About VFDs

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Statements are made that you can use any standard induction motor with a VFD system, forgetting some basic facts which can, and do, from time to time, lead to problems and motor failures.

The term 'drives' can mean many things. It applies to any means of rotating or driving a piece of equipment - steam drives (engine and turbines), combustible fuel burners (petrol, diesel, paraffin etc) and electric motors of various types. Today when drives are referred to most people think of variable speed electric motors, and since the 1980s - VFDs.

We should note that VSD is an abbreviation for variable speed drive and this could refer to any type of variable speed drive system including mechanical variable speed arrangements. VFD stands for variable frequency drive and this specifically refers to variable frequency variable speed ac motors.

'Efficiency' - the buzz word - should also be a major consideration in line with the current and future power considerations accompanied by environmental objectives.

Steam driven turbines, in particular coal fired boilers (our prime source of electric power) are inherently inefficient compared to electric motors; basically this applies to many prime movers such as gas turbines, diesel and petrol engines etc. However we are constantly striving to improve the efficiency of electric driving systems.

Electric induction motors were the backbone of modern electric driven equipment in inherently a fixed speed device until the 1980s when solid state power supplies became economically viable. By the 1980s, ac motor drive technology became reliable and inexpensive enough to compete with traditional dc motor control. The VFDs accurately control the speed of standard induction and synchronous motors. VFD's speed control with full rated torque is achieved from 0 to rated 50 Hz rpm and, if required, at reduced torque above 50 Hz.

Dc motors were extensively used prior to the advent of VFDs as dc drives offer accurate speed control and significant power output through the whole range, in fact, high torque (twice or more) can be achieved at 0 speed by increasing the field strength and armature current during the starting period. Dc motor control is basic but the motor and maintenance costs tend to be on the high side.

Operation

The principle of operation of VFDs is to rectify the incoming ac voltage/current into dc and then using pulse width modulation to recreate an ac voltage/current waveform at the desired frequency.

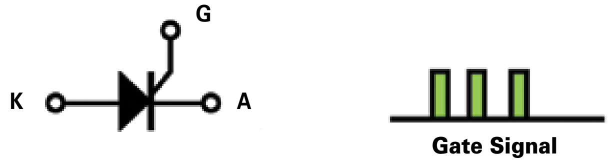
There are three common types of VFD - current source (CSI), voltage source (VSI) and pulse-width modulation (PWM). Pulse width VFDs are the most commonly used in industry.

Insulated gate bipolar transistors (IGBTs) or silicon-controlled rectifiers (SCRs) are used in the inverter stage; other forms of devices such as GTOs, IGCT and SGCT - under SCRs; Mosfet, Bi-polar, Darlingtons and IGBTs - under the heading of transistors. As usual there are developments in the electronic world and other devices could be used as and when developed.

Thyristors

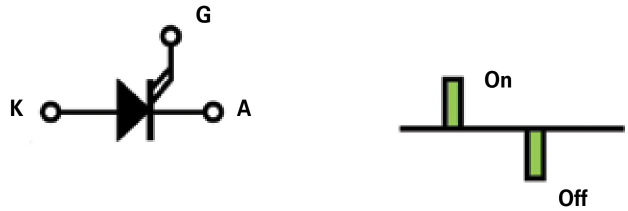
SCRs allow one way current flow only after a gate signal and only turn off when current drops to a very low value or reverses. SCRs have no inherent current limit.

Thyristor (SCR)



Gate Turn-off Thyristors

Gate turn-off thyristors (GTOs, ICGTs and SCGTs) require a pulse to turn on and a pulse to turn off.



Insulated Gate Bipolar Transistors (IGBTs)

IGBTs require low gate power for operation, are simple to control (few components) and are self-protecting (short-circuit proof). IGBTs have a faster switching time than transistors and therefore have lower losses. (Transistors typically 0,1 to 5 ns whereas IGBT switching time could be as low as 0,07 ns).

Advantages of IBGTs are:

Perfect classical bearing current damage – fluting – dc machine.

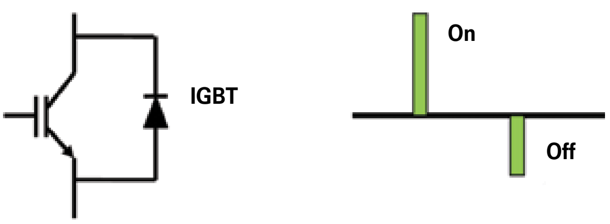
(Photo - courtesy Rob Melaia).

CSI – Current Source Inverter
EDM – Electrical Discharge Machining
GTO – Gate Turn Off
IGBT – Insulated Gate Bipolar Transistor
IGCT – Integrated Gate-Commutated Thyristor
LCR – Inductor - Capacitor - Resistor
PWM – Pulse Width Modulation
rpm – revolutions per minute
SCR – Silicon-controlled Rectifiers
SGCT – Symmetrical Gate Commutated Thyristor
VFD – Variable Frequency Drive
VSD – Variable Speed Drive
VSI – Voltage Source Inverter.

Abbreviations

- Lower losses
  - Smaller heatsinks
  - Smaller product packages
- Economical control
  - On/Off with low level signal
- More 'robust'
  - Faster turn-off after fault sensing
  - = easier protection
- Up to 20 kHz switching speed

Transistor (IGBT)



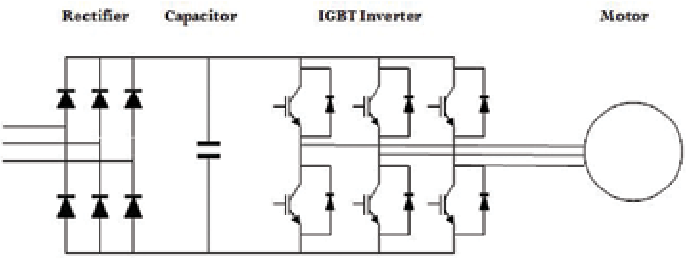


Figure 1: Typical VFD unit configuration.

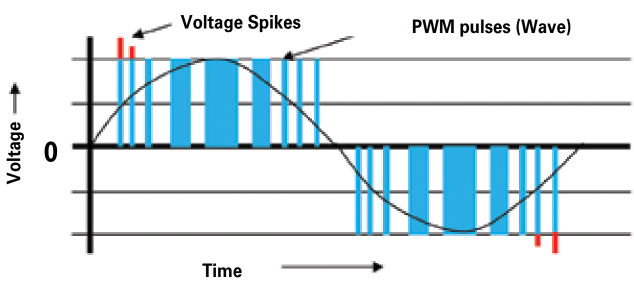


Figure 2: Pulse Width Modulation Wave.

Power output of VFD

Induction motor designs have to be competitive and therefore the manufacturers of induction motors design close to the limits. It is not economically feasible to design a 'universal' induction motor that can handle all the factors that cover all possible scenarios.

We should not forget the basic equation V = 4,44 x f x ϕx t

Where f is frequency, ϕ = flux and t is turns

Designers design close to the knee point on the saturation curve of the lamination steel used in the motor; once you have selected a frequency, the turns are fixed for a particular voltage and you cannot change the number of turns in operation. The interaction of the flux and rotor current determines the torque.

From this you can see that the voltage has to be decreased as frequency is decreased maintaining a constant flux. Generally, if you try to increase the flux you will drive the iron core into saturation. Hence the constant torque operation up to design frequency 50 Hz for a standard induction motor.

At a frequency above the design frequency 50 Hz for standard induction motors as the voltage is fixed at a supply level the flux will decrease resulting in reduced torque and therefore the constant power scenario.

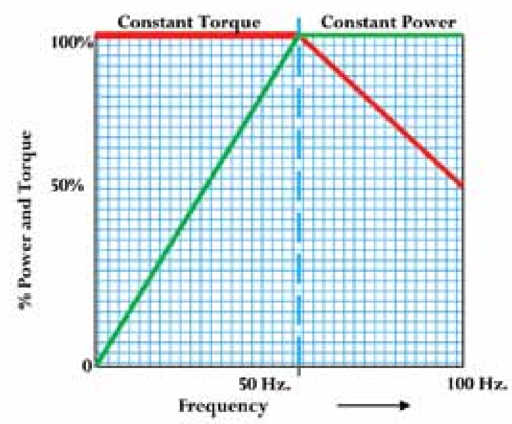


Figure 3. Typical torque power curve for a VFD.

Problems often neglected

- Heat generated in the VFD unit and the motor would have to be catered for under all operating conditions.

$M = H_{loss}/(C_p\ DT)$
M = Mass flow rate (Kg/s)
C_p = Specific heat of air (kJ/(kg x K)
DT = Difference in air temperature
(Incoming and outgoing) (K)

Perfect classical bearing current damage – fluting – dc machine.

(Photo - courtesy Rob Melaia).

- Heat generated in VFD unit

The heat loss in the drive is governed by the following equation:

$H_{loss} = P_t\ (1-\eta)$

Where H_{loss} is the power loss in Watt, P_t is the power through the drive in Watts and η is the efficiency of the drive. The usual efficiency of a drive is between 95% and 98% [1].

The amount of air that must be moved through the drive is governed by the equation:

$M = H_{loss}\ /(C_p\ \Delta T)$.

This is usually covered by the VFD designer and supplier unless the VFD is placed in an enclosure where the air flow is inhibited.

Possible problems with matching VFDs to existing motors

Standard induction motors are designed for 50 Hz operation at a specified sine wave voltage, the designer allowing for a particular temperature rise taking the designed losses into account.

As such, you have to question whether or not a new VFD can be matched to your existing motor and still have the motor perform reasonably well. In other words, will the motor be able to handle additional factors that may cause greater vibration, temperature rise, insulation failure, etc?

Motors connected to VFDs receive power that includes a changeable fundamental frequency, a carrier frequency, and very rapid voltage build-up. These factors can have negative impacts, especially when existing motors are used.

There are a number of potential problems that can become real when a VFD is used to power an existing induction motor. As such, you should carry out a careful study to determine if these problems could be sufficiently bad to cause reconsideration of such an installation. With a VFD, an existing motor normally having a number of useful years left in it could abruptly fail [1].

High frequencies can cause problems

We should be aware of possible side effects caused by high pulsing frequency when applying a VFD to an existing motor. These negative effects include additional heat, audible noise, and vibration. Also, PWM circuitry, which causes a high rate of voltage rise of the carrier frequency, can cause insulation breakdown of the end turns of motor windings as well as feeder cable insulation (see *Figure 2*). The losses in an induction motor are as follows:

- Iron losses: Predominantly hysteresis and eddy current losses in the stator, rotor iron losses are generally negligible due to the very low frequency in the rotor under normal operation and practically pure sine wave supply
- Windage and friction losses
- Stray losses
- I^2R losses in rotor and stator

The carrier frequency, a by-product of obtaining current at a variable fundamental frequency, is the cause for having additional watts in the motor; this power is essentially wasted energy that adds heat to the motor. The amount of such loss varies, depending upon the motor's stator and rotor designs, and frequency of the carrier wave.

With the harmonics generated in the drive the motor rotor will effectively run at a high slip which could affect the motor output, the high slip more importantly affects the losses in the motor generating additional heat. Slip is the difference between the rotational speed of the stator's magnetic field (the synchronous speed of the induction motor) and the speed of the rotor. (Note that the high-frequency ripples in the current are at low magnitude, but the rotor effectively sees a high frequency which induces additional currents in the rotor resulting in additional I^2R losses; iron losses would also increase resulting in additional heat losses).

If the motor is to be run a slower speed on a continuous basis the cooling could be insufficient if an external driven fan is not fitted for cooling of the motor. As VFD systems do not all operate at a standard carrier frequency, and the fundamental frequency could vary between 5 and 50 Hz (or even higher) problems could be encountered in the overall electrical system due to resonance in components.

We should also consider the fact that the motor is designed for 50 Hz operation and the mechanical component of the motor could go into resonance.

Bearings

High frequency inherently associated with the voltages and currents in PWM may cause trouble with motor bearings. When these high frequency voltages find a path to earth through a bearing, transfer of metal or electrical discharge machining (EDM) sparking occurs between the bearing's ball and the bearing's race. Over time, EDM-based sparking causes erosion in the bearing race that can be seen as a fluting pattern. In some motors, the stray capacitance of the windings provides paths for high frequency currents that pass through the motor shaft ends, leading to a circulating type of bearing current.

Conductor voltage breakdown

PWM circuitry, which causes the high rate of voltage rise at the carrier frequency, can cause insulation breakdown of the end turns of the motor windings, as well as possible breakdown of the feeder cable insulation.

This relates to the high rate of rise of the voltage (rate of voltage change with respect to time) in combination with the rapidly repeating voltage pulse caused by the VFD.

Since the transmission-line impedance of the cable and motor are different, pulses tend to reflect back from the motor terminals into the cable. The resulting voltages can produce over-voltages equal to twice the dc bus voltage or up to 3,1 times the rated line voltage for long cable runs, putting high stress on the cable and motor windings and eventual insulation failure [2].

On 460 or 575 V systems and inverters with third generation 0,1 microsecond rise time IGBTs, the maximum recommended cable distance between VFD and motor is about 50 m [2].

Conductor insulation failures in motors have occurred because of this phenomenon. This subject is not completely understood and is presently being researched. The known facts about the matter are summarised as follows.

- Switches in the inverter section of VFDs currently being used could result in instantaneous turn-to-turn voltage inside a motor's windings to be significantly higher than what an equivalent normal sine wave supply produces.
- Each cycle of the fundamental voltage consists of numerous pulses of voltage.
- Long distance between a motor and its VFD causes the turn-to-turn voltage to get even higher.

High frequency motors

There are a number of motors in use specifically designed for high frequency operation. These motors, when sent for repair, are sometimes treated like standard induction motors and consequently fail soon after installation. Because the motor is connected to a VFD source which the manufacturers state can operate at frequencies up to 100 Hz or more, this does not mean a standard induction motor will operate satisfactorily at these higher frequencies even if de-rated. Recently, a motor sent in for repair had been specifically designed for 200 Hz 6 000 rpm operation. This motor had to be treated as a special winding designed for 200 Hz; the core was manufactured from special thin lamination plates – and balancing was critical.

It must be noted that the hysteresis loss increase is directly proportional to frequency; and eddy current loss is proportional to the square of the frequency.

Conclusion

Solutions to over-voltages caused by long lead lengths include minimising cable distance, lowering carrier frequency, installing dV/dt filters, using inverter duty rated motors (motors wound with inverter grade wire) and installing LCR low-pass sine wave filters.

Ensure the stator core is not damaged; that it is tested and in good condition. Consider having the motor rewound with 'inverted grade' covered wire if a repair is required. Use some form of earthing the shaft to prevent bearing current; there are some unique micro carbon fibre 'brushes' available that are easy to fit for protection against bearing currents.

References

[1] 'Mating new variable frequency drives to existing motors'. Manz, Lester B, Morgan, Robert B. Electrical Construction and Maintenance. March 1999.
[2] The basics of Variable Frequency Drives.

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