Energy Conservation Using Variable Frequency Drive

Annapurna Birdar and Ravindra G. Patil

Abstract: The paper describes the use and importance of VFD drive in firing of ceramic insulators. The ceramic insulators undergo certain physical treatments before being subjected to some mechanical and electrical test. Heat treatment is the most important one. This treatment makes the insulator durable, bonded and moisture less. The heating process is generally carried out in kiln. It requires gas or oil as fuel and air as medium.

Volume of air pumped into the kiln is controlled by air blower motor, which is necessary for firing of insulators. Variable frequency drives (VFDs) are used to control three phase induction motor which intern controls the output of an air blower motor. VFDs are used to vary supply frequency to control the speed of air blower motor.

Installation of VFDs offers high efficiency ease of operation and savings in cost due to less power consumption. VFDs require less maintenance, improve process control and have become the drive of choice in the majority of applications. In addition, speed control is generally the most energy efficient flow control technique because it requires the least amount of energy to meet the given load.

The project is designed to highlight the use of VFDs for the control of air flow in the kiln used for firing of insulators by varying the supply frequency.

Keywords: Blower Control, Energy Conservation, Speed Control, Supply Frequency Control, VFD.

I. INTRODUCTION

Motors are designed to run at a constant speed. However, motor drive systems are often operated at variable load. In particular, fans and pumps have highly irregular load profiles. This means, the motors on these systems either run at constant speed bypassing the excess capacity, or use some form of capacity regulation such as dampers, valves or inlet guide vanes, all of which are very inefficient. System output can be controlled by adjusting the speed of the motor using Variable Frequency Drives. VFDs offer higher efficiencies are easier to control, require less maintenance, improve process control and have become the drive of choice in the majority of applications. In addition, speed control is generally the most energy efficient flow controls technique because it requires the least amount of energy to meet the given load.

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II. INDUCTION MOTORS

Induction motors [3] are the most common motors used in the industrial motion control systems as well as in main powered home appliances. Although induction motors are easier in design than DC motors, the speed and torque control in various types of induction motors require a greater understanding of the design and the characteristics of these motors. Three phase induction motors are commonly used in adjustable-speed drives. Their main advantages over other motors are self-starting property, higher power factor, good speed regulation and robust construction.

Working principle

The working principle of the three-phase induction motor is based on the production of rotating magnetic field (RMF). Such a field is produced by supplying currents to a set of stationary windings, with the help of three phase ac supply. The current carrying windings produce the magnetic field or flux, due to the interaction of three fluxes produced due to three phase supply, resultant flux has a constant magnitude and its axis rotating in space, without physically rotating the windings. The RMF gets cut by rotor conductors as RMF sweeps over rotor conductors. As a result emf gets induced in the rotor conductors called rotor induced emf. Any current carrying conductor produces its own flux. Thus, the rotor produces its flux called rotor flux. As all the rotor conductors experience a force due to the interaction of the two fluxes, the overall rotor experiences a torque and starts rotating. Thus, interaction of the two fluxes is essential for motoring action.

Speed of an induction motor:

The magnetic field created in the stator rotates at a synchronous speed (Ns), which is given by

$$N_s = \frac{120f}{P}$$

Where, N_s= the synchronous speed of the stator magnetic field in RPM, P= the number of poles on the stator, f= the supply frequency in hertz

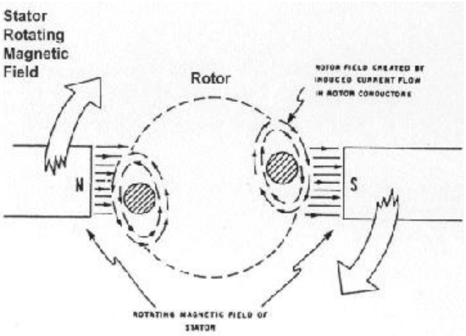

Figure 1: Operating principle of Induction motor

The magnetic field produced in the rotor because of the induced voltage is alternating in nature. To reduce the relative speed, with respect to the stator, the rotor starts rotating in the same direction as that of the stator flux and tries to catch up with the rotating flux. However, in practice, the rotor runs slower than the stator field. This speed is called the Base speed (N_b). The difference between N_s and N_b is called the slip. The slip varies with the load. An increase in load will cause the rotor to slow down or increase slip. The slip is expressed as a percentage and can be determined by the following expression.

$$\%slip = \left(\frac{N_s - N_b}{N_s}\right) * 100$$

Speed control of ac induction motors:

Speed control of a motor is a provision for intentional change of speed according to the requirement of workload connected with the motor.

A three-phase induction motor is inherently a constant speed motor and it is very difficult to achieve smooth speed control and if speed control is achieved by some means, the performance of the induction motor in terms of its power factor, efficiency etc gets adversely affected.

The speed of the induction motor depends on the frequency (f) and the number of poles. The synchronous speed can be obtained by the following expression.

$$N_r = (1 - s) * N_s$$

Where, 'Nr' is the rotor speed and s is the slip which has an operational range of 0.01 to 0.05.

Methods of Speed Control:

1. *Speed control by changing the rotor resistance*

Torque produced in case of three-phase induction motor is given by

$$T = \frac{k * s * E_2^2 * R_2}{R_2^2 + (s * X_2^2)}$$

Where, E_2 = rotor induced emf per phase on standstill condition

X_2= rotor reactance per phase on standstill

R_2= rotor resistance per phase on standstill

S= slip.

For low slip region $(s * X_2^2) \ll R_2$ and can be neglected and for constant supply voltage E_2 is also constant. Therefore, torque is inversely proportional to rotor resistance. Thus if the rotor resistance is increased, the torque produced decreases. But when the load on the motor is same, motor has to supply same torque as load demands. Thus, motor reacts by increasing its slip to compensate decrease in T due to R_2 and maintains the load torque constant. So due to additional rotor resistance R_2, motor slip increases i.e. the speed of the motor decreases. But this method has the following disadvantages:

- Large speed changes are not possible. This is because, for large speed change, large resistance is required to be introduced in rotor which causes large rotor copper loss to reduce the efficiency.
- The method cannot be used for squirrel cage induction motor.
- Speed above rated values cannot be obtained.
- Large power losses occur due to large losses and reduced efficiency.
- Sufficient cooling arrangements are required, which make the external rheostats bulky and expensive.

2. *Speed control by changing number of poles*

In the pole changing method, the stator winding of each phase is divided into two equal groups of coils. These coil groups are connected in series or parallel with the current direction being reversed only in one group to create two different numbers of poles (even) in the ratio 2:1 respectively. When the connection is changed from series to parallel or vice versa, the current in one of the group of coils is also reversed at the same time. This technique is called consequent pole method, which is applied to all the three windings (phases). This type of speed control is suitable for squirrel cage rotor which can adapt to any number of stator poles. This method has the following disadvantages:

- Smooth speed control is not possible.
- Two different stator windings are to be wound; hence increases the cost of the motor.
- Complicated from design point of view.

3. *Speed control by changing stator voltage*

The torque developed by an induction motor is proportional to the square of the voltage applied. If the supply voltage is reduced below rated value, torque also reduces. To supply the same load it is necessary to develop same torque hence the value of slip increases so that torque produced remains the same. Increase in slip means motor runs at a lower speed. This method of speed control is suitable for a narrow band of speeds. Starting currents of such motors is very high.

Also, the rotor must have high inherent resistance to limit the inrush of the current. This in turn means that the losses in the rotor will be very high since the power is dissipated as heat. This results in overheating of the rotor. This method is usually employed for slip ring induction motor. This method has the following drawbacks:

- Due to the reduction in voltage, current drawn by the motor increases and this may result in the overheating of the motor.

- Large change in voltages is required for small change in speed.
- Due to reduced voltage, rotor induced emf decreases the value of maximum torque. Additional voltage changing equipment is necessary.

4. *Supply frequency control or V/f control*
Since motor depends on the speed of the rotating field, which depends on the supply frequency, speed control can be affected by changing the frequency of the AC power supplied to the motor.
As in most machines, the induction motor is designed to work with the flux density just below the saturation point over most of its operating range to achieve optimum efficiency.
The flux density B is given by

$$B = \frac{k_2 * V}{f}$$

Where V is the applied voltage, f is the supply frequency and k_2 is a constant which depends on the stator winding constant stator turns per phase. In other words, if the flux density is constant, Volts per hertz is also a constant. This is an important relationship and it has the following consequences. For, speed control, the supply voltage must increase in step with frequency; otherwise the flux in the machine will deviate from the desired optimum operating point. Practical motor controllers based on frequency control must therefore have a means of simultaneous controlling the motor supply voltage. This is known as Volts/Hertz control.
Increasing the frequency without increasing the voltage will cause the reduction of the flux in the magnetic circuit thus reducing the motor's output torque. The reduced motor torque will tend to increase the slip with respect to the new supply frequency. This in turn causes a greater current flow in the stator, increasing the IR volt drop across the winding as well as I^2R copper losses in the windings. The result is a major drop in the motor efficiency. Increasing the frequency, still further will ultimately cause the motor to stall.
Increasing the voltage without increasing the frequency will cause the material in the magnetic circuit to saturate. Excessive current will flow giving rise to high heat dissipation due to I^2R losses in the windings and high eddy current losses in the magnetic circuit and ultimately damage to the motor due to overheating. Increasing the voltage will not force the motor to exceed the synchronous speed because as it approaches the synchronous speed, the torque drops to zero.
Hence, in this method, the supply to the induction motor required is variable voltage variable frequency supply and can be achieved by electronic scheme using converter and inverter scheme.

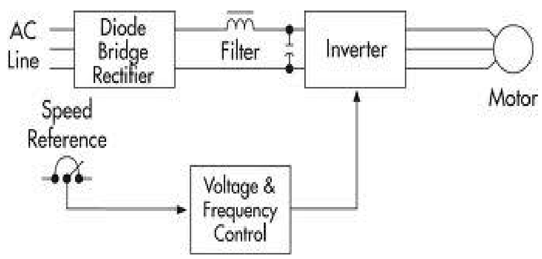

Figure 2: Electronic scheme for V/f control

The control system converts the desired speed to a frequency reference input to a variable frequency, variable voltage inverter. At the same time, it multiplies the frequency reference by the Volts/Hertz characteristic ratio of the motor to provide the corresponding voltage reference to the inverter. Changing the speed reference will then cause the voltage and frequency outputs from the inverter to change in unison.

III. VARIABLE FREQUENCY DRIVE

Brief Overview

Insulators are designed to work under variable atmospheric conditions and are subjected to high mechanical stress. They have to undergo certain physical treatments before they are used in practical applications. One of the main treatments is the heat treatment or firing. This process makes the insulator lose its moisture content and makes it durable and bonded. Insulators are heated at different pressures for different periods of time. The heating of insulators is done inside the kiln and air inside this heating chamber has to be maintained under certain pressure so as to maintain the necessary temperature. Air is used for combustion. The passage of air inside the kiln is done by using air blower which is driven by three phase induction motor. The amount of air sent into the kiln by this blower is controlled by using damper arrangement. The position of the damper is adjusted to let the required amount of airflow into the kiln. But, this method of controlling air pressure offers various disadvantages which are dealt with in detail in later in this chapter. This necessitated developing an efficient, economical, accurate and flexible method for the heating of insulators.
The paper involves the basic study of a VFD, its use in efficient firing of insulators, effective speed control method of air blower motor and obtaining the cost saving analysis for the same.
The VFD arrangement converts the supply as desired and this converted supply is given to the motor. The speed of rotation of the motor is controlled efficiently. [1]

Heat Treatment of Insulators

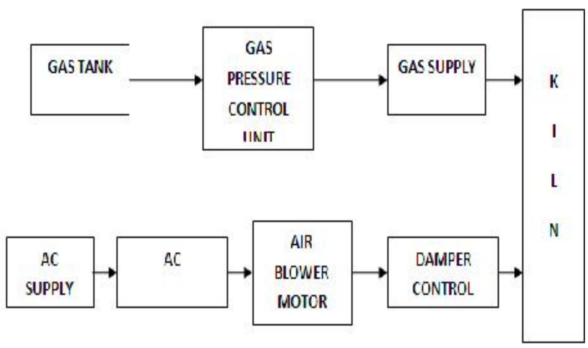

Figure 3: Block Diagram of treatment process

The parameters of the block diagram are explained below:

Fuel Tank: The fuel used in this kiln is gas. Huge cylinders made of steel are used for storing the gas fuel. This is placed in a remote place and the fuel is carried through steel pipes to the required areas.

Fuel Pressure Control: The pressure of the incoming fuel plays as important role in the prevailing temperature inside the kiln. The pressure and the air to the kiln decide the temperature inside the kiln. Dampers are used for the fuel pressure control and they are witnessed by using manometers.

Burner: Gas is supplied to the kiln using burners made of heat resistant materials. These burners are connected to the gas supply pipes through valves. The figure shows one of the burners in the kiln. A mixture of air and gas is sent inside the heating chamber. There is an ignition spark plug called a lighter which ignites the flame whenever required. The lighter operation is controlled manually.

Gas Supply: The gas is supplied to the kiln by using burners made of heat resistant materials. These blowers are connected to the gas supply pipes through valves.
The mixture of air and gas is sent inside the heating chamber. Using igniting spark plug which is called a lighter ignites the flame whenever required. The lighter operation is controlled manually at the remote station as the lighter is electrical igniter.

Kiln: The kiln is the heating chamber where the insulators are treated. The kiln is build with bricks and they are coated with heat resistive paints. Care is taken such that heat does not leak out as this leakage not only reduces the efficiency of the process but also affects the quality of the insulator.

Air Blower motor: Air blower controls the internal heat of the chamber. This setup consists of a three phase induction motor connected to a fan or blower. The pressure of air entering the kiln is controlled by using damper of speed drive arrangement. Separate pipes and tubes maintained for gas and air.

Burning Process: Liquid petroleum gas (L.P.G.) is used as a fuel in the burner. A small amount of fuel is passed through pilot valve to the ignition chamber and at the same time a voltage of about 5kV is applied across the spark plug through the ignition transformer. If the fuel is ignited the ultra violet (U.V.) sensor senses the blue flame and correspondingly a feedback is sent to the main valve for the continued supply of fuel. If the U.V. sensor doesn't sense the blue flame a feedback is sent to stop the further supply of fuel.
Air is supplied to the ignition chamber from primary and secondary air panel through blowers. The primary air panel supplies air necessary for burning and secondary air panel helps in the uniform distribution of air throughout the chamber.
Blowers work on the principle of centrifugal force. The amount of air flow into the blower is controlled by variable frequency drive (V.F.D's).

Dampers: An air damper comprises a cylinder having air ports at its upper and lower portions, a piston rod, a piston movably mounted on one end of the piston rod, a return spring, an air passage provided between upper and lower chambers within the cylinder which passage is opened and closed by the movement of the piston and an air regulating valve press-fit into the lower air port portion of the cylinder.

VFD System Description
A variable frequency drive system generally consists of an AC motor, a controller and an operator interface. A general block diagram of a VFD system is as shown in fig 4.

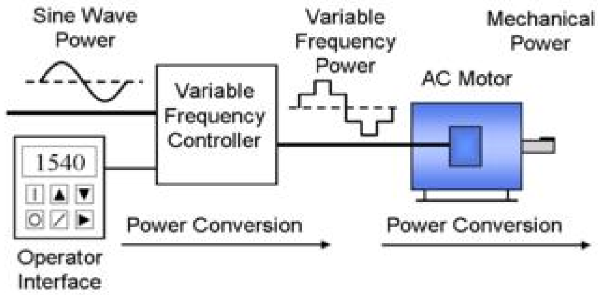

Figure 4: Variable frequency drive system

VFD Motor
The motor used in a VFD system is usually a three-phase induction motor .Some types of single-phase motors can be used, but three-phase motors are usually preferred. Various types of synchronous motors offer advantages in some situations, but induction motors are suitable for most purposes and are generally the most economical choice. Motors that are designed for fixed-speed mains voltage operation are often used, but certain enhancement to the standard motor designs offer higher reliability and better VFD performance.

VFD Operation
When a VFD starts a motor, it initially applies a low frequency and voltage to the motor. The starting frequency is typically 2Hz or less. Starting at such low frequency avoids the high inrush current that occurs when a motor is started by simple applying the utility (mains) voltage by turning on a switch. When a VFD starts, the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load without drawing excessive current. This starting method typically allows a motor to develop 150% of its rated current. When a motor is simply switched on at full voltage, it initially draws at least 300% of its rated current while producing less than 50% of its rated torque. As the load accelerates, the available torque usually drops a little and then rises to a peak while the current remains very high until the motor approaches full speed. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed while drawing only 150% current.
With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. A small amount of braking torque is available to help decelerate the load a little faster than it would stop if the motor were simply switched off and allowed to coast. Additional braking torque can be obtained by adding a braking circuit to dissipate the braking energy or return it to the power source.

Functional Block Diagram

As already mentioned in the VFD operation the conversion process incorporates three functions:

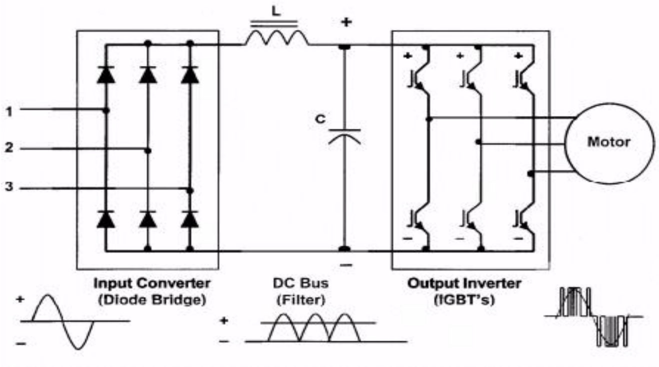

Figure 5: Circuit Diagram of Variable Frequency Drive

- *Rectifier Stage:* A full-wave, solid-state rectifier converts three-phase 50Hz power from a standard 440 or higher utility supply to either fix or adjustable DC voltage. The system may include transforms if higher supply voltage is used.
- *Inverter Stage:* Electronic switches-power transistors or thyristors- switches the rectified DC on and off, and produce a current or voltage waveform at the design of the inverter and filter.
- *Control System:* An electronic circuit receives feedback information from the driven motor and adjusts the output voltage or frequency to the selected values. Usually the output voltage is regulated to produce a constant ratio of voltage to frequency (V/Hz). Calculation may incorporate many complex control functions.

Advantages of VFD [5]

1. Bearing and winding life increases.
2. Smooth control of temperature, pressure and speed.
3. Maintenance and break down time decreases

IV. ENERGY SAVING ANALYSIS

Observations

Heating Cycle:

Consider the below mentioned temperature table 1which gives data for firing of insulators at different time Periods.

Table 1: The heating cycle of hollow insulators

Hours	Burner Temperature
1-5	175.83
6-10	274
11-15	413.2
16-20	554.4
21-25	735.6
26-30	871.6
31-35	912.4
36-40	975.4
41-45	1027.8
46-50	1035.2
51-55	1100.2
56-60	1109.4
61-65	1120.2
66-70	1181.4
71-75	1209.8
76-80	1259.0

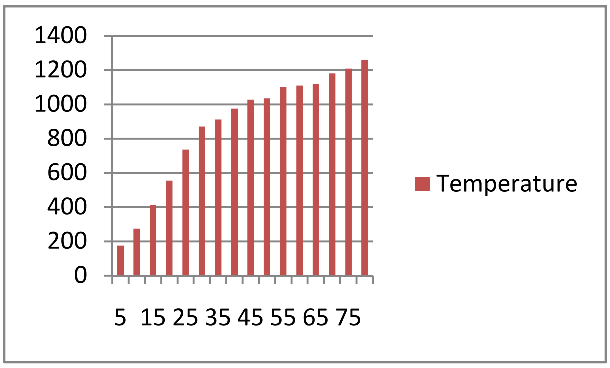

Figure 6: The Temperature Required for Firing at Different Time Periods

Table 2: The readings obtained for power consumption during the heating cycle of hollow insulators with the damper system

F[illegible] rate ([illegible]3/hr)	Hours	With damper	
		KW	KWh
300	19	11.3	215.1
350	2	11.4	22.8
400	14	11.9	166.2
625	2	11.9	23.8
800	2	12	24
825	2	12.5	25
860	2	12.6	25.2
875	2	12.6	25.2
725	2	12.5	25
850	5	12.5	62.5
900	2	13.2	26.4
770	2	12	24
330	2	12	24
360	2	12.3	24.6
400	2	11.6	23.2
500	2	11.6	23.2
600	2	11.4	22.8
850	2	11.9	23.8
900	3	12.6	37.8
950	2	12.7	25.4
1060	2	13.3	26.6
1775	2	14.4	28.8
Total	**77**		**925.38**

Table 3: The readings obtained for power consumption during the heating cycle of hollow insulators after installation of VFD

Flow rate (m³/hr)	Hours	With VFD			
		Speed	**Frequency**	**KW**	**KWh**
300	19	840	14	4.14	78.8
350	2	1080	18	4.41	8.8
400	14	1320	22	4.8	67.1
625	2	1340	22.3	5.57	11.1
800	2	1410	23.5	6.09	12.1
825	2	1490	24.8	6.14	12.8
860	2	1560	27.5	6.55	13.1
875	2	1620	27	6.59	12.2
725	2	1680	28	6.14	12.3
850	5	1740	29	6.48	32.4
900	2	1800	30	6.97	13.9
770	2	1830	30.5	6.02	12
330	2	1845	30.75	4.55	9.1
360	2	1920	32	4.8	9.6
400	2	2010	33.5	4.69	9.4
500	2	1845	30.75	5.04	10.1
600	2	1845	30.75	5.26	10.5
850	2	1830	30.5	6.17	12.3
900	3	1860	31	6.65	20
950	2	1950	32.5	6.83	13.7
1060	2	2000	33.3	7.41	14.8
1775	2	2040	34	9.51	19
Total	**77**				**416.3**

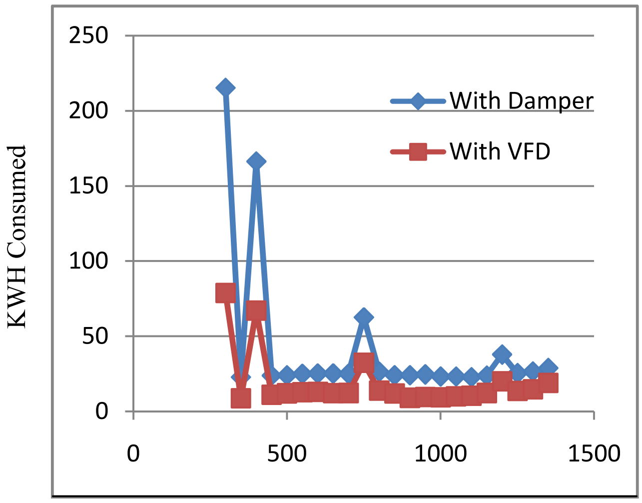

Figure 7: The Comparison of KWH Consumed When Damper and VFD are Used

The above graph infers that with the use of VFD, which controls the speed of air blower motor by varying the supply frequency and voltage, the power consumed by motor can be saved. As we know that the power consumed will be proportional to the cube of the motor speed, the power saved will be quite large. Thus for the best energy conservation, the Variable Frequency Drives can be used.

Saving Calculation

As already mentioned, the employment of VFDs result in considerable saving in energy for the industries and the payback period of the invested amount into the VFD is also very less. From the comparison of power consumption in between damper technique and the VFD system of speed control, the energy saving[1] per annum was calculated as below:

- Energy consumed (in KWh) with damper: 925.3 KWh
- Energy consumed (in KWh) with VFD: 416.3 KWh
- Difference in KWh per cycle : 925.3 – 416.3= 509 KWh
- No. of cycles per year : 55
- KWh saving per annum : 55*509=27995 KWh

Cost paid per unit of energy consumed for commercial purpose is *Rs 6.25*

- Total cost saving per annum: 27995*6.25 = 1.75 Lakh
- Cost of VFD : 1.5 Lakh
- Simple payback period : 1 year

Advantages of VFD System over Damper System

1. The method of firing the insulators became accurate
2. The temperature control of the firing chambers was easily done with the help of AC drives
3. Loss of energy of the dampers while firing the insulators was minimized
4. There was considerable increase in the production of the insulators as the number of fault pieces is minimized.
5. Increased efficiency

V. CONCLUSION

The declining resources combined with environmental global warming concerns and increasing energy prices make energy efficiency a crucial objective. Furthermore, improving energy efficiency is often the cheapest, fastest and most environmentally friendly way to meet the world's energy needs. [4]

The paper is designed to highlight the use of VFDs for the control of air flow in the kiln used for firing of insulators by varying the supply frequency.

Replacing the dampers by VFDs in the firing of insulators gives more accurate firing and reduces the cost of production of insulators. By the use of VFDs, loss of energy in damper operation can be minimized and man power is reduced.

From the above estimation we can conclude that the efficiency is increased and energy can be conserved economically.

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