Variable Frequency Drive Evaluation Protocol

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Acronyms

ASD	Adjustable-speed drive
BAS	Building automation system
CV	Constant volume
DOE	U.S. Department of Energy
HVAC	Heating, ventilation, and air conditioning
IPMVP	International Performance Measurement and Verification Protocol
M&V	Measurement and verification
OAT	Outside air temperature
RMS	Root mean square
RTF	Regional Technical Forum
TMY	Typical Meteorological Year
VAV	Variable air volume
VFD	Variable-frequency drive
VSD	Variable-speed drive

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1 Measure Description

An adjustable-speed drive (ASD) includes all devices that vary the speed of a rotating load, including those that vary the motor speed and linkage devices that allow constant motor speed while varying the load speed. The VFD Motor Drives Evaluation Protocol presented here addresses evaluation issues for variable-frequency drives (VFDs) installed on commercial and industrial motor-driven centrifugal fans and pumps for which torque varies with speed.[1] Constant torque load applications, such as those for positive displacement pumps, are not covered by this protocol. Other ASD devices, such as magnetic drive, eddy current drives, variable belt sheave drives, or direct current motor variable voltage drives, are also not addressed. The VFD is by far the most common type of ASD hardware. With VFD speed control on a centrifugal fan or pump motor, energy use follows the affinity laws, which state that the motor electricity demand is a cubic relationship to speed under ideal conditions. Therefore, if the motor runs at 75% speed, the motor demand will ideally be reduced to 42% of full load power; however, with other losses it is about 49% of full load power.

VFDs are commonly used on other motor-driven equipment such as air compressors, refrigeration compressors, vacuum pumps, and high-pressure blowers. These devices are typically positive displacement machines and are not included under this protocol, but in some cases will be addressed in protocols that are specific to them.

This protocol is also not intended to address conditions where there is significant interaction with other end uses, such as heating or cooling. For example, VFDs on refrigeration evaporator fans are not addressed because the fans significantly impact refrigeration load. VFDs on cooling tower fans are not addressed because the fans are often combined with condenser water temperature control, which impacts the chiller energy use. Conversion of constant volume (CV) heating, ventilation, and air conditioning (HVAC) systems to variable air volume (VAV) systems can have significant impacts on heating and cooling loads.

In some cases no interaction may occur, such as CV-to-VAV conversion of parking garage ventilation fans. These may be applicable to this protocol because no interaction with other end uses takes place. Other cases may be considered if the interaction is expected to be small compared to the fan motor energy savings.

[1] As discussed in *Considering Resource Constraints* in the Introduction of this report, small utilities (as defined under the U.S. Small Business Administration regulations) may face additional constraints in undertaking this protocol. Therefore, alternative methodologies should be considered for such utilities.

2 Application Conditions of Protocol

Market transformation is occurring for VFDs on HVAC fans and pumps for new construction. Building codes vary by jurisdiction, but some require VFDs on all HVAC fans and pumps for a certain size, such as the California Title 24 building code, which requires VFDs on all HVAC fans and pumps greater than 10 horsepower. Some jurisdictions continue to use building codes that do not yet address VFDs as a requirement.

In general, building codes do not address VFD requirements for industrial process fans and pumps. Retrofit of existing HVAC pumps and fans with VFDs remains a common application.

Generally, VFDs for HVAC applications tend not to save electricity during system peak hours, because that is often the time of peak HVAC fan and pump demand. The VFD electricity demand will be greater during peak use (if the drive is operating at full speed or faster during peak periods), because the VFD is typically about 97% efficient at full speed. Given that this depends on the peak savings definition and defined peak period, some jurisdictions may have peak savings. To determine if peak savings may occur, care should be taken to understand the load profile during the peak period of the motor on which VFD is installed. There are some specific cases where savings do occur during peak periods, such as a chilled water pump that has a throttling valve that is opened fully after the VFD is installed, which allows the VFD to operate at less than full speed even at peak flow.

Energy efficiency programs encourage the use of VFDs (as retrofits and in new construction) on fans and pumps that serve loads that vary over time, even if the local energy code does not require them. Three mechanisms for program delivery are commonly used across the United States.

- **Prescriptive.** This approach provides an incentive and deems energy savings based on the installed motor horsepower[2]. The incentive and energy savings may also vary based on the building type and fan/pump application where the VFD is installed, because the energy savings will typically vary for different installations (e.g., hospitals versus office buildings). In other cases, incentives and deemed energy savings may be designed based on horsepower and the annual operating hours of the equipment.
- **Standard calculator.** This approach provides an incentive for the VFD based on the expected annual energy savings, in kilowatt-hours, estimated using a standard calculation tool. The standard calculator usually incorporates the default performance curves used in DOE-2.X, based hourly simulation models such as eQUEST[3] or EnergyPlus.[4] Standard

[2] A recent study (Cadmus Loadshape, 2014) has derived average kWh and kW savings values for VFD installation on HVAC fans and pumps based on direct and long-term measurements of nearly 400 VSD installations accounting for the diversity of motor sizes, building types, HVAC loads, operating strategies, and seasonal differences across the northeast. These values will be useful for program implementers to deem VFD energy savings for future programs. The report makes several recommendations to implementers to maximize program effectiveness as well as important factors that evaluators should consider (consistent with this protocol).
[3] The eQUEST building energy simulation software is supported as a part of the Energy Design Resources program, which is funded by California utility customers and is available with documentation at the website: http://www.doe2.com/equest/.

assumptions for operating hours are specified for the annual time that the VFD will operate at various speeds. These calculations may be customized if additional information is available, such as pre metering used to develop a flow profile. The baseline performance will also use the appropriate default curve for the baseline condition, such as for a fan with outlet dampers.

- **Custom.** This approach also provides an incentive for the VFD based on the expected annual energy savings (in kilowatt-hours), but savings are calculated using a custom calculation tool. This may be the result of a complete hourly building model that is developed using a program such as eQUEST or EnergyPlus. This custom calculation approach is more common for facilities that are applying incentives for a variety of measures in a building. Other calculation approaches may be used, such as developing a bin model for the HVAC systems in a building or for an industrial process, and may include metering data. Custom programs may require measurement and verification (M&V) after VFD installation to verify energy savings and determine incentive amounts based on actual equipment performance.

[4] The EnergyPlus building energy simulation software is provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. The software with documentation is available at the website: http://apps1.eere.energy.gov/buildings/energyplus/.

3 Savings Calculations

This section presents a high-level gross energy savings equation that applies to all VFD measures.[5] Detailed direction on how to apply this equation is presented under the Measurement and Verification Plan section of this protocol. Two approaches (performance curve and default curve methods) are presented based on the specifics of the pre- and post-implementation operating conditions for the specific application.

Energy savings should be determined using the following general equation (EVO 2012):

$$\text{Gross Energy Savings} = (\text{Baseline Energy} - \text{Reporting Period Energy}) \pm \text{Routine Adjustments} \quad (1)$$

Where,

Gross Energy Savings	=	Estimated typical annual energy consumption savings
Baseline Energy	=	Pre-implementation annual consumption
Reporting Period Energy	=	Post-implementation annual consumption
Routine Adjustments	=	Adjustments made to account for routine changes to independent variables (variables that drive energy consumption) that are not caused by the installation of the VFD. Savings should be normalized to typical meteorological year (TMY) weather data (preferably TMY3 data) as well as other significant independent variables (e.g., occupancy schedules, production data), if applicable. If first year energy savings is desired, then savings should be normalized to the actual weather for the 12-month period following commissioning of the new controls.

[5] This protocol focuses on gross energy savings and does not include other parameter assessments, such as net-to-gross, peak coincidence factors, or cost-effectiveness.

4 Measurement and Verification Plan

This section contains two approaches for determining VFD energy savings—the Performance Curve Method and the Default Curve Method—and guidance on how and when to use each. Both methods use post-installation metered data. Neither requires pre-installation metered data, but use of such data will improve reliability of savings estimates. The Performance Curve Method is more reliable, using the performance curves specific to the fan or pump on which the VFD is installed. This method is preferred whenever it is applicable. However, this method applies to a relatively narrow set of eligibility conditions.

The Default Curve Method uses default performance curves and is less precise, but it is applicable to a much wider set of conditions. This method could also be used for the conditions that specifically apply to the Performance Curve Method, but with less accuracy.

An alternative variation on the second method includes pre-installation (baseline) metering. This will improve the accuracy, but requires difficult and potentially expensive- baseline data and is therefore rarely used. This alternative requires metering both fan/pump motor power and air/water flow to develop the in-situ flow versus power relationship, which can be used instead of the default baseline curves. The flow trends can be expensive and difficult to accurately obtain and may delay project implementation. However, in some cases, flow measurements are available from the building automation system (BAS) and can be trended.

Timing of the post-installation evaluation is important. Customers may take a year or longer after installing the VFD to set up controls and fully commission the system. Performing evaluation activities within a year of installation will provide accurate first year results, but may not accurately reflect long term performance (Cadmus Loadshape, 2014).

4.1 Performance Curve Method

This method is consistent with International Performance Measurement and Verification Protocol (IPMVP) Option A (Isolation Retrofit, Key Parameter Measurement) (EVO 2012). The method incorporates kilowatt metering of the VFD installed on the fan/pump along with concurrent outside air temperature (OAT), if the load is temperature sensitive, and/or on another parameter such as production or schedule. The method estimates energy savings based on trended or logged power measurements, together with fan/pump performance specifications and site operating characteristics.

The basis for the calculation is that the post-installation power trend, combined with site system specification, allows the derivation of the post-installation flow trend. This flow trend is assumed to apply in the baseline case, where it is used to derive the baseline power trend from the pump performance curve. The OAT or other sensitive parameter is used to extrapolate individual savings values to an annual profile, which is summed to annual savings.

The Performance Curve Method has been developed as a standard protocol for fans (SBW Fan, 2012) and for pumps (SBW Pump, 2012), with provisional status, for the Regional Technical Forum (RTF). The RTF is an advisory committee established in 1999 to develop standards to verify and evaluate conservation savings in support of member utilities and other stakeholders in the Pacific Northwest Region. The specific protocol specifications are available for fans and pumps separately at the RTF website.[6] An Excel-based calculator has been developed for the pump application of this method and is also available at the RTF website. This section is a condensation of both the fan and pump RTF protocol documents. It lays out the data requirements as inputs to the calculator and describes the savings calculation methodology.

4.1.1 Eligible Projects

The primary eligibility requirement for the Performance Curve Method is that the system curve remains constant in post-installation operation. The system curve defines how pressure varies with flow due to the resistance to flow defined by the system configuration. More specifically, the following system requirements are necessary for this method to be accurately applied:

- Loads served must be similar pre- and post-installation, but airflow and water flow may vary by a different mechanism (outlet dampers and outlet throttling valve). If VFD controls are overridden and manually set, the only valid baseline would be if the flow were also manually set in a similar fashion. Controls in the baseline that change the fan or pump curve such as inlet vanes are not applicable.
- To ensure that the system curve remains constant in the post-installation period, operable dampers and throttling valves must be removed or disabled, and no dampers or throttling valves that change position during operation may remain. This is necessary to ensure that the system curve does not change, because any change would invalidate the methodology.
- The method may be applied to a single fan or pump. Multiple fans or pumps must be treated separately. Fans and pumps that are configured in parallel and that are controlled to operate at the same speed can be evaluated by this method, but fans in series would be excluded. Backup fans and pumps or multiple fans and pumps where the same number operate in parallel can also be evaluated with this method.
- Fan or pump motors retrofit with a VFD must be single-speed motors.
- Baseline control strategies that are not eligible for this method include, but are not limited to, variable-pitch blades, bypass, or cycling.

4.1.2 Data Collection Requirements

4.1.2.1 Fan/Pump and Motor Specifications

- **Fan/pump curve.** Data points from the manufacturer's performance curve include flow, pressure, and efficiency points from the appropriate fan/pump curve. The fan/pump curve must match the conditions at the site for impeller size and speed (revolutions per minute). Impeller size may be difficult to confirm, so as-built documents and maintenance records should be referenced to identify the original impeller size and to determine if the impeller has been trimmed.
- **Fan/pump motor hp.** These data are obtained from the motor nameplate.
- **Motor revolutions per minute.** These data are obtained from the motor nameplate.

[6] http://rtf.nwcouncil.org/

- **Motor enclosure type.** This information is obtained from the motor nameplate.
- **Motor rated efficiency.** This information is obtained from the motor nameplate.

4.1.2.2 Fan/Pump Operations

- **Determinants of fan or pump speed.** Possible determinants are: (1) facility operation schedule, (2) OAT combined with operation schedule, and (3) production level.
- **Typical OAT.** Determine if the OAT is a significant determinant through discussion with the facility operator and consideration of the types of load being served by the fan or pump.
- **Facility operation schedule.** This information is obtained from the facility operator. If the facility's operation schedule has established different operation modes for the fan or pump unit (e.g., setback of flow during night and weekend hours), determine the period for each mode, defined as needed by hour of day, day of week, and season. This method requires that all schedule modes be metered.
- **Facility production level.** This information is obtained from the facility operator. If the facility's production schedule has established different operation modes for the fan or pump unit (e.g., two production lines for one work shift and one line for other shift), determine the period for each production level, defined as needed by hour of day, day of week, and season. This method requires that all production modes be metered.
- **Weather station.** If OAT is a significant determinant, identify the TMY (Typical Meteorological Year) weather station that is representative of the project site. If the weather station is not close by, adjustments may be needed (e.g., altitude differences).
- **Static head.** The head at zero flow—the net static head including elevation head for pumps—must be known. Site personnel should be able to provide this value or describe the means to acquire it.
- **System operating point.** This operating point (flow, pressure) must be with all dampers and valves removed or wide open. The point may be taken from the equipment schedule on the facility's mechanical plan. Alternatively, this value may be determined by: (1) inspecting facility control system trend logs of flow rate, if the system has a calibrated flow sensor and the log contains values at or near 100% speed; or (2) based on a pair of values (measured kilowatts and corresponding VFD speed).

4.1.2.3 Post-Period Measurements

- **True root mean square (RMS) power.** This protocol prefers a trend log of true poly-phase RMS power for the circuit powering the VFD and 15-minute intervals for the trend data. In general terms, a measurement period should be long enough to observe significant variation of dependent operating variables, such as OAT, to reduce uncertainty in the annualized estimate. If the fan or pump unit speed is primarily determined by the facility operating schedule, a measurement period duration of one month or longer tends to be appropriate. If there is no seasonality to the operating schedule; e.g., summer session in schools or peak production month in manufacturing, monitoring potentially can start at any time of the year. If seasonality exists, measurement across multiple seasons may be warranted to capture variation and reduce uncertainty. If long-term VFD speed is available from a control system, short-term kilowatt metering can be obtained concurrently with speed data to develop the relationship between speed and kilowatts. This may allow a shorter metering period when the kilowatts then can be calculated for a longer term using the relationship applied to the speed trend data. If the system has two identical pumps that alternate operation, make sure both are metered, or that only one is allowed to operate during the metering period.

- **Alternative power measurement.** In lieu of true power trending, it is acceptable to use current trends combined with one-time true power measurement of the circuit powering the VFD at three levels of percent speed, including one at 100% speed.
- Care should be taken with the acquisition of any power measurements and should conform to Chapter 9: Metering Cross-Cutting Protocols.
- **Trend log of VFD facility OAT.** These data may be obtained from the facility's control system, if it can be programmed to record OAT at 15-minute intervals. Data must be collected for the same period as the VFD current trend log. These data are required only if fan or pump speed is primarily a function of OAT (such as for a heating or cooling units). If OAT data are not available from the facility's control system or appear unreliable, an OAT data recorder should be installed to create this trend log.
- **TMY OAT.** For sites that are OAT dependent, typical hourly OAT data for the weather station nearest or most representative of the M&V site should also be obtained for extrapolating the measurement period savings to a typical operation year.

4.1.3 Savings Estimation Steps

This Performance Curve Method estimates energy savings based on power measurements taken post-VFD-installation, together with fan/pump performance specifications and site operating characteristics. The basis for the calculation is that the post-installation power trend, combined with site system specification, allows the derivation of the post-installation flow trend. This flow trend is assumed to apply in the baseline case (with exceptions for recirculation, which can be added to the baseline flow), where it is used to derive the baseline power trend from the pump performance curve.

The post-operating curve (system curve) is assumed to not vary. All valves either have been removed or are fixed. The system curve is specified with two points: the static head and an operating point based on the equation:

$$h = h_0 + aQ^C \qquad (2)$$

Where,

h_0	=	static head, or the head at zero flow
h	=	head
Q	=	flow

Exponent *c* = defaults[7] to 1.7

a = correlating coefficient

Baseline power is derived from the flow profile. Flow, head, and efficiency points from the performance curve are used to correlate a flow-to-power relationship. To account for cases where a recirculation flow exists in the baseline for a pump system that does not exist in the post-installation period, the minimum flow or constant circulation flow can be used to modify the flow profile.

Savings from the period of measurement are annualized based on annual schedules or a correlation with OAT, if relevant.

The general overall equation describing this method is:

$$\text{Annual Savings} = \sum_{Bins}(Baseline\ kW - Installed\ kW) \times Bin\ Hours \quad (3)$$

Where,

Annual Savings = is in kWh

Baseline kW = the calculated kW averaged into the appropriate bins (OAT, production, schedule) and extrapolated to the full range of the bin parameter(s) for the site

Installed kW = the metered kW averaged into the appropriate bins (OAT, production, schedule) and extrapolated to the full range of the bin parameter(s) for the site

Bin Hours = the number of hours in each parameter bin

The specific steps are as follows. Steps 4a and 4b are mutually exclusive alternatives.

Step 1. Derive flow versus power relationship for post-installation period.

System curve. Use the full-flow operating point to correlate an equation for the system curve (flow versus pressure) as the parabola (or lower order equation) from the static head value through the point on the fan or pump curve matching the operating point.

Flow versus power curve. The fan or pump will operate along the system curve as the VFD changes fan or pump speed. Fan/pump efficiency may vary along this curve and is included in the flow versus power calculations. Derive an equation for flow as a function of power

[7] The default value of 1.7 is based on a consensus of the RTF subcommittee responsible for the technical review of this protocol. The theoretical value based on the affinity laws is 2.0, with actual in situ values less than the theoretical. The actual system curve for a specific system configuration can be determined through flow and pressure measurements, but is beyond the scope of this protocol.

(kilowatts) along this curve. Motor efficiency and VFD efficiency are based on default relationships (U.S. Department of Energy [DOE] tables[8]) according to motor percent load.

Step 2. Derive flow versus power relationship for baseline period.

Flow versus power curve. Assuming constant speed, the fan/pump will operate along the fan/pump curve. Using the fan/pump curve data points, derive an equation for power as a function of flow along the fan/pump curve. The manufacturer's curve usually provides power as brake horsepower, so the values will need to be converted to kilowatts and divided by the motor efficiency to obtain comparable kilowatt values.

Step 3. Compute savings for trend log intervals.

Post-installation flow. Calculate flow as a function of kilowatts, using the equation derived from the system curve.

Baseline flow. The assumption is that the baseline flow profile is identical to the post-installation flow profile, with the exception of recirculation adjustments to the baseline flow.

Baseline kilowatts. Calculate kilowatts as a function of flow, using the equation derived from the fan/pump curve.

Savings for trend log period. Calculate the kilowatt savings profile as the difference between baseline kilowatts and post-installation kilowatts.

Step 4a. Annualize savings: fan/pump speed determined by OAT.

This method for annualizing savings assumes the load can be modeled as driven by OAT.

Average savings by trend log bin. Average kilowatt savings by 2°F temperature bins for all trend log intervals during operating hours, as defined by facility operation schedules. If the facility has more than one operation mode (which determines fan/pump speed), temperature bin averages are separately computed for each operation mode.

Operating hours by TMY bin. Divide the 8,760 TMY OAT data into 2°F temperature bins and compute the frequency of annual operating hours for each bin, as defined by facility operation schedules.

Average savings by TMY bin. TMY average bin savings equal trend log average bin savings for each matching bin. Extrapolate average savings for TMY bins that do not have trend log data. A linear change point correlation model often produces a good relationship between bin temperature and savings. No bin value is allowed to exceed the rated fan/pump motor kilowatts.

Saving by bin. For each TMY bin, multiply the average bin savings by the number of operating hours in each bin to see kilowatt-hour savings in each bin.

[8] Table from DOE Motor Tip Sheet 11, June 2008.

Annual savings. Sum the kilowatt-hour values across TMY bins.

Alternatively, the savings can be averaged into 1°F temperature bins, and the savings can be applied to 8,760 hourly TMY temperatures to obtain a complete profile.

Step 4b. Annualize savings: fan/pump speed determined by facility schedule.

This method makes two assumptions: (1) there is a strong correlation between schedule periods and savings; and (2) power trends for the post-installation period are available for all schedule periods.

Average savings for trend period. For the trend log period, average the savings for each operation mode, as determined by facility operation schedule (Section 4.1.2.2).

Annual operating hours. Determine the number of operating hours for each operating mode.

Savings by operating mode. Multiply the number of annual operating hours by the average saving for each operating mode.

Annual savings. Sum savings across operating modes.

4.2 Default Curve Method

This section describes the method for determining the baseline consumption from using the appropriate default curve that describes the flow-versus-power relationship of the fan or pump. This method is consistent with IPMVP Option A (Isolation Retrofit, Key Parameter Measurement). This relationship for the VFD is assumed to be determined from metering data. However, a default curve is also available if either flow or power cannot be metered for the VFD system.

The primary application of this method is for conditions where the system curve changes due to system damper or valve adjustments downstream of the fan or pump. However, because default curves, [9] instead of curves specific to the fan or pump, are used to define the baseline operation, the method is less accurate. The best method would be to meter baseline power and flow to define the *in situ* performance directly, but this requires extensive and potentially costly baseline measurements and therefore is not generally done. These default curves are industry standard practice, are readily available, and are used in DOE-based hourly simulation models such as eQUEST and EnergyPlus.

4.2.1 Eligible Projects

The advantage of the Default Curve Method is that it is applicable to a much broader range of fan or pump configurations and control schemes than the Performance Curve Method. For each valid combination, the relationship of flow to power is described by a quadratic equation of the form.

[9] The curves were developed in the early 1970s by Westinghouse (see reference), although the raw data and information describing the conditions of the data collection have not been published.

$$\text{Flow} = a + b \times (\text{Power}) + c \times (\text{Power})^2 \quad (4)$$

Where,

Flow	=	the decimal percent of full flow
Power	=	the decimal percent of full power
a, b, c	=	correlation coefficients

Tables 1 and 2 list the correlation coefficients for the applicable fan or pump and control type combinations.

Table 1. Fan Default Curve Correlation Coefficients

Fan Control Strategy	Coeff	Fan Type		
		Forward Curved	Backward Curved or Airfoil	Vane Axial
Discharge dampers	A	0.190667	0.227143	n/a
	B	0.310000	1.178929	n/a
	C	0.500000	–0.410714	n/a
Inlet vane	A	0.339619	0.584345	n/a
	B	–0.848139	-0.579167	n/a
	C	1.495671	0.970238	n/a
Variable pitch	A	n/a	n/a	0.3544
	B	n/a	n/a	–0.9691
	C	n/a	n/a	1.6104
VFD	A	0.219762	0.219762	0.219762
	B	–0.874784	–0.874784	–0.874784
	C	1.652597	1.652597	1.652597

Table 2. Pump Default Curve Correlation Coefficients

Pump Control Strategy	Coeff	Pump Type
		Centrifugal
Throttle valve	A	0.55218
	B	0.63701
	C	–0.18996
VFD	A	0.219762
	B	–0.874784
	C	1.652597

Limitations remain for the fan or pump eligibility when the Default Curve Method is used:

- Loads served are similar pre- and post-installation, but airflow or water flow is varied by a different mechanism, as listed in Table 2. If VFD controls are overridden and manually set, the only valid baseline would be if the flow were also manually set in a similar fashion.
- The method is applied to a single fan/pump. Multiple fans/pumps must be treated separately. Fans/pumps configured in parallel that are controlled to operate at the same speed can be evaluated by this method, but fans in series would be excluded. Backup fans/pumps or multiple fans/pumps where the same number operate in parallel can also be evaluated with this method.
- Fan or pump motors must be single-speed motors.
- Baseline control strategies that are not eligible for this method include bypass or cycling.

4.2.2 Data Collection Requirements

4.2.2.1 Fan/Pump, Motor and Variable-Frequency Drive Specifications

- **Fan/pump motor horsepower.** This information is obtained from the motor nameplate.
- **Fan/pump motor revolutions per minute.** This information is obtained from the motor nameplate.
- **Motor enclosure type.** This information is obtained from the motor nameplate.
- **Motor efficiency.** This information is obtained from the motor nameplate.
- **VFD rated efficiency.** This information is obtained from the VFD or from manufacturer's specifications.

4.2.2.2 Fan/Pump Operations

- **Determinants of fan/pump speed.** Possible determinants are: (1) facility operation schedule, (2) OAT combined with operation schedule, and (3) production level.
- **Typical OAT.** Determine if OAT is a significant determinant through discussion with the facility operator and consideration of the types of loads being served by the fan/pump.
- **Facility operation schedule.** Obtained from facility operator. If the fan/pump unit has different operation modes determined by the facility's operation schedule (e.g., setback of flow during night and weekend hours), determine the period for each mode, defined as needed by hour of day, day of week, and season. This method requires that all schedule modes be metered.
- **Facility production level.** This information is obtained from the facility operator. If the facility's production schedule has established different operation modes for the fan or pump unit (e.g., two production lines for one work shift and one line for other shift), determine the period for each production level, defined as needed by hour of day, day of week, and season. This method requires that all production modes be metered.
- **Weather station.** If OAT is a significant determinant, identify the TMY weather station that is closest to the project site.

4.2.2.3 Post-Period Measurements

- **True RMS power.** This protocol prefers a trend log of true poly-phase RMS power for the circuit powering the VFD, and 15-minute intervals are desired for the trend data. In general terms, a measurement period should be long enough to observe significant variation of dependent operating variables, such as OAT, to reduce uncertainty in the annualized estimate. If the fan or pump unit speed is primarily determined by the facility operating schedule, a measurement period of 1 month or longer tends to be appropriate. If there is no seasonality to the operating schedule; e.g., summer session in schools or peak production month in manufacturing, monitoring potentially can start at any time of the year. If seasonality exists, measurement across multiple seasons may be warranted to capture variation and reduce uncertainty. If long-term VFD speed is available from a control system, short-term kilowatt metering data can be obtained concurrently with speed data to develop the relationship between speed and kilowatts. This may allow a shorter metering period when the kilowatts then can be calculated for a longer term using the relationship applied to the speed trend data. If the system has two identical pumps that alternate operation, make sure both are metered, or that only the one is allowed to operate during the metering period.
- **Alternative power measurement.** In lieu of true power trending, it is acceptable to use trending of current combined with one-time true power measurement of the circuit powering the VFD at three levels of percent speed, including one at 100% speed.
- **VFD speed measurement.** Coincident with the power trending, the VFD percent speed or hertz should also be trended. This may be available from the building control system or as a control point output from the VFD. If it is not possible or reasonable to trend VFD speed, the default curve (Equation 4) will be used to determine an airflow fraction based on the power trend data. If both power and speed trends are available, these will be used as the actual VFD performance curve instead of the default curve.
- **Maximum power point.** This is the power, in kilowatts, at 100% speed for the VFD. The Default Curve Method is based on the decimal fraction of flow and power relative to this maximum point. This value can be determined in one of the following ways.
    - **One-time true RMS power measurement with the system operating at 100% speed.** Operation should be consistent with normal parameters. If the VFD is manually set to 100% speed (overriding normal control), the power value may not be accurate because operation under these conditions will be at static pressure greater than normally controlled.

  If neither power measurement at 100% speed nor speed trending is available, the following methods can be used to determine the power at 100% speed.

    - **Take one-time power measurement, record the speed, and convert to fraction of full speed.** Calculate power at 100% speed by using the one-time power and fraction of full speed measurement with the VSD default curve.
    - Testing and balancing documents may contain measured power at 100% speed.
    - **Design documents or mechanical schedule from as-built plan set will show an anticipated brake horsepower value at full flow, which is the horsepower required for the fan/pump without the motor.** To get the motor horsepower

energy demand (motor input power), multiply the brake horsepower by 0.746 to convert to kilowatts and divide by motor efficiency (from nameplate or from MotorMaster Plus based on motor horsepower, rated speed, and enclosure type) to achieve an approximate value for maximum kilowatts.

Care should be taken with the acquisition of any power measurements and should conform to Chapter 9: Metering Cross-Cutting Protocols.

- **Trend log of VFD facility OAT.** These data may be obtained from the facility's control system if it can be programmed to record OAT at 15-minute intervals. Data must be collected for the same period as the VFD current trend log. These data are required only if fan/pump speed is primarily a function of OAT (such as for a heating or cooling units). If OAT data are not available from the facility's control system or appear unreliable, an OAT data recorder should be installed to create this trend log.
- **TMY OAT.** For sites that are OAT-dependent, typical hourly OAT data for the weather station nearest or most representative of the M&V site should also be obtained to extrapolate the measurement period savings to a typical operation year.

4.2.3 Savings Estimation Steps

The Default Curve Method estimates energy savings based on trended measurements taken of the post-VFD-installation.

The general overall equation describing this method is:

$$\text{Annual Savings} = \sum_{Bins}(Baseline\ kW - Installed\ kW)\ \times Bin\ Hours \quad (5)$$

Where,

Annual Savings	=	in kWh
Baseline kW	=	the calculated kW averaged into the appropriate bins (OAT, production, schedule) and extrapolated to the full range of the bin parameter(s) for the site
Installed kW	=	the metered kW averaged into the appropriate bins and extrapolated to the full range of the bin parameter(s) for the site
Bin Hours	=	the number of TMY hours in each parameter bin

The specific steps are as follows.

Step 1. Derive flow versus power relationship for post-installation period.

- Convert the trend log data to decimal percent of full flow values by dividing the speed trend values (hertz) by 60 Hz and the power value by the power at 100% speed.
- If speed trends are available, correlate the fractional flow values to the fractional power values to obtain an *in situ* VFD curve.

- If no VFD speed trends are available, calculate the decimal percent flow for each power value using the VFD default curve.

Step 2. Annualize flow fractions determined by OAT.

This method for annualizing savings assumes the load (flow fraction) can be modeled as driven by OAT.

Average flow by trend log bin. Average fractional flow values by 2°F temperature bins for all trend log intervals during operating hours, as defined by facility operation schedules. If the facility has more than one operation mode (which determines fan or pump speed), temperature bin averages are separately computed for each operation mode.

Operating hours by TMY bin. Divide the 8,760 TMY OAT data into 2°F temperature bins and compute the frequency of annual operating hours for each bin, as defined by facility operation schedules.

Average flow fractions by TMY bin. TMY average bin flow fractions equal trend log average bin flow fractions for each matching bin. Extrapolate average flow fractions for TMY bins that do not have trend log data. For higher temperature bins, extrapolation by a linear equation fitted to the trend log bins above 57°F works well; this is also true for lower temperature bins by a linear equation fitted to the bins below 57°F. No bin value is allowed to exceed the full flow value of 1.0.

VFD power by bin. For each TMY bin, calculate the VFD power by using the flow-to-power correlation developed from the trend data. If no speed trend data are available, use the VFD default equation. The trend data will inherently include the part load VFD efficiency, and if the default equation is used the part load efficiency is also included, because it was based on measured data.

Baseline power by bin. For each TMY bin, calculate the baseline power by using the flow with the appropriate default equation; i.e., the equation along with Tables 1 and 2 provide the expression for flow as a function of power. The equation needs to be rearranged and solved for power as a function of flow to calculate baseline power. Alternatively, the default curves can be used to generate flow and power data points and the data can be correlated using a quadratic equation in the form of power as a function of flow for the desired baseline fan or pump type and control type. The resulting power must be multiplied by the rated VFD efficiency to obtain baseline power without the VFD attached. If the rated efficiency is not available, a default efficiency of 97% may be assumed.

Savings by bin. For each TMY bin, calculate the savings as the difference between baseline and VFD power.

Annual savings. Sum the kilowatt-hour values across TMY bins.

Alternatively, 1°F temperature bins can be used instead of 2°F bins, and the savings can be applied to 8,760 hourly TMY temperatures to obtain a complete annual profile.

Step 3. Annualize savings: fan/pump speed determined by facility schedule.

This method makes two assumptions: (1) there is a strong correlation between schedule periods or production level and flow fractions; and (2) trend data for the post-installation period are available for all schedule periods or production levels.

Average flow fractions for trend period. For the trend log period, average the flow fractions for each operation mode, as determined by facility operation schedule or production level.

Annual hour of schedule or production bins. Determine the number of operating hours for each operating mode or production level.

VFD power. For each schedule or production level bin, calculate the VFD power by using the flow-to-power correlation developed from the trend data. If no speed trend data are available, use the VFD default equation.

Baseline power. For each schedule or production level bin, calculate the baseline power by using the flow with the appropriate default equation; i.e., the equation along with Table 1 or 2 that describes the baseline fan/pump type and control type.

Savings by bin. For each schedule or production level bin, calculate the savings as the difference between baseline and VFD power.

Annual savings. Sum the kilowatt-hour values across bins.

4.3 Regression Modeling Direction

To calculate normalized savings, whether following the IPMVP's Option A, Option C, or Option D, the baseline and reporting period regression model must be developed for most projects. [10] This section is for general reference when developing correlations or extrapolation in the sections above. Three types of analysis methods can be used to create a model:

- Linear regression: For one routinely varying significant parameter (e.g., OAT).[11]
- Multivariable linear regression: For more than one routinely varying significant parameter (e.g., OAT, process parameter).
- Advanced regression: Such as polynomial or exponential.[12]

[10] This could either be (1) a single regression model that uses a dummy variable to differentiate the baseline/reporting period data or (2) two independent models for the baseline and reporting period respectively.

[11] One of the most common linear regression models is the three-parameter change point model. For example, a model that represents cooling electricity consumption would have one regression coefficient that describes nonweather-dependent electricity use; a second regression coefficient that describes the rate of increase of electricity use with increasing temperature; and a third parameter that describes the change point temperature, also known as the balance point temperature, where weather-dependent electricity use begins.

[12] Advanced regression methods might be required if a chiller plant is providing cooling for manufacturing or industrial processes.

When required, these models should be developed in accordance with best practices, and they should be used only when they are statistically valid (see Section 4.3.1). If no significant independent variables are present, no model is required, because the calculated savings will be inherently normalized.

4.3.1 Testing Model Validity

To assess the accuracy of the model, review the parameters listed in Table 3 (EVO 2012).

Table 3. Model Statistical Validity Guide

Parameter Evaluated	Description	Suggested Acceptable Values
Coefficient of determination (R2)	A measure of the extent to which variations in the dependent variable from its mean value are explained by the regression model.	> 0.75
T-statistic	An indication of whether the regression model coefficients are statistically significant.	> 2
Mean bias error	An indication of whether the regression model overstates or understates the actual cooling load.	Will depend on the project, but generally < ± 5%

If any of these parameters fall outside their acceptable range, attempts should be made to enhance the regression model by increasing or shifting the measurement period in one of these three ways: (1) incorporating more data points, (2) including independent variables that were previously unidentified, or (3) eliminating statistically insignificant independent variables.

After enhancement attempts, if the model is still outside the suggested range, this indicates that parameter coefficients are quite poorly determined and that normalized consumption will have relatively high statistical prediction error. Ordinarily such a model should not be used for normalization, unless the analysis includes appropriate statistical treatment of this prediction error. Discussion of how to proceed in such circumstances is outside the scope of these guidelines.

5 Sample Design

Chapter 11: Sample Design describes general sampling procedures that should be consulted if the VFD project population is sufficiently large or if the evaluation budget is constrained.

Ideally, stratified sampling should be undertaken by partitioning VFDs by application (fan, pump, or process versus HVAC load), operating hours, size, and/or the magnitude of claimed (*ex-ante*) project savings. This stratification ensures that sample findings can be extrapolated confidently to the remaining project population.

The confidence and precision-level targets that influence sample size are typically governed by regulatory or program administrator specifications.

6 Other Evaluation Issues

When claiming net program VFD measure impacts, the following evaluation issues should be considered in addition to first-year gross impact findings:

- Net-to-gross estimation
- Realization rates.

6.1 Net-to-Gross Estimation

The cross-cutting chapter, *Estimating Net Savings: Common Practices*, discusses various approaches for determining net program impacts. Best practices include close coordination between gross and net impact results and teams collecting site-specific impact data to ensure that there is no double-counting of adjustments to impacts at a population level.

6.2 Realization Rates

For program-induced projects, realization rates are calculated as the evaluated (*ex-post*) gross savings /claimed (*ex-ante*) gross savings.

References

The Cadmus Group. (Cadmus Loadshape) 2014. *Variable Speed Drive Loadshape Project – Draft Report.* Sumitted to Northeast Energy Efficiency Partnerships. August 2014.California Energy Commission. 2007. *Nonresidential Alternative Calculation Method for the 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings.* November 2007.

Efficiency Valuation Organization (EVO). 2012. *International Performance Measurement and Verification Protocol – Concepts and Options for Determining Energy and Water Savings Volume 1.* January 2012.

SBW Consulting, Inc. (SBW Pump). 2012. *Standard Savings Estimation Protocol for Pump VFD.* Submitted to the Regional Technical Forum. October 17, 2012. http://rtf.nwcouncil.org/subcommittees/Fan&PumpVFD/

SBW Consulting, Inc. (SBW Fan). 2012. *Standard Savings Estimation Protocol for Fan VFD.* Submitted to the Regional Technical Forum. November 29, 2012. http://rtf.nwcouncil.org/subcommittees/fanvfd/

Westinghouse. Westinghouse. Bulletin B-851, F/86/Rev-CMS 8121. *Flow Control.*

Resources

Bernier, Michel A., and Bernard Bourret. 1999. "Pumping Energy and Variable Frequency Drives." *ASHRAE Journal*. December 1999. Pg. 37.