Work Paper PGECOAGR121
VFD (Enhanced Specifications) on Agricultural Pumps
Revision 0

Pacific Gas & Electric Company

Customer Energy Solutions

Variable Frequency Drives (Enhanced Specifications) on Agricultural Pumps

Measure Codes: IR012, IR013, IR014, IR015

11/1/2017

At-A-Glance Summary Table

Applicable Measure Codes:	IR012	IR013	IR014	IR015
Measure Description:	VFD ON AG WELL PUMPS (<=75HP) This measure involves installing a variable frequency drive (VFD) on an agricultural well pump used for irrigation purposes in place of throttling the flow.	VFD ON AG BOOSTER PUMPS (<=75HP) This measure involves installing a variable frequency drive (VFD) on an agricultural booster pump used for irrigation purposes in place of throttling the flow.	VFD ON AG WELL PUMPS (>75 to <=600HP) This measure involves installing a variable frequency drive (VFD) on an agricultural well pump used for irrigation purposes in place of throttling the flow.	VFD ON AG BOOSTER PUMPS (>75 to <=150HP) This measure involves installing a variable frequency drive (VFD) on an agricultural booster pump used for irrigation purposes in place of throttling the flow.
Energy Impact Common Units:	per rated pump HP	per rated pump HP	per rated pump HP	per rated pump HP
Base Case Description:	Source: CEC-500-2011-049. Majority of pumps do not operate with VFD control.	Source: CEC-500-2011-049. Majority of pumps do not operate with VFD control.	Source: CEC-500-2011-049. Majority of pumps do not operate with VFD control.	Source: CEC-500-2011-049. Majority of pumps do not operate with VFD control.
Base Case Energy Consumption:	1,752.32 kWh/hp and 0.740 kW/hp	1,752.32 kWh/hp and 0.740 kW/hp	1,767.78 kWh/hp and 0.747 kW/hp	1,772.05 kWh/hp and 0.748 kW/hp
Measure Energy Consumption:	1,468.16 kWh/hp and 0.620 kW/hp	1,515.52 kWh/hp and 0.640 kW/hp	1,491.79 kWh/hp and 0.630 kW/hp	1,515.52 kWh/hp and 0.640 kW/hp
Energy Savings (Base Case – Measure)	284 kWh/hp and 0.120 kW/hp	237 kWh/hp and 0.100 kW/hp	276 kWh/hp and 0.117 kW/hp	257 kWh/hp and 0.108 kW/hp
Costs Common Units:	Cost per HP	Cost per HP	Cost per HP	Cost per HP
Base Case Equipment Cost ($/unit):	Existing equipment. $0.0	Existing equipment. $0.0	Existing equipment. $0.0	Existing equipment. $0.0
Measure Equipment Cost ($/unit):	$272/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report	$272/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report	$159/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report.	$190/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report
Measure Incremental Cost ($/unit):	$124/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report, and PGECOAGR119R3	$138/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report, and PGECOAGR119R3	$124/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report, and PGECOAGR119R3	$138/hp Source: “VFD Specifications for Agricultural Irrigation Pumping” Report, and PGECOAGR119R3
Effective Useful Life (years):	EUL_ID: Agr-VSDWellPmp: 10 years Source: DEER 2016	EUL_ID: Agr-VSDWellPmp: 10 years Source: DEER 2016	EUL_ID: Agr-VSDWellPmp: 10 years Source: DEER 2016	EUL_ID: Agr-VSDWellPmp: 10 years Source: DEER 2016
Program Type:	Retrofit Add-On (REA), New Construction (NC)	Retrofit Add-On (REA), New Construction (NC)	Retrofit Add-On (REA), New Construction (NC)	Retrofit Add-On (REA), New Construction (NC)
Net-to-Gross (NTG) Ratio:	Agric-Default>2yrs: 0.6 Source: DEER 2016	Agric-Default>2yrs: 0.6 Source: DEER 2016	Agric-Default>2yrs: 0.6 Source: DEER 2016	Agric-Default>2yrs: 0.6 Source: DEER 2016

Document Revision History

Revision #	Date	Section by Section Description of Revisions	Author (Company)
Revision 0	10/30/2017	Original Work: PGECOAGR121 R0.docx Enhanced Specifications Variable Frequency Drives on Agricultural Pumps	Randy Kwok (PG&E)

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Section 1: General Measure & Baseline

1.1 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 being promoted by irrigation dealers and incentivized by power utilities through rebate programs. The combination of improved product quality and utility incentives helps to accelerate the adoption of VFDs in the agricultural irrigation sector.

In early 2017, PG&E contracted with the Irrigation Training & Research Center (ITRC) at California Polytechnic State University (Cal Poly), San Luis Obispo to develop the technical specifications requirement for a new enhanced VFD rebate offering. The specifications requirement was completed and submitted to PG&E in August 2017 in a report titled "Variable Frequency Drive (VFD) Specifications for Agricultural Irrigation Pumping." See attachment A for the report.

According to the authors of this report, there are very few VFDs in pre-existing operations at the moment, but the number of VFD systems installation is increasing and areas for improvement still remain. Most importantly, a specific agricultural VFD system 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

The authors also cited that without specifications requirements and special design attention, the basic VFD installations can be the source of power quality and radio interference issues that affect can affect other customers. Other problems caused by poor VFD system design that can affect VFD system owners are: 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.

PG&E currently offers rebate programs for agricultural pumping VFD installations. However, the agricultural VFD installation rebates have no minimum performance standards requirement. As such, PG&E does not have the ability to filter out sub-optimal VFD installations that participate in the existing rebate programs.

The primary goal of the specifications requirement is to improve PG&E's agricultural VFD rebate program for low voltage (≤480 VAC) well pumps (600HP or less) and booster pumps (150HP or less) by setting minimum requirements for high quality VFD installations. It was anticipated that detailed VFD specifications will directly benefit new rebate participants and PG&E by helping to:

- Increase energy efficiency, VFD life expectancies, and reliability
- Minimize power quality issues

1.2 Product Measure Description

This work paper documents the rationale for the VFD on agricultural pumps" measure as listed in the PG&E Agricultural and Food Processing Rebate Catalog, part of Pacific Gas and Electric Company's Customer Energy Efficiency Program. PG&E offers incentives to non-residential customers for installing qualifying lighting, refrigeration, air-conditioning, food service, and agricultural equipment.

The following table provides a brief overview of the measures included in this work paper.

Table 1 Measure Names

Measure Code	Measure name
IR012	WELL PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION
IR013	BOOSTER PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION
IR014	WELL PUMPS (GT 75HP TO LTE 600HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION
IR015	BOOSTER PUMPS (GT 75HP TO LTE 150HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION

Program Requirements and Guidelines

- Customer must have electricity distributed by PG&E to the installation address.
- Customer must be under a PG&E agricultural rate schedule.
- Customer must have an existing electrically operated agricultural booster or well pump installed on site or customer is planning on installing a new agricultural booster or well pump.
- Customer must install a VFD system on the pump motor.
- The installed VFD system must conform to the specifications outlined in the "Attachment 1 VFD Specifications" of the (Attachment A) report "Variable Frequency Drive (VFD) Specifications for Agricultural Irrigation Pumping"
- VFD must be installed on a pressurized irrigation system (no flood irrigation).
- VFD must be used for controlling the flow/pressure of the pump.
- Pumping application must currently have the means of varying the pressure/flow (i.e. throttle valve, control valve, etc.).
- Minimum operation of 1,000 hours per year.

Terms and Conditions:

- VFD must be used to adjust operation of pump to meet flow/pressure requirements and not simply as a soft starter, or for cavitation control.
- The VFD must NOT be used for the following pumping applications:
  - A well pump used to fill a reservoir
  - A well pump discharging directly into a canal
  - A mixed flow pump (high volume, low head)
- These rebates are provided to directly installed VFDs on new or existing pumps.
- The customer must supply an invoice or other supporting documentation that includes the quantity of VFDs, type (well and/or booster), horsepower rating of motor(s) and VFD(s), area map showing physical location of pumps, and the manufacturer make/models of the VFDs installed.
- Additional required documentation as stated in the VFD specification which can be found at www.itrc.org/VFD/

Market Applicability:

This measure is applicable to agricultural pumps in the PG&E service territory that rely on electric pumping to water crops in the downstream and direct install delivery channels. Pumps with horsepower outside of allowable ranges must be considered under the customized retrofit or new construction programs, as applicable. Pumps that do not meet the other restrictions outlined above may also be considered under the customized retrofit or new construction programs.

1.3 Product Technical Description

This measure encourages agricultural customers to install quality VFD systems in lieu of throttling control on their irrigation pumping systems.

The most common pumps used in agricultural irrigation systems are:

- Well Pumps (typically either vertical turbine or submersible)
- Booster Pumps (typically vertical turbine, with some inline centrifugal)

Vertical turbine pumps are commonly installed in wells and used to pump groundwater to be used for irrigation either directly (provides lift and pressurization) or just pumping well water to the ground level. Booster pumps are typically used to pressurize water for irrigation systems.

Variations and uncertainties in irrigation systems lead designers to frequently over-design irrigation pumps since it is favorable to have too much pressure rather than too little pressure. Some of the variations or uncertainties include, but are not limited to:

- For drip/micro-irrigation systems, designers typically include a safety factor of at least 5 psi
- Pressure from irrigation pipelines turnouts vary over time
- Well water levels vary year to year, and from Spring to Fall
- Pumps may serve more than one type of irrigation system (i.e. drip and sprinkler)
- Pumps may serve multiple fields at different elevations and/or acreage

Based on conversations the report authors had with experts in the field, designers commonly can over-design by at least 10% (very conservative estimate)[1]. Thus, VFDs for irrigation pumps have great potential for energy savings by adjusting the pump speed to produce the desired flow and/or pressure for the irrigation system.

Operating the pumps at very low capacities should be avoided. If the capacity is too low, overheating of water caused by friction between water and impeller can damage the pump. Also operating at capacities less than 30% of the design capacity will not only significantly reduce the pump efficiency, but also it can increase the radial load on the impeller and cause early failure of bearings. Operating at near 100% of design capacity will consume more energy than prior to VFD installation.

Irrigation pump operating hours vary widely depending on the type of crop. Additionally, farms may provide irrigation to more than one crop type. Operating hours typically vary from around 1000 hours to over 3000 hours based on the project data received for analyses in this work paper.

1.4 Measure Application Type

Table 2 Measure Application Type

Code	Description	Comment
REA	Retrofit Add-On	Single baseline (above pre-existing), full measure costs required
NC	New Construction	Single baseline (above code/standard), incremental measure costs required

The Base Case assumes a constant speed well or booster agricultural pump controlled to operate by throttling the flow based on irrigation needs. The Measure Case is considered to be a pump that will use a VFD system for adjusting the flow/pressure to the facility's irrigation needs. The measure application types considered for this work paper are as follows:

- Agricultural Well Pumps (<=600HP): REA, NC
- Agricultural Booster Pumps (<=150HP): REA, NC

1.5 Product Base Case and Measure Case Data

1.5.1 DEER Base Case and Measure Case Information

The IR values were obtained using the DEER READI tool. The relevant IR values for the measures in this work paper are in the table below:

Table 3 Installation Rate

GSIA ID	Description	Sector	BldgType	ProgDelivID	GSIAValue
Def-GSIA	Default GSIA values	Any	Any	Any	1

Spillage rates are not tracked in work papers; they are tracked in an external document which will be supplied to the Commission Staff.

The EUL and RUL values were obtained using the DEER READI tool. DEER defines the RUL as 1/3 of the EUL value. The RUL value is only applicable to the first baseline period for an RET measure with an applicable code baseline. The relevant EUL and RUL values for the measures in this work paper are in the table below:

Table 4 DEER2017 EUL and RUL

EUL ID	Description	Sector	UseCategory	EUL (Years)	RUL (Years)
Agr-VSDWellPmp	Well Pump Variable Speed Drive	Ag	Irrigate	10	3.3

The NTG value was obtained using the DEER READI tool. The relevant NTG value for the measures in this work paper is in the table below:

Table 5 Net-to-Gross Ratio

NTGR ID	Description	Sector	BldgType	Measure Delivery	NTGR
Agric-Default>2	All other EEMs with no evaluated NTGR; existing EEM in programs with same delivery mechanism for more than 2 years	Ag	Any	Any	0.6

1.5.2 Codes & Standards Requirements Base Case and Measure Information

Title 20: These measures do not fall under Title 20 of the California Energy Regulations.

Title 24: These measures do not fall under Title 24 of the California Energy Regulations.

Federal Standards: These measures do not fall under Federal DOE or EPA Energy Regulations.

1.5.3 EM&V, Market Potential, and Other Studies – Base Case and Measure Case Information

This work paper used the report titled “Variable Frequency Drive (VFD) Specifications for Agricultural Irrigation Pumping” by the Irrigation Training & Research Center (ITRC) at California Polytechnic State University (Cal Poly) San Luis Obispo.

- Type of pump
    - *Booster pump supplying micro/drip system*
    - *Well pump supplying a booster with a micro/drip system downstream*

- Pump horsepower
- Pump annual electrical energy consumption
- Whether pump efficiencies were checked annually
- Average pumping efficiency
- Whether VFDs were installed on the pumps

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

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

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

- Two large VFD vendors
- Four irrigation and pump dealers

The pre-existing datasets of the authors of the report

There were no EM&V studies identified that addressed the potential energy savings associated with installing VFDs on agricultural pumps.

1.5.4 Assumptions and Calculations from other sources – Base and Measure Cases

This work paper used no other sources.

Section 2: Calculation Methods

2.1 Electric Energy Savings Estimation Methodologies

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 typically 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 do wear out 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: Enhanced 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 7, Category 2 installations are capable of providing more energy savings. While Category 2 has the potential of achieving more savings, the additional hardware and automatic VFD control included in Category 2 installations are considered optional and not universally applicable. Moreover, the potential additional savings would be difficult to quantify. Therefore Category 2 installation is excluded from this analysis.

Table 6 Comparing potential energy savings between enhanced 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 (enhanced) – follows the proposed specifications	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

The analysis focuses on potential 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 7. Some values reported are referenced from ITRC Report No. R 11-005, while others are readily available in accepted design literature.

Table 7 Potential pressure savings (feet) for each pump type with VFD systems

Pressure savings category	Potential pressure savings (feet) for each pump type	
	Booster Pumps	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 used for the computations are listed in Table 8 and Table 9.

Table 8 Assumed 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	hour
$ / kW-hr	0.17	0.17

Table 9 Assumed 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 10, the TDH values were adjusted up slightly from the minimum values reported in Table 9 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 10 to determine if there was a difference on a per horsepower basis.

First, solve for the Initial Overall Pumping Plant Efficiency (OPPE), starting with one set of horsepower-specific values reported in Table 10:

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 9.

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

Where,

Input HP = selected from Table 10
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 10 (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 (enhanced 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 10 (feet) used in **Eq. 3**

Total Potential TDH Savings = Values from Table 8 (feet)

Solve for the new input kW:

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

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

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

Energy Savings = Computed using **Eq. 7** (kW)
Annual Operating Hours = Value shown in Table 8 (hours)

Solve for the average annual dollar savings:

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

Annual Energy Savings = Computed using **Eq. 7** (kW-hours)
Cost per kW-hour = Listed in Table 9

The computation results are listed in Table 10 and Table 11. Table 10 summarizes energy savings for VFD system installations on well pumps supplying a booster pump for drip/micro irrigation, with a VFD system on the well pump only.

Table 10 Energy savings for VFD system installations on well pumps 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
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 11 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

2.2 Demand Reduction Estimation Methodologies

The average demand savings (DS) for this measure can be estimated as follows:

$$DS = EES / OH_{total}$$

Where,

EES = electrical energy savings, kWh/yr

OH_{total} = total operating hours, hr/yr

The Peak demand reduction depends on the climate zone of the agricultural pump, the flow that the pump is providing during the Peak period as well as the associated pump head and pump efficiency. This varies significantly and would be difficult to estimate. Thus, the Peak demand reduction is assumed to be the average demand of the pump.

Please note that due to a Memorandum dated December 28, 2015 from the CPUC for custom Project No. NC0128786 (X493) subject titled "EAR Final Findings Memo," the kW peak demand savings is under consideration, and PG&E is conducting due diligence of the peak demand operation brought forward in the memo. The discoveries and analyses will be shared with the CPUC and reflected in the next update of this work paper in 2018.

2.3. Gas Energy Savings Estimation Methodologies

There will not be any natural gas savings for this measure.

2.4. Categorized Energy Savings Estimation Methodologies

The energy savings and demand savings for each measure in this work paper were analyzed then the weighted averages were calculated based on the number of pump motors in each horsepower bin.

Well pumps larger than 600-hp and booster pumps larger than 150-hp are recommended to go through Customized Retrofit Incentives or New Construction, as applicable, as this was the range of pumps that most projects have seen come through these programs.

For well pump VFD - The unit energy savings were first calculated for each of the twelve pump horsepower bins, then the average kW and kWh per horsepower savings was then calculated from that. See table 11 for the horsepower bins and the pump data.

For booster pump VFD - The unit energy savings were first calculated for each of the three pump horsepower bins, then the average kW and kWh per horsepower savings was then calculated from that. See table 11 for the horsepower bins and the pump data.

Table 13 below shows the result of the unit energy savings per horsepower calculations:

Table 12 Savings Estimates

Measure Code	Measure name	Average kWh/hp	Average kW/hp
IR012	WELL PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	284	0.120
IR013	BOOSTER PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	237	0.100
IR014	WELL PUMPS (GT 75HP TO LTE 600HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	276	0.117
IR015	BOOSTER PUMPS (GT 75HP TO LTE 150HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	256	0.108

Section 3: Load Shapes

This section of the work paper explains the measure's load shape, which indicates what fraction of annual energy usage and savings occurs in each time period of the year.

The difference between the base case load shape and the measure load shape would be the most appropriate load shape; however, only end-use profiles are available. Therefore, the closest load shape chosen for this measure is the Agricultural load shape based on E3 calculators. See table below for the measure Load Shape. Please refer to Attachment A for reference regarding the load shapes for this measure.

Table 13 Load Shapes

E3 Target Sector	Load Shape	Code
Agricultural	14 = Agricultural	PGE:AGRICULTURAL:14 = Agricultural

Section 4: Base Case & Measure 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

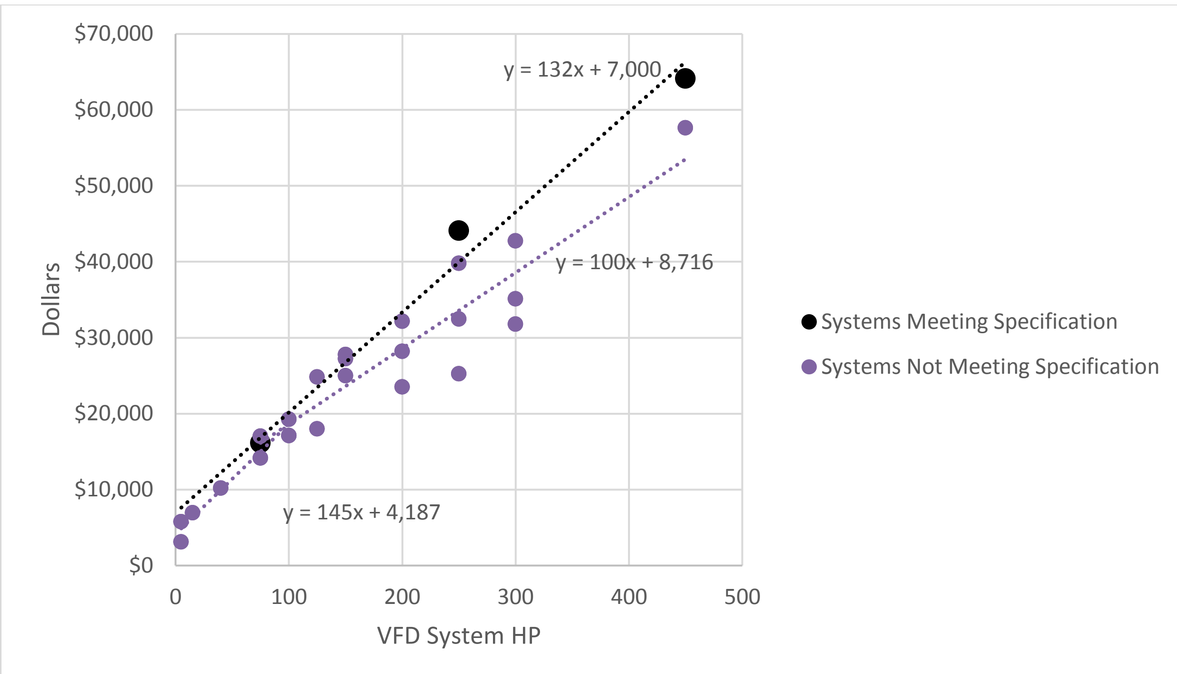
Multiple submissions were received from:

- Two VFD vendors
- 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).

The installed VFD system cost (including materials, labor and tax) dataset is plotted in Figure 1. Only three of the 24 invoices met the specifications. The VFD systems that did not meet the specifications are considered "typical".

Figure 1 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.

The most common technologies for harmonic mitigation for the quotes received were either:

- Passive harmonic filters, or
- Input line reactors

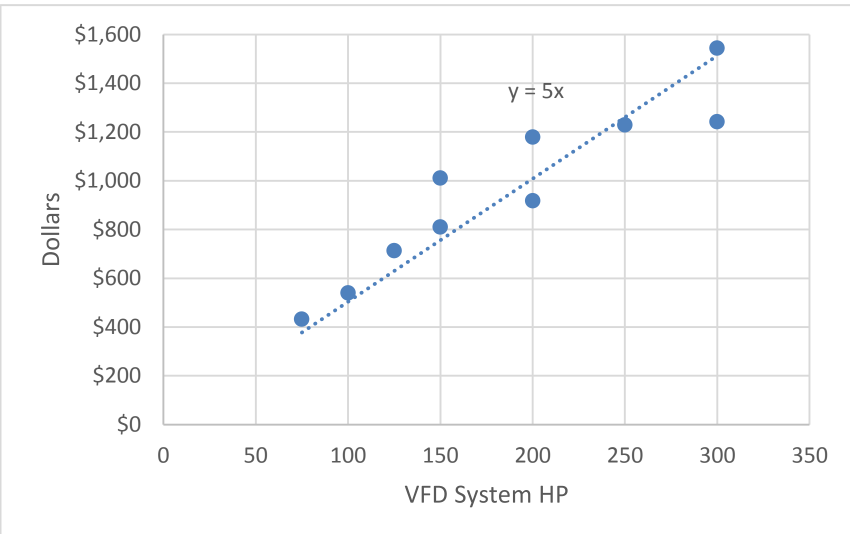
Passive harmonic filters are capable of providing harmonic mitigation that meet the specifications for VFD systems over 75 HP. A range of approximate consumer costs for adding passive harmonic filters is listed in Table 14.

Table 14 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% 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 2Error! Not a valid bookmark self-reference.**

Figure 2 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.

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 15.

Table 15 Approximate unit costs for VFD cooling unit

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

4.1 Base Case(s) Costs

For the REA measure category, the base case cost is assumed to be zero because these are no modifications to the customer's existing equipment. The customer's alternative is to make no changes to their existing irrigation pumping system.

For NC measure categories, the base case cost is assumed to be the cost of a pump motor equipped with a VFD system not meeting the specifications, or "typical" VFD system. On average, it is more expensive to meet the specifications.

4.2 Measure Case Costs

The measure cost, for both REA and NC, is the total specification-compliant VFD system installed cost that includes materials, labor and tax. The costs for pumps in the eligible horsepower bins were averaged and the resulting cost for each ach pump type is given in Tables 16 and 17 below.

Table 16 Gross Measure Cost

Market	Pump Type	Measure Code	Measure	Gross Measure Cost/hp
AG	Well	IR012	WELL PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$272/hp
AG	Booster	IR013	BOOSTER PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$272/hp
AG	Well	IR012	WELL PUMPS (GT 75HP TO LTE 600HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$159/hp
AG	Booster	IR013	BOOSTER PUMPS (GT 75HP TO LTE 150HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$190/hp

4.3 Incremental Measure Costs

Table 17 Incremental and Full Measure Costs

Market	Pump Type	Measure Code	Measure	Incremental Measure Cost/hp
AG	Well	IR012	WELL PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$124/hp
AG	Booster	IR013	BOOSTER PUMPS (LTE 75HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$138/hp
AG	Well	IR012	WELL PUMPS (GT 75HP TO LTE 600HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$124/hp
AG	Booster	IR013	BOOSTER PUMPS (GT 75HP TO LTE 150HP) VFD - ENHANCED SPECIFICATIONS, RETROFIT AND NEW CONSTRUCTION	$138/hp

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