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Analysis and Assessment of Motor Drive Speed Control through Variable Frequency Drive

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Abstract— Electric Motor Drive System is employed in the various industrial applications such as pumping, air blowing, cooling and compression refrigeration. The motor drive speed control can be achieved by variety of techniques, but an emerging one is Variable Frequency Drive System. The motor driven equipment on a typical industrial site accounts for approximately two thirds of the electricity consumption. Therefore, any type of measure taken to improve the efficiency of a motor system consequently can offer major energy savings. There are multiple benefits of variable frequency drive system utilizing along with speed control. For the technical and economic reliability of such integrated approach of motor with variable frequency drive, analysis and assessment is the key tool. This paper first outlines the benefits of Variable Frequency Drives (VFD) compared to classical drivers or control methods (i.e. steam/gas turbines, hydraulic coupling and Direct-On-Line operation with, for example, valve/damper control). The paper then focuses on analysis and assessment of typical variable frequency drive applications in the sugar industry and also describes a real case study, namely a VFD soft-starter application at Narmada Sugar Factory, Bharuch.

Keywords- *Electric Motor Drive Control, Variable Frequency Drives (VFD), harmonics, soft starter*

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I. INTRODUCTION

An Electrical Motor Drive is defined as a form of machine equipment consist of Electric Motor together with its electronic control equipment & energy transmitting links design to convert electrical energy into mechanical energy and provide electronics control of this process.

Adding a Variable Frequency Drive (VFD) to a motor-driven system can offer potential energy savings in a system in which the loads vary with time. VFDs belong to a group of equipment called Adjustable Speed Drives or Variable Speed Drives. It is very obvious that Variable Speed Drives (VSD) can be electrical or mechanical, whereas VFDs are electrical. The operating speed of a motor connected to a VFD is varied by changing the frequency of the motor supply voltage. This allows continuous process speed control. VFD coupled to motors provide a reliable and cost effective solution to many applications including water pumping, fans, conveyors, etc. in industries. In specific applications, a VFD can provide energy conservation benefits and improvements in operational control.

A VFD is basically an electrical circuit, which is connected between a supplying network and a motor. Unlike a Direct-On-Line (DOL) operated motor, the speed of which is fixed to the frequency of the supplying AC network, the main purpose of a VFD is to provide the motor with an AC supply voltage (or AC current)of variable frequency, enabling a variable motor speed and torque. In general, a state-of-the-art VFD consists of a rectifier section, a DC-link section and an inverter section. The rectifier section rectifies the supplying AC network voltage of fixed frequency (usually 50 or 60Hz) into a DC voltage (or DC current), which then, in the inverter section of the VFD, will be transformed in to an AC voltage (or AC current) of variable amplitude and frequency, see also Fig.1.

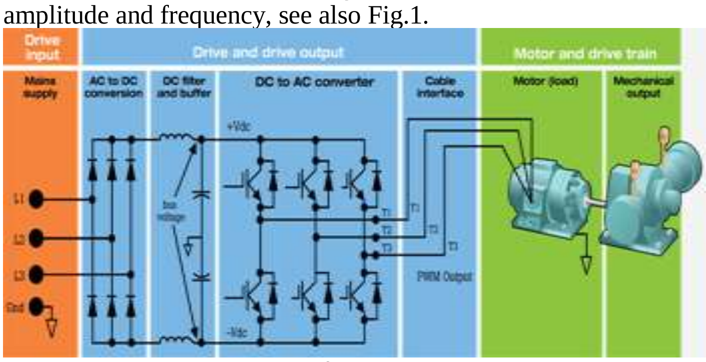

Fig.1 Block Diagram of Electric Motor Drive System

II. OPERATION OF VARIABLE FREQUENCY DRIVE

Understanding the basic principles behind VFD operation requires understanding the three basic sections of the VFD: the rectifier, dc bus, and inverter. The voltage on an alternating current (ac) power supply rises and falls in the pattern of a sine wave. When the voltage is positive, current flows in one direction; when the voltage is negative, the current flows in the opposite direction. This type of power system enables large amounts of energy to be efficiently transmitted over great distances.

The rectifier in a VFD is used to convert incoming ac power into Direct Current (DC) power. One rectifier will allow power to pass through only when the voltage is positive. A second rectifier will allow power to pass through only when the voltage is negative. Two rectifiers are required for each phase of power. Since most large power supplies are 3- Φ, there will be a minimum of 6 rectifiers used. Appropriately, the term “6 pulse” is used to describe a drive with 6 rectifiers. A VFD may have multiple rectifier sections, with 6 rectifiers per section, enabling a VFD to be “12 pulse,” “18 pulse,” or “24 pulse.” Rectifiers may utilize diodes, Silicon Controlled Rectifiers (SCR), or transistors to rectify power. Diodes are the simplest device and allow power to flow any time voltage is of the proper polarity. SCR include a gate circuit that enables a microprocessor to control when the power may begin to flow, making this type of rectifier useful for solid-state starters as well. Transistors include a gate circuit that enables a microprocessor to open or close at any time, making the transistor the most useful device of the three. A VFD using transistors in the rectifier section is said to have an “Active Front End.”

After the power flows through the rectifiers it is stored on a dc bus. The dc bus contains capacitors to accept power from the rectifier, store it, and later deliver that power through the inverter section. The dc bus may also contain inductors, dc links, chokes, or similar items that add inductance, thereby smoothing the incoming power supply to the dc bus. The final section of the VFD is referred to as an “inverter.” The inverter contains transistors that deliver power to the motor. The “Insulated Gate Bipolar Transistor” (IGBT) is a common choice in modern VFDs. The IGBT can switch on and off several thousand times per second and precisely control the power delivered to the motor. The IGBT uses a method named “Pulse Width Modulation” (PWM) to simulate a current sine wave at the desired frequency to the motor. Motor speed (rpm) is dependent upon frequency. Varying the frequency output of the VFD controls motor speed:

Speed (rpm) = frequency (Hz) x 120 / no. of poles (1)

III. Motor Drive Speed Control Strategies

For decades a variety of adjustable speed drives are being used in process industries like pulp and paper, cement, textile plants, chemical plants and power plants. Speed variation of industrial drives, over the years was achieved by using drives such as,

1) Steam Turbines
2) Variable cone pulleys and stepped pulleys
3) PIV (Positive infinite variable drives
4) Hydraulic couplings
5) Gears with stepped change over facility
6) Multispeed cage motors
7) Eddy current couplings
8) Slip ring motors with rotor control devices
9) DC motors with armature and field control devices
10) Commutator (Schrage) motors
11) AC variable drives (Inverters)

Typical pump power absorption curve and fan power absorption curve below illustrate the power drawn by centrifugal pump (Fig. 2) and centrifugal fan (Fig. 2) at different flow rates using different methods of flow control.

IV. Analysis of VFD in Industrial System

As VFD usage in industrial applications has increased, fans, pumps, air handlers, and chillers can benefit from speed control. Variable frequency drives provide the following advantages:

A. *VFD Capacity Control Saves Energy*

Most applications do not require a constant flow of a fluid. Equipment is sized for a peak load that may account for only 1% of the hours of operation. The remaining hours of operation need only a fraction of the flow. Traditionally, devices that throttle output have been employed to reduce the flow. However, when compared with speed control, these methods are significantly less efficient.

a. *Mechanical Capacity Control*

Throttling valves, vanes, or dampers may be employed to control capacity of a constant speed pump or fan. These devices increase the head, thereby forcing the fan or pump to ride the curve to a point where it produces less flow as shown in Fig.3.

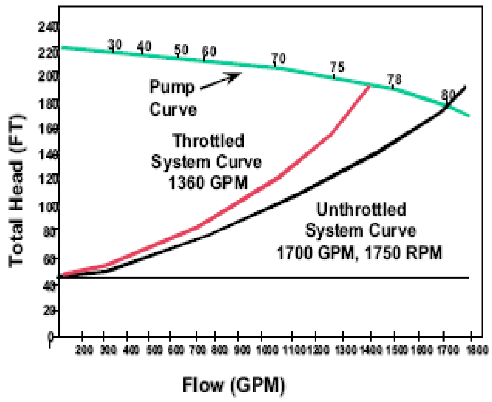

Fig. 3 Capacity Control by Throttling

Power consumption is the product of head and flow. Throttling the output increases head, but reduces flow, and provides some energy savings.

Pump power = flow x head / 39601 (2)

b. *Variable Speed Capacity Control*

For centrifugal pumps, fans and compressors, the ideal fan (affinity) laws describe how speed affects flow, head and power consumption

TABLE-1
EFFECTS OF CHANGE OF SPEED FOR FAN

Flow change linearly with speed	$Flow\ Rate_2 = Flow\ Rate_1 \times (RPM_2/RPM_1)$
Head varies as the speed squared	$Head_2 = Head_1 \times (RPM_2/RPM_1)^2$
Power varies as the speed cubed	$Power_2 = Power_1 \times (RPM_2/RPM_1)^3$

Assume fluid is fresh water, specific gravity =1

When using speed to reduce capacity, both the head and flow are reduced, maximizing the energy savings. A comparison of mechanical and speed control for capacity reduction (see Fig. 2 and 3) shows that variable speed drive is the most efficient means of capacity control.

B. *Low Inrush Motor Starting*

Motor manufacturers face difficult design choices. Designs optimized for low starting current often sacrifice efficiency, power factor, size, and cost. With these considerations in mind, it is common for AC induction motors to draw 6 to 8 times their full load amps when they are started across the line.

When large amounts of current are drawn on the transformers, a voltage drop can occur, adversely affecting other equipment on the same electrical system. Some voltage sensitive applications may even trip off line. For this reason, many engineers specify a means of reducing the starting current of large AC induction motors.

a. VFDs as Starters

A VFD is the ideal soft starter since it provides the lowest inrush of any starter type as shown in Table B. Unlike all other types of starters, the VFD can use frequency to limit the power and current delivered to the motor. The VFD will start the motor by delivering power at a low frequency. At this low frequency, the motor does not require a high level of current. The VFD incrementally increases the frequency and motor speed until the desired speed is met. The current level of the motor never exceeds the full load amp rating of the motor at any time during its start or operation. In addition to the benefit of low starting current, motor designs can now be optimized for high efficiency.

TABLE 2
COMPARISONS OF STARTERS TYPES BASED ON INRUSH CURRENTS

Starter type	Starting Current (% of Full Load Current)
VFD	100
Star/ Delta	200-275
Soft starter	200
Auto transformer	400-500
DOL	600-800

C. Energy Savings

VFDs offer a wide range of benefits such as improving the quality of a product by having a better control of the process and, due to an optimal pressure or flow control, substantial energy savings.

Where are these energy savings coming from? As an example, we assume a Direct-On-Line (DOL), also called fixed speed motor, driving a pump. An electrical motor, which is directly connected to the power grid, will operate at a fixed speed, which is defined by the network frequency and the motor pole number.

Therefore, the connected load machine is always rotating at the same speed. The process requirements however may change, depending on various factors such as change in production quantity or quality, change of the media or deviations from the nominal power grid parameters (change in frequency), varying temperatures or simply new requirements such as production increase.

These changes in process requirements also require control actions in the driving system. The only possible control methods for fixed speed solutions are throttling, bypass control, On/Off control or the upgrade with a VFD solution as indicated in Fig. 4.

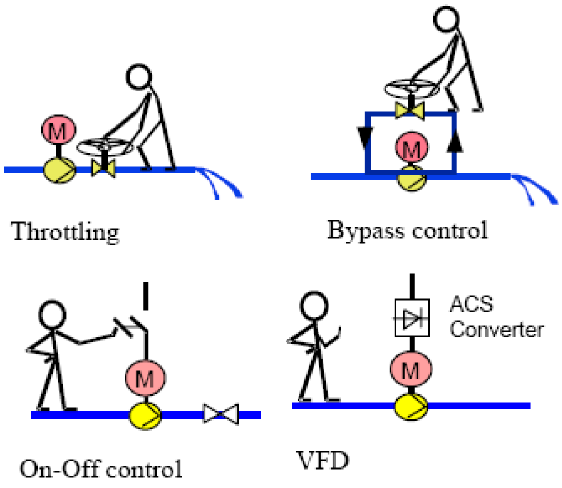

Fig. 4 Fluid Control Methods

The least efficient control method is the bypass control followed by the On/Off control. With bypass control, the superfluous flow is redirected back to the pump via the bypass valve. With On/Off control, the system is switched on and off depending on the actual flow or level requirement. This control method is often used in applications where a certain fluid level or capacity is controlled. The control method usually used for fixed speed operation is throttling where opening or closing a valve controls the flow. Depending on the valve position the motor has to work against the valve. This results in a waste of energy and higher maintenance cost. The use of a VFD is the optimal, most energy-efficient control method, which ensures that only the energy, which is required by the driven mechanical load, will be consumed. The VFD system losses are comparably low.

D. Improved process control performance

Compared to mechanical solutions such as damper/throttle, vane-, On/Off- or pitch control, VFDs provide a much smoother and more accurate way of controlling a process. With a VFD system, speed and torque can be adjusted and maintained with accuracies of 0.1% and better. As a result, depending on the application, the process is controlled in a more efficient way and the process output is of better quality. Other benefits include a lower system noise level and the integrated motor protection equipment, which is part of the VFD scope of supply. At DOL operation the motor protection equipment has to be supplied separately.

E. Elimination of voltage sags during motor startup

The start-up of a motor connected Direct-On-Line (DOL) typically comes with high inrush currents as pointed out in the previous paragraph. These currents are mainly of an inductive nature and therefore will cause remarkable voltage sag at the Point of Common Coupling (PCC) where the motor is connected and also at upstream and downstream PCCs. As a result, many other electrical loads connected to one of these PCCs can be severely disturbed and therefore malfunction. Opposed to that, during the start-up of a motor which is controlled via a VFD system, none or only negligible voltage drops will occur and no other electrical equipment in the plant will be negatively affected.

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F. Improved immunity against supply disturbances

Typically, disturbances in the supplying network such as

1) Transient spikes
2) Unbalance
3) Voltage dips lasting over a few cycles
4) Frequency deviations
5) Most severe, interrupts will have an impact on the performance of a DOL operated motor.

Especially voltage dips above a certain magnitude (typically >10%) will instantly result in a reduced output power or a complete loss of the driven process. With a VFD system, "ride through" capabilities will ensure that the process will not at all or to a reduced amount be affected by supply disturbances of the kind mentioned above. This is achieved with a DC link, which, as a part of the VFD system, decouples the motor side from the feeding supply side, as well as sophisticated motor control schemes. Also a short circuit in a DOL-operated motor will have a remarkable negative impact on the supplying network. With a VFD between the network and the motor, these short circuits are handled by the VFD system in a very fast manner and will have a minimum impact on the supply system.

G. Extended lifetime of motor and mechanical equipment

Due to the soft-start capabilities and the smooth, in a wide range adjustable speed and torque control capabilities of a MV-VFD system, the lifetime of the motor and the driven mechanical equipment will be extended. For example, due to the reduced pressure at partial load, the lifetime of pipes and other components is increased. By applying a VFD system, vibrations can be reduced which increases the lifetime of the equipment.

V. PERFORMANCE ASSEMENT OF VFD

For the assessment of performance and suitability of the VFD with a particular motor drive application in the industry, authors examined following criteria.

A. Repetitive Voltage Stresses

General-purpose induction motors are not designed for repetitive voltage overshoots that exceed line voltage plus 1000 volts. With a 230 VAC system, overshoots may not exceed this limit, but with a 575 VAC system, overshoots are likely. Repeated voltage stresses may lead to insulation breakdown and premature motor failure. To use a VFD with an existing general-purpose motor, additional filtering and transient protection may be required. NEMA definite-purpose motors rated "Inverter Duty" are recommended for use with VFDs. These motors can withstand repetitive voltage spikes that are 3.1 times the rated RMS voltage.

B. Adequate cooling for extended operation at very low speeds

Cooling often depends on motor speed, such as with Totally Enclosed Fan-Cooled (TEFC) motors. To meet constant torque loads, therefore, a motor should not be operated at less than 30 percent speed without additional cooling. Consider a larger motor, constant speed cooling or a Totally Enclosed Non-Ventilated (TENV) motor for these conditions. Motor thermal protection devices will prevent high-temperature damage when motors operate continuously at very low speeds. With variable torque loads such as centrifugal machines, the rapidly decreasing power at low speed reduces cooling problems.

C. Effect of Harmonic to sensitive equipment

Additional line filtering is often required to reduce the propagation of harmonics and Radio Frequency Interference (RFI) to other equipment. Short leads between the motor and the VFD help minimize RFI propagation. When leads are longer than 15 meters (50 feet), reactive filters are recommended. Motor leads should also be enclosed in a rigid conduit to reduce RFI.

D. starting torque and acceleration/deceleration adequate for the load

The VFD breakaway torque is less than the motor locked rotor torque and is limited by the VFD maximum current rating. This current rating also limits the rate of load acceleration. Acceleration, deceleration and maximum current are user-programmable.

E. Usability for the different types of loads

VFDs for use with constant torque loads should be rated for operation at 150 % load for a period of one minute. Variable torque loads such as fans and pumps are easier to start, and therefore the VFD overload rating is lower. The drive should be matched to the load.

F. Suitability for application have a high static pressure or head

Applications in which a minimum pressure must be maintained may not be suitable candidates for a VFD. For example, if high pressure is required even at low flow, it may not be possible to significantly reduce pump speed. When speed and flow reduce, so does pressure. For this application, other energy-saving strategies such as parallel pumps may offer more energy savings. Authors have to assess the pressure limitations in the system.

G. Types of Enclosure

Authors have to ensure the ratings of both the drive and its enclosure to make sure that they are suitable for the climate to which they will be exposed (i.e., outdoor weather protection).

H. Harmonic Distortion and Industry Standard

A discussion of the benefits of VFDs often leads to a question regarding harmonics. When evaluating VFDs, it is important to understand how harmonics are provided and the circumstances under which harmonics are harmful. A harmonic is any current form at an integral multiple of the fundamental frequency. For example, for 50-Hz power supplies, harmonics would be at 100 Hz (2 x fundamental), 150 Hz, 200 Hz, 250 Hz, etc.

VFDs draw current from the line only when the line voltage is greater than the DC Bus voltage inside the drive. 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 VFD design affects the harmonics

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produced. For example, VFDs equipped with DC link inductors produce different levels of harmonics than similar VFDs without DC link inductors. The VFDs with active front ends utilizing transistors in the rectifier section have much lower harmonic levels than VFDs 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 harmonics.

The number of Power Electronic Circuits (PEC) connected to the grid is steadily increasing. Each VFD is such a circuit. Due to their non-linear nature, these circuits have the inherent attribute of generating harmonics, which have to be limited in order not to cause undesired interactions with other electrical and electronic loads connected to the same bus. For that purpose, there are standards recommending strict harmonic limits. Examples of these standards are IEEE 519-1992, IEC 61000-2-4 or G5/4 [3]-[5]. In many cases, a 12-pulse input diode rectifier design will fulfill the above-mentioned harmonic standards. In some cases, where the network is weak, an 18-or 24-pulse configuration may be required. This has to be evaluated on a case-by-case basis. It is, however, questionable to extensively exceed the harmonic standards by means of overly complex transformer configurations and a high parts count, since this contradicts the reliability requirement. In the context of line friendliness, common mode components (i.e. harmonic orders being an odd multiple of three: 3, 9, 15…) should also be considered.

a. Soft-start of Mechanical Vapor Compressors with MV-VFDs

Narmada Sugar in Bharuch, India has been using VFDs for all previously mentioned applications for the past ten years. The installation of Mechanical Vapor Compressors (MVC) to reuse waste vapor is the latest ongoing innovative project at Narmada Sugar.

In this specific application, the starting sequence can be sub-divided into three phases. In the first phase, a selected motor is smoothly accelerated with the VFD from standstill up to nominal speed. This is followed by the second phase, in which the motors are synchronized with the supply network. Once the synchronization is completed, the motors will then, in the third phase, be bumplessly transferred to the grid. Due to the fact that the start-up and transfer is performed at low compressor load, the VFDs can also be designed for a lower power rating. The basic one-line diagram in Fig. 5 illustrates the equipment line-up

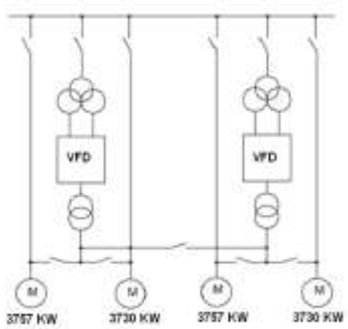

Fig. 5 Basic Electrical Diagram

At present, only a few benefits of a VFD system are utilized in this application. However, in case the MVC application proves to be a successful innovation, it is planned to upgrade the installation with VFDs that are rated for the full motor power in order to fully control the process with VFDs. The additional benefits of such a system, in particular energy savings, can then be fully exploited. For further information about the mechanical vapor compressor project at Narmada Sugar, the reader is referred to Fig. 6 and Fig. 7.

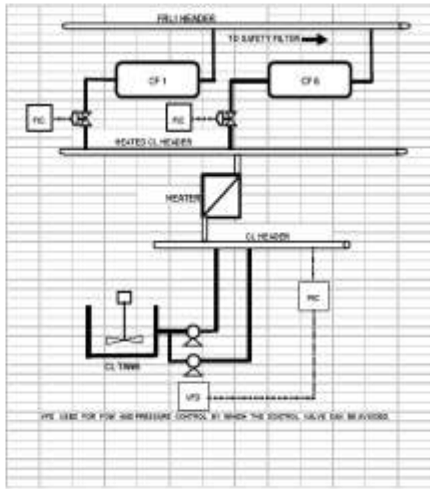

Fig. 6 Schematic of the Mechanical Vapor Compression System

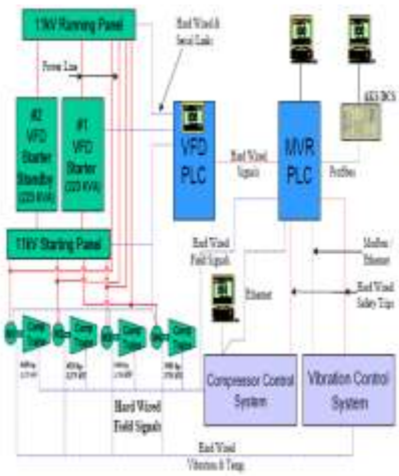

Fig. 7 Control system configuration for the Mechanical Vapor Compressors with VFD as soft-starting device

VI. CONCLUSION

The speed control of the motor drive system through Variable Frequency Drive (VFD) offers many benefits such as soft-starting, increase service life, protect against voltage disturbances and energy saving which is the prime requirement today. VFD along with motor drive system is a proven and efficient technology and its utilization is increase drastically in the industrial applications such as pump, fan, compressor, blower etc.

For the technical and economic reliability of such integrated approach of motor with VFD, analysis and assessment of the performance of the VFD is the key tool.

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Without analysis and assessment of VFD shown in this paper, the benefits of VFD may be realistic. Compare the VFD performance with others and benchmark for achieving highest benefits.

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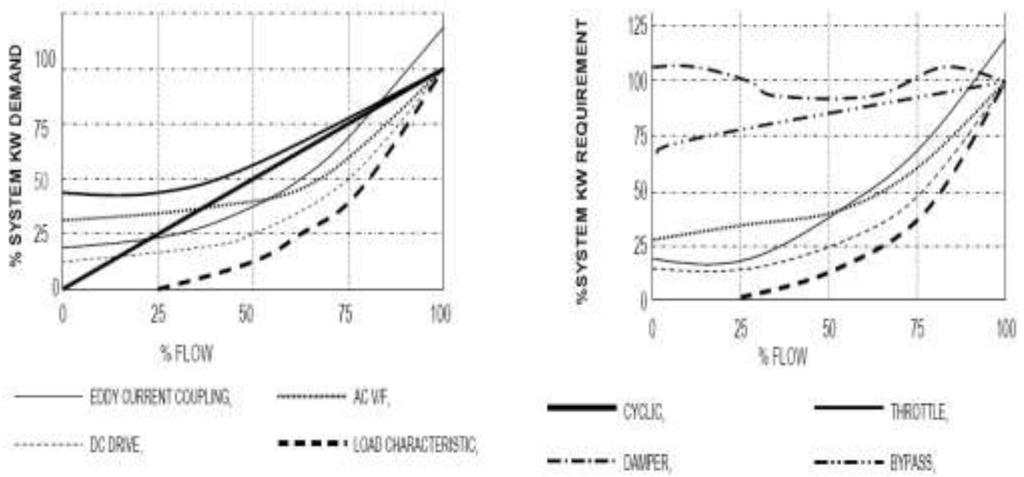

Fig. 2 Comparison of different Flow Control Methods for Pump and Fan