10/24/11, both VFD and On/Off. Note the reduced short cycling from the VFD fan.

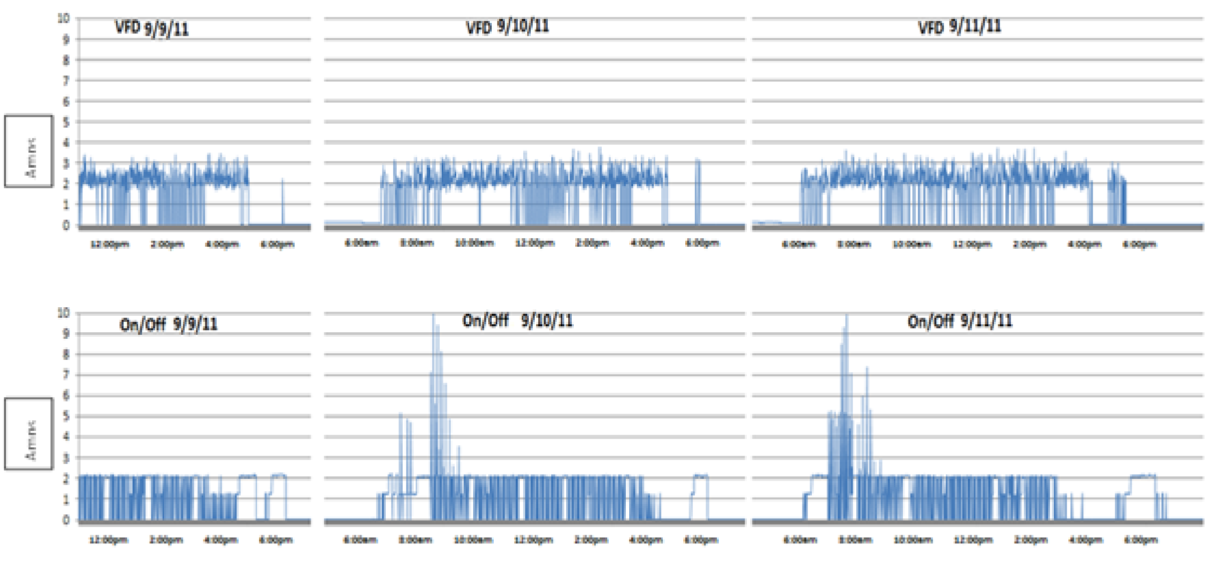


Fig. 8 : Instantaneous amperage data using amp clamps and HOBO U12 data loggers for the days of 9/9/11 to 9/11/11, both VFD and On/Off. Note the large spikes of in-rush current from the On/Off fan.

	A	B	C	D	E	F	G	H
1								
2	Date Time, GMT-06:00	AC Curr, Amps	On/Off	State Change	ABSVAL			
3	10/7/2011 9:45	0.055	0	0	0		Sum ABSVAL	1108
4	10/7/2011 9:46	0.043	0	0	0		Divided by 2	554
5	10/7/2011 9:46	2.618	1	1	1			
6	10/7/2011 9:47	2.313	1	0	0			
7	10/7/2011 9:47	1.923	1	0	0			
8	10/7/2011 9:48	2.399	1	0	0			
9	10/7/2011 9:48	2.509	1	0	0			
10	10/7/2011 9:49	2.118	1	0	0			
11	10/7/2011 9:49	0.043	0	-1	1			
12	10/7/2011 9:50	0.043	0	0	0			
13	10/7/2011 9:50	0.043	0	0	0			
14	10/7/2011 9:51	0.043	0	0	0			
15	10/7/2011 9:51	2.887	1	1	1			
16	10/7/2011 9:52	2.02	1	0	0			
17	10/7/2011 9:52	1.91	1	0	0			
18	10/7/2011 9:53	2.191	1	0	0			

Fig. 9: A sample of the instantaneous amperage data showing how on/off cycles were quantified. The “Divided by 2” data is the number of on/off cycles over the recorded period.

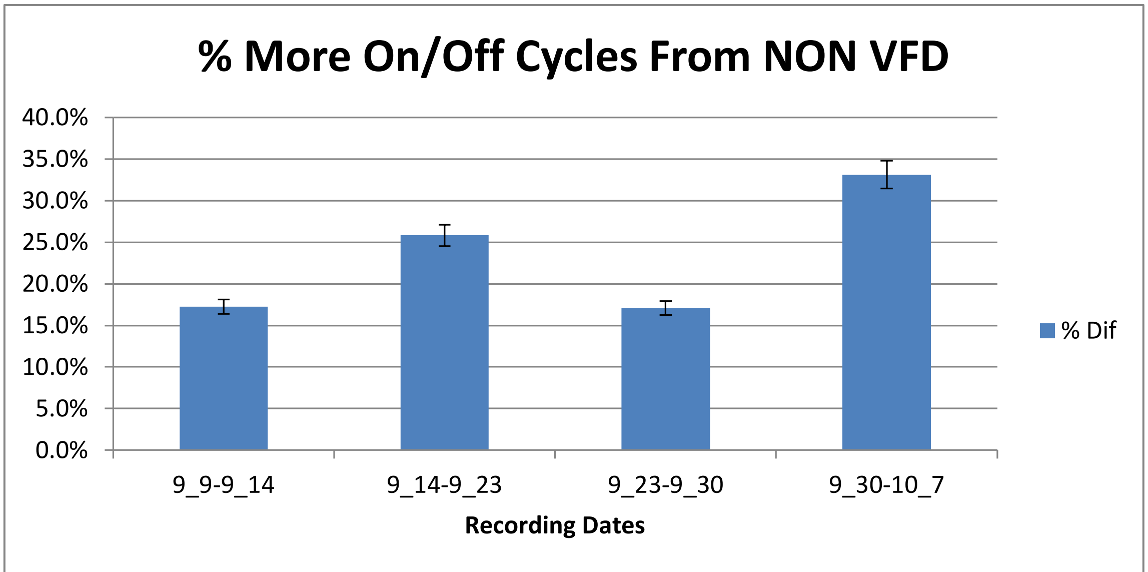


Fig. 10: The percent difference in on/off cycles between the VFD and NON VFD fans. In each recording period the NON VFD fan cycled more than the VFD fan.

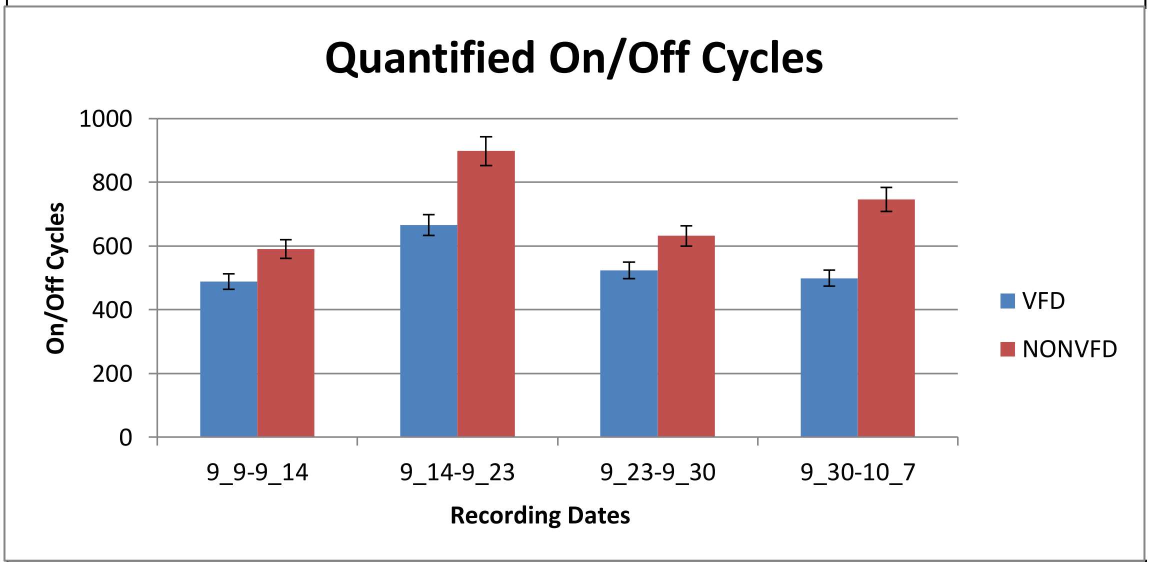


Fig. 11: On/Off cycles were quantified, revealing how much more the NON VFD fan cycled.

Energy Use

A continuous electricity usage meter was hooked up to both the On/Off and VFD fans and monitored for a period of 30 days, yielding accurate power data for comparison (fig. 12). There was no energy savings after only one day, but after 7 days, a savings was already observed. Here the VFD fan used 7 kWhs whereas the On/Off fan used 10 kWhs. The biggest difference is when the data was looked at for 30 days, where a difference of 20 KWhs was observed; the On/Off fan used 40 kWhs when the VFD fan only used 20 kWhs. So the VFD fan system used exactly half of what the On/Off fan used.

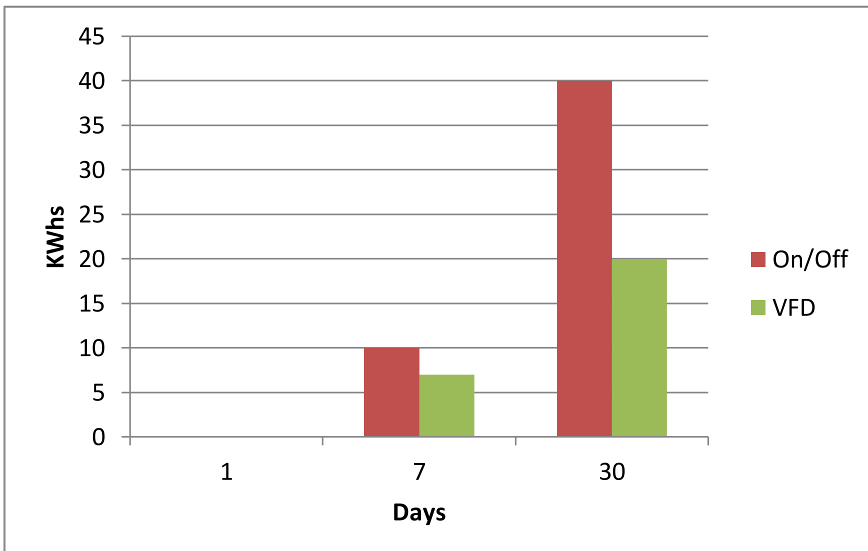


Fig. 12 Left: Power usage data for 30 days, both VFD and On/Off fan setups. Right: The data logger used to monitor electricity usage.

Water Use

A large portion of the overhead required to run a greenhouse is the water bill. An aim of this study was to determine if using a VFD in a greenhouse could help reduce water transpired by plants and lost from evaporation of soil surface. Although these processes are distinctly different, they were not decoupled for this experiment as it was an objective to look at total water use in a real world scenario, not determine which process yields the most water loss. Over a period of 28 days and 4 watering events that the lysimeters (fig.14) recorded, it was seen that the On/Off fan system increased water loss from plant and soil surface (fig. 13) by an average of almost 0.10 grams/min/m^2.

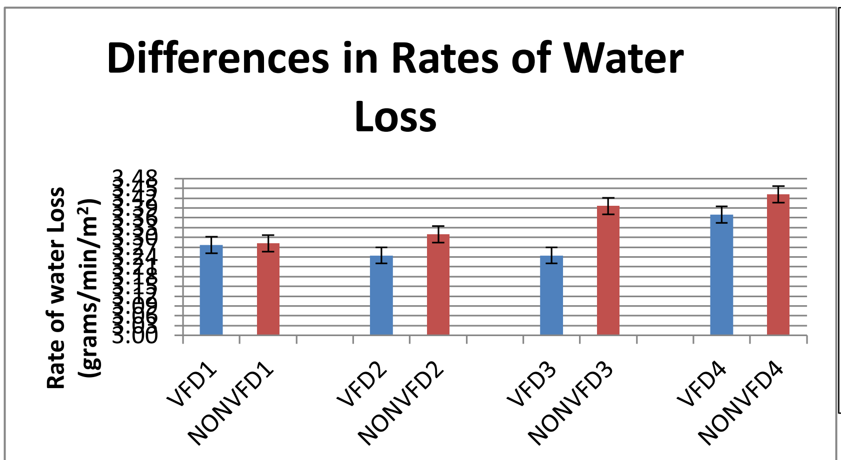


Fig. 13 Rate of water loss over a period of 28 days and 4 watering events. VFD1 and NONVFD1 represent the averaged water loss of all plants in first watering cycle, VFD2 and NONVFD2 the second watering cycle

Fig. 14 Hanging lysimeter setup used to determine water loss rate characteristics in both VFD and On/Off fan greenhouses simultaneously.

Crop Growth

62 *Syngonium podiphylum* plants were grown in both the On/Off greenhouse and the VFD greenhouse (124 plants total) for a comparison of crop growth and uniformity. The plants in both greenhouses started with an average leaf count of about 12.5 leaves and were grown for five months, from 11/3/11 to 3/2/12. The final leaf counts indicate how much the plants grew; the On/Off greenhouse ending average was 35.6, while the VFD greenhouse was up to 39.4, showing that the plants grew slightly faster in the VFD greenhouse (fig.15).

The plants were spaced evenly around the greenhouses and the growth data was also used to look at variation of growth at different areas around each greenhouse. Individual location's growth rates were compared as well as general areas between both greenhouses and around each greenhouse. A pattern of higher or lower growth rates could not be found. It could not be determined whether the VFD fan system made any improvement in crop growth uniformity over the On/Off fan system.

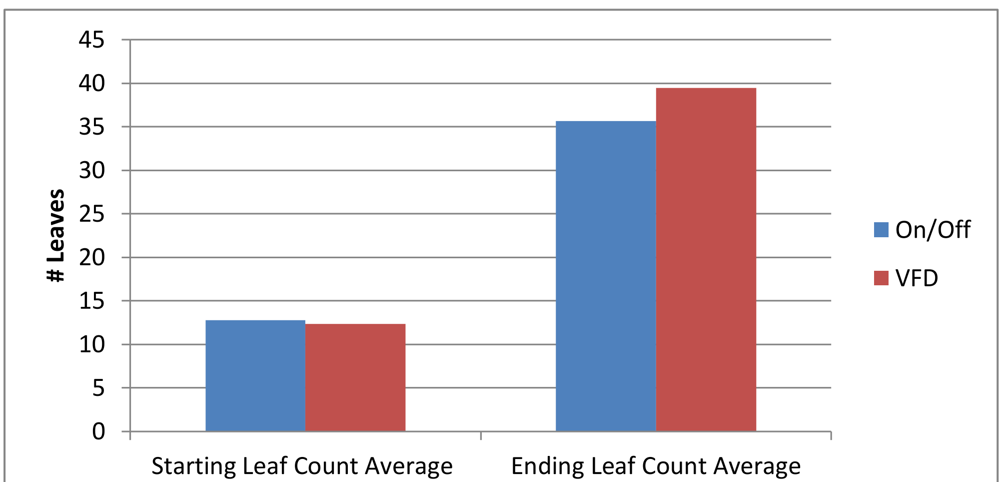


Fig. 15 Average leaf Counts of all plants in each greenhouse at transplanting and after 5 months.

Table 1: Leaf Count/Growth Data from the VFD Greenhouse

Plant #	11/7/2011	3/2/2012	difference	Plant #2	11/7/20113	3/2/20124	difference5
1	8	31	23	32	11	59	48
2	22	57	35	33	18	47	29
3	10	35	25	34	8	37	29
4	10	23	13	35	17	47	30
5	8	26	18	36	12	41	29
6	14	25	11	37	12	33	21
7	12	38	26	38	12	46	34
8	13	72	59	39	9	43	34
9	15	46	31	40	10	37	27
10	8	18	10	41	18	39	21
11	11	44	33	42	11	48	37
12	16	50	34	43	16	40	24
13	24	44	20	44	12	35	23
14	5	33	28	45	10	24	14
15	9	31	22	46	14	52	38
16	10	48	38	47	7	32	25
17	12	24	12	48	9	43	34
18	9	28	19	49	13	44	31
19	4	36	32	50	13	35	22
20	10	32	22	51	21	48	27
21	10	33	23	52	11	42	31
22	16	75	59	53	13	25	12
23	9	45	36	54	6	33	27
24	18	44	26	55	8	35	27
25	19	40	21	56	11	32	21
26	13	40	27	57	9	21	12
27	17	58	41	58	9	32	23
28	11	28	17	59	10	45	35
29	12	41	29	60	16	29	13
30	15	50	35	61	8	25	17
31	23	57	34	62	17	44	27

Strtavrg	Endavrg	Difavrg
12.3	39.4	27.1

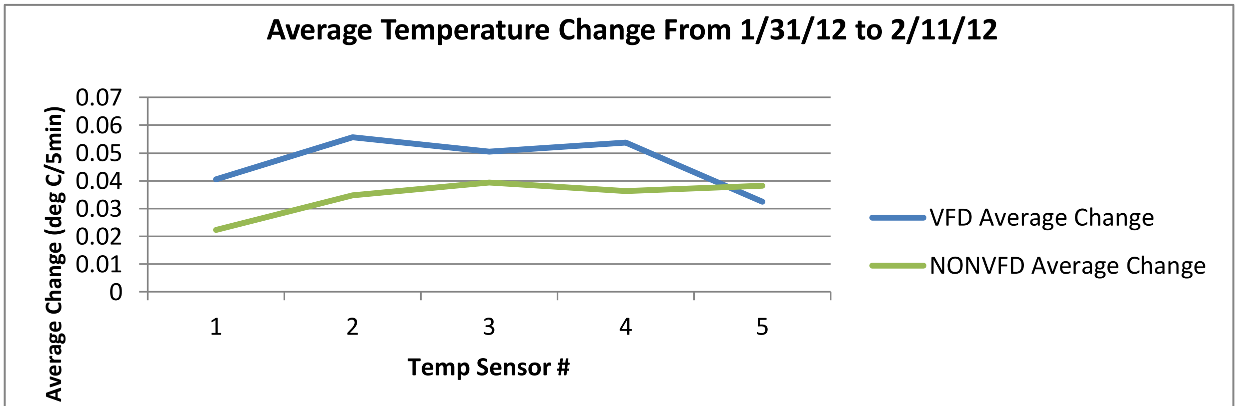
Table 2: Leaf Count/Growth Data from the NON VFD Greenhouse

Plant #	11/7/2011	3/2/2012	Difference	Plant #	11/7/20113	3/2/20124	Difference
63	11	28	17	94	8	35	27
64	5	27	22	95	7	28	21
65	12	36	24	96	14	41	27
66	16	40	24	97	9	33	24
67	13	31	18	98	9	31	22
68	8	25	17	99	13	50	37
69	27	51	24	100	19	51	32
70	7	16	9	101	14	39	25
71	13	36	23	102	18	40	22
72	20	59	39	103	11	38	27
73	18	28	10	104	18	45	27
74	17	40	23	105	19	40	21
75	9	42	33	106	6	36	30
76	6	28	22	107	8	25	17
77	15	37	22	108	12	45	33
78	7	24	17	109	16	37	21
79	8	38	30	110	17	43	26
80	12	41	29	111	11	41	30
81	16	43	27	112	19	23	4
82	13	32	19	113	19	43	24
83	10	25	15	114	8	21	13
84	11	45	34	115	10	25	15
85	16	31	15	116	12	35	23
86	9	30	21	117	24	51	27
87	12	36	24	118	6	25	19
88	15	37	22	119	14	28	14
89	11	30	19	120	14	40	26
90	18	31	13	121	13	39	26
91	12	45	33	122	15	43	28
92	7	26	19	123	11	33	22
93	10	38	28	124	14	29	15

Strtavrg	Endavrg	Difavrg
12.4	35.63	22.85

Climate Variability

It was thought that the VFD fan system would reduce the amount of change in temperature in the greenhouse as well as create a more even climate throughout the greenhouse. From the data collected and analyzed, it is evident that the VFD greenhouse actually has a slightly higher average change than the On/Off greenhouse during both periods of measurement (fig. 16). Looking at the actual values, however, reveals that a very small difference, around 0.01-0.02 degrees C, is seen which is statistically insignificant. Both of these greenhouses are actually maintaining very similar temperature characteristics throughout.



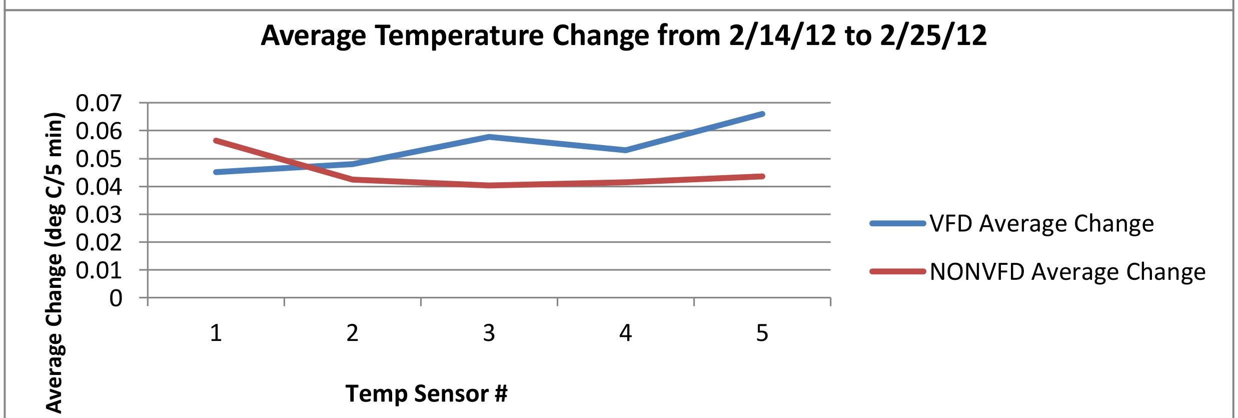


Fig. 16: Average change in both VFD and On/Off from two different periods. Sensor 1 was farthest from fan, sensor 5 was closest to fan.

DISCUSSION AND CONCLUTIONS

VFD drives definitely have a place in the greenhouse industry and this technology could be applied to multiple types of systems for increased control and efficiency. With the rapid improvement of semi-conductors, VFDs will show increased performance at a lower cost. It was an aim of this study to look at some of the possible benefits that using a VFD to run fans can bring to a greenhouse owner. Power used from exhaust systems is something that must be reduced as an industry whole to remain competitive, while reducing overhead in other areas such as water use is also important. Some of the greenhouse characteristics that could be affected by VFD exhaust fans were analyzed.

There are two exhaust fan characteristics that pertain to VFDs ability to reduce energy use, short cycling creating many in-rush current events and the affinity law that allows for significantly reduced energy use at lower fan RPMs. Amperage data, taken every 30 seconds, revealed a few things about both VFD and On/Off exhaust fans. The first is that On/Off style fan systems, where the fan is turned on at full power until cooling requirement is met then shuts off, cycle repeatedly throughout the day. This cycling is caused by a single size and speed fan being used to cool when its max air flow is way overboard for what's needed at that time. Sunlight can heat a greenhouse very quickly, even when outdoor temperatures are colder, and its intensity can change dramatically throughout a given day. Fans need to be large and powerful enough to meet the cooling demand when temperatures and sunlight intensities are the highest. However, the maximum cooling requirement comes not nearly as often as lower cooling requirements, and when only one exhaust fan size and speed is used, inefficiencies are seen in the monthly electric bill. From the amperage data recorded, it was observed that the

On/Off fan system cycled about 24% more over a 1 month period than the VFD fan system (fig. 10), inefficiently using electricity with each cycle.

The big advantage of using a VFD for an exhaust system in a greenhouse is a dynamic fan system that adapts to changes in outdoor environment. They can easily be setup so that the fan speed increases as the indoor temperature gets farther away from the set point and slowly ramp the speed back down when temperatures dictate. During morning and evening hours, the sun is still heating up the greenhouse to the point where ventilation is needed. With a VFD installed, the fans will turn on at a low RPM around 20% of full speed. This will still move enough air to open louvers and ventilate, but the fan will only be using around 10% of its full horsepower. Looking at the amperage data, the VFD fans are changing speeds, quite rapidly at times. It was actually a surprise at how quickly the VFDs ramp up and slow down the fans during periods of low to medium cooling requirement (figs. 7 and 8). The benefit of this adaptability is namely a reduction in electricity use, saving the greenhouse owner money. There are also other possible long term benefits including: reduced wear and tear on motors increasing motor life expectancy, reduced stress on whole greenhouse electrical system (no in-rush current events), better climate and pest control capabilities.

With in-rush current gone and a multi-speed fan system, a large portion of electricity can be saved. An aim of this research was to gather data about just how much energy could be saved and was done so using a continuous power monitor from Current Cost Systems. This monitor allowed for continuous electrical use data collection for up to ten separate locations. For each location to be measured a transmitter is needed and the monitor connects wirelessly so installation is very simple. It also works with both single-phase and three-phase systems, only needing an extra wire clamp for three-phase monitoring to get accurate total power use data. This monitor was set up with two transmitters; one was connected to the On/Off fan and the other connected to the VFD fan.

Over a period of thirty days, the electricity monitor recorded some interesting data. After 7 days of recording, a power savings was already seen, although it was not a large difference. It wasn't until after 20 days of recording past that a significant power usage difference was observed. After thirty days, the VFD fan had used exactly half the electricity as the On/Off fan. This shows that VFDs really do have the capability to reduce total energy consumption. The electric rates in Fort Collins, CO are about \$0.09 per kWh and the VFD system used 20 kWhs less than the On/Off fan. This equates to a savings of about \$1.80 a month, which doesn't seem like much at first, but these data were recorded for only one fan of each type. Also data were taken during a month when cooling requirement was lower than average (1/2/12-2/3/12), reducing the energy needs of the cooling system in whole. Larger greenhouses using multiple fans and over the course of a year will see greater dollar savings. The main point is that the VFD fan used only half the electricity that the On/Off fan used during the study period, showing that there is significant potential in overhead reduction for the greenhouse owner.

A potentially profound area of study is the possible different loading arrangements using VFD fans with On/Off fans. As VFDs can be expensive to install on every fan, different ways of using them with already installed On/Off style fans could reduce initial installation costs while still gaining some of the benefits of a VFD. For example, if a greenhouse has eight large On/Off exhaust fans already installed but the owner wants to begin to convert to VFD systems, they can start with only a couple fans. The fans that get the VFDs can be set up so that they interact with the On/Off fans in an efficient and effective manner. The ways in which this could

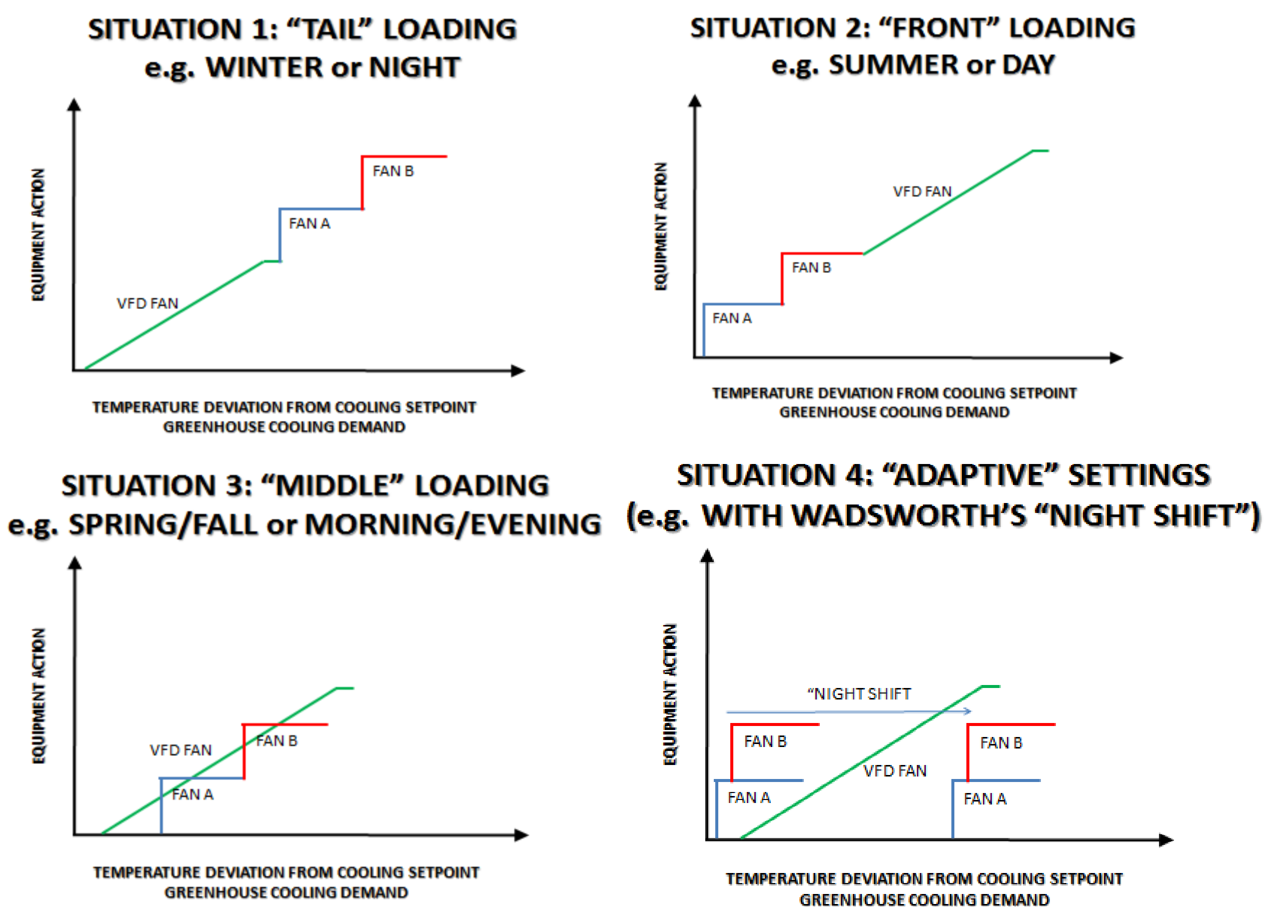


Fig. 17: Different loading situations that can be utilized, each having certain advantages and disadvantages. These situations are just a few examples of how a VFD can be setup with On/Off fans already in place. (Credit goes to John Ray for making these diagrams)

be done are very broad and considerable research needs to be done to determine the most effective loading methods (fig. 17). Loading scenarios can allow the greenhouse grower most of the energy saving advantages of a VFD system, without having to install a VFD on every fan.

The different loading situations, tail, front, middle and adaptive, are usable for different equipment setup and climactic variables and each has its own pros and cons. Tail loading is when the first fan to turn on is the VFD fan. It will increase in speed until it reaches 100% and stay there, then if more cooling is needed, on/off fans turn on sequentially to meet the demand. Since the VFD fan turns on first and will be running the most often, this setting is good for winter when the cooling requirement is lowest. This keeps the on/off fans from turning on and wasting power with in rush current and short cycling. Front loading is essentially the opposite of tail loading in that the on/off fans turn on first and the VFD comes on last, acting as a buffer. During times of intense cooling demand running fans at 100% is often necessary; however, with evaporative pad cooling systems, the cooling demand can go up and down throughout a day. Using the VFD fan to help reduce short cycling from the on/off fans by acting as a buffer can greatly reduce energy consumption. Middle loading is when the VFD fan turns on first, but instead of waiting until it reaches 100% RPM, an on/off fan will come on at desired VFD RPM percentages. For example, when the VFD reaches 25%, one on/off fan will turn on. Then another on/off fan will turn on at 50%, and another at 75% etc. This setting can be useful in fall and spring when cooling is still needed but is lower than average. The last loading situation is only usable is the greenhouse controller has adaptive settings. For the best energy efficiency, using all three of the aforementioned loading situations throughout a day or season is best. Adaptive control can change the loading responses from tail to middle to front, greatly improving not only the energy efficiency, but the cooling capabilities and equipment life of a greenhouse cooling system.

In a greenhouse, water use can be high from plant transpiration to greenhouse cooling needs; there is a consistent requirement to replace lost water. Sabeh (2006) found that water lost from a greenhouse is a function of ventilation speeds. Faster air speeds will increase evaporation and reduce boundary layer thickness, thus increasing transpiration (Monteith, 1965; Zhang, 1992). So it is of interest, then, to control ventilation speeds more precisely to limit water loss. With the dynamic nature of VFD exhaust fans, it is possible that greenhouse water consumption will decrease and this aspect was analyzed here.

Hanging lysimeters were used to monitor total water loss from the soil surface and plant transpiration together. As mentioned previously, these processes were not decoupled because the results of this study are meant for use by a greenhouse grower, so data that is usable by the industry was gathered. Over a period of four watering events (28 days), the lysimeters recorded weights every five minutes. A regression was fit to each of the plants data on the lysimeter for each watering event with an average R^2 of about 97%, yielding accurate water loss characteristics. What was found is that the greenhouse with the VFD fan system did show consistently reduced water loss compared with the On/Off greenhouse, calculated at close to 0.10 grams/min/m^2. In a production greenhouse there can be upwards of 4.5×10^6 m^2 of leaf surface area. With such a large leaf surface area, saving 0.10 grams/min/m^2 can add up to significant savings over the course of a growing season. The reduced water loss is due to a lower average fan speed and no large changes in ventilation speed observed when an On/Off fans turns on at full power. The ramping up and slowing down of fan speed allows the plant time to respond to changing air speeds, reducing its evapotranspiration. Slower average air speeds also increase boundary layer thickness (Monteith, 1965; Zhang, 1992) around the plant leaves and soil surface, limiting water loss further.

It was hypothesized that the VFD fan system would create a better and more consistent growing environment in the greenhouse than an On/Off fan system. Fans running for longer periods of time should increase mixing and reduce microclimate variability, while also maintaining set points more precisely. This, in turn, will allow the plants to grow more evenly around the greenhouse. The more consistent environment, coupled with reduced water loss characteristics, should also help the plants grow more rapidly. Two sets of data were analyzed for growth and temperature variation around and between each greenhouse.

The growth data is somewhat limited due to only a six month grow out, but results show slightly faster plant growth in the VFD greenhouse. The average plant per leaf was almost identical at transplanting, yet at final measuring, the plants in the VFD greenhouse had an average of almost four more leaves, or about 10% more, than plants in the On/Off greenhouse. The time between watering these plants was long enough that the soil would be almost completely dry; a plant that uses less water will have more water available for a longer time. It is a possibility that the reduced water use characteristics from the VFD greenhouse are allowing the plants to grow more rapidly due to increased water accessibility.

One interesting pattern worth future investigation is that the temperature sensors farthest from the fans (designated sensor 1 in the results) and closest to the fans (sensor 5) showed differing responses during separate measurement periods. For the data starting on 1/31/12 (fig. 16), sensor 5, closest to the fans, revealed a lower average change in the VFD greenhouse, whereas the opposite is true during the period starting on 2/14/12. This data set shows a lower average change only in sensor 1, farthest from the fans. Greater average change in the On/Off greenhouse is actually what was expected for ALL of the sensors, but there must be an effect caused by distance from the fan. It would be interesting to look at how a VFD affects the environmental differences along the length of a greenhouse with higher resolution, over multiple outdoor conditions, and also while using evaporative cooling.

In conclusion, this study was able to determine that there are definitely benefits of using VFDs on the exhaust fan system in a greenhouse. The energy use reduction is the biggest, and most money saving aspect, while the water use was reduced also. A higher growth rate was seen in the VFD greenhouse, but an extended study needs to be done to full quantify possible microclimate and crop growth benefits. This study only looked at VFDs on fans, but the application of this technology is much farther reaching than just that. VFDs can be applied to any type of pump, be it air or liquid, and have purpose with both heating and cooling. Irrigation systems could also be enhanced using VFDs. Variable frequency drives in greenhouses is a rich topic full of possible research and it will be exciting to see where the full potential of this technology can take the horticulture industry.

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