Variable Frequency Drive (VFD) Specifications for Agricultural Irrigation Pumping

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- RDO Water
- Tatung Electric Motors
- US Electric Motors
- Yaskawa

LEGAL NOTICE

ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AHJ	Authority Having Jurisdiction
dV/dT	The rate of voltage change over time
FLA	Full Load Amps
HP	Horsepower
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
ITRC	Irrigation Training & Research Center
IEEE	Institute of Electrical and Electronics Engineers
NEC	National Electric Code
NEMA	National Electric Manufacturers Association
NIST	National Institute of Standards and Technology
psi	Pounds per square inch (Pressure)
PVM	Pulse Wave Modulation
SF	Service Factor
NIST	National Institute of Standards and Technology
THiD	Total Harmonic Current Distortion
UL	Underwriters Laboratory
VAC	Volts Alternating Current
VFD	Variable Frequency Drive

FIGURES

TABLES

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EXECUTIVE SUMMARY

PG&E currently offers rebate programs for agricultural and industrial VFD installations. Qualified well and booster pump VFD installations (rebate codes: IR006 and IR007) receive $30 per HP from PG&E, compared to $140 per HP for industrial fan or blower rebates (PR002).

The agricultural VFD installation rebates have no minimum performance standards. As such, PG&E does not have the ability to cost effectively filter out sub-optimal VFD installations from participation in the existing rebate programs.

Under contract with Pacific Gas & Electric Company (PG&E), the Irrigation Training & Research Center (ITRC) at California Polytechnic State University (Cal Poly) San Luis Obispo was tasked with developing the technical outline for a new, modified VFD rebate program.

PROJECT GOAL

The primary goal of this project was to improve the existing PG&E VFD rebate programs for low voltage (≤ 480 VAC) well and booster pumps 600 HP or less by setting minimum requirements for qualified VFD installations. It was anticipated that detailed VFD specifications will directly benefit PG&E and new rebate participations by helping to:

1. Increase energy efficiency, VFD life expectancies, and reliability – benefitting the customer and PG&E
2. Minimize power quality issues – benefitting PG&E

A secondary goal of the project focused on collecting consumer costs for "typical" VFD installations as well as the estimated cost premiums necessary to meet the new specifications. It was envisioned that cost data would aid in rebate structuring.

PROJECT DESCRIPTION

Throughout the process of developing the VFD system specifications, a variety of external entities participated in discussions and review of the proposed specifications:

1. Technical staff from five (x5) major VFD manufacturers
2. Two major AC motor manufacturers
3. Two large VFD vendors
4. Multiple, independent registered electrical engineers
5. PG&E Power Quality Group and other staff

Additionally, cost data was collected from a variety of sources:

1. Two large VFD vendors
2. Four irrigation and pump dealers
3. The authors' pre-existing datasets

PROJECT FINDINGS/RESULTS

Critical Concepts

1. A VFD system is required to meet the new specifications.

   A VFD system is defined in this report, and the attached specifications, as "The VFD plus all peripheral equipment typically contained in (or attached to) the enclosure (such as filters, reactors and cooling) but not including the motor and motor conductors. Cable termination filters mounted on the motor shall be considered part of the VFD system."

   In most cases, a VFD system contains devices from multiple manufacturers.

2. Professional VFD system fabrication firms are usually Underwriters Laboratory (UL) listed, meaning they hold a certification for motor/industrial control panel fabrication

Specifications

1. The attached specifications (Attachment 1) are the result of a general consensus on the content between the authors and reviewers. In other words, there are no lingering disagreements or contentious items.
2. The specifications are a combination of minimum performance levels and prescriptive requirements. The prescriptive requirements are intended to simplify the design and quotation process as well as avoid known problems. On the other hand, the performance standards provide some flexibility for manufacturers and vendors.
3. There are a number of components required by the specifications. Many VFD owners will likely choose to add additional options to the VFD system for advanced control features or convenience.
4. A standard checklist (Attachment 1 – Table 3.G.3) must be followed during installation commissioning. In addition, a list of documentation items are required to be submitted to PG&E and the VFD system owner.

VFD System and Unit Costs

Any additional cost required to comply with the specifications is an important consideration for designing a new VFD system rebate. Actual invoices from irrigation dealers and VFD vendors were collected and combined with pre-existing VFD system cost datasets. The results are provided in Figure 1.

The data were analyzed and grouped into two categories:

- VFD systems not meeting the specifications, or "typical" VFD systems
- The VFD systems that meet the specifications

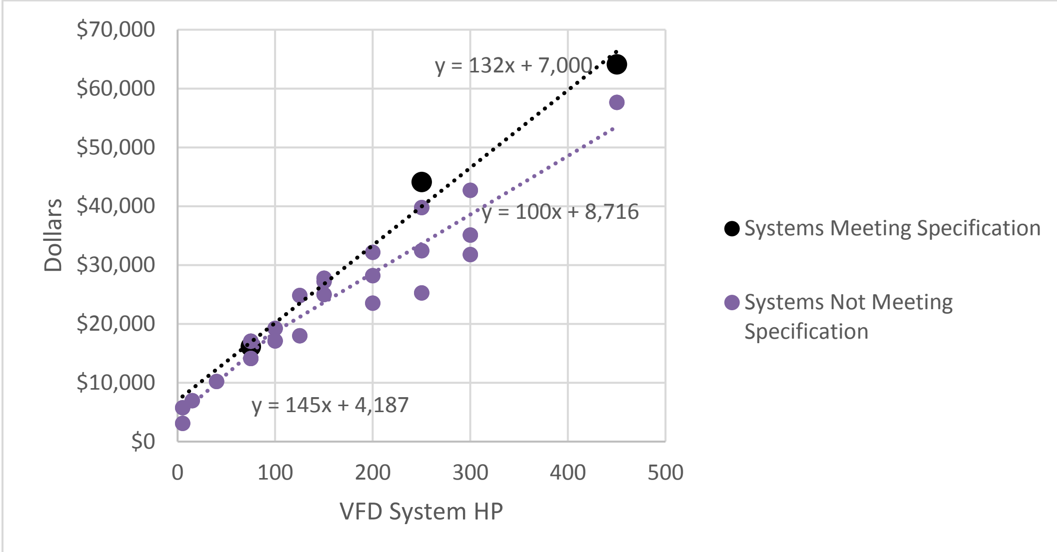

FIGURE 1. COMPARISON OF "TYPICAL" AND SPECIFICATION-COMPLIANT VFD SYSTEM INSTALLED COSTS (INCLUDING MATERIALS, LABOR AND TAX)

The data indicate that:

1. On average, it is more expensive to meet the specifications. The additional costs to meet the specifications are listed below:
    - Less than 75 VFD HP – the cost premium is about $2,000

      Note: Differences in premium costs required to meet the specifications for "typical" VFD systems less than 75 HP are relatively small. Therefore, the flat rate premium of $2,000 is a simplification.

    - Greater than 75 VFD HP – the cost premium is about $27 per VFD HP
2. There are numerous options when buying a VFD system. Some options are intended to improve performance. Other options are for convenience. Without the attached specifications, it is possible for a consumer to pay more for less performance.
3. "Typical" VFD system costs are highly variable.
4. Very few systems met the specifications (3 of 24 data points). The majority lacked one or any combination of the following features:
    - Line-side harmonic mitigation
    - Surge suppression
    - Acceptable cooling methods
5. The most common component used for specification-compliant line side harmonic mitigation was found to be either:
    - Integrated passive harmonic filters (costs are listed in Table 1).

TABLE 1. COST TO ADD INTEGRATED PASSIVE HARMONIC FILTER TO VFD SYSTEM FROM ONE VENDOR, INCLUDING TAX

VFD System HP	Dollars per VFD system HP for integrated passive harmonic filter, plus tax
75	25
250	15
450	46

- 3% AC input line reactors (one of three options meeting the specifications for motors 75 HP or less), which cost consumers about $6 per motor horsepower, including tax.

  NOTE: There are advantages and disadvantages to any harmonic mitigation method. For example, AC line reactors provide some harmonic mitigation as well as a degree of protection for the VFD from transients. On the other hand, AC line reactors cause a slight drop in VFD system energy efficiency as well as a drop in VFD AC input voltage. Therefore, a good designer will consider alternative harmonic mitigation methods to comply with the proposed specifications in some cases.

6. The most common solution for lightning and overvoltage protection is a surge protection device or assembly. Specification-compliant surge suppression costs about $500-$2000, including tax.
7. Cooling systems that meet the specifications do not circulate outside (dirty) air around sensitive electronics. A common and acceptable cooling method is a panel-mounted HVAC unit costing about $1,600 plus $4 per VFD HP.

General Findings

1. There is a very low level of awareness by most consumers and irrigation dealers of the technical details of VFD systems. VFD-related technical expertise is concentrated within select VFD manufacturer and vendor staff that in most cases have little to no contact with farmers.
2. Cost estimates and quotes provided to consumers are void of technical information. In other words, most farmers don’t know what they are buying. Similarly, irrigation dealers don’t know the technical specifications of what they are selling.
3. There is significant variability in performance and features between different VFD systems. The differences are not transparent to consumers and sometimes not reflected in the VFD system price.
4. A 6-pulse VFD using Pulse Wave Modulation (PWM) technology is currently the most common VFD sold for agricultural pumping applications. High-quality 6-pulse VFDs are available from a variety of well-known manufacturers with comparable performance.

Additional Commentary

1. Few of the VFD installations involving only the replacement of an on-farm across-the-line starter with a VFD system are inspected by the Authority Having Jurisdiction (AHJ). On the other hand, projects that include a new or upgraded utility service are usually permitted and inspected.
2. There are some promising new VFD technologies (e.g., active front ends and matrix technology) that may largely eliminate harmonic problems associated with 6- and

12-pulse VFDs. The new technologies are too expensive for adoption in the agricultural market; however, prices may become more affordable over time.

3. Additional costs, operational complexity, and an incomplete understanding of VFD benefits remain as barriers for successful VFD adoption in agricultural pumping.
4. Harmonics and power quality in PG&E power distribution will become a larger issue in the future with more non-linear loads, such as VFD and solar inverter installations.

Project Recommendations

The following are recommendations for PG&E regarding a future VFD rebate program:

1. Adopt the specifications provided in Attachment 1.
2. Avoid Qualified Product Lists (QPL). In most cases, the specifications require a custom designed, installed and commissioned system rather than an off-the-shelf component. While PG&E's motivation for a QPL is acknowledged, it does not fit this rebate. Perhaps in the future, manufacturers will start providing off-the-shelf, specification-compliant VFD systems.
3. Increase the rebated horsepower range to include both well and booster pumps up to 600 HP. While the existing rebate covers well pumps no greater than 300 HP and booster pumps no greater than 150 HP, it is now more common for new installations to exceed these limits in California. Moreover, larger VFD system installations are expected to result in proportionally larger energy demand savings.
4. Proceed with one of the following rebate structures:
    a. **Option 1.** Increase the existing rebate to cover the average cost premiums required for following the specifications, as listed in Table 2.

Table 2. Current and proposed VFD rebates for booster pumps

VFD HP	Existing VFD rebate for well and booster pumps (IR006 and IR007)	Premium required to meet specifications for "typical" VFD system	Proposed new VFD system rebate
75 or less	$30/HP	$2000	$30 per VFD HP plus $2000
Greater than 75 up to and including 600	$30/HP	$27 per VFD HP	$57 per VFD HP

    b. **Option 2.** Ignore the existing rebate and develop a new rebate structure considering the information provided in this document, including:
        i. Specification-compliant VFD system and unit costs
        ii. The cumulative benefits of specification-compliant VFD systems listed in Table 3
        iii. Calculated baseline energy efficiency improvements and simple payback calculations provided in Attachment 3 and summarized in the next section (see Figure 2)

TABLE 3. SPECIFICATION-COMPLIANT VFD SYSTEM BENEFITS TO PG&E AND CUSTOMERS

Benefit	Beneficiary	
	PG&E	Customer
Power savings	X	X
Peak load reduction	X	
Eliminating in-rush current when starting a single speed motor	X	
Minimizing water hammer in piped systems		X
Over-speed capability to make up for dropping water levels or worn pumps		X
Decreased well casing fatigue		X
Decreased sediment pumped from well		X

Other recommendations:

1. Invest in developing and distributing additional educational material and workshops that focus on the benefits of VFDs to the agricultural irrigation sector. It is critical that the economics, operations, and maintenance topics are covered. The target audiences should be irrigation dealers and farmers.
2. Assess and improve, if necessary, grid-tied solar rebate programs and specifications to improve solar inverter resilience as more non-linear loads (VFD systems and solar inverters) increase statewide.

REBATE OPTION 1

The proposed rebate amounts from Table 2 are illustrated in Figure 2.

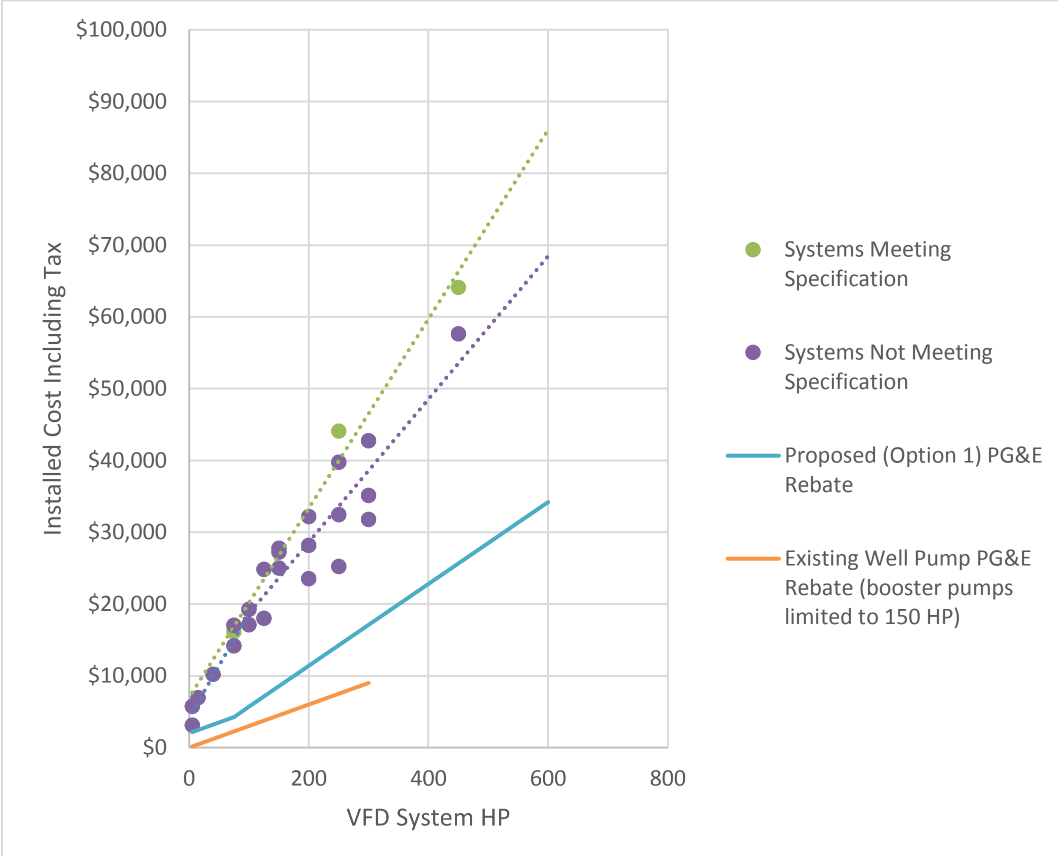

Figure 2. Comparison of "typical" and specification-compliant VFD system installed costs (including materials, labor and tax) with existing and proposed PG&E rebates

Rebate Option 1 Economics

There are two components of potential energy savings related to the installation of a new, high-quality VFD system:

1. Baseline energy savings anticipated for a typical pressurized agricultural irrigation system. Estimated energy savings are computed in Attachment 3 and summarized in this section.
2. In some cases energy savings will be significantly higher than the baseline but are difficult to predict and were therefore not included in the calculations. Examples include:
    - Automatic downstream pressure control for irrigation systems supplied by district pipelines with variable inlet pressures
    - Fields on hilly ground or significant elevation differences (i.e., more than 15 feet) between irrigation blocks

Baseline energy savings computations are based on the following assumptions that are, in the authors' experience, realistic:

1. It is typical and considered good design practice to over-design pumps to accommodate uncertainties and/or worst-case hydraulic conditions (ITRC report No. R 11-005). For example:
   a. Groundwater levels fluctuate and pumps wear.
   b. Published performance data for new pumps and emitters are not always accurate.
   c. Reasonable safety factors are applied to pump designs to cover unknowns such as losses across partially plugged pump suction screens.
   d. Most agricultural fields are on relatively flat ground and rectangular in shape. Even so, a slightly different minimum pump discharge pressure is typically required when irrigating different portions (blocks) of a field.
2. The new VFD system will be operated at a reduced speed to avoid developing excess pump discharge pressure.

Computed energy and demand savings, and simple payback values are reported in Table 4.

TABLE 4. ESTIMATED ENERGY SAVINGS AND SIMPLE PAYBACK COMPARISON FOR WELL AND BOOSTER PUMP VFD SYSTEM INSTALLATIONS MEETING THE SPECIFICATIONS – ASSUMING ENERGY SAVINGS ARE EQUIVALENT TO $0.17 PER KW-HOUR

Pump Type	Average baseline kW (demand) savings per year per HP	Average baseline kWh savings per year per motor HP	Anticipated Customer Payback (years)
Booster pump	0.1	242	2.7
Well pump		278	2.3

The reported values in Table 4 indicate that:

1. The energy and demand savings as well as simple payback periods are similar per horsepower for booster and well pump applications.
2. The baseline energy savings are significant and provide short payback periods for the customer.
3. It is unnecessary for PG&E to collect extensive information during or after the rebate application process in an effort to quantify installation-specific energy savings if the estimated baseline energy savings alone justify the rebate.

Additionally, the results indicate that annual energy savings and simple payback periods improve as horsepower increases, while the demand savings remain relatively constant with respect to horsepower increases.

BACKGROUND

Electrical demand from irrigated agricultural fields is expected to increase in the future. The conversion from surface to pressurized irrigation systems is ongoing in the western United States and is expected to continue. Additionally, new irrigation wells continue to be developed throughout California.

Most new well and booster pumps will be driven by induction AC electric motors due to increasing regulations on internal combustion engines. Variable frequency drives (VFDs) are sometimes installed on irrigation pumps to enable adjustment of the pump speed. Adjustment of the pump speed can provide energy savings as well as additional benefits to the farmer and power utility. The use of VFDs is promoted by good irrigation dealers and incentivized by power utilities through rebate programs.

PG&E currently offers rebate programs for agricultural and industrial VFD installations. Qualified well and booster pump VFD applicants (rebate codes: IR006 and IR007) can receive $30 per HP from PG&E. PG&E rebates for well pumps are currently limited to installations up to and including 300 HP. For booster pumps the existing limit is up to and including 150 HP. For comparison, PG&E also offers industrial fan or blower VFD rebates (PR002) at $140 per HP up to a maximum rebate of $10,400 (equivalent to a 75 HP maximum).

PG&E's agricultural VFD rebate programs have historically lacked minimum performance standards. As such, PG&E does not have the ability to cost effectively filter out sub-optimal VFD installations from participation in the existing rebate programs.

Under contract with Pacific Gas & Electric Company (PG&E), the Irrigation Training & Research Center (ITRC) at California Polytechnic State University (Cal Poly) San Luis Obispo was tasked to develop the technical outline for a new, modified VFD rebate program.

INTRODUCTION

The recent combination of high-quality products, utility-provided incentives, and an increasing number of successful installations have helped accelerate the adoption of VFDs in the agricultural irrigation sector. Irrigation dealers that service western Kern County estimate that:

- Roughly 80% of recent sales (new or retrofitted irrigation systems) include VFDs
- Only about 10-20% of all irrigation systems in the area have VFDs

Although anecdotal, these estimates reflect the authors' experience – that there are few VFDs in operation at the moment but the number of VFD systems is growing rapidly. However, areas for improvement remain. Most importantly, a complete VFD performance standard has not been historically available. While various standards and codes related to VFDs exist, in general the codes and standards can be described as:

- Piecemeal, individually designed to cover narrow aspects of a VFD installation
- Not publicly available, and most of them are relatively expensive
- Unenforced, especially if the installation is not inspected by an authority

It is well documented that without special design attention, VFD installations can be the source of power quality and radio interference issues that affect others. Other problems caused by poor VFD system design can affect VFD system owners such as frequent nuisance tripping (automatic resetting or shutdowns) or even preventing the pump motor from starting. Without standards, mitigating or avoiding these issues for new VFD installations is optional, rather than obligatory.

Moreover, the following topics are rarely discussed during the process of bidding and commissioning an agricultural VFD system:

1. Expected performance
2. Alternative components and their tradeoffs
3. Technical specifications

KEY CONCEPTS

VFD SYSTEM

A VFD system is required to meet the new specifications.

> *A VFD system is defined in this report, and the attached specifications, as "The VFD plus all peripheral equipment typically contained in (or attached to) the enclosure (such as filters, reactors and cooling) but not including the motor and motor conductors. Cable termination filters mounted on the motor shall be considered part of the VFD system."*
>
> In most cases, a VFD system contains devices from multiple manufacturers.

Common components within a VFD system are illustrated in Figure 3.

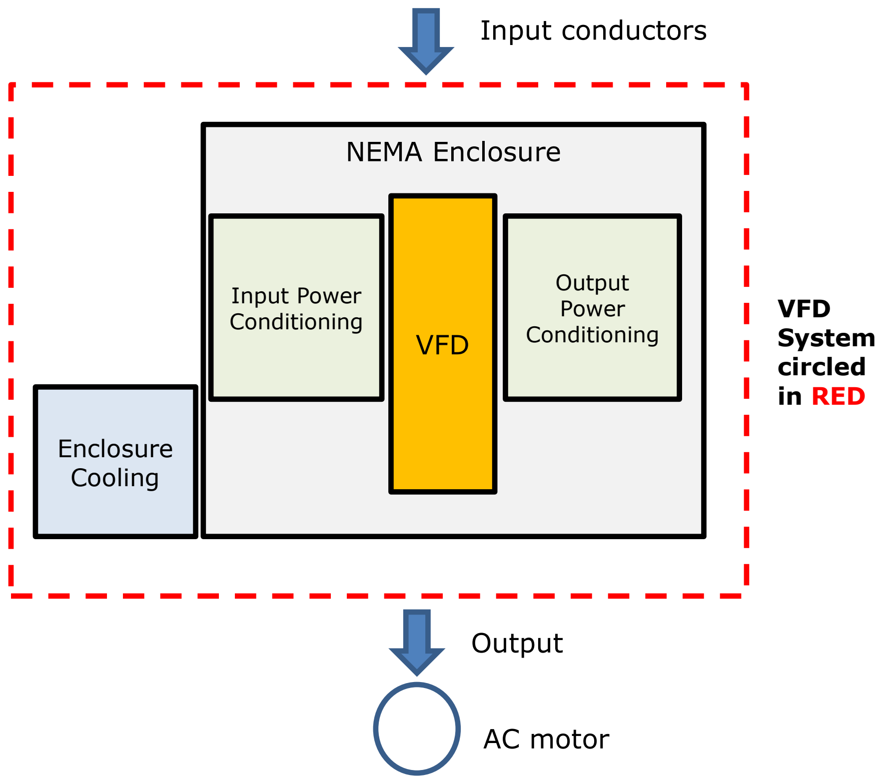

FIGURE 3. TYPICAL VFD SYSTEM COMPONENTS

Key points:

1. The VFD unit, provided by a major manufacturer, is only one part of a VFD system.
2. The remaining components are selected and sized by VFD experts, usually employed by a VFD vendor or other special firm.
3. Each component must be considered as part of a system, with potential tradeoffs.
4. The VFD system is usually assembled by an industrial control panel shop. Professional panel shops tend to pay fees for certification by the Underwriters Laboratory (UL) or equivalent organizations. Certified panel shops are also described as "UL Listed".
5. There are a number of optional VFD system add-ons to provide additional functions or features. Some can be considered essential for the customer's application, while others are for convenience.

HARMONIC DISTORTION

The standard IEEE 519 is often cited as the benchmark for line side harmonic mitigation analysis and design criteria; however, IEEE 519 is incompatible as a prescriptive requirement for PG&E's VFD rebate program for the following reasons:

1. Applying IEEE 519 requires a licensed electrical engineer and is typically considered unnecessary and overly expensive for smaller VFD systems. A common threshold for considering IEEE 519 in VFD system design varies between 60-100 HP. Under the

threshold horsepower is it more cost effective to install standard harmonic mitigation devices such as DC chokes or AC line reactors than pay for the IEEE analysis.

2. Agricultural pump motors over the threshold HP range are typically fed by an individual service drop and pole-mounted transformer. Therefore, the point of common coupling (PCC), an important reference location for IEEE 519, is on the line side of equipment installed and maintained by the utility.
3. IEEE 519 requires knowledge of PG&E-owned equipment, which may not be readily available. It is also unknown if PG&E has sufficient staff to meet the potential demand for information and coordination.

As such, the proposed specifications provide future VFD system rebate program participants with the option for VFD system over 75 HP to:

a. Install a VFD system that meets prescribed, yet conservative harmonic performance targets, or
b. Hire an electrical engineer to conduct an IEEE 519 analysis when it is likely that the engineered design will result in net monetary savings.

VFD SYSTEM COOLING

VFD units as well as other components within the VFD system generate heat. To maximize the life expectancy of the components, it is prudent to maintain temperatures in and around the components within their temperature ratings, if not lower.

While there are a number of methods used to dissipate VFD system heat, most VFD vendors provide VFD systems that use filtered fans to circulate outside air within the NEMA enclosure. In most cases circulating outside air is the most simple and least expensive option. On the other hand:

1. Agricultural fields are extremely dusty environments
2. Fine dust can travel through the filters
3. VFD system owners may neglect to, or unknowingly fail to service the filters as prescribed

The common result is early failure of the VFD or accessory components. As such, the specifications <u>require</u> alternative cooling systems that are less problematic for agricultural applications. It is important to note that the proposed specifications do not mandate a specific cooling method. Instead, the proposed specifications enable the VFD designer to select the most appropriate cooling method based on local conditions and experience such as:

- Closed loop heat exchangers including air-to-air and air-to-water
- Closed loop HVAC (air conditioning units)
- Passive cooling using:
    a. The VFD system NEMA enclosure itself as a convective and radiant heat sink
    b. Exterior, panel-mounted heat sinks usually mounted to the back of the VFD system enclosure
    c. Heat pipes and heat exchanges that use conductive, convective and phase change heat transfer

PROJECT OBJECTIVES

The primary objective of this project was to improve the existing PG&E VFD rebate programs for low voltage (≥ 480 VAC) well and booster pumps up to and including 600 HP. It was anticipated that a detailed and complete VFD specification would provide the following benefits:

1. Increase energy efficiency, VFD life expectancies, and reliability – benefitting the customer and PG&E
2. Minimize power quality issues – benefitting PG&E

Throughout the project, the authors focused on the following:

1. Reasonable and achievable performance. It was important to verify that the requirements are measurable and can be met by a variety of manufacturers with existing technology.
2. Flexibility to absorb new technology. Many of the requirements are performance-based rather than prescriptive so that new technology can be incorporated without periodic overhauls of the specifications.
3. Costs and benefits. The specifications focus on achieving excellent performance levels without requiring overly expensive components.

A secondary goal of the project was to determine consumer costs for VFD systems commonly purchased (a "typical" VFD installation) as well as the estimated cost premiums necessary to meet the new specifications. It was envisioned that cost data would aid in rebate structuring.

PROCESS

The project was composed of two main components:

1. VFD system specification development
2. VFD system and unit costs

VFD SYSTEM SPECIFICATIONS DEVELOPMENT

Throughout the process of developing the VFD system specifications, a variety of external entities participated in discussions and review of the proposed specifications:

1. Technical staff from five (x5) major VFD manufacturers
2. Two major AC motor manufacturers
3. Two large VFD vendors
4. Multiple, independent registered electrical engineers
5. PG&E Power Quality Field Investigation Team and Energy Efficiency Product Management Team

VFD and motor manufacturers were contacted to collect information on VFD technology, performance metrics and components. Because most agricultural VFDs are combined with additional, third party components, the designers and dealers of these VFD systems were also contacted.

Each manufacturer and vendor was provided the latest version of the proposed specifications for review and discussion. Then the final draft specifications were sent to PG&E for internal review. Constructive feedback was received by the PG&E Power Quality Field Investigation Team and incorporated into the contents of this report.

VFD System and Unit Costs

The authors sent out requests for cost data to over 10 VFD vendors and irrigation dealers with the latest VFD specifications attached. The information request was designed so that the VFD vendors and irrigation dealers would:

- Submit three (x3) previous invoices for previously sold and/or installed VFD systems with a range of VFD horsepower, rather than develop new cost estimates for the project
- Indicate which of the VFD system specifications were met by the VFD system
- Provide a cost estimate for any additional equipment needed to meet the specifications
- Subtract the cost of any equipment that was originally provided, but would be replaced by equipment required to meet the specifications

Multiple submissions were received from:

1. Two VFD vendors
2. Four irrigation and pump dealers

In order to increase confidence in the returned data, a pre-existing VFD system cost dataset was incorporated in this analysis. Some cost adjustments were made in order to compare equivalent values (e.g., adding sales tax where missing from the invoice or quote).

Project Results

Specifications

The proposed VFD system specifications are provided in Attachment 1. The specifications are comprised of the following major parts:

1. Definition of terms
2. Applicability standards (e.g., applicants of the PG&E rebate program installing VFD systems on pumps less than or equal to 600 HP)
3. Minimum VFD system requirements
4. Minimum VFD system installation and commissioning checklist
5. Documentation requirements to the owner and PG&E

6. Requirements for special cases
7. Optional additional features and equipment

Key points:

1. The attached specifications are the result of a general consensus on the content between the authors and reviewers. In other words, there are no lingering disagreements or contentious items.
2. The specifications are a combination of minimum performance levels and prescriptive requirements. The prescriptive requirements are intended to simplify the design and quotation process as well as avoid known problems. On the other hand, the performance standards provide some flexibility for manufacturers and vendors.
3. There are a number of components required by the specifications. Many VFD owners will likely choose to add additional options to the VFD system for advanced control features or convenience.

PROJECT FINDINGS

VFD SYSTEM COSTS

The installed VFD system cost (including materials, labor and tax) dataset is plotted in Figure 4. Only three of the 24 invoices met the specifications. The VFD systems that did not meet the specifications are considered "typical".

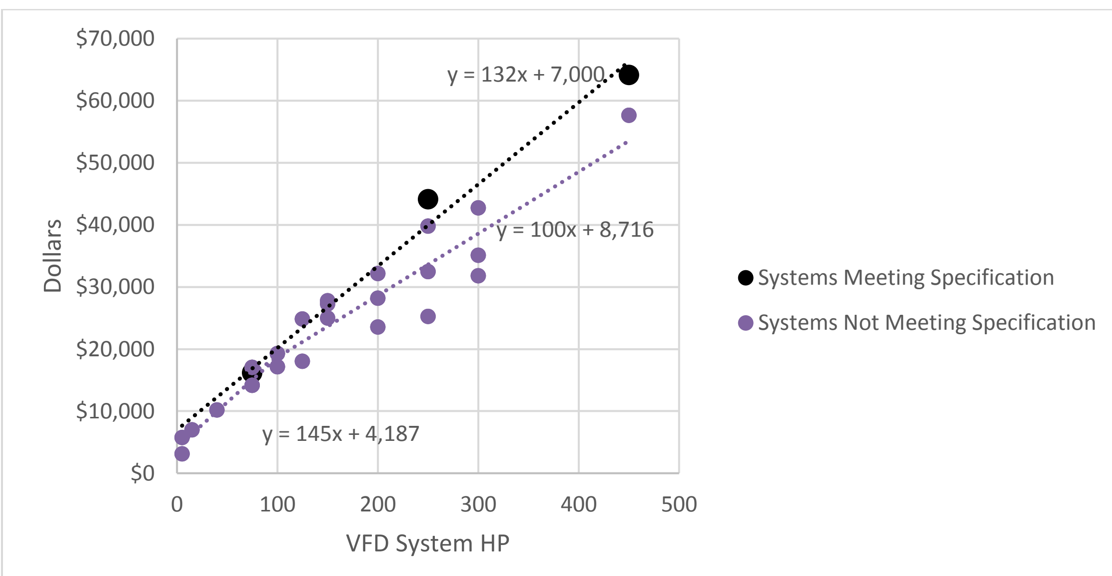

FIGURE 4. COMPARISON OF "TYPICAL" AND SPECIFICATION-COMPLIANT VFD SYSTEM INSTALLED COSTS (INCLUDING MATERIALS, LABOR AND TAX)

The data indicate that:

1. Most of the VFD system costs were missing one of, or any combination of, the following features:
    - Harmonic mitigation
    - Surge suppression
    - Acceptable cooling (without outside air circulation across electronics)
2. Some of the "typical" VFD system costs are more expensive, but cannot meet the specified performance standards.
3. On average, it is more expensive to meet the specifications. The additional cost to meet the specifications are listed below:
    - Less than or equal to 75 VFD HP – the cost premium is about $2,000

      Note: While they exist, differences in premium costs required to meet the specifications for "typical" VFD systems less than or equal to 75 HP are relatively small. Therefore, the flat rate premium of $2,000 is used as a simplification.
    - Greater than 75 VFD HP – the cost premium is about $27 per VFD HP
4. "Typical" VFD system costs are highly variable.

Unit Costs

1. The most common technologies for harmonic mitigation for the quotes received were either:
    a. Passive harmonic filters, or
    b. Input line reactors
2. Passive harmonic filters are capable of providing harmonic mitigation that meet the specifications for VFD systems over 75 HP. A range of approximate consumer costs for adding passive harmonic filters is listed in Table 5.

Table 5. Approximate unit costs for integrated passive harmonic filters

VFD HP	Integrated passive harmonic filter unit costs, plus tax ($)	Approximate dollars ($) per VFD HP
75	1848	25
250	3629	15
450	20714	46

3. 3% input line reactors are one of many prescribed harmonic mitigation measures for VFD systems 75 HP or less. Line reactors can serve dual functions: harmonic mitigation and some degree of transient voltage protection. The consumer costs for adding 3% line reactors is approximately $5 per VFD HP as shown in Figure 5.

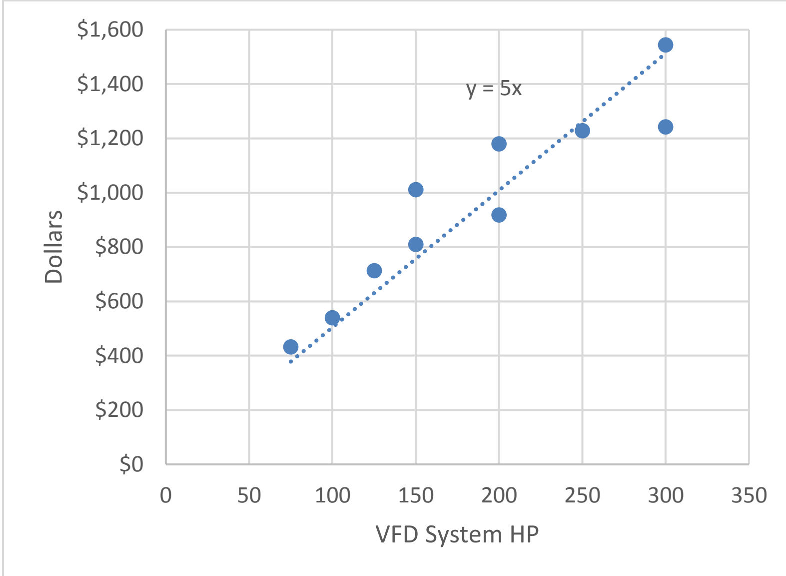

FIGURE 5. APPROXIMATE UNIT COSTS FOR INPUT LINE REACTORS, PLUS TAX

Because line reactors operate with a voltage drop, AC line reactors may not be appropriate for certain installations that:

- Experience frequent utility sag events. The additional line reactor voltage drop could cause more frequent nuisance tripping and possibly damage internal VFD components as the voltage sag normalizes.
- Long cable runs will compound the voltage drop caused by the line reactors and can increase current requirements above expected levels to produce the same brake horsepower at the motor.

4. One of many VFD system cooling methods that comply with the specifications is a panel-mounted HVAC unit. HVAC units are usually more expensive than other acceptable cooling methods, but it is relatively easy to incorporate HVAC units into a VFD system design. The approximate costs for adding an HVAC unit for VFD system cooling listed in Table 6.

TABLE 6. APPROXIMATE UNIT COSTS FOR HVAC COOLING UNITS

VFD HP	Nominal HVAC (ton)	Installed HVAC unit cost plus tax
50	0.5	1850
100	1	2100
200	2	2550
400	3	3050
600	5	4000

General Findings

Throughout the project a number of initial hypotheses were validated or updated:

1. There is a very low level of awareness by most consumers and irrigation dealers of the technical details of VFD systems. VFD-related technical expertise is concentrated within select VFD manufacturer and vendor staff that in most cases have little to no contact with farmers.
2. Cost estimates and quotes provided to consumers are void of technical information. In other words, most farmers don't know what they are buying. Similarly, irrigation dealers don't know the technical specifications of what they are selling.
3. There is significant variability in performance and features between different VFD systems. The differences are not transparent to consumers and sometimes not reflected in the VFD system price.
4. A 6-pulse VFD using Pulse Wave Modulation (PWM) technology is currently the most common VFD sold for agricultural pumping applications. High quality 6-pulse VFDs are available from a variety of well-known manufacturers with comparable performance.
5. Few of the VFD installations on-farm are inspected by the Authority Having Jurisdiction (AHJ)

Findings 1-3 above are problematic for both agricultural VFD owners and power utilities. Market conditions could be expected to improve once:

- A complete performance standard has been accepted by the VFD industry. Without a standard, high-quality VFD systems will continue to be undercut by poor performing and less expensive alternatives.
- Good quality and equivalent VFD systems (meeting the universal standards explained above) become commoditized.

Additional Commentary

1. There are some promising new VFD technologies (e.g., active front ends and matrix technology) that may largely eliminate harmonic problems associated with 6- and 12-pulse VFDs. The new technologies are too expensive for adoption in the agricultural market; however, prices may become more affordable over time.
2. Additional costs, operational complexity, and an incomplete understanding of VFD energy efficiency benefits remain as barriers for widespread VFD adoption in agricultural pumping. Indeed, irrigation dealers report that the flexibility provided by VFD systems is the primary factor when agricultural consumers are considering a VFD purchase.

   However, it is anticipated that more on-farm management attention will be diverted to improving energy efficiency in an effort to reduce operational costs. Additional education is expected to help accelerate this shift.
3. Harmonics and power quality in PG&E power distribution will become a larger issue in the future with more VFD and solar inverter installations.

PROJECT RECOMMENDATIONS

The following are recommendations for PG&E regarding a future VFD rebate program:

1. Adopt the specifications provided in Attachment 1
2. Avoid Qualified Product Lists (QPL) for now. In most cases, the specifications require a custom designed, installed and commissioned system rather than an off-the-shelf component. While PG&E's motivation for a QPL is acknowledged, it does not fit this rebate. Perhaps over time, manufacturers may start providing specification-compliant VFD systems as a standard offering.
3. Proceed with one of the following rebate structure alternatives:
    a. **Option 1.** Increase the existing rebate to cover the average cost premiums required for following the specifications, as listed in Table 7.

TABLE 7. CURRENT AND PROPOSED VFD REBATES

VFD HP	Existing VFD rebate for well and booster pumps (IR006 and IR007) ($/HP)	Premium required to meet specifications for "typical" VFD system	Proposed new VFD system rebate
<= 75	30	$2000	$30 per VFD HP plus $2000
> 75	30	$27 per VFD HP	$57 per VFD HP

    b. **Option 2.** Ignore the existing rebate and develop a new rebate structure considering the following:
        i. Average VFD system costs
        ii. The cumulative benefits of specification-compliant VFD systems listed in Table 8
        iii. Typical energy savings and simple payback calculations provided in Attachment 3 and summarized in a later section
        iv. The results of a an ongoing analysis of PG&E's Advanced Pumping Efficiency Program
        v. Revisiting and comparing the economic justification for other PG&E VFD rebate programs such as the "VFD for Process Fan or Blower" (PR002) which provides $140/HP (up to $10,500) with a minimum of 3 HP

TABLE 8. SPECIFICATION-COMPLIANT VFD SYSTEM BENEFITS TO PG&E AND CUSTOMERS

Benefit	Beneficiary	
	PG&E	Customer
Energy efficiency improvements	X	X
Peak load (demand) reduction	X	
Eliminating in-rush current when starting a single speed motor	X	
Minimizing water hammer in piped systems		X
Over-speed capability to make up for dropping water levels or worn pumps		X
Ramped well start/stop for decreasing well casing fatigue and sediment		X

Additional recommendations:

1. Invest in developing and distributing additional educational material and workshops that focus on the benefits of VFDs to the agricultural irrigation sector. It is critical that the economics, operations and maintenance topics are covered.
2. Assess and improve, if necessary, grid-tied solar rebate programs and specifications to improve solar inverter resilience for future operations in an environment with more non-linear loads (VFDs and solar inverters).

Rebate Option 1

The proposed rebate amounts listed in Table 7 are illustrated in Figure 6.

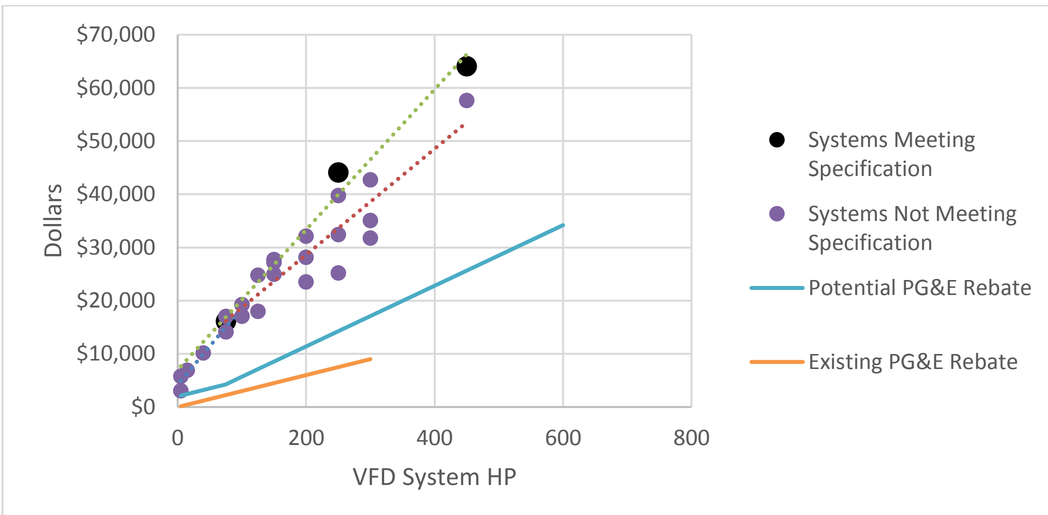

Figure 6. Comparison of "typical" and specification-compliant VFD system installed costs (including materials, labor and tax) with existing and potential PG&E rebates

Rebate Option 1 Economics

There are two components of potential energy savings related to the installation of a new, high-quality VFD system:

1. <u>Baseline</u> energy savings anticipated for a typical pressurized agricultural irrigation system. Estimated energy savings are computed in Attachment 3 and summarized in this section.
2. In some cases energy savings will be significantly higher than the baseline but are difficult to predict and were therefore not included in the calculations. Examples include:
   - Automatic downstream pressure control for irrigation systems supplied by district pipelines with variable inlet pressures
   - Fields on hilly ground or significant elevation differences (i.e., more than 15 feet) between irrigation blocks

Baseline energy savings computations are based on the following assumptions that are, in the authors' experience, realistic:

1. It is typical and considered good design practice to over-design pumps to accommodate uncertainties and/or worst-case hydraulic conditions (ITRC report No. R 11-005). For example, there are good reasons to over-design pumps:
    a. Groundwater levels fluctuate and pumps wear over time.
    b. Published performance data for new pumps and emitters are not always accurate.
    c. Reasonable safety factors are applied to pump designs to cover unknowns such as losses across partially plugged pump suction screens.
    d. Most agricultural fields are on relatively flat ground and rectangular in shape. Even so, a slightly different minimum pump discharge pressure is typically required when irrigating different portions (blocks) of a field.
2. The new VFD system will be operated at a reduced speed to avoid developing excess pump discharge pressure, resulting in reduced energy consumption.

Computed energy savings and simple payback values are reported in Table 9, Table 10 and Table 11. Additional details and assumptions are provided in Attachment 3.

TABLE 9. ESTIMATED BASELINE ENERGY SAVINGS AND SIMPLE PAYBACK COMPARISON FOR WELL AND BOOSTER PUMP VFD SYSTEM INSTALLATIONS MEETING THE SPECIFICATIONS – ASSUMING ENERGY SAVINGS ARE EQUIVALENT TO $0.17 PER KW-HOUR

Pump Type	Average baseline kW (demand) savings per input HP	Average baseline kWh savings per year per motor HP	Anticipated Customer Payback (years)
Booster pump	0.1	242	2.7
Well pump		278	2.3

TABLE 10. ESTIMATED DEMAND AND ENERGY SAVINGS BASED ON HORSEPOWER FOR WELL PUMPS SUPPLYING BOOSTER PUMPS IN DRIP/MICRO APPLICATIONS – ASSUMING ENERGY COSTS ARE $0.17 PER KW-HOUR

Arbitrary Input HP	Computed kW (demand) Savings Per Input HP	Computed New kW Savings	Computed Annual kWh savings Per Input HP	Computed New Annual kWh savings	Estimated Total Installed VFD System Cost Plus Tax ($)	Annual Savings ($) Due To New VFD System
50	0.1	6.1	289	14,449	13,600	2,456
100		12.0	289	28,441	20,200	4,835
150		17.9	284	42,325	26,800	7,195
200		23.6	282	55,990	33,400	9,518
250		29.3	280	69,440	40,000	11,805
300		35.1	278	83,002	46,600	14,110
350		40.4	277	95,710	53,200	16,271
400		46.2	273	109,383	59,800	18,595
450		52.0	273	123,056	66,400	20,919
500		57.5	273	136,199	73,000	23,154
550		63.3	272	149,819	79,600	25,469
600		69.0	272	163,438	86,200	27,785

TABLE 11. ESTIMATED ENERGY SAVINGS BASED ON HORSEPOWER FOR BOOSTER PUMPS IN DRIP/MICRO APPLICATIONS – ASSUMING ENERGY COSTS ARE $0.17 PER KW-HOUR

Arbitrary Input HP	Computed kW (demand) Savings Per Input HP	Computed New kW Savings	Computed Annual kWh savings Per Input HP	Computed New Annual kWh savings	Estimated Total Installed VFD System Cost Plus Tax ($)	Annual Savings ($) Due To New VFD System
50	0.1	5.6	264	13,207	13,600	2,245
100		10.9	258	25,846	20,200	4,394
150		16.0	253	37,944	26,800	6,450
200		20.9	248	49,527	33,400	8,420
250		25.6	242	60,618	40,000	10,305
300		30.1	237	71,242	46,600	12,111
350		34.7	235	82,260	53,200	13,984
400		39.3	233	93,050	59,800	15,818
450		44.2	233	104,681	66,400	17,796
500		49.1	233	116,312	73,000	19,773
550		54.0	233	127,943	79,600	21,750
600		58.9	233	139,574	86,200	23,728

The reported values indicate that:

1. The baseline energy savings are significant and provide short payback periods for the customer.
2. It is unnecessary for PG&E to collect extensive information during or after the rebate application process in an effort to quantify installation-specific energy savings if the estimated baseline energy savings alone justify the rebate.
3. Annual energy savings and simple payback periods improve as horsepower increases.

Additional details are provided in Attachment 3.

Significant additional energy savings are possible in some cases, but are difficult to predict and therefore not included in the energy analysis. One example could involve configuring the VFD to automatically maintain a target pressure with variable upstream or downstream conditions in the following scenarios:

1. A booster pump supplied by a pipeline irrigation district turnout. Typically, the pressure available at the turnout is variable.
2. Temporarily increasing the speed of the pump to supply the irrigation flow rate in addition to the required filter backflush flow rate (during backflush cycles only).

REBATE IMPLEMENTATION

It is envisioned that the future VFD rebate program be designed to support VFD installations that meet the following criteria:

1. A VFD designed to drive a 480VAC electric motor less than or equal to 600 HP
2. Complies with the specifications
3. Has been installed to control the speed of a well or booster pump that supplies a pressurized irrigation system

One of the more difficult tasks for implementing the rebate is verifying Item (2) above. A few options to implement Item (2) are discussed:

- Analyzing proposed VFD systems for compliance. This onerous option was considered and discarded.
- Qualified Product List (QPL). While a QPL would simplify a rebate implementation, the VFD market is just not there. It is possible that in the future, manufacturers will transition to pre-packaged VFD systems that meet the specifications. At this time, a QPL is not achievable.
- Transfer the responsibility of verifying compliance to third-party experts. This option can be implemented now, as explained below.

Recommendation: To meet Item 2 above, PG&E should consider requiring all of the following signatures and contact information on the application:

1. The designer or UL listed shop, certifying that the design meets the specifications
2. The installer, certifying that the commissioning meets the specifications
3. The owner, certifying that the specified training and documentation was provided

It is envisioned that the signatures may be useful to the field investigation team in the future should problems be reported. At the very least, the VFD system designer may be a helpful contact that could ideally reproduce shop drawings or documentation.

NOTE: The above recommendations are conceptual in nature and do not constitute legal advice.

ATTACHMENT 1: VFD SPECIFICATIONS

Proposed Specifications for PG&E Agricultural Pumping VFD Incentive Program	References used in Specification
Section 1 - Applicability	
1.A. This document applies to Variable Frequency Drive (VFD) system installations meeting all of the following criteria:	
1.A.1. The project owner or authorized representative is applying to participate in the "PG&E Agricultural Pumping VFD Incentive Program", which involves a rebate for a complete VFD system, rather than components	
1.A.2. The project involves a VFD system designed to control the speed of a 60 Hz alternating current motor that is rated for:	
1.A.2a. 480VAC or less	
1.A.2b. 600 HP or less	
1.A.3. The VFD-controlled motor will be used specifically for pumping agricultural irrigation water into a pressurized irrigation system.	
Section 2 - Definitions	
AC - Alternating current	
AHJ - Authority having jurisdiction, such as the local county building department	
CEC – California Electric Code	
dv/dt - the rate of voltage change over time	
FLA - Full load amps. The current (in amperes) required to deliver the rated horsepower at the rated voltage, speed, and frequency. The value is found on the motor nameplate.	
GFCI – Ground Fault Circuit Interruptor	
HP - Horsepower	
IEC - International Electrotechnical Commission	IEC 61800-5-1:2007 ; IEC 60721-3-3
IEEE - Institute of Electrical and Electronics Engineers	IEEE 519
NEC - National Electric Code, published by the National Fire Protection Agency (NFPA)	
NEMA - National Electric Manufacturers Association	NEMA MG-1 : 2011
NFPA – National Fire Protection Agency	NFPA 70
RPM – Revolutions per minute	
SF - Service factor	
Terminal - A mechanical device used to make secure wire connections using a screw or other means to put pressure on the connection	
THiD - Total harmonic current distortion (also called "TDD")	
UL - Underwriters Laboratories	UL 508
VAC - Volts alternating current	
VFD - Variable frequency drive, which is a system of electronic components assembled by a manufacturer for sale as the most basic unit used in practice to adjust the rotational speed of alternating current motors.	
VFD System - The VFD plus all peripheral equipment typically contained in (or attached to) the enclosure (such as filters, reactors, and cooling), but not including the motor and motor leads. Cable termination filters shall be included in the VFD system	

Proposed Specifications for PG&E Agricultural Pumping VFD Incentive Program	Comments	More information	Link
Section 3 - Minimum Requirements			
3.A. General			
3.A.1. The design and installation shall conform to the latest editions of the National Electric Code (NFPA 70), the California Electric Code (CEC) and any local codes.	References used in this specification are from the 2014 NEC. It may be necessary to refer back to the 2014 publication or modify the reference number if the references are renumbered in future versions	See NFPA website for free online access to NFPA (and NEC) codes	www.nfpa.org
3.A.1a. All of the VFD manufacturer guidelines and instructions regarding materials, components, environment, and installation must be followed. Many of those requirements are not repeated in this specification.	Extensive recommendations and guidelines are readily available online from most VFD manufacturers	See manufacturer websites	

3.A.1b. The owner shall provide proof that the Authority Having Jurisdiction (AJH) over the installation, such as a County Building Department that issues permits and conducts inspections of work done, has approved the completed work	In some cases, the AHJ might be a city or similar entity	Inquire with local city or county staff	
3.A.2. The VFD shall be permanently marked with the manufacturer's name or identification, the voltage, current (or HP) rating, the short circuit (Isc) rating, and other necessary information to properly indicate the applications for which the VFD is suitable for. For VFDs that are an integral part of equipment approved as a unit, the above markings shall be permitted on the equipment nameplate.	The label provides information that may be useful for future installations if the VFD is used again in another application		
3.A.3. The VFD and all associated equipment shall be contained in (an) enclosure(s) rated per the NEC for the environment in which the enclosure(s) will be located. Typical enclosure ratings are: Indoor NEMA 1 (dry location) NEMA 12 (wet location) Outdoor NEMA 3 (dusty) NEMA 3R NEMA 4X (corrosive environment)	NEMA enclosure ratings describe protection against ingress of water and dust. Corrosion resistance is also described.	See ***NEC Article 110*** and ***NEC Table 110.28*** for more environmental protection details	www.nfpa.org
3.A.4. All internal VFD electronics shall be protected for the environment to which they are exposed.	Some manufacturers can provide additional protection to electronics through coatings to minimize corrosion and shorting of printed circuit boards (PCB), connectors and other sensitive equipment. Levels of PCB protection are standardized into classes in IEC 60721-3-3 (Operation Environmental Conditions). For example, a VFD manufacturer may state: "Protection to IEC 60721-3-3 class 3C2"	See ***Conformal Coating for Variable Speed Drives. Rockwell Automation***	http://literature.rockwellautomation.com/idc/groups/literature/documents/wp/drives-wp021_-en-p.pdf
3.A.5. The VFD system shall conform to all other applicable PG&E performance requirements, including harmonic distortion.	These specifications do not supersede other PG&E requirements, which are subject to change over time		
3.B. Motors			
3.B.1. Sizing. New motors shall be sized to provide the required load at a service factor (SF) of no more than 1.0.	Designing a motor to run at a service factor of less than or equal to 1 provides a buffer against overloading or overheating the motor due to intermittent increases in ambient temperatures, loads, and low or unbalanced voltages,	See: ***Service Factor: What is it and what does it do?***	http://www.avonmore-electrical.com/contentfiles/Service%20Factor%20-%20What%20is%20it%20and%20What%20does%20it%20do.pdf
3.B.2. New motors shall meet NEMA MG-1 Part 31 Standard.	NEMA NMG-1 Part 31 Standard outlines minimum requirements for motors designed to operate in conjunction with VFDs	See **NEMA MG-1: 2011**	www.NEMA.org
3.B.3. A silicon rubber, flexible motor heater shall be provided for all new motors larger than 50 HP. The motor heater shall be controlled by an automatic thermal switch or relay and switch on at temperatures below the dew point.	Motor heaters are designed to minimize condensation build-up inside the motor. Condensation inside the motor can accelerate insulation degradation and other problems	See ***Application Manual for NEMA motors*** Section 7 for further details, installation and wiring methods are provided in "	https://www.industry.usa.siemens.com/drives/us/en/electric-motor/nema-motors/literature-and-technical-resources/documents/app-man-section7-rev1.pdf
3.B.4. Bearing current mitigation:	Driving a motor with a VFD generates shaft voltages for various reasons. Motor bearings act as a conductor between the higher shaft voltage and the grounded motor frame. Bearing material is removed (i.e., corrosion occurs) and the bearing is damaged if current passes through it	Discussion on the types of bearing currents, their causes and impacts, is provided in ***Dealing with Shaft and Bearing Currents*** and ***Technical Guide No. 5***	http://www.kyservice.com/wp-content/uploads/2017/03/EASA-Shaft-Bearing-Currents.pdf https://library.e.abb.com/public/8c253c2417ed0238c125788f003cca8e/ABB_Technical_guide_No5_RevC.pdf
3.B.4a. Properly installed shaft grounding rings shall be provided on the drive end of all motors over 50 HP.	Shaft grounding rings provide a lower resistance path to ground, to bypass the motor bearings		
3.B.4b. An insulated bearing carrier at the upper bearing shall be provided for all vertical hollow shaft motors over 100 HP.	Insulated bearings provide additional protection against voltage arcs across the motor bearings		
3.C. Wiring between the motor and the VFD			
3.C.1 Motor leads shall be selected based on the VFD manufacturer's recommendations, applicable codes and standards. Voltage rating, motor type, amperage, and length must be considered.	Many VFD manufacturers provide extensive guidelines that cover selecting conductor or cable assembly types, sizing, shielding, etc. Selecting good conductors or cable assemblies help minimize EMI/RFI noise, motor bearing currents, and motor efficiency	A good example of extensive recommendations is provided in ***Wiring and Grounding Guidelines for Pulse-Width Modulated (PWM) AC Drives. E***ach manufacturer may have different recommendations.	http://literature.rockwellautomation.com/idc/groups/literature/documents/in/drives-in001_-en-p.pdf
3.C.2. Wiring must be specifically designed for VFD applications and include the following minimum features:			
3.C.2a. Shielding or armoring	Shielding the VFD cable helps contain EMI/FRI noise emittance and can also reduce shaft voltages/bearing currents		
3.C.2b. Grounding conductor(s)	Good grounding systems help reduce noise emittance and ground currents from common mode voltage		
3.C.2c. XLP or similar insulation rather than thermoplastic			
3.D. Transformer			
3.D.1 If there is an ungrounded system (Delta-Delta transformer), provisions must be made to avoid shorting out various components such as Metal Oxide Varistors			

<table>
<tr><td>3.E. Technical specifications for VFD systems</td><td></td><td></td><td></td></tr>
<tr><td>3.E.1. VFD selection:</td><td></td><td></td><td></td></tr>
<tr><td>3.E.1a. The VFD shall be rated to provide 110% of the nominal output rating of the drive for 1 minute every 10 minutes</td><td>This is common criteria for variable torque applications such as agricultural water pumping. VFDs are rated differently for constant torque applications, such as conveyor and fixed displacement pump applications.</td><td></td><td></td></tr>
<tr><td>3.E.1b. The VFD and associated equipment shall be of sufficient current or horsepower rating to meet or exceed all of the following:</td><td>Undersizing VFDs shall be avoided. For existing motor applications, there are some cases in which the VFD must be sized greater than the motor nameplate current or HP rating.</td><td></td><td></td></tr>
<tr><td>(i) the motor nameplate FLA or the maximum current required by the motor at full load when supplied by the VFD system, whichever is greater</td><td>Designers shall consider and account for differences between actual motor current and nameplate current. Existing motors can experience a loss in efficiency over time, or as a direct result of poor quality motor rewinds.</td><td>For details on good motor rewind practices and test results, see The Effect of Repair/Rewinding on Motor Efficiency</td><td>http://www.easa.com/sites/files/resource_library_public/EASA_AEMT_RewindStudy_1203-0115.pdf</td></tr>
<tr><td>(ii) Derating adjustments as recommended by the manufacturer of each component, for the specific application</td><td>Example reasons for derating components include low air pressure (high altitude) and expected ambient temperatures above the ambient temperature rating of each component</td><td></td><td></td></tr>
<tr><td>3.E.2. Operating efficiency at full load. The following shall apply for VFDs driving motors with a nameplate rating greater than or equal to 20 HP:</td><td>VFD and motor efficiency decreases with partial loads, especially below 50% of the rated load</td><td></td><td></td></tr>
<tr><td>3.E.2a. The VFD output power shall be no less than 96.5% of the VFD input power.</td><td>This efficiency requirement includes only the VFD, and excludes other equipment that may be supplied with the VFD system by the vendor</td><td>A good reference for typical VFD efficiencies at full and partial loads is provided by the Department of Energy</td><td>https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/motor_tip_sheet11.pdf</td></tr>
<tr><td>3.E.2b. The VFD system (including harmonic and surge mitigation) output power shall be no less than 93% of the VFD system input power.</td><td></td><td></td><td></td></tr>
<tr><td>3.E.3. VFD systems shall be UL508 compliant, and be assembled in a UL listed facility. Unwitnessed factory acceptance testing shall be conducted and documented. A document certifying the successful test results shall be provided with the equipment during shipment.</td><td>UL508 lists standards to promote user safety for electric motor control systems. Requiring assembly in a UL-listed facility promotes a minimum standard for design and workmanship that is audited by an independent entity.</td><td></td><td></td></tr>
<tr><td>3.E.4. Line side</td><td>The VFD input side</td><td></td><td></td></tr>
<tr><td>3.E.4a. VFD systems shall meet the minimum line side requirements listed in the table below regarding harmonic distortion and mitigation</td><td>In general, the negative impacts affecting adjacent utility customers for line side harmonic distortion are relative to: (a) the magnitude of the distortion, and (b) the ratio of distorted current/voltage to non-distorted current/voltage at the point of common coupling as defined in IEEE 519.

NOTE: Harmonic distortion just downstream of agricultural transformers is also important but is usually mitigated if the requirements in the Table are followed.

The magnitude of the distortion can be mitigated by various technologies. In agricultural applications, electric motor driven pumps are typically the largest loads on transformers. However, agricultural pumping loads are usually small relative to the capacity of medium voltage line at the point of common coupling (which in most cases is just upstream of PG&E's transformer for a pump).</td><td>A good overview of harmonic distortion is provided by PG&E</td><td>https://www.pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/powerquality/harmonics.pdf</td></tr>
<tr><td>Minimum VFD system line side harmonic performance and components<table><tr><th>Motor HP</th><th>Minimum line side component</th><th>Maximum THID measured at the input terminals of the VFD system</th></tr><tr><td><= 75</td><td>3% AC line reactor of DC bus equivalent, or active front end</td><td>n/a</td></tr><tr><td>> 75</td><td>n/a</td><td>5% or certified by a registered electrical engineer to meet IEEE 519 at the Point of Common Coupling</td></tr></table></td><td>For smaller motors (≤ 75 HP), 3% line reactors and DC bus equivalents, are considered acceptable because they decrease harmonic distortion by about 40%, are relatively inexpensive, and do not have a significant impact on VFD system efficiency. Active front ends are more expensive but provide excellent reductions to harmonic distortion.

For larger motors, the impact of harmonic distortion has a greater potential to affect others; therefore, additional requirements are listed.</td><td></td><td></td></tr>
<tr><td>3.E.4b. Transient voltage protection must be compliant with IEC 61800-5-1:2007</td><td>Surge or impulse voltage protection is important to minimize damage from lightning strikes, for example.</td><td>More details are provided in Isolation in AC Motor Drives</td><td>http://www.ti.com/lit/wp/slyy080/slyy080.pdf</td></tr>
<tr><td>3.E.4c. Displacement power factor shall be between 1.0 - 0.95 lagging at all speeds and loads down to 50% of rated load.</td><td>A lower power factor requires conductors and other equipment to be upsized to handle larger reactive power</td><td>See PG&E white paper</td><td>More details are provided at: https://pge.com/includes/docs/pdfs/myb</td></tr>
</table>

			usiness/customerservice/energystatus/powerquality/understanding.pdf
3.E.5. The VFD system shall have EMI/RFI emittance compliant to IEC 61800-3	EMI/RFI noise can create interference for sensitive electronic and wireless radio signals, including AM/FM radio, data radios and televisions. Panels can be shielded internally with a variety of materials to block emittance.	See PG&E white paper	https://pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/powerquality/vfd_emi.pdf
3.E.6. Temperature rating. The VFD shall be rated for continuous full load output at 50 degrees Celsius (122 degrees Fahrenheit).	To achieve a 50 deg C (122 deg F) temperature rating, most manufacturers will take a larger HP VFD and derate its output accordingly. In other words, a 100 HP VFD rated at 40 deg C (104 deg F) may only be rated at 75 HP for operations in 50 deg C. This is quite common.		
3.E.7. Cooling:			
3.E.7a. Cooling shall be designed to maintain VFD operating conditions below the temperature rating of the VFD systems, under continuous full load and under all expected environmental conditions. The cooling system shall also comply with the requirements listed in 3.E.7b and 3.E.7c	Cooling loads are determined by the VFD size and other field conditions such as daily ambient temperatures, indoor/outdoor locations, etc.		
3.E.7b. VFD systems installed outdoors shall be provided with one of the following	Outdoor installations must be designed to operate in all expected environmental conditions, such as extremely hot days in peak summer.	A good reference for heat dissipation methods is provided by Hoffman and probably other enclosure manufacturers.	http://www.hoffmanonline.com/stream_document.aspx?rRID=233309&pRID=162533
(i) Fully shaded by an additional structure, or shielded with sheet metal attached (with an air gap) to the VFD system enclosure. The air gap in any location shall be no less than 1 inch or otherwise designed to provide passive venting of the air gap space.	Shading, and painting enclosures white are simple methods to significantly reduce heat buildup in outdoor installations		
(ii) All exterior enclosures shall be white in color if exposed to the sun.			
3.E.7c. Outside air shall not come into contact with VFD electronics under normal operations for cooling purposes.	Agricultural installations are very dusty. Dust buildup on electrical devices can cause problems such as shorts/faults and increased heat buildup. VFDs shall not utilize outside air, even if filtered, for cooling. Filters can quickly accumulate dust which decreases or can completely block the flow of air flow for cooling. Additionally, filters are rarely cleaned as often as they should be.		
3.E.8. User configuration. A user interface device with a display and input keys shall be provided to enable the configuration of the VFD without the use of a computer.	User interfaces provide for the initial configuration and ongoing operation/adjustment of VFD parameters without an external device such as a laptop computer.		
3.E.8a. The user interface shall provide a user with the capability of adjusting the following configuration parameters:			
(i) Motor data, such as voltage, RPM, FLA and frequency	Basic VFD configuration parameters for every VFD installation		
(ii) Carrier frequency from 2 kHz to 8 kHz at minimum	Extremely <u>low</u> carrier frequencies increase VFD system efficiency but can create larger harmonics and audible motor noise. Extremely <u>high</u> carrier frequencies will decrease VFD system efficiency but reduce audible motor noise and harmonics. There is an optimum range of carrier frequencies that is a balance between efficiency, noise and harmonics.	A good reference for optimizing carrier frequency is provided by Allen Bradley	https://library.e.abb.com/public/a05e87eeb064df20c12571b600587bff/SOUND.pdf
(iii) Maximum rate of motor speed change, including acceleration and deceleration of the motor	Fast motor speed changes can cause problems such as water hammer with wells and piped water systems, and should therefore be avoided. The designer of the irrigation system or another qualified individual should be consulted to determine acceptable acceleration/deceleration rates for the pump		
(iv) The number of restart attempts and restart delay. The system shall be capable of automatically restarting as configured by the parameters listed.	The VFD shall have the capacity to automatically restart after tripping so that pumping can continue without user input if the problem has been resolved		
3.E.8b. A user display shall be provided with visual indication for the items listed above.			
3.E.9. Load side.			
3.E.9.a The VFD system outputs shall not exceed the motor ratings for peak voltage and dv/dt at the motor terminals. Motor efficiency must not have more than a negligible drop due to hardware that is added to resolve the peak voltage and dv/dt problems.	Motors are usually manufactured with a peak voltage and dv/dt rating (provided by NEMA) that could be exceeded when using a VFD, if precautions are not taken. Various devices can be added to the VFD system (or at the motor end of the cables) to mitigate problems with voltage characteristics at the motor - each with advantages and disadvantages.	A good discussion of voltage overshoot and mitigation techniques is provided by ABB (see link to the right) and **Application Paper AP043001EN** "Applying dV/dT	https://library.e.abb.com/public/fec1a7b62d273351c12571b60056a0fd/voltstress.pdf

		filters with AFDs" (2014)	
3.F. VFD system enclosures			
3.F.1. A door-mounted disconnect switch shall be provided that is capable of being padlocked in the "off" position.	While NFPA79 requires the disconnect to be capable of accepting a padlock, UL508A does not specifically require a padlock for the "locking mechanism". This requirement is used to clarify that the locking mechanism must accept a padlock, which is a typical in agricultural operations	See ABB white paper for details and compliant disconnect switch options	https://www.logic-control.com/datasheets/45/Control%20Products/Brochure/NFPA79%20and%20UL508A;%20Industrial%20Machinery%20Operating%20Handle%20Requirements.pdf
3.F.2. A door-mounted 3-position "VFD-Off-Bypass" switch shall be provided along with a panel-mounted, momentary "Start/Stop" switch, unless equivalent capabilities are provided by other external components. These components shall provide the capability of starting the motor across-the-line in emergencies.	The equipment used to bypass the VFD shall be provided and labeled. in emergencies for starting the motor across-the-line		
3.G. Installation and commissioning			
3.G.1. VFD and VFD control panel anchoring requirements shall be compliant with the California Building Code.			
3.G.2. The VFD system owner shall be given a minimum of 3 hours of training covering basic operations and maintenance activities			
3.G.3. A trained VFD installer shall inspect and certify that the installation is compliant with the items listed in Table 3.G.3	The long-term success of the VFD system is dependent on a quality installation, configuration and good documentation		

Table 3.G.3. Installation and Commissioning Checklist

Item Description	***Notes***
Sensors used for automatic control have been installed per manufacturer's recommendations	Sensors may include flow meters or pressure transmitters or transducers
Conduits, conductors and earth grounds have been installed per manufacturer and/or engineer recommendations	
Motor parameters have been configured within the VFD that match motor nameplate or designer's parameters	Example parameters include name plate: RPM, voltage, full load amperage, frequency, etc.
Sensor calibration within the VFD has been completed and verified	
Motor acceleration and deceleration ramp speeds have been configured	"Optimum" values for these parameters may depend on the system supplied by the water pump rather than electrical or motor constraints. The designer of the irrigation system should be consulted for a recommendation if possible.
VFD display has been programmed to display the following instantaneous values	Motor speed (RPM, %, or engineering units)
	Motor current (Amps)
	Output voltage
	Input voltage
	For VFDs used in closed loop control applications, provide both the instantaneous (or averaged) reference measurement and target set point
The VFD system, including cooling systems, have been function tested in all designed operating modes (manual and automatic as applicable) without faults under normal operating conditions	
Automatic restart after trip functions have been configured and tested	
The carrier frequency has been adjusted as recommended by the system designer	Adjustment of the carrier frequency shall consider all of the following: achieving acceptable audible motor noise, maintaining voltage overshoot and dv/dt ratings of the motor, dv/dt filter requirements, as well as maintaining minimum VFD system and motor efficiencies
Motor input terminal voltages have been measured and the motor voltage and rise time ratings are not exceeded	
All space heaters have been adjusted to maintain temperatures above the maximum dew point temperature, or minimum VFD temperature ratings, based on the space heater purpose, and have been function tested	
Wiring diagrams have been verified to as-built conditions	
A complete documentation package and field training has been provided to the owner per Specification 3.G.2	Documentation includes wiring diagrams, user manual, warranty information, maintenance activities, and step-by-step instructions for adjusting set points
The VFD system is fully shaded, or the enclosure(s) are painted white	
The installation has met all requirements of PG&E and the ~~the~~ authority having jurisdiction (AHJ)	
A oil-filled pressure gauge has been installed just downstream of the VFD-controlled pump discharge that provides a NIST-traceable pressure measurement (psi) within +/- 1 psi, with a measurement range no greater than 150% of the maximum pump discharge pressure at zero flow and full speed	

3.H. Documentation to the owner.			
3.H.1 Provide a standalone documentation package to the customer. All information shall be complete and reflect as-built conditions. Include the following at minimum:	A good documentation package is useful for future operation and maintenance		
3.H.1.a. Single line diagram showing all major devices located between the branch circuit and the VFD-controlled motor.	The single line diagram is a schematic used to easily identify major components and their relative location in the circuit		
3.H.1.b. An as-built configuration sheet has been developed listing the as-built programming parameters configured for the project	A record of the configuration parameters is critical for record-keeping		
3.H.1.c. Maintenance program. Provide a written description of the recommended maintenance tasks and schedule based on operating hours and/or calendar year.			
3.H.1.d. A wiring diagram showing all of the following at minimum:	A VFD system wiring diagram will be more detailed than the single line diagram		
(i) All power and control conductors terminated by the panel builder			

(ii) All field wiring connections			
(iii) Labeled wires and terminal blocks			
(iv) Identification of all major unique components not including terminal blocks or DIN rail			
(v) A bill of materials table listing the brand, part number and a description for all components			
3.H.1.e. Unwitnessed factory acceptance testing results covering successful testing of all circuits, control loops and wiring workmanship			
3.I. Documentation to PG&E			
3.I.1. The owner shall provide proof to PG&E:			
3.I.1.a That the installation has met all requirements of the AHJ	This is the same procedure used by PG&E when providing service to new or upgraded drops.		
3.I.1.b The final installation checklist with installer signature certifying all tasks have been completed			
3.J. Warranty			
3.J.1. All VFD installations shall be warrantied by the installer for a period no less than 1 year after all of the following:			
3.J.1.a. the day of final commissioning			
3.J.1.b. the owner has received all documentation and training			
3.J.1.c. the system handed over to the owner for normal operations			
Section 4 - Considerations for special cases			
4.A. The owner shall consider implementing the recommendations in the table below on a case-by-case basis is listed in **Table 4.A.**			

Item	Reasons, beyond the specifications to purchase the item	Minimum specifications
Megger and surge testing	Existing motors should be evaluated for insulation degradation prior to being reused in VFD systems.	Megger testing procedures and result interpretation is listed in IEEE 43-2000 Surge testing procedures and result interpretation is listed in IEEE 522
Automatic space heater for VFD system enclosure	Manufacturers also provide a minimum VFD temperature rating for operating and storage conditions.	VFD applications in areas that can experience winter freezes shall install a heater to maintain enclosure temperatures within the VFD temperature rating.

Section 5 - Optional Additional Features and Equipment			
NOTE: The minimum specifications listed above do not cover automatic control of external devices, or automatic flow rate/pressure control of the water pump. These capabilities are considered optional "add-ons". Refer to the list below for common "add-ons" that facilitate additional VFD capabilities. It is recommended that these items be discussed with the VFD designer on a case-by-case basis.			

5.1. Equipment/items that may be necessary for control of external equipment such as well pump oilers, filter backflush controllers, or fertigation systems/pumps

Optional Items Specific to Automatic Actuation of External Equipment	Descriptions and Notes
Externally mounted, outdoor rated GFCI duplex receptacle(s) or branch circuits	120VAC, 15 amp or as needed, and energized only when the pump motor is running – commonly used for fertigation systems/pumps or backflush controllers. A transformer and subpanel may be required if single phase AC is not already available at the location.
Programmable digital input/output terminals for external monitoring and control	AC or DC, low amperage. Useful for oiler solenoid control or other capabilities

5.2. Equipment/items that may be necessary for automatic, closed loop control, such as automatically maintaining a relatively constant target flow rate or downstream pressure

Optional Items Specific to Automatic, Closed Loop VFD control	Descriptions and Notes
Analog input terminals or a supplemental analog input card (a printed circuit board with multiple analog input terminals)	Analog input terminals (0-5VDC or 4-20mA) are a basic requirement for closed loop automatic control, which enables the VFD to interface with standard industrial sensors. Sometimes the analog input terminals come standard with the VFD. In other cases, an additional analog input card needs to be purchased as an add-on.
Pulse signal input terminals or supplemental printed circuit board (card) for flow meters	High or low frequency pulses are common output signals to many agricultural flow meters used in automatic pump flow control applications

Sensors. Examples include: (a) Pressure transmitter with cable, or (b) flow meter with electronic output	At minimum, one sensor is required to provide automatic closed loop control. The type of control target (flow rate or pressure) will determine what type of sensor is needed. Sensors are usually add-on items. Ask the VFD designer about sensor accuracy and resolution and how that affects the automatic control performance.
Serial or Ethernet communication port	Communication ports are necessary to pass VFD, integrated sensor or other data to other devices. An example application is remote monitoring or control of the VFD and/or pump parameters

5.2. Equipment/items that may be necessary for general or specific uses

Optional Items Specific to Automatic, Closed Loop VFD control	Descriptions and Notes
A panel mounted 3-position Hand-Off-Auto (HOA) switch and speed potentiometer. a. When in “Hand”, the VFD will be manually started, and the speed will be controlled from a panel-mounted speed potentiometer. b. When in “OFF”, the VFD will be stopped. c. When in “Auto”, the VFD will start and adjust its speed automatically to maintain a target set point (flow or pressure)	The combination of these devices provides the user with a very simple method of manually starting a pump and setting a desired speed, downstream pressure or flow rate - all without using the keypad. Sometimes, the keypad overloads the user with complexity, or grants the user too much access to unauthorized modification to VFD parameters.
A panel mounted multi-position switch to select between various automatic VFD closed loop control programs	This option is useful for simplifying operations that have multiple target pressure or flow set points. An example use case is explained below. Example: A vineyard irrigation system with frost protection sprinklers. When the VFD is turned ON and in AUTO mode, operators use a physical switch to select program "A" to configure the VFD to automatically maintain a low discharge pressure (e.g., 35 psi) for drip irrigation events. Then during frost events, operators simply switch to program "B" to configure the VFD to automatically maintain a higher discharge pressure (e.g., 55 psi) to operate the frost protection sprinkler system. Combining this multi-position switch with other physical switches, and the necessary VFD programming (completed by the installer) could eliminate the need for operators to use the manufacturer's keypad. Learning to use the VFD keypad is unnecessarily complicated for some users who prefer to keep it simple.
Externally mounted, outdoor rated GFCI duplex receptacle(s)	120VAC, 15 amp for convenience (mobile device chargers, work lights, etc.). A transformer and subpanel may be required if single phase AC is not already available at the location.
Automatic space heater for VFD system enclosure	Automatically maintains the inside of the enclosure to prevent condensation on electronics
VFD interface language switchable to other languages such as Spanish	The capability to switch languages on the VFD keypad can be useful for some operations and users
Pilot lights	Door mounted pilot lights provide a fast and easy-to-understand indication of pump status (e.g., running) or problems such as faults or alarms. Controlling the pilot light circuit requires digital (on/off) output terminals integrated into the VFD or add-on printed circuit boards
Lockable shade cover over VFD keypad and/or door-mounted switches	Provides some resistance to UV damage of the keypad and door-mounted switches/labels as well as provides some level of protection against unauthorized control of the VFD system (and vandalism protection)
Extended warranty	For example: 5-year parts and workmanship
Enclosure access door lock	Provides additional protection against unauthorized access to VFD system internal components. There is both a safety and vandalism-resistance component. Many users prefer to use door handles that accept padlocks
Vandalism enclosure for VFD system	Additional vandalism protection is common in rural areas to help prevent wire theft and system damage. Some vandalism enclosures enclose the VFD system inside of 1/4" or thicker mild steel plate. Plates of AR500 steel are used to stop most bullets. Vandalism enclosures should be discussed with the VFD system designer and accounted for in the cooling system design
Internal, door-mounted document holder	Provides the ability to keep an organized set of documents inside the VFD for future reference

ATTACHMENT 2: REFERENCES

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ATTACHMENT 3: CALCULATIONS

VFD Energy Savings

It is common, and considered good design practice, to over-design irrigation pumps to meet the worst-case hydraulic conditions, considering:

1. Estimated individual irrigation flow rate and pressure demands can vary at the head of each block (portions of a field irrigated when a single valve is opened). Farmers irrigate one or multiple blocks at a time. Each combination of blocks irrigating simultaneously requires a unique pump discharge pressure and flow rate. Sometimes farmers must decrease the number of blocks normally operated at one time in response to water supply constraints.
2. Good designers always include a "safety factor" of at least 5 psi to the design pump discharge pressure requirement.
3. The pressures available from district pipeline turnouts are variable over time and depend on the instantaneous irrigation flow rate.
4. Published hydraulic performance data from pumps, pressure regulating valves, filters, and emitters are not always accurate, or even available.
5. Pumping water levels vary with changes in hydrology and well efficiency.
6. Automatically cleaned filters require temporary increases in pump flow rate during the cleaning cycle.
7. Pumps wear over time.

Given the factors above, reasonably over-designed pumps will continue to be installed. Adding a VFD system to an over-designed pump provides sufficient capacity in worst-case conditions, but also the capability of reducing the pump speed most of the time to avoid:

1. Developing excess pressure
2. Consuming excess electricity

There are two categories of VFD system implementations.

Category 1. Simple VFD system, capable of manually adjusting motor speed based on a target set point (in units such as percent of full speed, Hertz or RPM)

Category 2. More complex installations with automatic control and instrumentation

As shown in Table 3-1, Category 2 installations are capable of providing more energy savings.

TABLE 3-1. COMPARING POTENTIAL ENERGY SAVINGS BETWEEN SIMPLE AND MORE COMPLEX VFD SYSTEM INSTALLATIONS

Energy savings component	Achievable interval for pump speed adjustments after conditions change	Achievable Energy Savings Component, by VFD System Installation Category: Category 1 (simple) – follows the proposed minimum specifications	Achievable Energy Savings Component, by VFD System Installation Category: Category 2 (complex) – requires automatic control and sensors
5 psi safety factor	n/a	X	X
Inaccurate design data from pumps, filters, emitters, etc.	n/a	X	X
Changes to district pipeline pressure	n/a		
	Minute-to-minute		X
Changes to pumping water level, pump wear, and well efficiency	Annual to monthly	X	
	Minute-to-minute		X
Unknown pressure from district pipeline turnout	n/a	X	X
Temporary boost of pump speed during filter cleaning cycles	Minute-to-minute		X

However, the additional hardware and automatic VFD control included in Category 2 installations are considered optional and not universally applicable. Moreover, the additional savings provided cannot be predicted and are difficult to quantify even when all the necessary parameters are data logged (which is only feasible in research applications). <u>Therefore, while additional and sometimes significant energy savings can be provided by Category 2 installations in some applications, the additional savings are not included in this analysis.</u>

Potential Baseline Energy Savings

The analysis focuses on potential baseline energy savings that could be expected from a Category 1 VFD system installation on a typical field with pressurized irrigation. Values were allocated to each of the potential energy savings components as listed in Table 3-2. Some values reported are referenced from ITRC Report No. R 11-005, while others are readily available in accepted design literature.

TABLE 3-2. POTENTIAL BASELINE TOTAL DYNAMIC HEAD (TDH) SAVINGS FOR WELL AND BOOSTER PUMPS WITH VFD SYSTEMS

Pressure savings category	Potential pressure savings (feet) for each pump type: Booster Pumps	Potential pressure savings (feet) for each pump type: Well Pumps
General 5 psi safety factor	11.5	11.5
Pressure requirements when irrigating different blocks	6	6
10% of pumping water level for groundwater variability (ft)	n/a	32.1
Future pump wear	5	5
Loss of well efficiency	n/a	5
Total potential baseline TDH savings	**22.5**	**64.5**

Computations

The energy savings analysis for this project focused on two scenarios:

Scenario 1: Booster pump supplying micro/drip system

Scenario 2: Well pump supplying a booster with a micro/drip system downstream

Assumptions

Assumptions used for the computations are listed in Table 3-3 and Table 3-4.

Table 3-3. Assumed general values for computations

Assumption	Value	Unit
Well pumping level (San Joaquin Valley)	300	feet
Minimum well pump TDH	321	feet
Minimum booster pump TDH	120	feet
Annual operating hours (deciduous orchard)	2368	2368
$ / kW-hr	0.17	0.17
Potential PG&E Rebate (<= 75 VFD-HP)	$30/ VFD-HP + $2000	n/a
Potential PG&E Rebate (greater than 75 VFD-HP; less than or equal to 600 VFD-HP)	$57/VFD-HP	n/a

Table 3-4. Assumed general values for new pumping plants on a horsepower basis

Electrical Input HP	New Motor Efficiency (%/100)	New Impeller Efficiency	Initial Booster Pump TDH (ft)**	Initial Well Pump TDH (ft)**	Reduction in new OPPE due to VFD (%/100)	Reduction in new OPPE due to decreased impeller efficiency at different operating points (%/100)
50	0.9	0.7	120	321	0.965	0.99
100	0.91	0.77	122	325		
150	0.92	0.8	124	327		
200	0.92	0.81	126	329		
250	0.92	0.81	128	331		
300	0.92	0.84	130	332		
350	0.92	0.84	131	335		
400	0.92	0.84	132	335		
450	0.92	0.84	132	335		
500	0.92	0.84	132	336		
550	0.92	0.84	132	336		
600	0.92	0.84	132	336		

***As shown in Table 3-4, the TDH values were adjusted up slightly from the minimum values reported in Table 3-3 to represent an increasing field size with additional mainline friction losses.*

The calculations outlined below follow the procedure used to solve for a single input horsepower. The process was repeated for the arbitrary range of input horsepower listed in Table 3-4 to determine if there was a difference on a per horsepower basis.

Procedure

First, solve for the Initial Overall Pumping Plant Efficiency (OPPE), starting with one set of horsepower-specific values reported in Table 3-4:

Eq. 1: $\text{Initial OPPE}\left(\frac{\%}{100}\right) = \text{New Motor Efficiency} \times \text{New Impeller Efficiency}$

With the Initial OPPE, compute the estimated water horsepower requirement. Use values shown in Table 3-4.

Eq. 2: $\text{Initial Water Horsepower (WHP)} = \frac{\text{Initial Input HP}}{\text{Initial OPPE}}$

Where,

Input HP = selected from Table 3-4
Initial OPPE = computed using **Eq. 1** (%/100)

In order to separate the flow and pressure (TDH) demand, estimate the initial pump flow rate from the WHP:

Eq. 3: $\text{Initial Pump Q}\left(\frac{gal}{min}\right) = \frac{\text{WHP}*3960}{\text{Initial Pump TDH}}$

Where,

WHP = Computed using **Eq. 2** (HP)
Initial Pump TDH = Values from Table 3-4 (feet)

Compute the Initial Input kW:

Eq. 4: $\text{Initial Input kW (kilo} - \text{watts)} = \text{Input HP} \times 0.746\ \frac{kW}{HP}$

Compute the new pump TDH with a Category 1 VFD (simple, no automation):

Eq. 5: $\text{New Pump TDH (feet)} = \text{Initial Pump TDH} - \text{Total Potential TDH Savings}$

Where,

Initial Pump TDH = Value from Table 3-4 (feet) used in **Eq. 3**
Total Potential TDH Savings = Values from Table 3-2 (feet)

Solve for the new input kW:

Eq. 6: $\text{New Input kW (kilo} - \text{watt)} = \text{Initial Input kW} \times \frac{New\ TDH}{Initial\ Pump\ TDH}$

Where,

Initial Input kW = Computed using **Eq. 4** (kW)
New Pump TDH = Computed using **Eq. 5** (feet)
Initial Pump TDH = same value used in **Eq. 3 & 5** (feet)

Solve for the average energy savings:

Eq. 7: $\text{Energy savings, kW (kilo} - \text{watt)} = \text{Initial Input kW} - \text{New Input kW}$

Where,

Initial Input kW = Used in **Eq. 6** (kW)
New Input kW = Computed using **Eq. 6** (kW)

Solve for the average annual energy savings:

Eq. 8: $\text{Annual energy savings, kW (kilo} - \text{watt)} = \text{Energy Savings} \times \text{Annual Operating Hours}$

Where,

Energy Savings = Computed using **Eq. 7** (kW)
Annual Operating Hours = Value shown in Table 3-3 (hours)

Solve for the average annual dollar savings:

Eq. 9: $\text{Annual dollar savings}\left(\frac{\$}{year}\right) = \text{Annual Energy Savings} \times \frac{\$0.17}{kW-hour}$

Where,

Annual Energy Savings = Computed using **Eq. 7** (kW-hours)
Cost per kW-hour = Listed in Table 3-3

The computation results are listed in Table 3-5 and Table 3-6.

Table 3-5. Energy savings for VFD system installations on well pumps supplying a booster pump for drip/micro, with a VFD system on the well pump only

Arbitrary Input HP	Assumed Motor Efficiency	Assumed Impeller Efficiency	Overall Pumping Plant Efficiency, OPPE (%/100)	Old Well Pump Total Dynamic Head (feet)	Water Horsepower (WHP)	Computed Pump Flow Rate (GPM)	Computed Old Input Power (kW)	Computed New Pump TDH (ft)	Reduction Factor For New OPPE Due To VFD System (%/100)	Reduction Factor For Variable Impeller Efficiencies At New Operating Points (%/100)	Computed New Input kW	Computed New kW Savings	Computed New Annual kWh savings	Estimated Total Installed VFD System Cost Plus Tax ($)	Annual Savings ($) Due To New VFD System
5	0.8	0.5	0.4	321	2.0	25	4	256.5	0.965	0.99	3	0.6	1,445	7,660	246
50	0.9	0.7	0.63	321	31.5	389	37	256.5	0.965	0.99	31	6.1	14,449	13,600	2,456
100	0.91	0.77	0.70	325	70.1	854	75	260.5	0.965	0.99	63	12.0	28,441	20,200	4,835
150	0.92	0.8	0.74	327	110.4	1337	112	262.5	0.965	0.99	94	17.9	42,325	26,800	7,195
200	0.92	0.81	0.75	329	149.0	1794	149	264.5	0.965	0.99	126	23.6	55,990	33,400	9,518
250	0.92	0.81	0.75	331	186.3	2229	187	266.5	0.965	0.99	157	29.3	69,440	40,000	11,805
300	0.92	0.84	0.77	332	231.8	2765	224	267.5	0.965	0.99	189	35.1	83,002	46,600	14,110
350	0.92	0.84	0.77	335	270.5	3197	261	270.5	0.965	0.99	221	40.4	95,710	53,200	16,271
400	0.92	0.84	0.77	335	309.1	3654	298	270.5	0.965	0.99	252	46.2	109,383	59,800	18,595
450	0.92	0.84	0.77	335	347.8	4111	336	270.5	0.965	0.99	284	52.0	123,056	66,400	20,919
500	0.92	0.84	0.77	336	386.4	4554	373	271.5	0.965	0.99	315	57.5	136,199	73,000	23,154
550	0.92	0.84	0.77	336	425.0	5009	410	271.5	0.965	0.99	347	63.3	149,819	79,600	25,469
600	0.92	0.84	0.77	336	463.7	5465	448	271.5	0.965	0.99	379	69.0	163,438	86,200	27,785

TABLE 3-6. ESTIMATED ENERGY SAVINGS FOR BOOSTER PUMPS SUPPLYING DRIP/MICRO IRRIGATION

Arbitrary Input HP	Assumed Motor Efficiency	Assumed Impeller Efficiency	Computed Overall Pumping Plant Efficiency, OPPE (%/100)	Old Well Pump Total Dynamic Head (feet)	Water Horsepower (WHP)	Computed Pump Flow Rate (GPM)	Computed Old Input Power (kW)	Computed New Pump TDH (ft)	Reduction Factor For New OPPE Due To VFD System (%/100)	Reduction Factor For Variable Impeller Efficiencies At New Operating Points (%/100)	Computed New Input kW	Computed New kW Savings	Computed New Annual kWh savings	Estimated Total Installed VFD System Cost Plus Tax ($)	Annual Savings ($) Due To New VFD System
50	0.9	0.7	0.63	120	31.5	1040	37	97.5	0.965	0.99	32	5.6	13,207	13,600	2,245
100	0.91	0.75	0.68	122	68.3	2215	75	99.5	0.965	0.99	64	10.9	25,846	20,200	4,394
150	0.92	0.76	0.70	124	104.9	3349	112	101.5	0.965	0.99	96	16.0	37,944	26,800	6,450
200	0.92	0.77	0.71	126	141.7	4453	149	103.5	0.965	0.99	128	20.9	49,527	33,400	8,420
250	0.92	0.77	0.71	128	177.1	5479	187	105.5	0.965	0.99	161	25.6	60,618	40,000	10,305
300	0.92	0.78	0.72	130	215.3	6558	224	107.5	0.965	0.99	194	30.1	71,242	46,600	12,111
350	0.92	0.78	0.72	131	251.2	7592	261	108.5	0.965	0.99	226	34.7	82,260	53,200	13,984
400	0.92	0.78	0.72	132	287.0	8611	298	109.5	0.965	0.99	259	39.3	93,050	59,800	15,818
450	0.92	0.78	0.72	132	322.9	9688	336	109.5	0.965	0.99	291	44.2	104,681	66,400	17,796
500	0.92	0.78	0.72	132	358.8	10764	373	109.5	0.965	0.99	324	49.1	116,312	73,000	19,773
550	0.92	0.78	0.72	132	394.7	11840	410	109.5	0.965	0.99	356	54.0	127,943	79,600	21,750
600	0.92	0.78	0.72	132	430.6	12917	448	109.5	0.965	0.99	389	58.9	139,574	86,200	23,728

Simple Rebate Payback

Assuming PG&E provides a rebate as proposed, both PG&E and the customer will incur costs. Simple paybacks were calculated for both PG&E and the customer as shown in Table 3-7 and 3-8.

TABLE 3-7. ESTIMATED SIMPLE PAYBACKS FOR PG&E AND THE CUSTOMER – WELL PUMPS SUPPLYING BOOSTER PUMPS FOR DRIP/MICRO

Input HP	Installed VFD system cost	Annual energy savings ($/year) assuming $0.17/kW-hr	PG&E Rebate ($)	Customer portion of installed VFD system cost ($)	Customer Payback (years)
50	13,600	2,456	3,500	10,100	4.1
100	20,200	4,835	5,700	14,500	3.0
150	26,800	7,195	8,550	18,250	2.5
200	33,400	9,518	11,400	22,000	2.3
250	40,000	11,805	14,250	25,750	2.2
300	46,600	14,110	17,100	29,500	2.1
350	53,200	16,271	19,950	33,250	2.0
400	59,800	18,595	22,800	37,000	2.0
450	66,400	20,919	25,650	40,750	1.9
500	73,000	23,154	28,500	44,500	1.9
550	79,600	25,469	31,350	48,250	1.9
600	86,200	27,785	34,200	52,000	1.9

TABLE 3-8. ESTIMATED SIMPLE PAYBACKS FOR PG&E AND THE CUSTOMER – BOOSTER PUMPS FOR DRIP/MICRO

Input HP	Installed VFD system cost	Annual energy savings ($/year) assuming $0.17/kW-hr	PG&E Rebate ($)	Customer portion of installed VFD system cost ($)	Customer Payback (years)
50	13,600	2,245	3,500	10,100	4.5
100	20,200	4,394	5,700	14,500	3.3
150	26,800	6,450	8,550	18,250	2.8
200	33,400	8,420	11,400	22,000	2.6
250	40,000	10,305	14,250	25,750	2.5
300	46,600	12,111	17,100	29,500	2.4
350	53,200	13,984	19,950	33,250	2.4
400	59,800	15,818	22,800	37,000	2.3
450	66,400	17,796	25,650	40,750	2.3
500	73,000	19,773	28,500	44,500	2.3
550	79,600	21,750	31,350	48,250	2.2
600	86,200	23,728	34,200	52,000	2.2