POWER QUALITY
Measurement and Conditioning Related to Variable Frequency Drives in Irrigation Districts

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TABLE OF CONTENTS

PROJECT OVERVIEW

Introduction

The Irrigation Training and Research Center (ITRC), California Polytechnic State University (Cal Poly), San Luis Obispo, working under agreement with the California Energy Commission (CEC) as part of its Public Interest Energy Research Program, completed a study to examine the quality of electric power that supplies motors for irrigation pumps. This study was performed in three phases: a literature review, field research, and simulation testing. Work was conducted by Dr. Ali Shaban and Dr. Ahmad Nafisi of the Electrical Engineering Dept. of Cal Poly. Dr. Charles Burt of ITRC was project coordinator.

Project Goals

1. Determine if there is an economical benefit to using filters for conditioning the electric power used by electric pump motors.
2. Quantify the harmonics that are generated by typical irrigation district Variable Frequency Drive controllers.

Technology Path

Both active (very expensive) and broad band passive (less expensive) filters are available to condition the power at the point of common coupling. However, they are not used in agricultural motor installations. The economics of their future usage will depend upon (i) the amount of harmonics that are present in the power supply, (ii) the degree to which the poor incoming power quality impacts the motor efficiency, and (iii) the relative costs of the filters and benefits of improved motor efficiency. Documentation of these three aspects will indicate if it is worthwhile for CEC and electric utilities to encourage farmers (and others) to install power filters. Documentation will also assist others in determining the value of investigating source control of harmonics.

A possible source of power harmonics is existing Variable Frequency Drive (VFD) controllers, which are becoming more popular with irrigation districts. The popularity arises from advantages in both improved water pressure/water level control and power savings. The non-linear loads of VFDs generate voltage and current harmonics that can have adverse effects on utility equipment designed for 60 Hz operation. Transformers that bring power into an industrial environment are subject to higher heating losses due to harmonic generating sources to which they are connected. When capacitors are used for power factor improvements (where non-linear loads exist), resonance conditions can occur that may result in even higher levels of harmonic voltage and current distortion, thereby causing equipment failure and disruption of power service.

A question to be addressed by this second aspect of this project is: By how much does the power quality on the line degrade due to typical agricultural irrigation district VFD installations? The answer may show that there is a negligible impact, that improved design and installation standards should be developed and enforced, or that it is best to concentrate upon the usage of filters for incoming power.

Project Description

This project initially included three aspects: a literature review and analysis, field testing of pumps, and test installations of transformer filters on pumps in the field. During the course of the project, the final category, filter test installations, was replaced with a simulation study to test the effects of transformer filter and VFD combinations on current and voltage total harmonic distortion (THD). It was determined that the simulation work would provide more transferable results than installing just a few filters in the field.

A brief description of each of these three project aspects follows.

Literature Review

This portion of the project investigated and analyzed literature and data pertaining to the following topics:

1. The power quality in the electric grids that supply agricultural customers in California.
2. The impacts of power quality on three-phase induction motor and transformer efficiency, power factor, core and hysteresis losses, and life.
3. The magnitude and qualities of harmonics problems, especially the different odd harmonic contents such as third, fifth, seventh, etc. that are present at VFD pump stations.
4. Solutions to minimize the total harmonic distortion (THD) and an estimate of the cost of each possible solution.

In addition to a computer search that examined electronic databases, direct contact was made with agencies/companies such as PG&E, Southern California Edison, CEC, and EPRI. Solutions and costs were derived from industry contacts as well as from the literature and agency contacts.

Pump Field Testing

This portion of the project involved two different kinds of pump tests:

1. Testing of agricultural (farm or irrigation) electric pumping sites throughout California for field measurement of *incoming* power quality.

2. Testing of pumping installations with Variable Frequency Drives (VFDs) for their impact on the harmonics *exiting* the VFD controllers and going into the power line.

Each incoming power test included measurements of the harmonic contents in the voltage and current waveforms, real power, reactive power, and power factor at the motor terminals. This collected data was analyzed for the presence of different types of harmonics and the total harmonic distortion (THD) of the voltage and the current.

The same measurements were made at pumping sites with VFDs to test for the possibility of harmonics generated by the VFDs that could be fed to the utility side. The collected data from the VFDs was analyzed and compared with the results from the tests without VFDs to determine the effect of VFD controllers on the power quality of the electric system.

Simulation/Testing

This task included computer simulation and laboratory testing of various electrical pump set-ups, with and without VFDs, to determine the effect of transformer and choke filtering. Voltages and currents were measured at different points in each configuration and analyzed for total harmonic distortion (THD).

Information Dissemination

The results of this project will be disseminated using the following methods:

a. The report will be published on Cal Poly ITRC website.

b. The report will be published on the CEC website.

c. Technical persons from the major electrical utilities will be provided with fact sheets.

d. Agricultural customer service representatives of the major electrical utilities will be provided with fact sheets.

e. A fact sheet will be sent to all the major agricultural irrigation dealerships and pump dealerships in California.

f. Irrigation List Servers, such as Irrigation-L and Trickle-L, that send e-mail to persons interested in irrigation-related topics, will receive a notice of the report.

g. A professional paper will be written for publication in the North America Power Symposium, as well as an article for Power Quality Magazine.

LITERATURE REVIEW AND ANALYSIS

Literature was gathered, reviewed and analyzed relating to the following topics:

- Harmonics present in the distribution system
- Harmonics produced by Variable Frequency Drives (VFDs)
- Effect of VFDs on the distribution system
- Effect of VFDs on the three-phase induction motor
- Effect of harmonics on the efficiency of the three-phase induction motor
- Types of filters used to mitigate the harmonics generated by the VFDs

The results of this review are presented below. A full list of the literature gathered can be found in the references section at the end of this report.

Harmonics Generated by Variable Frequency Drives

Variable Frequency Drives (VFDs), also known as Adjustable Speed Drives (ASDs), are sources of harmonic currents in the power system due to the non-linear nature of their power electronic circuits. The magnitude and phase of these harmonics can be evaluated from three basic approaches:

1. Analytical solution using approximate models for the components of the VFD, described below.
2. Computer simulation using established programs such as EDSA and ETAP.
3. Direct measurements of the harmonics using a spectrum analyzer such as the PowerSight PS 3000 analyzer, described in the Field Testing section of this report.

Using approximate models for the VFD components, the harmonic currents generated by a particular VFD converter can be calculated using the formula:

$$h = kp \pm 1$$

where h is the generated harmonic, k is an integer (k=1, 2, 3,...) and p is the number of the pulses of the converter. So, ideally, a 6-pulse converter generates characteristic harmonics at the 5th, 7th, 11th, 13th, ... multiples of the fundamental frequency. A 12-pulse converter generates harmonics at the 11th, 13th, 23rd, 25th… multiples. Most low voltage (480 volts) VFDs are of the 6-pulse type. Drives with higher pulses, such as 12-pulse, 18-pulse, and 24-pulse, are also available.

The magnitude of each harmonic current component can be calculated from the formula:

$$I_h = \frac{I}{h}$$

where I_h is the magnitude of the hth harmonic current and I is the magnitude of the current at the fundamental frequency. Table 1 shows the harmonic frequencies and their corresponding magnitudes for the 6- and 12-pulse converters. As can be seen, the magnitude of the harmonic current decreases with the number of pulses.

Table 1. Harmonic currents as an approximate percentage of the fundamental frequency current.

H	5	7	11	13	23
6 Pulse	20%	14%	9%	7%	4%
12 Pulse	-	-	9%	7%	4%

Although this calculation method can provide a "first estimate" for the generated harmonics, it is an idealized method and doesn't truly reflect all physical characteristics of the VFD components. The calculation method typically underestimates the true harmonic levels. Actual measurements at the terminals of the VFD are needed to determine accurate percentages of the harmonic current components.

Harmonic currents combined with the power system impedance result in a harmonic voltage distortion. For this reason it is also important to analyze the harmonic voltage levels of the VFD. Harmonic distortion of current and/or voltage can cause problems such as:

- Increased RMS current
- High frequency currents
- Malfunction of relays and circuit breakers
- Fuse operation
- Capacitor failures

- Motor and transformer overheating and reduced life
- Increased system losses

Shuter (1989) and Gunter (1992) present studies done by utility companies and the Electric Power Research Institute (EPRI) to determine the harmonic levels in the distribution system. Unfortunately, these studies do not concentrate on the sources of the harmonics and are more focused on the voltage harmonic levels and their impact on customer equipment irrespective of their origin. Although the results presented are not conclusive, they indicate that harmonic levels are overestimated and the impact on customers depends mostly on the sensitivity of the equipment being used by the customer rather than the presence of the harmonics alone.

Results of harmonics generated by VFDs, published in the literature, confirm that the actual measured harmonics depend on the VFD configuration (whether it is a current source or voltage source design). These studies also indicate that although the line current can have a total harmonic distortion (THD) as high as 104%, the resultant voltage distortion depends greatly on the system impedance measured at the point of common coupling (PCC), the point at which the VFD is connected to the electrical system. When the power system impedance is negligibly small, the voltage distortion remains small, irrespective of the current distortion injected by the VFD. It is also well documented that line inductors can reduce the harmonic current levels significantly.

EPRI has collected some harmonic data on low voltage VFDs (typically 5-350hp at 480V). Portions of the test results on a 6-pulse, Pulse Width Modulation (PWM), 10hp VFD are summarized in Table 2 (Grebe 1992). Added input inductance is given as a percentage of the transformer inductance.

Table 2. Harmonic Input Currents as a percentage of the fundamental frequency current with and without added input inductance.

	Added Input Inductance		
Current	**0%**	**1%**	**5%**
Fundamental	100.0	100.0	100.0
5th	78.3	59.7	45.0
7th	61.5	34.9	20.6
11th	26	8.8	8.5
13th	14.1	7.7	4.5
THD	**103.9**	**70.1**	**50.4**

Power quality engineers from the two major utility companies in California (PG&E and Southern California Edison) were contacted regarding the use of VFDs in irrigation pumping stations. The engineers indicated that they had not done any survey testing concerning power quality to determine the effect of VFDs used for irrigation. However, they did run tests on the VFD pumping stations when customers reported power quality problems at their sites. On January 26, 2001, we visited the power quality center of SCE in Tulare, California. The power quality engineer at the center showed us a 150hp VFD pumping station site where he was monitoring the power quality using a Dranetz-BMI 4300 power analyzer. He performed a live test at a distance of one-mile from the VFD location and measured a 4.6% voltage THD. The recommended THD voltage, according to the IEEE 519 guidelines, is 5%. The engineers expressed their interest in having a power quality survey study done on the effect of VFDs used in irrigation.

Impact of VFDs on Induction Motors

The use of Variable Speed Drives (VFDs) has become more prevalent in AC motor applications. This is due to the fact that AC motors, such as induction motors, can be operated under varying frequencies and voltages, which in turn adjust the speed. In many motor applications, such as HVAC fans and pumps, this feature provides added energy efficiency and dynamic performance. This is not to say, however, that VFDs are always good for motors.

Negative Impacts of VFDs on Induction Motors

All VFDs take advantage of power electronics technology to provide variable frequency and voltage through the use of solid state switching devices. This makes VFDs, and the motors, vulnerable to problems associated with power electronic converters. The following are known negative impacts on the induction motor as a result of utilizing a VFD:

- Increase in core loss
- Reduction of motor torque
- Skin effect
- Motor insulation deterioration
- Motor bearing material erosion
- Deviation in Torque-Speed Curve
- Electromagnetic Interference (EMI)

Increase in Core Loss

Manz 1997 shows that the components of core loss are proportional to frequency (hysteresis loss) and frequency squared (eddy current loss). Normally, these components do not introduce problems with core loss in induction motors. However, with today's modern VFDs, induction motors may be operated in a constant power region at a frequency in excess of 120Hz. This is significantly higher than the standard 60Hz. In this situation, core loss is a serious consideration. Furthermore, this increase in core loss will affect the overall efficiency of motor operation.

Reduction of Motor Torque

The fundamental frequency of the motor produces torque in the forward direction. However, extra frequency components or harmonics may produce torque in both forward and backward directions. The 5th, 11th, 17th, ... harmonics have been known to produce torque in the reverse direction, while the 7th, 13th, 19th, ... produce torque in the forward direction. Typically, the 5th harmonic is greater than the 7th in magnitude, the 11th is greater than the 13th, the 17th is greater than the 19th, and so on. As a result, the net effect of the harmonics will be a negative torque that will reduce the overall torque of the motor.

Skin Effect

Harmonics generated by VFDs can also be harmful in the form of skin effect. Skin effect is the phenomenon where the apparent resistance of a conductor increases as the frequency increases. A measure of the portion of the material that actively carries current is the skin depth δ, which is given by:

$$\delta = \sqrt{\frac{1}{f\pi\sigma\mu}}$$

where σ is the conductivity of the magnetic material and μ is the magnetic permeability of the core material. As frequency increases, skin depth decreases such that current flows more and more towards the surface of the material. This implies that at DC, the charge carriers have an even distribution throughout the area of the conductor. However, with AC, as the frequency increases, the magnetic field near the center of the conductor increases the local reactance. The charge carriers subsequently move towards the edge of the conductor, thereby decreasing the effective area and increasing the apparent resistance. This is not a desirable effect in a motor since the skin effect will cause the harmonic rotor wattage to increase (Von Jouanne 1996).

Motor Insulation Deterioration

In modern VFDs, especially for power levels over 500kW [13], a technique called PWM switching is typically used to produce an adjustable frequency and voltage AC output, using an Insulated Gate Bipolar Transistor (IGBT). The PWM technique pushes harmonics at much higher frequency than the fundamental component, and hence less filtering requirement. However, PWM also creates a problem due to its high, fast dv/dt switching. A common PWM dv/dt would be approximately 0 to 650V in less than 0.1us. This type of dv/dt will have adverse effects on the motor insulation, especially if this very short pulse rise time is combined with a long cable. This combination will cause an unequal distribution of the short rise time pulse over the motor winding. As a result, the steep front of the pulse will be applied to the motor winding so that there is a damped high frequency “ringing” at the front and rear of each pulse. This series of steep rising and falling pulses leads to an uneven distribution of voltage within the motor, especially during the transitions. This will contribute to insulation deterioration and subsequent failure of the motor.

In addition, the PWM produces short pulses which are reflected and magnified at the motor terminals when a long cable is used (Von Jouanne 1997). This is due to the fact that the motor winding becomes a transmission line for the pulses. The motor impedance is always several times the values of the cable impedance and will reflect the pulse. Furthermore, the pulse was found to travel at approximately half the speed of light. Hence, if the pulses take longer than half the rise time to travel from inverter to motor, then a full reflection will happen at the motor. As a result, the pulse amplitude will approximately double at the motor terminals. The doubling of the voltage at the motor terminals will once again deteriorate the motor insulation and hasten the failure of the motor. Table 3 shows the minimum cable length and rise time after which virtual voltage doubling occurs at the terminals of the motor (Van Jouanne 1997). The data were taken using a 460V, 5-kVA, 2-kHz, PWM VFD supplying a 5-hp motor.

Table 3. Minimum cable length after which voltage doubling occurs at motor terminals.

PWM pulse rise time [us]	Minimum cable length [m]
0.1	6
0.5	39
1.0	59
2.0	118
3.0	177
4.0	236
5.0	295

It has been shown that for a given length of cable, decreasing the dv/dt of the PWM inverter output voltage below a critical value will significantly reduce the over-voltages due to the high-frequency transmission line effects (Van Jouanne 1996).

Motor Bearing Material Erosion

Motor bearing material erosion (and ultimately, mechanical damage) results from the passage of large electrical currents through the bearing. According to Manz (1997), PWM-based VFDs promote the occurrence of bearing current because of the high frequency, step-like voltage source waveforms, and high dv/dt's impressed across the stator neutral-to-frame ground. Manz shows that a portion of this waveform is also present as rotor shaft voltage-to-ground. More importantly, the PWM signals cause the static breakdown threshold voltage on the rotor shaft to increase to at least ten times that of the same bearing monitored under a 60Hz sine wave operation. As a function of the shaft voltage rate of change, the bearing voltage breakdown threshold also increases. During bearing discharge, this increased breakdown level results in a much higher bearing current than that produced from a pure sinusoidal wave, causing increased bearing damage.

Bearing damage caused by electrical current is characterized by the appearance of either pits or transverse flutes (grooves) burnt into the bearing race. Electrical pitting continues until the bearing loses its coefficient of friction, further increasing the losses and breaking up the bearing surface. A good, first indication of the deterioration will be noisy bearings.

Deviation in Torque Speed Curve

VFDs attempt to produce sine wave power by switching the DC bus voltage to the motor windings ON and OFF. The resulting wave is not exactly sine, but rather contains higher frequency components known as the harmonic components. The harmonic power of the VFD is undesirable since it supplies additional losses that need to be dissipated by the motor. These extra harmonic-induced losses result in a deviation of the actual capability torque-speed curve from the theoretical one (Manz 1997). This will then require de-rating of the motor.

Electromagnetic Interference (EMI)

PWM inverters also generate high and fast dv/dt noise, which can cause harmful electromagnetic interference. Although this type of noise does not directly affect the motor, it may interfere with nearby control circuits, electronics, or communication systems. Furthermore, the high dv/dt can couple through the capacitance between the motor winding and frame, causing high currents to flow in the return ground conductors. This may heat up the conduit containing the cables connected to the motor and can also cause tripping of ground current relays installed for protection.

Mitigation Techniques

The negative impacts discussed previously can be remedied by several mitigation techniques. Van Jouanne (1996) presents two methods to mitigate motor terminal over-voltages: filter insertion and improved insulation. The first method suggests the insertion of series reactance that will act as a current-limiting device, attenuate electrical noise, and at the same time, filter the PWM waveform. However, this filtering method suffers from several disadvantages, namely: degradation of transient performance of the drive, bulkiness, and cost. An alternative for this would be to implement a motor terminal impedance matching filter, such as the First-Order RC terminal filter (Van Jouanne 1996). Here, the motor terminal over-voltage can be significantly reduced if the cable is terminated with the cable surge impedance. As a result, the incident voltage will not be reflected and significant over-voltages at the terminals of the motor can be prevented. Another alternative would be to install an inverter output filter. This can be in a form of a low-pass filter placed at the output terminals of the inverter (Van Jouanne 1997). The filter can be designed to decrease the inverter output pulse dv/dt and thereby reduce the over-voltage and ringing at the motor terminals.

Motor terminal over-voltages due to VFDs may also be overcome by increasing the insulation strength of the winding wire to withstand a high dv/dt. For example, a recent study has shown that a film wire coating called Thermaleze Quantum Shield, or TZ Q^s, can provide significantly longer winding wire insulation life and protection in PWM motor drive applications (Van Jouanne 1996). Moreover, TZ Q^s achieves this protection without increasing insulation thickness, thereby making it suitable for existing systems without the need for design changes.

According to Van Jouanne (1996), the motor bearing current phenomenon caused by VFDs can be eliminated by using a number of methods: insulating bearings to break the current path, applying conductive grease to the bearing, electrostatic shielding between the stator (Erdman 1996) and rotor structure, or employing a shaft grounding brush system.

Finally, EMI problems associated with the use of VFDs can be overcome through the use of EMI filters (Tarter 1993). The filter can vary in its configuration, but it is generally aimed to suppress both common mode and differential mode conducted emissions. To suppress the radiated electromagnetic energy, various methods can be used, such as metallic shields, good electrical bonding, and shielded cables. These methods have been found to not only reduce the radiation emitting from a unit, but also decrease its susceptibility to externally radiated energy by absorbing and reflecting the energy contained in the field (Tarter 1993).

Impact of VFD Harmonics on Transformers

Increase in RMS current

Harmonic current components generated by the VFD will increase the total RMS current supplied to the transformer, thereby increasing the copper losses and resulting in lower transformer efficiency.

Increase in eddy-current loss

Eddy-current losses in the transformer core are proportional to the square of the frequency and the transformer current. This is a major contributor to the transformer temperature rise. Eddy-current losses also result in increased core losses, which then result in lower transformer efficiency.

DC offset current saturation

Transformer saturation may occur prematurely even with a small DC offset. The DC offset is present with large VFDs (ANSI/IEEE Standard C57.110). It is recommended to limit the current THD of the transformer to 5% to avoid the de-rating of the transformer (ANSI/IEEE Standard C57.110, IEEE Standard 519).

General Harmonic Mitigation Techniques

Power quality measurements at the site of the Variable Frequency Drive help to answer the following questions (Peeran 1995):

1. Is there a need for a harmonic filter?
2. What types of filters (5th, 7th, or 11th or combinations) are required?
3. How to size the filter components?
4. What is the 60-Hz KVAR of the filters?
5. What is the effect of the filters on the total and displacement power factor?

Various techniques to improve the power quality at the input of a VFD are discussed below. The purpose of these techniques is to make the input current more continuous, which will reduce the overall current harmonic distortion. The different techniques can be classified as follows:

1. Three-Phase Input Reactors
2. Shunt Passive Filters
3. Low Pass Broad Band Passive Filters
4. Pulse Multiplication (12-pulse, 18-pulse rectifier systems)
5. Hybrid Harmonic Filter

Three-Phase Input Reactors

Reactors at the input of the VFD make the current waveform less distorted, thereby resulting in lower current harmonics. Since the reactor impedance increases with frequency, it offers larger impedance to the flow of higher order harmonic currents. It limits the flow of higher frequency current components, while allowing the fundamental component to pass. The effect of input reactors on the current THD is as shown in Table 2. Input reactance includes the added AC reactance, transformer reactance, and cable reactance (Swamy 2001).

Shunt Passive Filters

The shunt Passive Filter is common for three-phase applications. It provides very low impedance to the harmonic currents of the Variable Frequency Drive (VFD) and very high impedance for the fundamental currents. The fundamental frequency energy component flowing into the shunt filter provides leading VARs that can be used for power factor correction. A tuned filter is needed for each harmonic component. For a 6-pulse drive, a tuned filter is needed for the 5th, the 7th, and the 11th harmonics. Shunt filters must be protected from what is known as importing of harmonic phenomenon. If not protected, it will try to provide the harmonic energy needed by all non-linear loads connected to the same bus. The addition of series line reactors limits the flow of harmonic currents from neighboring non-linear loads such as the VFD and also limits the flow of harmonic currents from the VFD to the distribution system.

Shunt passive filters may interact with the system impedance and cause power system resonance. An in-depth study of the power system is needed before connecting the shunt passive filter. A filter for each VFD is highly recommended over one filter for a number of VFDs on the same bus. In this case, if resonance occurs, it will be a local problem (Swamy 2001).

Low Pass Broad Band Passive Filters

A shunt capacitor at the terminals of the VFD can be used as a filter to minimize the harmonic distortion of the system. However, shunt capacitor filters have two major problems. The first problem is that of importing harmonics. Any non-linear load, such as a VFD motor drive, that needs harmonic energy will extract it from the capacitor. This will overload the capacitor and can damage it. The second problem is that the capacitor behaves like a power factor correction capacitor at the fundamental frequency. Power factor correction capacitors tend to increase the voltage at the bus. This can cause an over-voltage condition at the terminals of the VFD and may cause false VFD tripping.

The use of Low Pass Broad Band Filters eliminates the above-mentioned problems of the shunt filter. Broad Band Filters consist of a series input reactor and a shunt capacitor. The series inductor minimizes the flow of harmonics to and from the VFD input terminals. In order to prevent the VFD from tripping due to over-voltage from the capacitor, a buck transformer is connected from the line side of the capacitor. The buck transformer will reduce the voltage fed to the capacitor and consequently prevents over-voltage tripping. The majority of the harmonic energy required by the VFD can be met by the proper sizing of the capacitor. The AC source will supply a small portion of the VFD harmonic energy. This will result in a low current THD (Swamy 2001). The estimated cost of a Broad Band Filter for a 150hp drive is $7000.

Pulse Multiplication (12-pulse, 18-pulse rectifier systems)

Harmonic currents generated by VFDs are a function of the pulse number of the drive. In a 12-pulse converter, the 5th and the 7th harmonic orders do not exist, which translates to a lower current THD. Higher pulse converters produce fewer harmonic components (Swamy 2001). The estimated cost of 12-pulse 150hp drive is about $22,000.

Hybrid Harmonic Filter

In order to provide an improvement in the harmonic control of the system, one possible solution would be to utilize a smaller passive filter that is combined with an active series filter. The active series filter will provide high impedance to the harmonic currents, thereby preventing their injection into the power system. These currents are then forced to flow into the passive filter. This significantly improves the passive filter performance for controlling harmonics without imposing severe design constraints on the filter (Banerjee 1992).

Solutions to the Power Quality Problems and Their Estimated Costs

The following table shows the solutions and their estimated costs (Swamy 2001):

Table 4. Price comparison of different filters and drives.

Solution	Expected Current THD	Cost of 150hp VFD + Solution
6-Pulse Drive w/o Solution	60-80%	$13K
6-Pulse Drive with 5% Line Reactor	25-35%	$15K
6-Pulse Drive with 5th Harmonic Trap	15-30%	$20K-$21K
6-Pulse Drive with 5th +7th Traps	10-20%	$22K-$24K
12-Pulse Drive	15%	$22K
18-Pulse Drive	<5%	$23K
Broad Band Low Pass Filter	8-12%	$17K-$19K

It is evident from the above table that adding a Broad Band filter to an existing 6-pulse drive will reduce the current total harmonic distortion to <12%.

FIELD TESTING

As part of its study to examine the quality of electric power that supplies motors for irrigation pumps, ITRC performed power quality tests on pumps throughout California, with a goal of testing 50 pumps and 5 VFD installations. Each pump was tested for its harmonic distortion, voltage, current, real power, reactive power, apparent power, power factor, and frequency. The objective was to determine whether power quality adversely affects the life and efficiency of electric motors.

ITRC sent out a letter to California irrigation and water districts in early June 2001, asking them for their cooperation in testing their pumps and the pumps of their farmers. By the end of July 2001, 30 pumps had been tested and ITRC sent out a follow-up letter to interested districts to solicit additional support. By early September 2001, ITRC had tested a total of 47 pumps, 40 pumps without VFDs and 7 pumps with VFDs.

Testing took approximately one hour for each pump and required access to a 120V outlet to power the testing instruments. Pumps had to be turned off twice – once to connect the instruments to the motor panel and once to disconnect them. The pump was run for at least 30 minutes with the instruments connected. VFD harmonics, if applicable, were tested before and after turning on the VFD.

Pumps tested at the irrigation/water districts are listed in Table 5.

Table 5. Pumps, without and with VFDs, tested at districts throughout California

	Pumps without VFDs	**Pumps with VFDs (brand)**
Arvin-Edison Water District	100, 200, 200 hp	100 hp (Westinghouse)
Berrenda Mesa Water District	100 hp	100 hp (Westinghouse)
Bella Vista Water District	60, 75, 100 hp	200 hp (Eurotherm Drive 584 SV Series)
Broadview Water District	60, 100, 250 hp	250 hp (ABB ACS 600)
Delano-Earlimart Irrigation District	100 hp	50 hp (Saftronics FP5 Reliable Frequency AC Drive)
Glenn-Colusa Irrigation District	60, 100 hp	
Lindsay-Strathmore Irrigation District	100 hp	200 hp (Toshiba)
Orange Cove Irrigation District	40, 60 hp	100 hp (Saftronics FP5 Reliable Frequency AC Drive)
Patterson Irrigation District	20, 25, 75 hp	
San Luis Water District	50, 60, 125 hp	
Solano Irrigation District	100, 100 hp	
Sutter Extension Water District	40, 60, 75 hp	
Thermalito Irrigation District	30, 50, 75, 100 hp	
West Stanislaus Irrigation District	200, 200, 300 hp	
Westside Water District	50, 100, 100, 150 hp	
Wheeler Ridge-Maricopa Water District	100, 100 hp	

In this study, we noticed that the voltage and current THDs of all pumps without VFDs were within the IEEE 519 Standard recommended limits. Their voltage THDs range from 0.5% to 4.26%, and their current THDs range from 0.76% to 8.66%.

Table 6. IEEE 519 standards/ VFD pumps.

District	IEEE 519 Standard Limits		Pump THD	
	Voltage	Current	Voltage	Current
Lindsay-Strathmore Irrigation District	5%	10%	11%	30.89%
Orange Cove Irrigation District	5%	10%	2.14%	63.26%
Delano-Earlimart Irrigation District	5%	10%	8.91%	29.72%
Broadview Water District	5%	10%	5.68%	38.37%
Bella Vista Water District	5%	10%	7.25%	59.08%
Berrenda Mesa Water District	5%	10%	1.92%	48.18%
Arvin-Edison Water District	5%	10%	3.09%	32.79%

Table 6 shows that the voltage THDs of four pumps with VFDs exceeded the IEEE 519 Standard recommended limits and all the pumps with VFDs exceeded the IEEE 519 Standard recommended limits for current THD.

SIMULATION TESTS

Overview

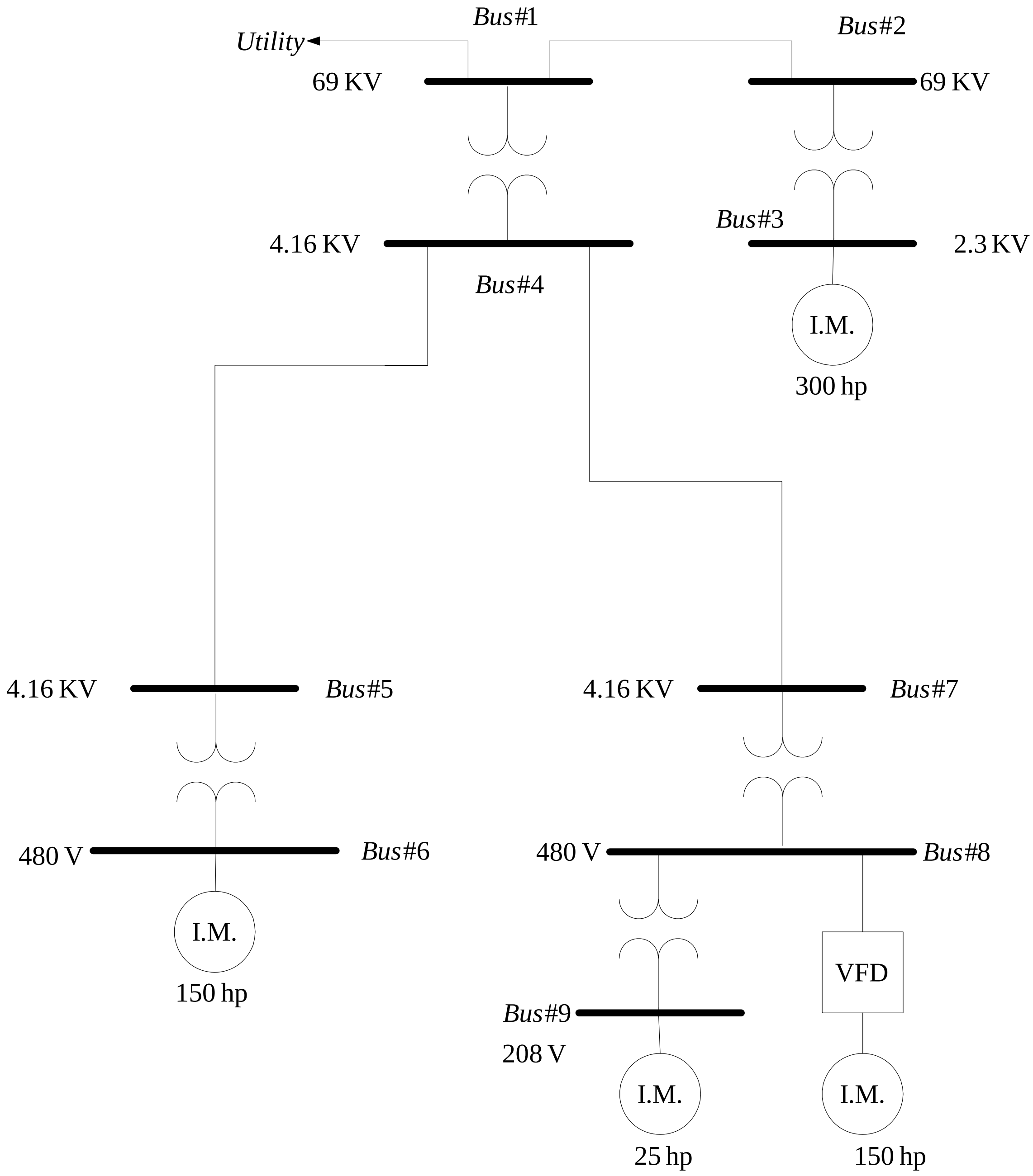
Several experimental simulation tests were run to determine the effects of transformer filtering in combination with VFDs. They included the following:

- Preliminary simulation to determine the effects of transformer filtering, computer simulation
- Load tests of a 1 hp VFD-motor system, laboratory test
- Load tests of a 1 hp VFD-motor system with a choke, laboratory test
- Load tests of a 1/3 hp motor with a 1 hp VFD-motor system running at full speed, laboratory test
- Test of a DC power supply, laboratory test
- Test of the VFD with different sampling frequencies

Simulation Tests

1. Preliminary study to determine the effect of transformer filtering

The following nine-bus network is used in the simulation study.



The following table shows the voltage THD due to 6-pulse/12-pulse VFDs connected to bus 8:

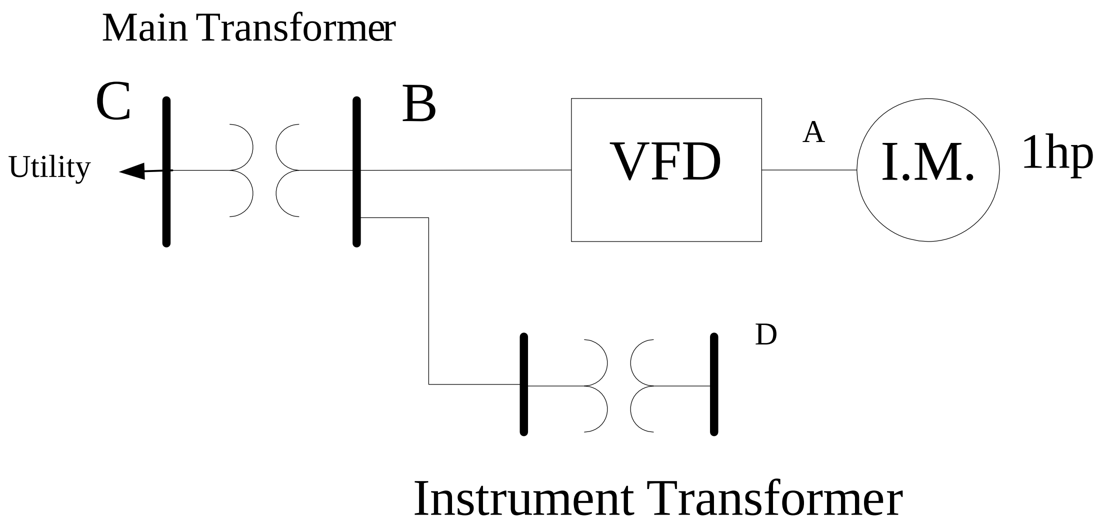
Bus Number	Rated Voltage	% THD-Voltage 6-pulse VFD	% THD-Voltage 12-pulse VFD
8	480-V	6.43	4.11
7	4.16-KV	4.32	2.76
6	480-V	1.56	.97
5	4.16-KV	1.73	1.11
4	4.16-KV	1.86	1.19
3	2.3-KV	0.02	0.01
2	69-KV	0.02	0.01
1	69-KV	0.02	0.01
9	208-V	6.17	3.95

The above results show that there is an approximate 33% reduction in the THD voltage between VFD bus (bus 8) and the other side of the transformer bus (bus 7). The THD-voltage decreases even further on buses further away from the VFD bus (bus 8).

2. Load tests of a 1 hp VFD-motor system

The VFD-Motor system was fed through a three-phase delta-wye transformer.

A: Induction Motor Terminals
B: Point of Common Coupling (PCC)
C: Utility
D: Instruments



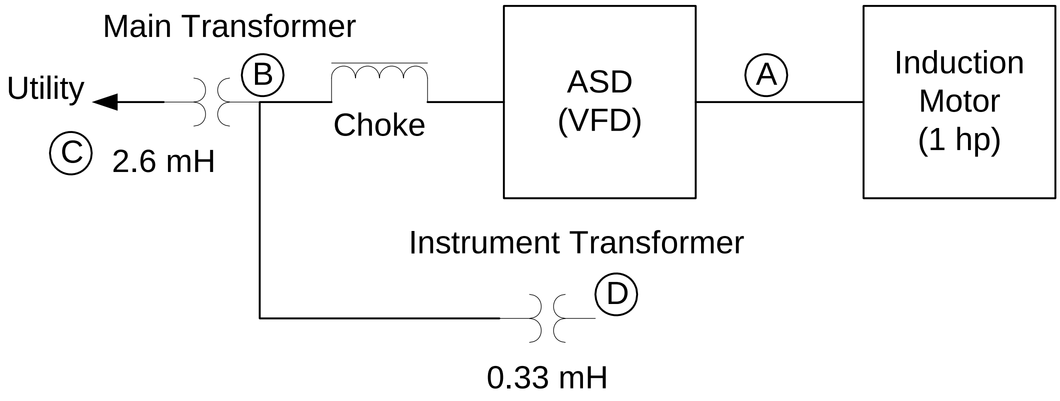
The following table shows the results of tests at buses B and C for different loads:

Load %Full-load	**Location B**		**Location C**	
	%THD-V	**%THD-I**	**%THD-V**	**%THD-I**
8	3.71	82.58	1.75	66.89
25	5.08	68.19	2.06	56.53
42	5.38	50.44	2.27	45.29
58	6.53	44.29	2.25	38.86
75	7.09	39.35	2.65	35.16
83	7.7	37.02	2.68	33.5
89	7.75	35.67	2.63	31.86
94	8.42	35.2	2.83	31.08
100	8.92	34.03	2.91	30.9

The above results show that there is more than a 50% reduction in THD-voltage and a 10-20% reduction in THD-current.

3. Load tests of a 1 hp VFD-motor system with a choke at location B

A: Induction Motor Terminals
B: Point of Common Coupling (PCC)
C: Utility
D: Instruments



a. Measurements at location B with and without a choke.

Load % Full-Load	Without the Choke		With the Choke	
	% THD_V	% THD_I	% THD_V	% THD_I
6	3.71	82.58	2.42	48.45
25	5.08	68.19	2.71	38.15
42	5.38	50.44	3.4	31.40
50	5.44	46.22	3.55	28.95
67	7.21	40.64	4.82	25.70
75	7.69	39.35	4.38	24.91
86	7.91	36.08	4.98	23.14
94	8.42	35.20	5.10	22.00
100	8.92	34.03	5.83	21.19

The presence of a choke (inductor) at the input of the VFD reduced the voltage THD and the current THD at location B approximately 35% and 37%, respectively.

b. Measurements at location C with and without a choke.

Load % Full-Load	Without the Choke		With the Choke	
	% THD_V	% THD_I	% THD_V	% THD_I
6	1.75	66.89	1.78	41.16
25	2.06	56.53	1.96	31.29
42	2.27	45.29	1.91	27.56
50	2.28	41.53	2.01	26.57
67	2.42	36.07	2.02	23.89
75	2.65	35.16	2.06	23.03
86	2.54	32.66	2.12	21.40
94	2.83	31.08	2.39	20.37
100	2.91	30.90	2.21	19.87

The presence of a choke (inductor) at the input of the VFD reduced the voltage THD and the current THD at location C approximately 24% and 35%, respectively.

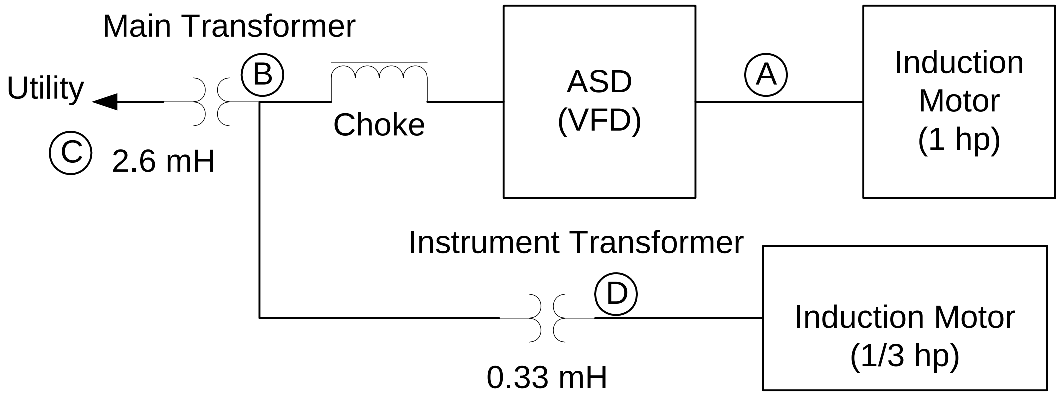
c. ***Measurements at locations B and C with the choke at the input of the VFD.***

Load % Full-Load	**Location B**		**Location C**	
	% THD_V	**% THD_I**	**% THD_V**	**% THD_I**
6	2.42	48.45	1.78	41.16
25	2.71	38.15	1.96	31.29
42	3.40	31.40	1.91	27.56
50	3.55	28.95	2.01	26.57
67	4.82	25.70	2.02	23.89
75	4.38	24.91	2.06	23.03
86	4.98	23.14	2.12	21.40
94	5.10	22.00	2.39	20.37
100	5.83	21.19	2.21	19.87

The main transformer reduced the voltage and current THDs approximately 50% and 10%, respectively.

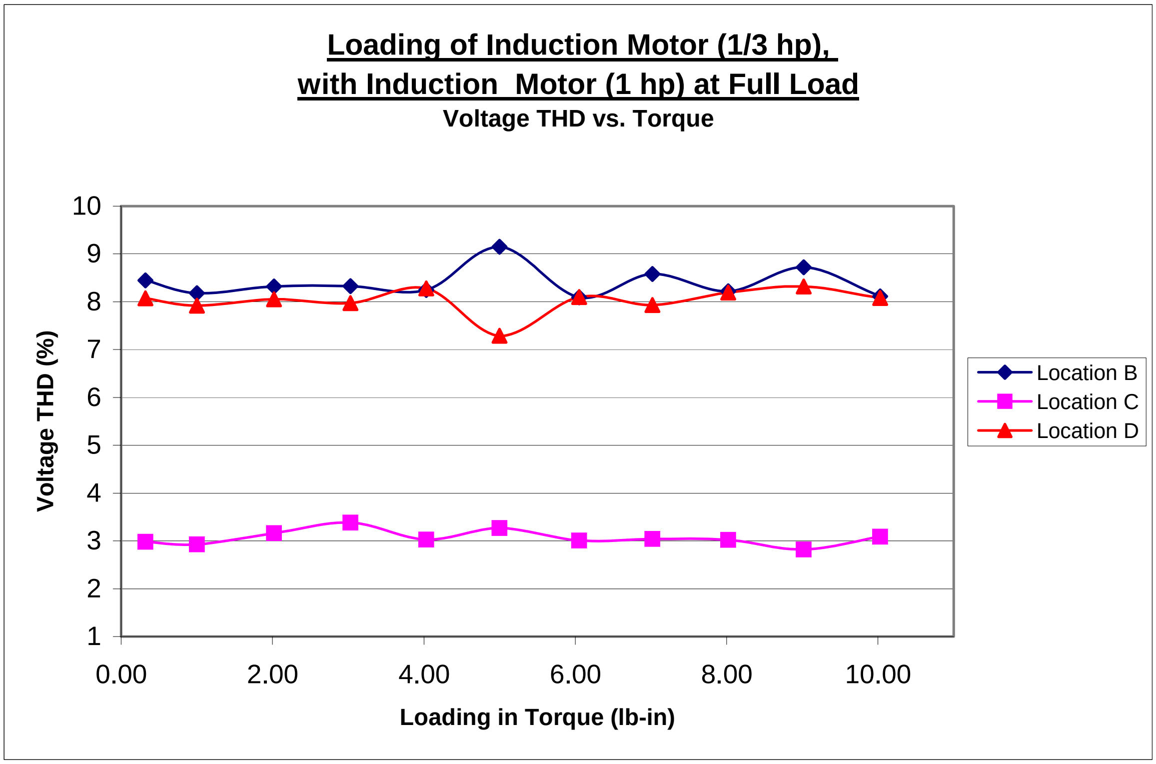
4. Load tests of 1/3 hp induction motor at location D with the 1 hp motor at location A running at full load

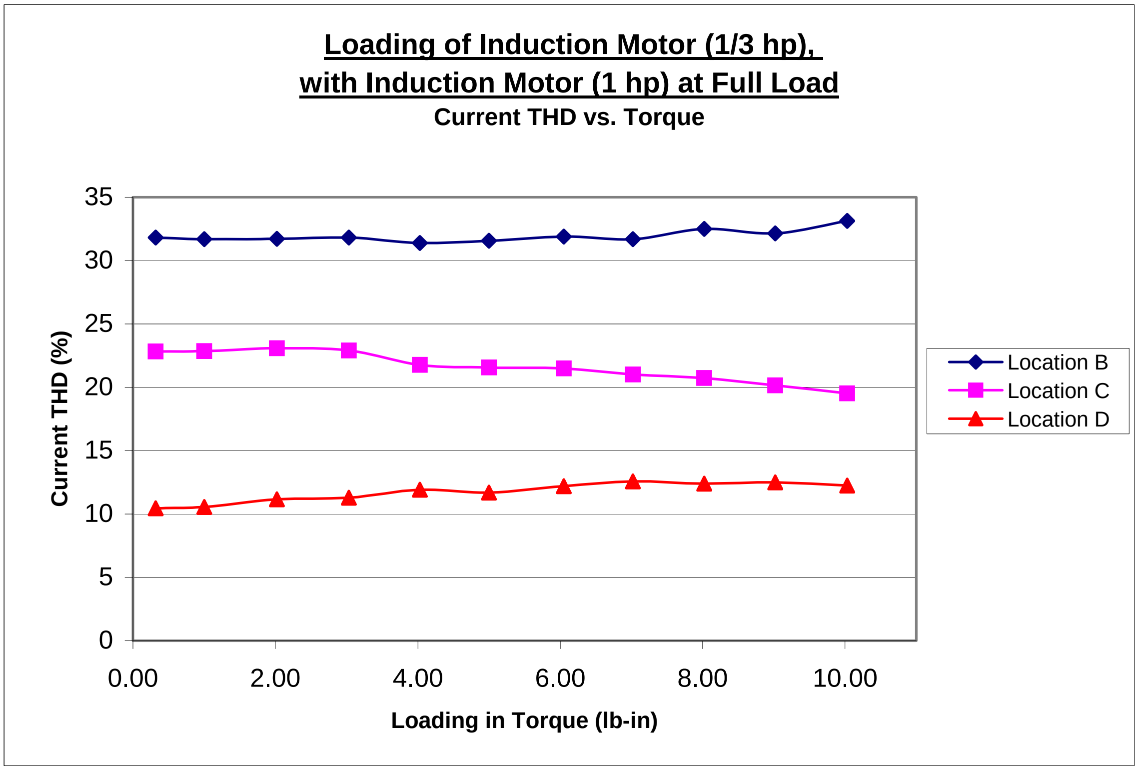
A: Induction Motor Terminals
B: Point of Common Coupling (PCC)
C: Utility
D: Instruments



Load % Full-Load	Location B		Location C		Location D	
	% THD_V	% THD_I	% THD_V	% THD_I	% THD_V	% THD_I
5	8.45	31.82	2.98	22.82	8.07	10.46
10	8.18	31.70	2.93	22.85	7.92	10.55
20	8.32	31.72	3.16	23.07	8.05	11.17
30	8.33	31.82	3.38	22.91	7.97	11.30
40	8.25	31.40	3.03	21.77	8.28	11.93
50	9.15	31.56	3.27	21.57	7.29	11.69
60	8.09	31.89	3.01	21.48	8.10	12.19
70	8.58	31.68	3.04	21.02	7.93	12.58
80	8.22	32.50	3.02	20.72	8.19	12.41
90	8.72	32.14	2.82	20.15	8.32	12.49
100	8.11	33.14	3.09	19.53	8.08	12.24

The above results show that the voltage and current THDs at location D are approximately 100% and 37% of the corresponding THDs at location B. This means that any instrument connected to terminal D will be exposed to the harmonics generated by the VFD.


Loading of Induction Motor (1/3 hp),
with Induction Motor (1 hp) at Full Load
Voltage THD vs. Torque
Voltage THD (%)
10
9
8
7
6
5
4
3
2
1
0.00
2.00
4.00
6.00
8.00
10.00
Loading in Torque (lb-in)
Location B
Location C
Location D


Loading of Induction Motor (1/3 hp),
with Induction Motor (1 hp) at Full Load
Current THD vs. Torque
Current THD (%)
35
30
25
20
15
10
5
0
0.00
2.00
4.00
6.00
8.00
10.00
Loading in Torque (lb-in)
Location B
Location C
Location D

5. Test of a DC power supply connected to terminal D.

a. ***Measurements taken at locations B and D for different resistive loads of the DC power supply without VFD.***

Load Resistance (Ω)	**Location B**		**Location D**	
	% THD$_V$	**% THD$_I$**	**% THD$_V$**	**% THD$_I$**
100	2.03	12.61	2.01	563.52
30	2.21	15.06	2.27	171.51
15	2.79	19.65	2.58	120.56
10	2.68	22.98	2.81	101.77
8	2.78	25.10	2.97	91.89
7	2.96	26.32	3.08	87.48
6	3.08	27.50	3.13	83.00
5	3.21	29.30	3.26	77.03

b. ***Measurements taken at locations B and D for different resistive loads of the DC power supply with the VFD and the 1-hp motor running at full load.***

c. Load Resistance (Ω)	**Location B**		**d. Location D**	
	% THD$_V$	**% THD$_I$**	**% THD$_V$**	**% THD$_I$**
100	8.79	11.71	8.91	158.49
30	8.55	11.48	8.51	89.23
15	9.10	14.84	8.71	73.48
10	9.59	18.18	8.92	66.14
8	8.84	20.47	9.10	63.39
7	9.74	21.89	8.87	63.80
6	9.26	24.12	8.63	62.97
5	8.67	25.25	8.68	59.77

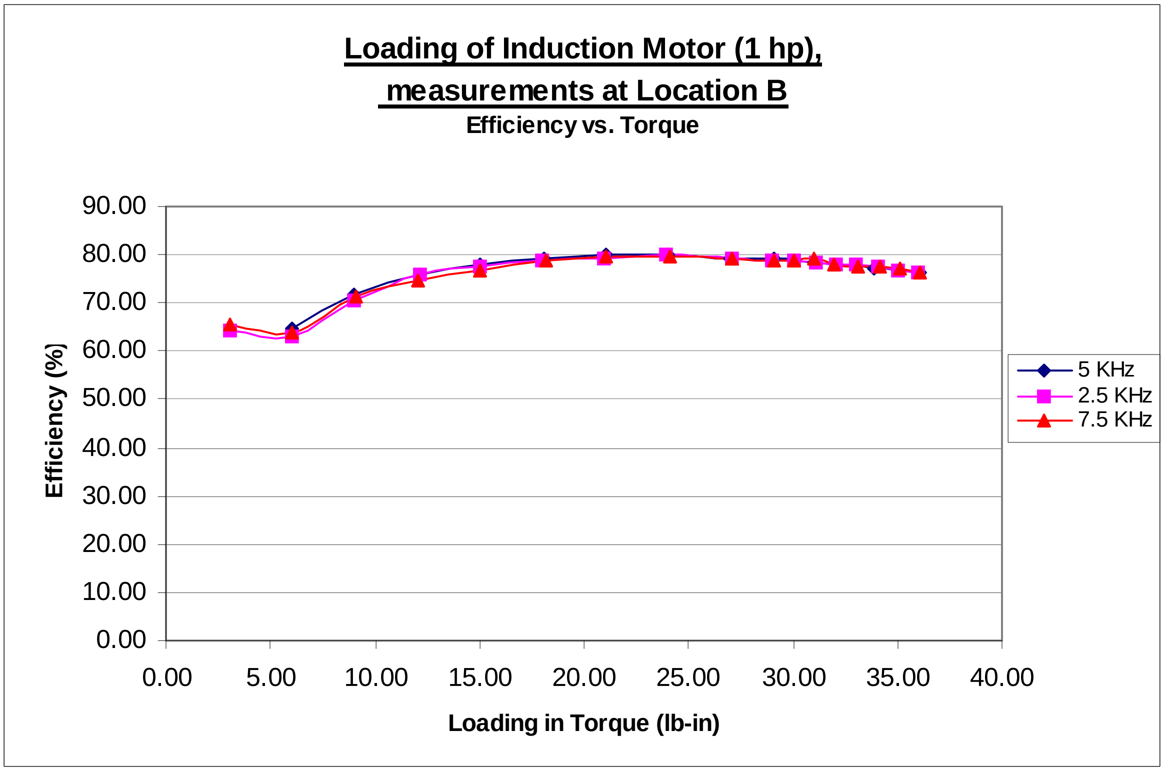
c. ***Measurements at locations B and D with a computer connected to terminal D.***

Connection	**Location B**		**Location D**	
	% THD$_V$	**% THD$_I$**	**% THD$_V$**	**% THD$_I$**
No VFD	4.58	40.50	4.91	101.80
With VFD	9.20	45.02	9.48	85.40

The presence of the harmonics at location D due to the VFD did not affect the performance of the DC power supply or the computer.

6. Test of the VFD with different sampling frequencies (2.5, 5, and 7.5 KHz)

Load % Full-Load	2.5 KHz		5 KHz		7.5 KHz	
	% THD_V	% THD_I	% THD_V	% THD_I	% THD_V	% THD_I
6	3.72	83.49	3.71	82.58	3.92	86.29
25	5.12	64.09	5.08	68.19	5.12	66.60
42	5.81	47.89	5.38	50.44	6.39	49.07
50	6.30	45.72	5.44	46.22	6.18	43.57
67	7.18	39.82	7.21	40.64	7.31	36.7
75	7.47	36.80	7.09	39.35	8.21	38.28
86	7.91	34.33	7.91	36.08	8.31	35.73
94	8.49	32.61	8.42	35.20	8.67	34.31
100	8.85	32.89	8.92	34.03	8.53	32.95



The above results show that changing the PWM sampling frequency of the VFD has almost no effect on the voltage THD, the current THD, or the efficiency of the induction motor.

VFD Manufacturers survey for 100 hp 3-phase induction motor

Company	**Pulses**	**Price**	**Model No.**	**AC Voltage**	**THD-V**	**THD-I**	**Efficiency**	**Carries freq. in (KHz)**	**Filter**	**Website**
Baldor	6-pulse	$15,239	ID15H4100-EO	460	N/A	N/A	>95% at Full Load	2.5 and 8	Separate	www.baldor.com
Motortronics	6-pulse	$11,400	ALX Series	380-500	5%	20%	>97% at Full Load	4 to 16	Built-in	www.motortronics.com
Mitsubishi	6-pulse	$14,330	FR-A540L-75K-NA	480	N/A	30%	94%	0.7, 1, and 2.5	N/A	www.meau.com
Danfoss Drives	6-pulse	$11,000	VLT5100	380-460	35-40%	<40%	>95% at Full Load	3 and 4.5	Built-in Option	www.danfossdrives.com
TDE Macno	6-pulse	$6,142	DFNT 100	400-440	N/A	N/A	>98%	3 to 8	Separate	www.tdemacno.com
US Drives, Inc.	6-pulse 18-pulse	$6,000 $15,500	Phoenix Sensorless AC Vector Drive Phoenix DX Clean Power	240 200-250	N/A <5%	N/A <5%	>97% at Full Load >97% at Full Load	1 to 3 1 to 3	Built-in Built-in	www.usdrivesinc.com
Toshiba	6-pulse 18-pulse	$17,000	G3 Series P3 Series	460,600	N/A	N/A	>97% at Full Load	0.5 to 10	Separate	www.tic.toshiba.com
Saftronics	6-pulse 18-pulse	N/A	GP10-4125-1 With Adder	460	N/A	N/A	98.1%at2KHz 97.8%at15KHz	0.75 to 10	Soft-Switching Not needed	www.saftronics.com
PDL	6-pulse	$22,229	Ultradrive Elite UE-140	460	N/A	<40% at Input	>97% at Full Load	Up to 10	Separate	www.pdl.co.nz
Fuji Electric	6-pulse	N/A	FRN G11S-4EN	380-480	N/A	30%	N/A	N/A	N/A	www.fujielectric.de
Fincor	6-pulse	$8,297	6600 Series-6601S1003A	460	<5%	<5%	99% at Full Load	Up to 10	Separate	www.fincor.net
Danfos Graham	6-pulse	$4,500	VLT6000H130 (VLT Type 6100)	460	N/A	N/A	>97% at Full Load	3 to 4.5	Built-in	www.grahamdrives.com
Reliance Electric	6-pulse	$14,985	GV3000/SE 100V2060	230	System Dependent	System Dependent	97% at Full Load	2.4 and 8	Separate	www.reliance.com

CONCLUSIONS

1. The field testing results indicated that filters are not necessary to condition the electrical power used by electric pump motors without VFDs. All pumps tested were within IEEE acceptable standards of current and voltage THD.

2. All of the VFD pumps tested in the fields exceeded standards for current THD, and over half (4 out of 7) also exceeded voltage THD standards.

3. In part because of (2) above, ITRC has developed recommendations for VFD panels, equipment, and installations. Those recommendations are found in ITRC Report No. R03-002 http://www.itrc.org/reports/vfd/vfdspecs.html

4. Electrical equipment upstream of transformers that supply VFDs is not vulnerable to damage from harmonics, because the harmonics are dissipated in the transformer.

5. If electrical equipment is located downstream of a transformer that supplies a VFD, it is advisable to install a separate transformer for that equipment. The transformer will prevent harmonics from reaching the electrical equipment.

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