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Effect of Voltage Variation on Efficiency of Motor- An Industrial Case Study

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Abstract:- The energy sector holds the key in accelerating the economic growth of India. To achieve Economic Growth, we need to and have to use more and more energy to increase the pace of development. On the consumption front, the industrial sector in India is a major energy user accounting for about 52 percent of commercial energy consumption. Electrical energy and thermal energy constitutes the major operating cost of any industrial sector. This paper deals with the energy conservation opportunities which can be taken forward by any industrial sector without major investments.

Keywords:- Energy conservation, Energy efficiency, Voltage variation, Constant power loads, constant torque loads.

I. INTRODUCTION

Energy intensive industries are provided with high tension supply which is transformed to the adequate voltage level through substations or its power requirement is met by the captive power generation. The total power produced is utilized in the industrial processes, lighting and residential needs. There is great diversity in industrial applications of electric motors and drives: pumps, fans, compressors, conveyors, machine tools, and other industrial equipment. Electric motors are used throughout the industry, and represent over 80% of all electricity use in the industry. A large fraction of electrical energy consumed in many facilities is used to run electric motors. The electric motors will be driving loads like constant torque loads, constant power loads and pumps. Constant torque loads like air compressors accounts for about 15%, pumps and fans accounts for around 70% and the rest are constant power loads likes coilers and other type of loads. Air compressor loads are least energy efficient and its efficiency comes to around 10-30%. In an industry the majority of the loads will be pumps, fans and blowers. Since around 80% of power is processed at the motors it is necessary to analyze the efficiency pattern of the motors with respect to its loading and the supply voltage. In the supply chain of power from the generating side, losses can occur all the way till the load. They are the transmission losses that include both cable and transformer and at the load end the losses constitute stator, rotor and the friction and windage losses. Therefore if the equipment is energy inefficient or the operating point is far away from that of the actual point of consumption then the whole system consumes more power. This requires increased power flow through the network which increases the transmission losses and is to be loaded high to cope with the increased power flow.

II. ENERGY EFFICIENCY APPROACH

In order to analyze these effects of input voltage and power drawn from the supply side, a variable voltage study is done on motors driving constant torque loads, constant power loads and pumps (centrifugal loads). Since the constant torque and power loads accounts only to a lower proportion, the main concentrated area is on pumps (centrifugal loads). Effect of voltage on slip, power and torque of centrifugal loads are discussed here. For the study, a motor of 40HP, 440V, 1500rpm, and 4 poles is considered. The results are obtained using per phase equivalent circuit of the system.

III. EQUIVALENT CIRCUIT OF INDUCTION MOTOR

The induction motor is represented using its equivalent circuit considering the stator resistance and inductance, rotor resistance and inductance and magnetizing resistance and inductance. The per phase equivalent circuit of a three phase induction motor is shown in the Fig.1 below. The rotor winding resistance and inductance is transferred to the stator side by considering turns ratio K. The load is an electrical load represented by $R_2'(\frac{1}{s}-1)$. Current I_1 is the total current drawn by the motor, I_1' is the current flowing through the stator and I_0 the magnetizing component of current.

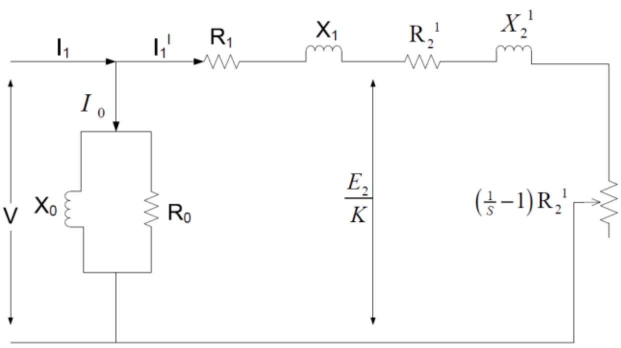

Fig. 1: Per phase equivalent circuit of a 3-phase induction motor

From the above equivalent circuit diagram we can write

$$(I_1^{'})^2 = \frac{V^2}{R_1^{\,2} + \frac{2R_1R_2^{'}}{s} + \frac{(R_2^{'})^2}{s^2} + X_{01}^2}$$

Where,'s' is the slip and X_{01} is the sum of the stator reactance and rotor reactance referred with respect to the primary. The equivalent circuit parameters per phase of the three phase induction motor are obtained from the no load test and the blocked rotor test and is shown in the Table 1.

Table 1: Equivalent circuit parameter values

Parameters	R_0	X_0	R_1	$R_2^{'}$	X_1	$X_2^{'}$
Values (Ω)	99.611	12.68	0.1234	0.1289	0.1914	1.5486

IV. CENTRIFUGAL LOADS AND MOTOR EFFICIENCY ANALYSIS

Majority of the loads driven by the motors are centrifugal loads in any industry. Among them centrifugal pumps constitutes major proportion. Therefore the energy consumption pattern of pump is very important in case of any type of industries. The pumps encounter endless combinations of pressure, density, viscosity, temperature, volatility, corrosiveness and solvent action, of solids in suspension and gases in solution. The volume of fluid delivered by the pump against a constant pressure head is proportional to the power output of the motor, that is, to cube of the speed. The power P_i absorbed by the pump is given by $P_i\alpha\omega^3$. So varying the rotational speed has a direct effect on the performance of the pump. Therefore doubling the speed of the centrifugal pump will increase the power consumption by 8 times. Conversely a small reduction in speed will result in drastic reduction in power consumption. This forms the basis for energy conservation in centrifugal pumps with varying flow requirements. Therefore with the increase in voltage supply to a motor-pump load system there will be an increase in speed and hence reduction in slip. The torque speed characteristic of a pump load is shown in the Fig.2 below. From the figure we can represent mechanical torque developed as $T\alpha\omega^2$

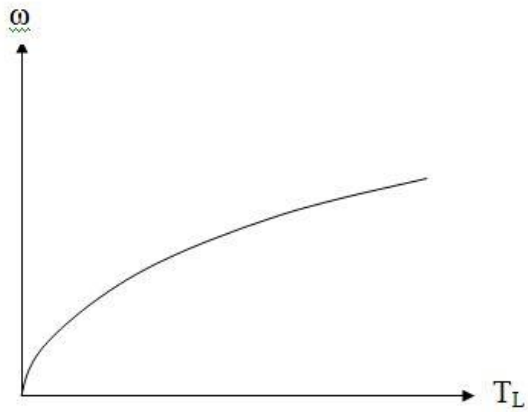

Fig.2: Torque speed characteristics of a pump load

The power output of the motor is given by

$$P = \frac{2\pi NT}{60}$$

Therefore Torque T can be represented in terms of equivalent circuit parameters as given below.

$$T = \frac{3}{\omega_{ms}} \times \frac{V^2 \frac{R_2^l}{S}}{\left[R_1 + \frac{R_2^l}{S}\right]^2 + \left(X_1^l + X_2^l\right)^2}$$

The value of rated torque is found by substituting the rated voltage and rated slip. The load torque T_L is proportional to (speed)^2. Thus we can write $T_L=K(1-s^2)$. The value of constant K is found by equating the full load torque T to load torque T_L. The actual value of slip is solved from the below mentioned equation for various values of voltages range of ±5% on the 440V level base.

$$K(1-s)^2 = \frac{3}{\omega_{ms}} \times \frac{V^2 \frac{R_2^l}{S}}{\left[R_1 + \frac{R_2^l}{S}\right]^2 + \left(X_1^l + X_2^l\right)^2}$$

The analysis of motor connected to a pump load is done for 100% loading, 80% loading and 60% loading. This is explained in the following sections.

A. 100% Load on motor

The rated torque of the motor is 106.45Nm and the value of K is calculated for the rated slip of 4%. The voltage is varied from 415V to 460V and the corresponding slip is solved form the below mentioned equation.

$$K(1-s)^2 = \frac{3}{\omega_{ms}} \times \frac{V^2 \frac{R_2^l}{S}}{\left[R_1 + \frac{R_2^l}{S}\right]^2 + \left(X_1^l + X_2^l\right)^2}$$

The slip will be having four solutions and three of them are beyond the range of the acceptable values of slip and the suitable value is taken into consideration to calculate the efficiency, current drawn, active power absorbed and reactive power drawn from the supply.

The variation of slip, efficiency, active power drawn and reactive power drawn are shown in the Fig.3. With the increase in voltage the slip goes on decreasing and hence the speed increases. As discussed above as the speed increases the power drawn from the supply increases at a higher rate, as $P_i \alpha \omega^3$. Thus we can observe that the efficiency for the machine taken into consideration varies from around 82% to 88% when the voltage is varied from 415 to 460.

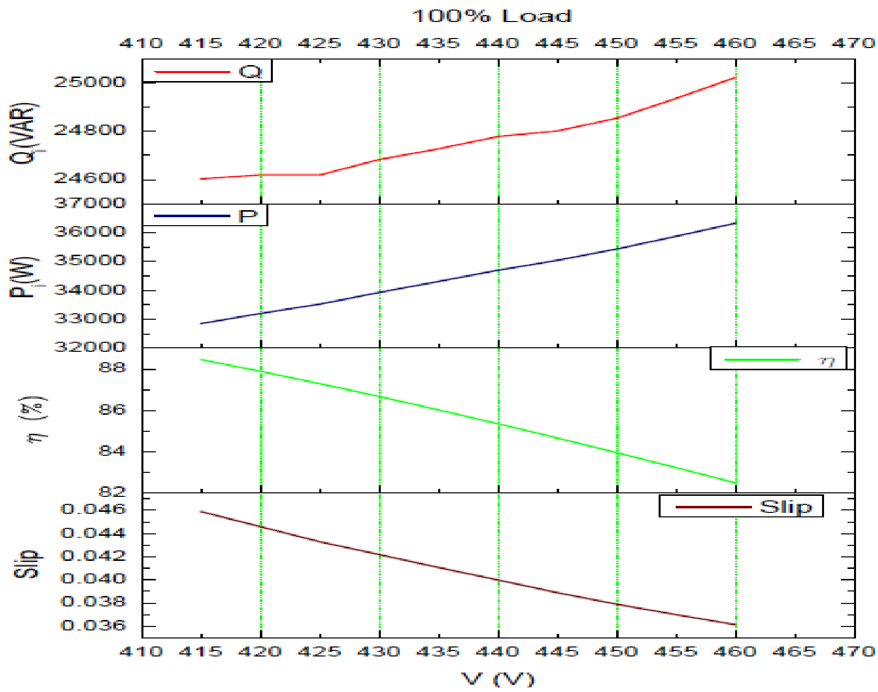

Fig 3. Variation with respect to voltage variation- 100% load

Thus higher the voltage, speed will be higher, power drawn also becomes higher and hence the efficiency drops steadily. It can be concluded that in order to draw higher power input the amount of losses occurring in the line also increases and also the generator has to supply that extra power required. This acts as an additional load on the system. The values and range over which the efficiency varies acts as a trend line which can be used to analyze the system. Therefore even if Variable Frequency Drives (VFDs) are also installed to control the operating speed, the input power drawn by the VFDs will be higher because of high voltage at the input. Therefore the savings made by the VFDs are counterfeited by the high input voltage supply which causes more loading on the generator and on the transmission lines.

B. 80% and 60% Load on motor

100% loading on the motor is not a practical case as the motor might be an over designed motor or the loading on it may be happening in the range of 60-80%. Therefore it is required to analyze the performance of the system under practical cases. For rated voltage and the corresponding percentage torque the values of slip is computed and the constant K is calculated. Then the voltage is varied to find the variation of speed and hence the efficiency. Fig 4 shows the parameter variation with respect to voltage variation for 80% load on motor.

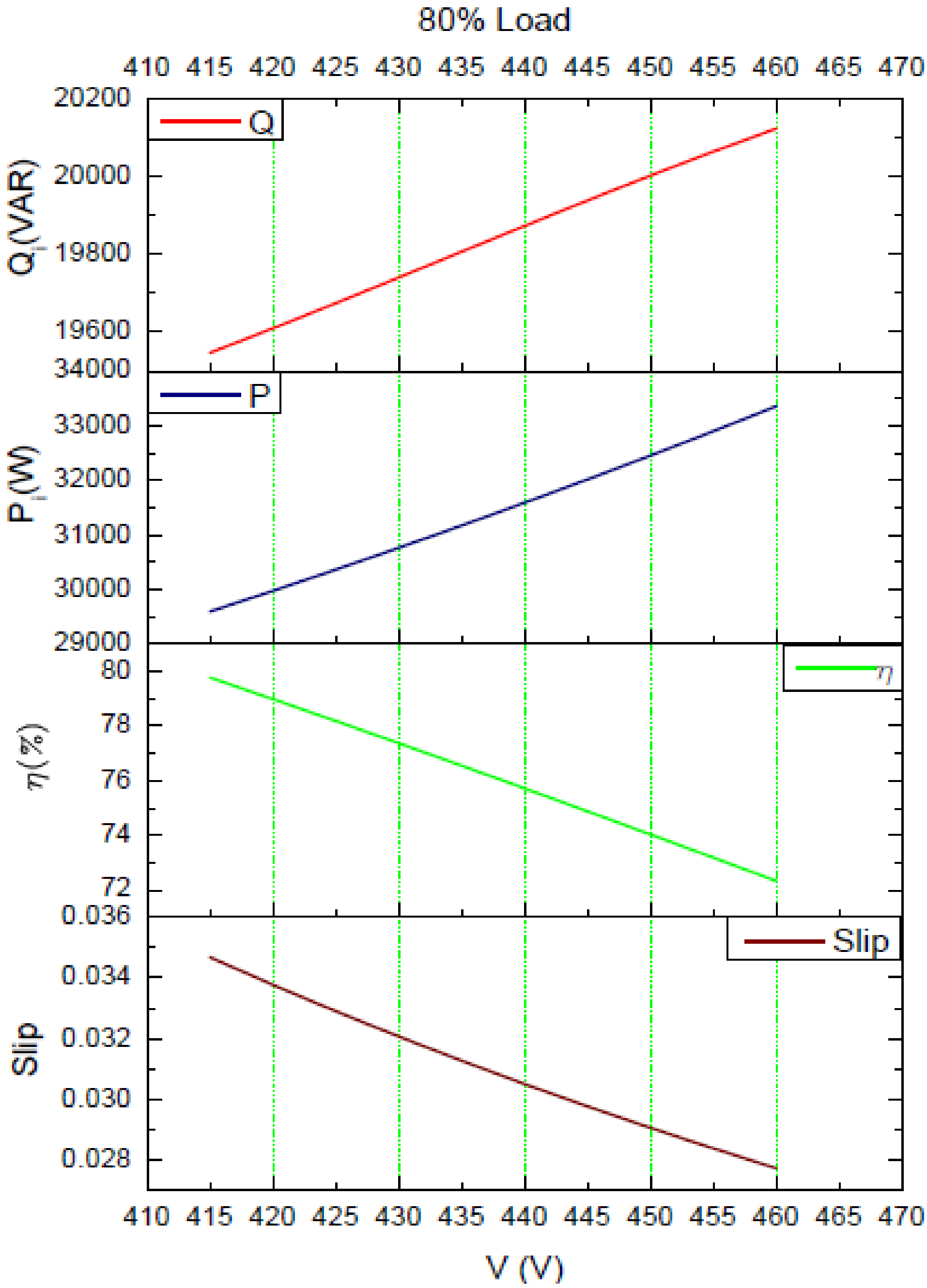

Fig 4. Variation with respect to voltage variation- 80% load

Similarly the efficiency variation for a motor which is loaded upto 60% is shown in Fig. 5.

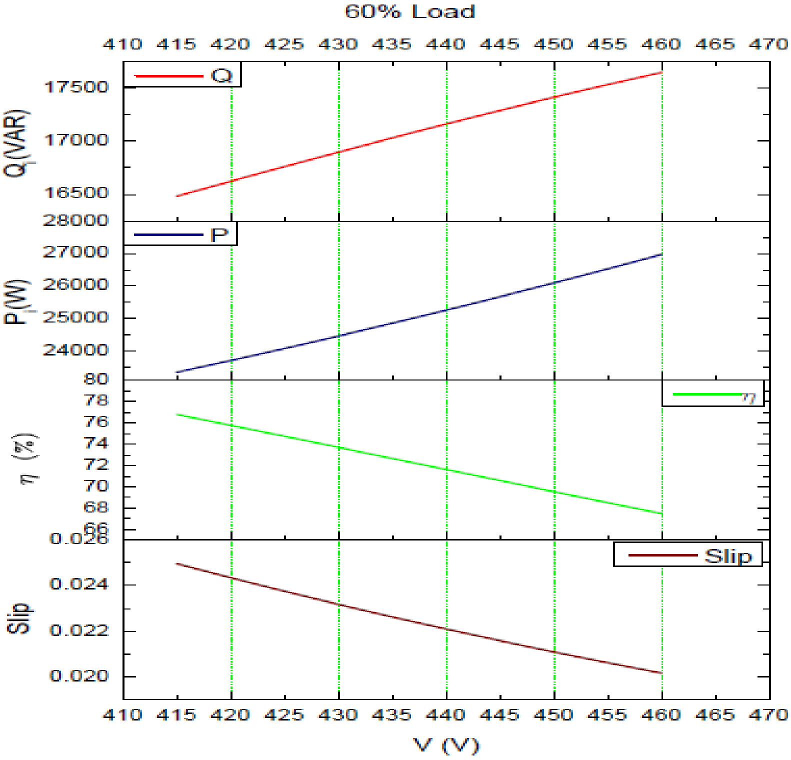

Fig 5. Variation with respect to voltage variation- 60% load

It is evident from the figure that with the reduction in loading the range over which efficiency swings increases and hence it is required to control the input voltage to a nominal value as the voltage input to all the equipment are mostly above the rated voltage of the equipment. The active and reactive power input also increases with the voltage and hence the efficiency drops. Also when the voltage increases and the loading reduce the magnetizing component of current which depends on the input voltage also starts increasing and hence the power factor of machine also reduces. All these effects will in effect reduce the efficiency of the motor-load combination.

It can be concluded that with the increase in the supply voltage to the equipment, the amount of active and reactive power drawn from the generators goes on increasing. This will unnecessarily load the transmission lines and increases the losses. Also operating the equipment at a voltage higher than the rated voltage will result in frequent failure of the equipment.

V. CONCLUSIONS

Majority of the industries maintain the bus voltages at 5-10% higher than that of the rated voltage of the equipment. From the analysis it can be concluded that the operating efficiency of the equipment is reduced by operating it at a higher voltage. This results in increased generation and hence increased transmission loss and power usage by the equipment. It is therefore recommended to operate the equipment at a rated voltage level to bring down the operating losses.

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