VARIABLE FREQUENCY DRIVE

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ABSTRACT

This paper presents the working principle of Variable Frequency Drive. The performance of VFD is also described. The use of Variable Frequency Drive has been increased dramatically in the field of HVAC applications. The common applications of VFDs are in air handler, chiller, pumps and tower fans. A better understanding of Variable Frequency Drives with leads to improve in application and selection of both equipment and HVAC system. This paper is intended to provide a basic understanding of VFD terms, VFD operations and Power Factor improvement, Harmonics mitigation by VFD.

Keywords : VFD operation, Harmonics, Harmonics mitigation

I.INTRODUCTION

A variable-frequency drive (VFD; also termed adjustable-frequency drive, “variable-voltage/variable-frequency (VVVF) drive”, variable speed drive, AC drive, micro drive or inverter drive) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. Over the last four decades, power electronics technology has reduced VFD cost and size and has improved performance through advances in semiconductor switching devices, drive topologies, simulation and control techniques, and control hardware and software. The Variable Frequency Drive (VFD) industry is growing rapidly and it is now more important than ever for technicians and maintenance personnel to keep VFD installations running smoothly. Variable Frequency Drives (VFD) change the speed of motor by changing voltage and frequency of the power supplied to the motor. In order to maintain proper power factor and reduce excessive heating of the motor, the name plate volts/hertz ratio must be maintained. This is the main task of Variable Frequency Drive.

1. Variable Frequency Drive (AC drives) are used to step less speed control of squirrel cage induction motors mostly used in process plants

2. due to its ruggedness and maintenance free long life.

3. 2. VFD control speed of motor by varying output voltage and frequency through sophisticated microprocessor controlled electronics device.

International Journal of Advance Research in Science and Engineering
Volume No.07, Special Issue No.02, April 2018
www.ijarse.com
IJARSE
ISSN: 2319-8354

4. 3. VFD consists of Rectifier and inverter units. Rectifier converts AC in DC voltage and inverter converts DC voltage back in AC voltage.[2,3]

VFD Operation :

For understanding the basic principles behind VFD operation requires understanding three basic section of VFD: the Rectifier unit, DC Bus and the Inverter unit.

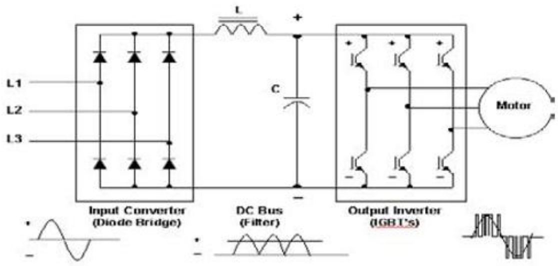

Fig : VFD circuit

The supply voltage is firstly pass through a rectifier unit where in gets converted into AC to DC supply, the three phase supply is fed with three phase full wave diode where it gets convert into DC supply. The DC bus comprises with a filter section where the harmonics generated during the AC to DC conversion are filtered out. The last section consists of an inverter section which comprises with six IGBT (Insulated Gate Bipolar Transistor) where the filtered DC supply is being converted to quasi sinusoidal wave of AC supply which is supply to the induction motor connected to it.

As we know that the synchronous speed of motor (rpm) is dependent upon frequency. Therefore by varying the frequency of the power supply through VFD we can control the synchronous motor speed:

Speed (rpm) = $\frac{frequency\ (hertz)\times 120}{no.of\ poles}$

Where; Frequency = Electrical Frequency of the power supply in Hz. No. of Poles = Number of electrical poles in the motor stator. Thus we can conveniently adjust the speed of a motor by changing the frequency applied to the motor. There is also another way to change the speed of the motor by changing the no. of poles, but this change would be a physical change of the motor. As the drive provides the frequency and voltage of output necessary to change the speed of a motor, this is done through Pulse Width Modulation Drives. Pulse width modulation (PWM) inverter produces pulses of varying widths which are combined to build the required waveform.

As the frequency can easily variable as compared with the poles of the motor therefore speed control drive is termed as Variable Frequency Drive

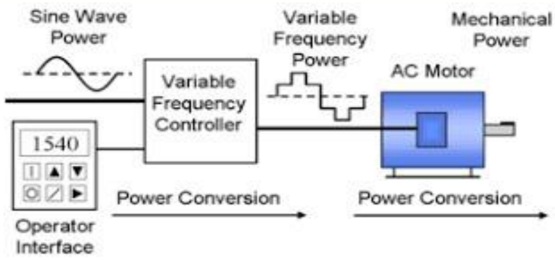

Fig: VFD operation

How Drive Changes Motor Speed :

As the drive provides the frequency and voltage of output necessary to change the speed of a motor, this is done through Pulse Width Modulation Drives. Pulse width modulation (PWM) inverter produces pulses of varying widths which are combined to build the required waveform. A diode bridge is used in some converters to reduce harmonics. PWM produce a current waveform that more closely matches a line source, which reduces undesired heating. PWM drive have almost constant power factor at all speeds which is closely to unity. PWM units can also operate multiple motor on a single drive.

Thus the carrier frequency is derived from the speed of the power device switch remains ON and OFF. It is also called switch frequency. Therefore higher the carrier frequency higher the resolution for PWM.[3]

Relation between VFD and Power Factor :

The Variable Frequency Drive (VFD) basically contains capacitors which are present in DC bus is used to maintain Power Factor on the line side. Therefore any additional use of other power factor correction.

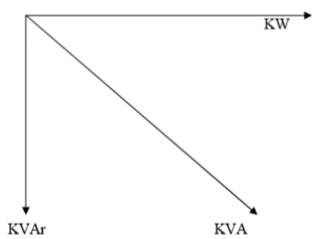

Fig: Power Triangle

Equipments on the line side supply to the motor or use of expensive capacitor bank is not require. The Variable Frequency Drive (VFD) itself offer high power factor in the line side supply to the motor.

We know that Power Factor = Cosϕ

From the above diagram-

1. KVA $= \sqrt{kw^2 + kvar^2}$

2. Cosϕ = KW/KVA

3. KW = KVA × Cosϕ

4. Tanϕ = KVAr/KW

clear that in order to reduce the flow of reactive the Power Factor will have to be improved. At unity Power Factor (i.e. Cosϕ =1) the flow of reactive power is zero and is thus the ideal condition.[3]

Constant V/F Ratio Operation:

All Variable Frequency Drives (VFDs) maintain the output voltage – to – frequency (V/f) ratio constant at all speeds for the reason that follows. The phase voltage V, frequency f and the magnetic flux ϕ of motor are related by the equation:-

$V = 4.444\ f\ N\ \phi m$

Or, $V/f = 4.444 \times N\ \phi m$

Where, N = number of turns per phase.

ϕm = magnetic flux[3]

Problems of Low Power Factor:

Low Power causes a variety of problems which result in increase in losses and in efficient system operation. The major problems that are created due to low power factor are elaborated below:-

1. Current Drawn
2. Cable Losses
3. Transformer Losses
4. Levy of Penalty Current Drawn
5. Voltage Regulation[3]

Harmonic:

In China, three-phase AC power typically operates at 50 hertz (50 cycles in one second). This is called the fundamental frequency.

A harmonic is any current form at an integral multiple of the fundamental frequency. For example, for 50-hertz power supplies, harmonics would be at 100 hertz (2 x fundamental), 150 hertz, 200 hertz, 250 hertz, etc.[1]

What Cause Harmonics:

Variable frequency drives draw current from the line only when the line voltage is greater than the DC Bus voltage inside the VFD. This occurs only near the peaks of the sine wave. As a result, all of the current is drawn in short intervals (i.e., at higher frequencies). Variation in variable frequency drive design affects the harmonics produced. For example, variable frequency drives equipped with DC link inductors produce different levels of harmonics than similar variable frequency drives without DC link inductors. The variable frequency drive with active front end utilizing transistors in the rectifier section have much lower harmonic levels than variable frequency drives using diodes or silicon controlled rectifiers (SCRs).

Electronic lighting ballasts, uninterruptible power supplies, computers, office equipment, ozone generators, and other high intensity lighting are also sources of harmonic problems.[1]

Are Harmonics Cause Problems? :

Harmonics that are multiples of 2 are not harmful because they cancel out. The same is true for 3rd order harmonics (3rd, 6th, 9th etc.). Because the power supply is 3 phase, the third order harmonics cancel each other out in each phase. This leaves only the 5th, 7th, 11th, 13th etc. to discuss. The magnitude of the harmonics produced by a variable frequency drive is greatest for the lower order harmonics (5th, 7th and 11th) and drops quickly as you move into the higher order harmonics (13th and greater).

Harmonics can cause some problems in electrical systems. Higher order harmonics can interfere with sensitive electronics and communications systems, while lower order harmonics can cause overheating of motors, transformers, and conductors. The opportunity for harmonics to be harmful, however, is dependent upon the electrical system in which they are present and whether or not any harmonic sensitive equipment is located on that same electrical system.[1]

Harmonic Terms:

Total Harmonic Voltage Distortion - THD (V)

As harmonic currents flow through devices with reactance or resistance, a voltage drop is developed. These harmonic voltages cause voltage distortion of the fundamental voltage wave form. The total magnitude of the voltage distortion is the THD (V). The IEEE-519 standard recommends less than 5% THD (V) at the point of common coupling for general systems 69 kV and under.[1]

Total Harmonic Current Distortion - THD (I)

This value (sometimes written as THID) represents the total harmonic current distortion of the wave form at the particular moment when the measurement is taken. It is the ratio of the harmonic current to the fundamental (non-harmonic) current measured for that load point. Note that the denominator used in this ratio changes with load.[1]

Total Demand Distortion – TDD

Total Demand Distortion (TDD) is the ratio of the measured harmonic current to the full load fundamental current. The full load fundamental current is the total amount of non-harmonic current consumed by all of the loads on the system when the system is at peak demand. The denominator used in this ratio does not change with load. Although TDD can be measured at any operating point (full or part load), the worst case TDD will occur at full load. If the full load TDD is acceptable, then the TDD measured at part load values will also be acceptable. To use our rock analogy, the full load fundamental current is the size of our pond and the harmonic current is the size of our rock.[1]

Table 1. Comparison of TDD and THD(I)

Fundamental Current (rms)	Harmonic Current (rms)	THD(I)	THD
1000	50	5%	5%
800	43.8	5.4%	4.4%
600	36.3	6.1%	3.6%
400	29.7	7.4%	3.0%
200	20.0	10%	2%
100	13.4	13.4%	1.3%

TDD - Total Demand Distortion
THD(I) - Total Harmonic Current Distortion

Short Circuit Ratio :

Short circuit ratio is the short circuit current value of the electrical system divided by its maximum load current. Standard IEEE-519 Table 10.3 defines different acceptance levels of TDD depending on the short circuit ratio in the system. Systems with small short circuit ratios have lower TDD requirements than systems with larger short circuit ratios. This difference accounts for the fact that electrical systems with low short circuit ratios tend to have high impedances, creating larger voltage distortion for equivalent harmonic current levels.[1]

Table 2. Representation of IEEE Table 10.3

I_{SC}/I_L	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4	2	1.5	0.6	0.3	5
20<50	7	3.5	2.5	1	0.5	8
50<100	10	4.5	4	1.5	0.7	12
100<1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

LEGEND: h = harmonic number
ISC = maximum short-circuit current at PCC
IL = maximum demand load current (fundamental) at PCC

Harmonics Mitigation:

Some utilities now impose penalties for introducing harmonics onto their grid, providing incentives for owners to reduce harmonics. In addition, reducing harmonic levels can prevent potential problems to sensitive equipment residing on the same system. There are many approaches to mitigating harmonics. Several commonly used methods are discussed here.[1]

Line reactor adds reactance and impedance to the circuit. Reactance and impedance act to lower the current magnitude of harmonics in the system and thereby lower the TDD. Line reactors also protect devices from large current spikes with short rise times. A line reactor placed between the variable frequency drive and the motor would help protect the motor from current spikes. A line reactor placed between the supply and variable frequency drive would help protect the supply from current spikes. Line reactors are typically only used between the variable frequency drive and the motor when a freestanding variable frequency drive is mounted more than fifty feet from the motor. This is done to protect the motor windings from voltage peaks with extremely quick rise times.[1]

Passive Filters

Trap Filters are devices that include an electrical circuit consisting of inductors, reactors, and capacitors designed to provide a low impedance path to ground at the targeted frequency. Since current will travel through the lowest impedance path, this prevents the harmonic current at the targeted frequency from propagating through the system. Filters can be mounted inside the VFD panel or as free standing devices. Trap filters are typically quoted to meet a THD (I) value that would result in compliance with IEEE-519 requirements if the system were otherwise already incompliance.[1]

Active Filter:

Some devices measure harmonic currents and quickly create opposite current harmonic wave forms. The two wave forms then cancel out, preventing harmonic currents from being observed upstream of the filter. These types of filters generally have excellent harmonic mitigation characteristics. Active filters may reduce generator size requirements.[1]

Variable frequency drives using Active Front End Technology (AFE)

Some variable frequency drives are manufactured with IGBT rectifiers. The unique attributes of IGBTs allow the variable frequency drive to actively control the power input, thereby lowering harmonics, increasing power factor and making the variable frequency drive far more tolerant of supply side disturbances. The AFE variable frequency drives have ultra-low harmonics capable of meeting IEEE-519 standards without any external filters or line reactors. This significantly reduces installation cost and generator size requirements. An AFE VFD provides the best way to take advantages of variable frequency drive and minimize harmonics.[1]

Multi-Pulse Variable frequency drives (Cancellation)

There are a minimum of six rectifiers for a three phase variable frequency drive. There can be more, however. Basically manufacturers offer 12, 18, 24, and 30 pulse VFDs. A standard six-pulse VFD has six rectifiers, a 12-pulse VFD has two sets of six rectifiers, and an 18-pulse VFD has three sets of six rectifiers and so on. If the power connected to each set of rectifiers is phase shifted, then some of the harmonics produced by one set of rectifiers will be opposite in polarity from the harmonics produced by the other set of rectifiers. The two wave forms effectively cancel each other out. In order to use phase shifting, a special transformer with multiple secondary windings must be used. For example, with a 12-pulse variable frequency drive, a Delta/Delta-Wye transformer with each of the secondary phases shifted by 30 degrees would be used.[1]

II.BENEFITS

Energy savings: Many fixed-speed motor load applications that are supplied direct from AC line power can save energy when they are operated at variable speed by means of VFD. Such energy cost savings are especially pronounced in variable-torque centrifugal fan and pump applications, where the load's torque and power vary with the square and cube, respectively, of the speed. This change gives a large power reduction compared to fixed-speed operation for a relatively small reduction in speed. For example, at 63% speed a motor load consumes only 25% of its full-speed power. This reduction is in accordance with affinity laws that define the relationship between various centrifugal load variables.

In the United States, an estimated 60-65% of electrical energy is used to supply motors, 75% of which are variable-torque fan, pump, and compressor loads. Eighteen percent of the energy used in the 40 million motors in the U.S. could be saved by efficient energy improvement technologies such as VFDs.

Only about 3% of the total installed base of AC motors are provided with AC drives. However, it is estimated that drive technology is adopted in as many as 30-40% of all newly installed motors.

An energy consumption breakdown of the global population of AC motor installations is as shown in the following table:[2]

	Small	General Purpose - Medium-Size	Large
Power	10W - 750W	0.75 kW - 375 kW	375 kW - 10000 kW
Phase, voltage	1-ph., <240V	3-ph., 200V to 1kV	3-ph., 1kV to 20kV
% total motor energy	9%	68%	23%
Total stock	2 billion	230 million	0.6 million

Global population of motors, 2009

Control performance : AC drives are used to bring about process and quality improvements in industrial and commercial applications' acceleration, flow, monitoring, pressure, speed, temperature, tension, and torque.

Fixed-speed loads subject the motor to a high starting torque and to current surges that are up to eight times the full-load current. AC drives instead gradually ramp the motor up to operating speed to lessen mechanical and electrical stress, reducing maintenance and repair costs, and extending the life of the motor and the driven equipment.[2]

Variable-speed drives can also run a motor in specialized patterns to further minimize mechanical and electrical stress. For example, an S-curve pattern can be applied to a conveyor application for smoother deceleration and acceleration control, which reduces the backlash that can occur when a conveyor is accelerating or decelerating.

Performance factors tending to favour the use of DC drives over AC drives include such requirements as continuous operation at low speed, four-quadrant operation with regeneration, frequent acceleration and deceleration routines, and need for the motor to be protected for a hazardous area. The following table compares AC and DC drives according to certain key parameters

Drive type	DC	AC VFD	AC VFD	AC VFD	AC VFD
Control platform	Brush type DC	V/Hz control	Vector control	Vector control	Vector control
Control criteria	Closed-loop	Open-loop	Open-loop	Closed-loop	Open-loop w. HFI^
Motor	DC	IM	IM	IM	Interior PM
Typical speed regulation (%)	0.01	1	0.5	0.01	0.02
Typical speed range at constant torque (%)	0-100	10-100	3-100	0-100	0-100
Min. speed at 100% torque (% of base)	Standstill	8%	2%	Standstill	Standstill (200%)
Multiple-motor operation recommended	No	Yes	No	No	No
Fault protection (Fused only or inherent to drive)	Fused only	Inherent	Inherent	Inherent	Inherent
Maintenance	(Brushes)	Low	Low	Low	Low
Feedback device	Tachometer or encoder	N/A	N/A	Encoder	N/A

III.AVAILABLE POWER RATINGS

VFDs are available with voltage and current ratings covering a wide range of single-phase and multi-phase AC motors. Low-voltage (LV) drives are designed to operate at output voltages equal to or less than 690 V. While motor-application LV drives are available in ratings of up to the order of 5 or 6 MW, economic considerations typically favor medium-voltage (MV) drives with much lower power ratings. Different MV drive topologies (see Table 2) are configured in accordance with the voltage/current-combination ratings used in different drive controllers' switching devicessuch that any given voltage rating is greater than or equal to one to the following standard nominal motor voltage ratings: generally either 2.3/4.16 kV (60 Hz) or 3.3/6.6 kV (50 Hz), with one thyristor manufacturer rated for up to 12 kV switching. In some applications a step-up transformer is placed between a LV drive and a MV motor load. MV drives are typically rated for motor applications greater than between about 375 kW (500 HP) and 750 kW (1000 hp). MV drives have historically required considerably more application design effort than required for LV drive applications. The power rating of MV drives can reach 100 MW, a range of different drive topologies being involved for different rating, performance, power quality, and reliability requirements.[2]

Switching frequency:

One drive uses a default switching frequency setting of 4 kHz. Reducing the drive's switching frequency (the carrier-frequency) reduces the heat generated by the IGBTs.

A carrier frequency of at least ten times the desired output frequency is used to establish the PWM switching intervals. A carrier frequency in the range of 2,000 to 16,000 Hz is common for LV [low voltage, under 600 Volts AC] VFDs. A higher carrier frequency produces a better sine wave approximation but incurs higher switching losses in the IGBT, decreasing the overall power conversion efficiency.

Noise smoothing: Some drives have a noise smoothing feature that can be turned on to introduce a random variation to the switching frequency. This distributes the acoustic noise over a range of frequencies to lower the peak noise intensity.

Long-lead effects: The carrier-frequency pulsed output voltage of a PWM VFD causes rapid rise times in these pulses, the transmission line effects of which must be considered. 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 overvoltages 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. Insulation standards for three-phase motors rated

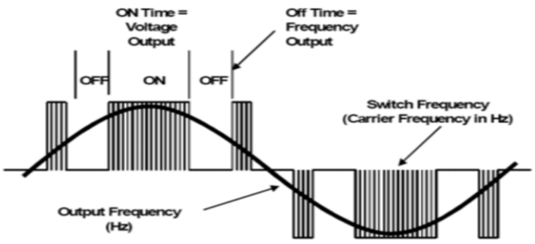

Fig: Drive Output Waveform Components

230 V or less adequately protect against such long-lead overvoltages. On 460 V or 575 V systems and inverters with 3rd-generation 0.1-microsecond-rise-time IGBTs, the maximum recommended cable distance between VFD and motor is about 50 m or 150 feet. Solutions to overvoltage caused by long lead lengths include minimizing cable distance, lowering cHarrier frequency, installing dV/dt filters, using inverter-duty-rated motors (that are rated 600 V to withstand pulse trains with rise time less than or equal to 0.1 microsecond, of 1,600 V peak magnitude), and installing LCR low-pass sine wave filters. Regarding lowering of carrier frequency, note that audible noise is noticeably increased for carrier frequencies less than about 6 kHz and is most noticeable at about 3 kHz. Selection of optimum PWM carrier frequency for AC drives involves balancing noise, heat, motor insulation stress, common-mode voltage-induced motor bearing current damage, smooth motor operation, and other factors. Further harmonics attenuation can be obtained by using an LCR low-pass sine wave filter or dV/dt filter.[2]

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