A Practical Guide for Using Variable Frequency Drive Systems In Air Movement Applications

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1. PURPOSE

This guide is intended to provide a high-level practical approach to using variable frequency drives (VFD). A VFD is an electrical device used to control the speed of an electric motor. The ability to alter the speed based on the load needs in the application may present large amounts of energy savings and improved efficiency. They are available to handle both single-phase and three-phase power in a great majority of service voltages seen across the globe. This guide covers several different areas relating to their selection, installation, commissioning, operation, and adjustment of parameters as a primer for their use in the field. The information contained in this guide should be used as a reference and considered supplemental to information provided directly by the manufacturer.

2. BACKGROUND

In building ventilation and industrial process systems, controlling fan motors equipped with Variable Frequency Drives (VFD) have the following advantages:

- Energy savings. Running a fan at a reduced speed during off-peak hours dramatically reduces the overall energy consumption and associated operating costs (although both the motor and the fan may operate in a less efficient regime at a reduced speed).
- Ability to set up and manage fan arrays or other redundant systems of parallel fans. In such systems, when one fan fails, the VFD starts running the remaining fans at a higher speed to maintain the required airflow and pressure
- Integration of VFD-driven fans into centrally managed and monitored ventilation systems
- Improved reliability, reduced initial and operating costs by eliminating belt transmissions
- Further cost reduction due to lower inrush current: a high-inertia impeller fan can be started with a VFD using a much smaller motor than would be otherwise required to start the same fan across the line.
- Efficient synchronous motor technologies that always require VFD control, such as permanent magnet and switched reluctance motors
- Better input power factor, close to unity.

Furthermore, the cost of silicon for VFD components keeps dropping when compared to copper and silver that are needed to build high-quality across-the-line motor starters. Soon, we might see applications where VFDs will replace motor starters merely due to savings in initial cost.

At the same time, VFD-powered variable speed fan systems are naturally subject to:

- High-voltage stress on motor winding insulation
- Excessive wear and premature failure of motor bearings when not properly addressed
- Additional motor heat and noise resulting from VFDs
- Undesired electrical interference from cables
- Limitation on load cable length, structure and type

Contamination of line input power with harmonics and radio frequencies

Mechanical resonances of fan, ductwork and structural components that were not present when the fan was powered directly across the line;

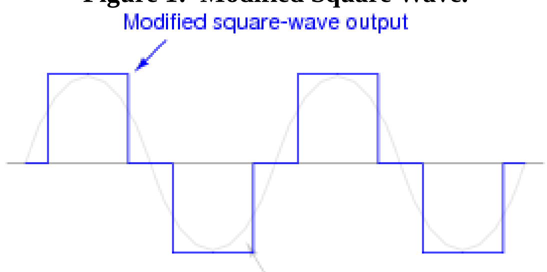
Lower motor service factor (typically S.F.=1.0 when powered through a VFD)

To the above list, one may also add improper drive selection, installation and operation due to the lack of knowledge. The present guide is intended to direct fan manufacturers, air movement OEMs, distributors, contractors and end users how to utilize the above advantages and minimize the drawbacks.

3. BASIC PRINCIPLES AND COMPONENTS OF A VFD

The simplest method to control fan motor speed is to switch it on and off. When switching frequency coincides with the motor input frequency, the motor windings are supplied with a waveform shown in Figure 1. This was typical for brushed DC motors and older modified-square-wave inverters.

Figure 1: Modified Square Wave.



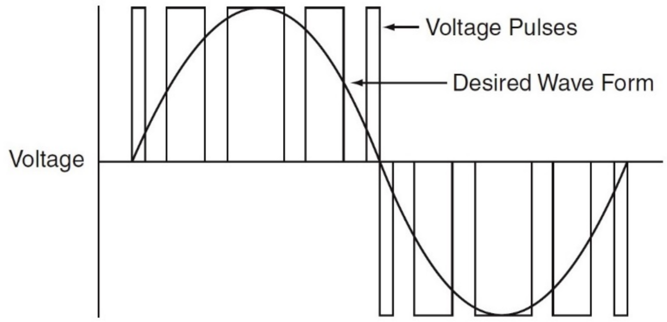
A more efficient and flexible method of AC motor speed control is switching the supply voltage in a fashion that results in nearly sinusoidal time-averaged voltage and current fed to the motor. The smooth variation is achieved through:

switching frequency that is much higher than the motor input frequency – typically, for motor fundamental input frequency at around 60Hz, the switching (or carrier) frequency may vary from 2 kHz to 16 kHz;

varying the width of the voltage pulses according to the desired variation of the time-averaged output voltage, current and/or torque.

The resultant voltage and current waveforms are illustrated in Figure 2. Over the years, this basic technique gave birth to a family of motor control methods commonly known as "Pulse Width Modulation" or PWM. Devices utilizing PWM techniques are commonly named "Switching Power Converters" or inverters.

Figure 2: Single-Phase, Three-Level PWM waveform.



To generate PWM waveforms, an inverter can be controlled in different ways.

Open loop control, also known as scalar, V/F, or Volts/Hz control, modulates a simple sine wave with preset frequency and amplitude. Scalar control receives limited feedback from the motor, such as time-averaged frequency, RMS load current and voltage, but no instantaneous feedback that would describe motor phase angle or rotor position.

Sensorless closed loop control uses some more detailed feedback from the motor. There are periods when the inverter output voltage is zero. During these "silent" periods, the motor still generates some voltage known as Back-EMF or Counter-EMF (counter electromotive force) and feeds it back to the VFD. By analyzing this Back-EMF waveform it is possible to determine phase angle of the motor current, its rotor position, and even instantaneous.

Vector Control is more dependable when PWM carrier frequency is higher while direct torque control (DTC) does not have a pre-set carrier frequency – switching is performed dynamically based on the measured torque demand.

In order to function, an inverter also needs a DC power source. In the majority of air-movement VFDs, inverters are powered from a DC bus, which serves as an interim energy storage bank, a buffer between the line and the load. The energy is stored in either oil-filled or electrolytic capacitors. Some DC buses are equipped with braking chopper resistors for rapid motor deceleration. Use a matrix converter to convert line AC power to variable frequency AC directly.

4. SELECTION, SIZING AND APPLICATION

A common assumption is that the motor and VFD should be sized for a similar horsepower rating. This is not necessarily the case as the rating of the unit should be dependent on the intended usage and operation. When selecting a VFD, items to take into consideration include:

Operating speed range (minimum and maximum power requirement)

Maximum expected operating amperage in-rush current at startup
Building controls compatibility (Modbus, Ethernet, etc.)
Amount of full load capability that will be most commonly used
Size, type, length, location, shielding and grounding of all power cables
Electrical supply service available
Ensure motor is compatible with VFD operation
Shaft grounding kit or insulated bearings
Minimizing outside electrical interference

There are numerous other factors that may require review based on particular conditions. These should be discussed with appropriate site personnel and a licensed electrician familiar with VFDs.

Programming a VFD is often needed to apply the device for a specific application. The entire list of adjustable parameters in a VFD is extensive, many of which will not require adjustment. Important items to review and set prior to starting the system for the first time include:

Control method: scalar, vector or DTC
Maximum voltage
Maximum amperage
Volts/Hertz (V/Hz or V/F). This is a linear relationship which controls the output voltage as the frequency is increased or decreased
How to view real-time frequency, amps, volts and power leaving the VFD
Adjusting frequency (motor speed) in real-time
Connectivity to a PC or building system to view and adjust parameters.

There are no pre-defined universal guidelines on what control method to choose: scalar, vector or DTC. It must be decided on a case-by-case basis.

Scalar control MUST be used with:

Significantly undersized motors (e.g. a 1hp motor on a 100hp VFD)
Multiple motors on a single VFD (Fan Array).
Heavy-duty load filters (e.g. sine wave filters).
Transformers (or any loads other than motors).

When using scalar control, one must set up V/F preferably within the motor nameplate range. If V/F is:

Too low – the motor will have higher slip, less torque, and hotter operation
Too high – the distorted, saturated PWM will cause frequent VFD tripping, undesired motor vibrations and noise.

When setting up V/F, do not follow an illusion to "exceed" the line voltage on a VFD: it is impossible; you will saturate and distort the PWM wave instead. In order to run the motor at a higher frequency, lower the V/F setting. If you need to run it at a higher voltage (e.g. medium voltage), use a step-up transformer. A VFD by itself is a poor voltage regulator.

Both vector control and DTC are preferred when:

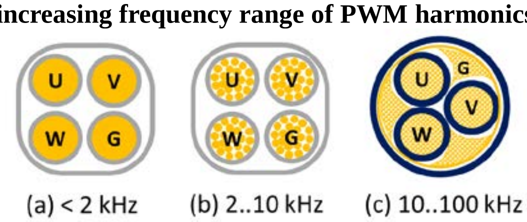
Controlling a permanent magnet synchronous motor
Trying to utilize "fly-start" motor capability when a fan is already coasting or "windmilling".
To set up vector control, most VFDs only require entering accurate nameplate information. DTC can fully auto-detect an induction motor if the nameplate data is missing. In addition, DTC adjusts the carrier frequency dynamically, and hence it is helpful when trying to reduce tonal sound prominence of a motor. In a DTC-controlled motor, PWM will create a somewhat broadband "swishing" sound instead of typical discrete inverter tones.

5. INSTALLATION

A VFD is a powerful and precise piece of electrical equipment comprised of numerous critical components. For that reason, installation must be performed by a licensed and qualified electrician for adherence to all local and national electrical codes. Aided by the specific requirements of the site personnel, electricians will be able to assess the proper wire types, size, location, breakers, and switches for the application. Best practices should be utilized to ensure safe operation that meets the needs of the application.

It is worth noting that, unless one exceeds the cable's rated voltage and/or ampacity, the cable itself is very unlikely to fail because its wire and insulation are much thicker than those of the motor windings. The major issue with PWM-powered load cables is that they introduce electrical noise and interference to the surrounding equipment, as well as to the VFD controller itself. The major source of this noise and interference comes from the PWM carrier frequency and its harmonics, which may range from 2 kHz to 100 kHz.

Figure 3: Three-phase motor cable design evolves with increasing frequency range of PWM harmonics.



Below 2 kHz, current density is fairly evenly distributed across the conductor cross-section. In this frequency range, a solid copper wire cable can be used for all conductors (see Figure 3a).
From 2 kHz to 10 kHz, the current is more concentrated towards the conductor surface. To increase the conductive surface area, it is recommended to use a stranded wire cable with about 20 strands per core (see Figure 3b).

From 10 kHz to 100 kHz, the current is almost fully concentrated at the conductor surface and may cause electro-magnetic interference (EMI) when its density gets too high. Hence, a 3-phase VFD motor supply cable for this application must satisfy some additional specifications (see Figure 3c)

- Very thin strands, about 80 per core for a 200A cable
- Ground wire is also stranded, split into 3 patches of nearly triangular cross-section each, and interwoven between the power wires.
- Power wires shall use low-capacitance, corona-resistant dielectric insulation.
- The entire cable is shielded with copper foil.
- Above 100 kHz, the current may leave the conductor surface completely and travel through the space as radio waves. To prevent the drive cable from becoming such an antenna, it is recommended to route it through a separate conduit that is made of steel, separated from and not shared with other power or signal cables.

Although the frequency ranges above are approximate and the overall behavior is qualitative, the drive cable specifications are standardized. NFPA 79 2018 edition – Article 4.4.2.8 specifies the following cable marking nomenclature as desirable:

RHH, RHW-2, XHH, XHHW, XHHW-2 or XLPE.

The following cables shall be avoided:

THHN, any designation beginning with "T…" (Thermoplastic), and cables that are only rated "AWM."

Due to the nature of a VFD output not being an ideal sine wave, it is recommended that precautions are taken to mitigate effects that may arise due to its operation. These effects may include added noise (audible and electrical), spikes at various harmonic frequencies, and higher motor temperatures among others.

VFDs output the PWM signal at a frequency known as the switching, or carrier, frequency. From the factory, this is often set between 2 and 16 kHz. In this range it is possible for the human ear to hear this narrowband tone. To protect the motor by reducing the amplitude of PWM-induced voltage spikes, reactors, sine wave filters and/or dV/dt filters can be installed between the VFD output and the motor supply cable. To further reduce or even completely remove carrier frequency content, sine wave filters and/or transformers may be applied. These devices relocate audible electrical noise from the motor to the device itself. Removing the filter makes the tones audible in the motor. Thus, filters shall be planned for and installed in applications where cool, quiet and safe motor operation outweighs the small power losses associated with their use.

Besides harmonic guard and PWM-related filters required in the two previous sections, it is generally a good practice to protect the line side of all VFD types with

EMI/RFI filters
Time-delay fuses
Disconnects
Circuit breakers

In many cases, minimum protections are required by law.

Over 40 years of continually improved development and operation made solid-state IGBT-based inverters sufficiently perfected with protective electronics and software, so generally, on the motor side, the VFD reliably protects itself. Yet it would be helpful to take some preventive steps:

Buy the VFD and the motor from the same vendor and follow that vendor's recommendations on installing and connecting the two.

Don't size the VFD based on motor horsepower ratings. Instead, size the VFD to the motor at its maximum current requirements at the peak torque demand.

Many modern VFDs have built-in software to trace faults. Use it and keep a separate, manual fault log. Investigate each fault and eliminate its root causes before putting the VFD back to service.

Setting proper limits on maximum current, maximum frequency and deceleration times protects both the VFD and the motor.

6. CONNECTION TO BUILDING MANAGEMENT

Building automation protocol systems, such as BACnet or Modbus are in widespread use in buildings across the country. Overall building efficiency is dependent on all manner of mechanical equipment. Obtaining, tracking and controlling these pieces of equipment are essential to understanding and increasing the overall efficiency. When using a VFD in a fan-drive system, the VFD must be ensured to be compatible with the protocol of the building it is installed in.

Variables related to fans and VFDs include vibration, temperature, pressure, flowrate, amperage, power consumption, etc. These all work cooperatively to allow building personnel to visualize the status of all equipment on a computer screen. Based on real-time information, fan speeds can be adjusted to provide more/less flow, more/less heating or cooling and more/less humidity. When filters become dirty, fan speed will increase to provide the same flowrate at a higher pressure. When new filters are installed, fan speed will reduce to maintain flowrate across a lower resistance.

There is often an override feature included in these software control packages. This allows field testing of a fan and ensuring that small changes in the system do not affect the test results. It is important that when testing fans in the field, operation of the fan and system need to remain constant for the duration of the test. No changes to speed, resistance, system controls, dampers, processes, heating/cooling load, etc. are allowed. Should a link exist between the software controls and the VFD, assurance is needed that bypass mode is in place for both devices.

New methods of recording and transmitting vital fan information to the user are being developed. These will be standalone systems used over the telecommunications network that provide real-time data to users. This remote monitoring system will inform users of bearing temperatures, fan pressures, vibration levels and other useful information. Information will be able to be presented to users via a smartphone app or PC application. Data will also be recorded to view trending information.

7. COMMISSIONING

Inspections of installed equipment are necessary to ensure adherence to all applicable local and national codes.

During the commissioning process, the VFD should be operated to the extents of the designed operating ranges. This includes minimum and maximum speeds, acceleration and deceleration times, assurance that inrush current for all operating modes does not trip any protective devices and for general operation of the unit.

Mechanical or audible resonances observed in the fan or motor at discrete speeds throughout the operating range should be recorded and locked out of the system. This effectively makes the VFD not dwell at these speeds on acceleration or deceleration, preventing any accelerated fatigue due to operation in resonance.

Startup service of the VFD itself is commonly offered by distributors of the equipment or local electrical contractors. This service may provide additional assurance that the VFD is properly setup before starting in normal operation.

Once this stage is complete, the system is ready for initial operation. Operation up to this point will have been in a temporary state. Once the unit is commissioned, all of the hardware (VFD, disconnect, breaker, electrical wiring, etc.) will be fixed in their permanent, physical locations.

8. OPERATION

Advantages of VFD use were described in previous sections. These advantages will not be fully realized in practice unless the proper operation of the unit is understood and implemented. Knowledge of the available functions will assist users in optimizing the VFD to fit their application. User manuals provided with the equipment are the best source of information to have on hand when learning controls and operation of the unit. Many manufacturers offer PC-based applications to remotely view and modify parameters via ethernet. Be sure to understand any limitations or consequences when making changes to a running system. The system will likely need to be turned off in order for the changes to take effect.

Viewing real-time data from the VFD is a useful reference to have in the field. Data on voltage, amperage, motor input wattage, frequency and other parameters are readily viewed on the keypad as the unit is operating. The information presented on the readout is provided for reference. A NIST-traceable calibration of the VFD readout is not normally performed, therefore calibrated standalone instruments may be required if more precise data is needed.

In order to obtain accurate measurements of PWM-distorted motor voltage, current and input power, one must take the following steps, in order:

Acquire current and power data on the line side input to the VFD. Such measurements will be clean but they will include all losses between the measurement and the fan such as VFD, motor, belts, etc.

Use analog ammeters and/or wattmeters between the VFD and the motor. Analog devices are relatively inexpensive and less sensitive to PWM distortions.

Use an advanced digital power meter. Many advanced power analyzers (e.g. Dranetz, Yokogawa, Tektronix) can synchronize on either voltage or current. PWM needs to be synchronized on current.

Finally, if none of the above succeeds, use “output power” readout from the VFD itself, if available.

When using the above methods to obtain power data on the fan-motor-drive system, be sure to understand the ratings from the fan manufacturer and compare accordingly. There are currently many methods of rating fan power. Be sure to validate with the manufacturer of the fan if any components in addition to the fan were accounted for.

Avoid air system applications where the fan is “windmilling”, meaning that the fan rotates despite power not being supplied to it. If windmilling is unavoidable, it is important to have the VFD programmed such that it is unable to operate below the windmilling speed. Trying to start a VFD while a fan is windmilling is not advised. It will trip the VFD and, if done repeatedly, may damage other components in the VFD. Some VFDs are capable of fly-start capability, meaning that the speed can be detected to resume operation as needed. Be careful using this feature. If done improperly the VFD may trip.

In most applications, it is recommended to use “COAST-TO-STOP” instead of “RAMP-TO-STOP”. That is, program the VFD in such a way that, when it is needed to stop the motor, it will simply cut off the power instead of ramping it down. In isolated instances where coastdown resonances are suspected, “RAMP-TO-STOP” should be used to investigate. When complete, revert back to “COAST-to-STOP”.

Inrush current is a common concern for electric motors. A VFD can assist in this regard by controlling the startup period. Acceleration times can be tailored to fit production needs or other site-specific conditions. Most commonly, acceleration times may be prolonged to decrease the instantaneous inrush current. Settings in the VFD can be adjusted such that a defined amperage is not exceeded during startup. The VFD will then take as long as it needs to slowly accelerate to full speed.

The exception to the inrush current scenario above is when the motor is not properly sized for the starting torque required by the fan. This will not allow the fan to reach full speed, as the motors starting torque capacity is also reduced at reduced speeds. In the case of the exception noted, the motor may be better suited to the fastest start possible. By decreasing the amount of time the inrush current is applied, the motor will be able to provide full starting torque. This is needed to overcome the inertia of the impeller.

Operation outside of 60Hz is a factor in the decision to use VFDs in the field. The capability to adjust the motor speed, and the subsequent process, is a great benefit to many users. Their adjustability, however, is not without limits. Motors are still limited by their physical and electrical capabilities. Foremost of their limits is the amount of horsepower available at partial speed. This relationship is generally linear, meaning motors have approximately half the horsepower rating at half speed. This is the constant torque region of the motor, from 0 to full rated RPM. Conversely, at operation above 60Hz, motors exhibit constant horsepower. Higher speed does not equal higher horsepower capability. Increasing the speed increases the frequency however voltage cannot exceed that provided into the VFD. Constant horsepower can also be viewed from a perspective of torque. In the standard power/speed/torque equation, if power is constant and the speed increases, then the torque must decrease. Thus, the load on the motor must be known as well as the required output demanded by the fan in order to be assured that the system will operate.

9. TROUBLESHOOTING

With any application, faults and trips of the equipment are possible. Steps noted in earlier sections of this document are useful in mitigating the occurrence these issues. Should issues arise, the first source of information should be the user manuals of the VFD and the fan. There is a plethora of online information available regarding VFDs and fans with respect to troubleshooting and faults. A list of the most common VFD faults observed is listed below with a suggested remedy.

<u>Overamperage VFD trip</u>

This can occur on acceleration or deceleration of the unit. Most commonly, the internal VFD equipment will trip out, cutting power, with the unit coasting to a stop. VFDs have a reset button which will restore all the previous parameters. This is often caused by sudden deceleration. If the DC bus cannot contain the braking energy needed to slow down a high inertia impeller, the internal VFD protection will cut off all power. Remedy is to increase the deceleration time or simply cut off power, known as “COAST-TO-STOP”.

<u>Mechanical resonance</u>

Typically, fans are designed to be resonance-free across the entire operating range of speeds. Manufacturers cannot fully guarantee resonance-free operation in the field where fan natural frequencies are affected by external support structures and/or ductwork. Therefore, problems may arise due to the specific conditions and equipment used in the field. Field vibration testing should be performed to determine any speed ranges of excessive vibration amplitude. A modern VFD can and should be programmed to prohibit continuous operation across ranges where natural frequencies exist.

<u>Unable to achieve full operating speed</u>

Several issues could be causing this problem.

- Improper VFD settings.
- Fan operating at a different density or starting condition than designed. Cold air starts on a normally high temperature process may exceed motor capability.
- Undersized motor power/insufficient starting torque.
- Other unit and/or process controls not allowing full speed.

<u>Electrical grounding</u>

Once the motor starts rotating it forms a thin, non-conducting oil film between the bearing balls and their tracks. The film is thin enough to allow intermittent arcing through the point of contact. This arcing results in gradual pitting of the bearing track surface. The following precautions are recommended:

- Reduce the PWM carrier frequency to below 6 kHz (although sound and vibration could be affected).
- Reduce the load cable length and use proper cable design between the VFD and the motor.
- Install light- to medium-duty load power conditioning devices, such as dV/dt reactors and filters.
- Obtain a motor with a combination of ceramic and/or insulated bearings.
- Install a shaft grounding kit. Shaft grounding kits can be either preinstalled by motor OEMs or available in the aftermarket (e.g. from Aegis). These components do wear.
- Make sure all stationary fan components, the motor, the cable and the VFD are all properly grounded to Earth.

To prevent corrosion, all bearings must follow the prescribed lubrication schedule, and shafts must be rotated regularly while in storage or standby.

10. RETROFIT

Installing a VFD into an existing system can present several roadblocks. Most notably:

- Motor compatibility
- Wiring type and capacity
- Inability of the system to be varied due to speed changes. It may have been designed for single-speed operation.

It is recommended that a thorough system review take place involving all affected site personnel along with a licensed electrician. Comments brought forth earlier in this guide regarding selection, sizing, installation and operation would all need to be vetted prior to purchase and implementation of a VFD.

11. ALTERNATIVE MOTOR AND SPEED CONTROL TECHNOLOGIES

Beyond induction motors and VFDs, other technologies exist that offer similar speed adjustment. Some are integrated into the motor assembly itself and some are standalone components requiring separate wiring. Many of these alternatives are available in a limited horsepower or speed range. Induction motors paired with VFDs remain the most common form of electrical speed control for heavy commercial and industrial applications. Some of the other options include:

Permanent magnet motors – There are multiple variations of this motor available. These motors use permanent magnets instead of the magnetic field being electrically induced as on an induction motor. Therefore, in order to operate at all, a VFD of some type is needed. In general, these motors are not available above 20HP.

Electrically commutated motors – This is a subset of permanent magnet motors which require the use of controls (integrated or separate) in order to adjust the speed. They are very common in horsepower ranges from 0-10HP.

Description	PROS	CONS
Induction Motor with VFD	Can be installed on existing motor	Relatively higher initial cost
	Wide range of HP availability	Requires add-on equipment for line filtering
	PC-based software used for drive setup	
Permanent Magnet Motor (EC)	Motor and drive in a single package	Limited HP availability
	Low-cost speed adjustability	Cannot be used on induction or PSC motor
	PC-based software used for drive setup	Adjustment limited to basic parameters, if any
	0-10VDC or 4-20mA fits existing control systems	

12. DISCLAIMER

There is a large database of valuable information available from motor and drive manufacturers and from local electrical supply distributors. Documents directly from the manufacturer of any equipment must be followed for proper operation. This document is being provided as supplemental information for startup and operation of a VFD in the field as related to fan-motor systems. Summarizations of best practices have been described and should be used as a reference. It is not intended to replace information obtained directly from the equipment manufacturers. In no event shall TCFC (Twin City Fan Companies) be liable for the use of the content in this document which includes, but is not limited to, misapplication, misuse, incorrect parameter setting or damage to the equipment as a result of using the information in this guide.