Comparison of Conventional Induction Motor-Pump System with One Containing a Variable Frequency Drive: A Quantitative Performance Analysis in Low-Voltage Conditions

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***Abstract*—Voltage variation is a common problem in Bangladesh. This gives rise to a considerable decline in the efficiency of motors that are employed in industries. If dynamic change in frequency can be provided in response to the voltage variation, the system efficiency can be enhanced to a significant degree. This paper compares two three-phase motor-pump systems. The first scheme is a model of the conventional motor-pump structure currently employed in industries, consisting of a three phase induction motor and a centrifugal pump. The second scheme incorporates a variable frequency drive (VFD) into the motor-pump system. This paper aims to evaluate the performance of each system with regards to power consumption at voltages that are lower than the rated voltage of the motor, as a means to demonstrate the advantage offered by the VFD. Simulation is done in MATLAB Simulink. The results show that, in low-voltage conditions, the system containing VFD exhibits near-constant efficiency throughout the entire voltage range, whereas the conventional system suffers from great reduction in efficiency accompanied by a decreasing voltage. Thus, it has been quantitatively proven in this paper that a VFD is an extremely beneficial tool in preserving the efficiency of a motor-pump system in low-voltage conditions.**

***Index Terms*—variable frequency drive (VFD), three phase supply, induction motor, input and output power, MATLAB Simulink**

I. Introduction

The energy-deprived situation of Bangladesh is a well documented fact. Here, up to 800 MW of load shedding occurs during summer [1]. In addition, significant amounts of technical and non-technical losses are incurred in the power sector, which account for 15% of total production cost [2]. In a time when the nation faces serious scarcity in its energy sector as the demand for power far surpasses the production capacity, it is imperative that we take every step possible to reduce wastage of energy to an absolute minimum.

The share of agriculture and industry sectors in electricity consumption is increasing gradually. According to statistics, about 45 percent of total electricity is consumed by these sectors [3]. Many industries, including petrochemical companies and the Water Supply and Sewage Authority (WASA), employ three phase motors and centrifugal pumps. The supply voltage from the Bangladesh Power Development Board (BPDB) and other major distributors vary to a certain extent, which does not fulfill the optimum condition for any motor-pump system. While most of the industries feel that they over-pay for the quality of power they receive, about 50% of them are willing to pay even more for higher power quality [4]. If dynamic change in voltage and frequency can be provided in correspondence with the input power, the system efficiency can be enhanced to a significant degree. A variable frequency drive (VFD) is a device that controls the voltage and frequency that is being supplied to the motor and therefore controls the speed of the motor and the system it is driving. By meeting the required process demands, the system efficiency is improved [5].

Most of the time, pump-motor systems are not operated at full load. Traditionally, devices that throttle output have been employed to reduce the flow. However, when compared with speed control, these methods are significantly less efficient [6]. Proper matching of overdesigned pumps with the electrical system, precise control of fluid level and pressure according to requirement, and minimization of fluid hammer due to soft start are a few compelling reasons to consider using a VFD [7].

A number of researches have been conducted in order to demonstrate the effect of incorporating VFDs into electrical systems. Ghafouri, *et al.* [8] attempted to model a constant speed pump-motor system and a variable speed system that employs a PID controller. Burt, *et al.* [9] analyzed motor efficiencies for variable speeds and loads by measuring various parameters with the help of data logging technique, in order to aid designers in estimating total pumping plant power usage with a VFD installation. Hanson, *et al.* [10] used a mobile VFD to perform tests at five different irrigation sites, where comparisons were made between normal operating system and VFD system

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with regards to pressure, pumping lift and input horsepower. Weber, *et al.* [11] presented the engineering fundamentals of a multi megawatt VFD along with some basic topologies and applications associated with each type.

This paper utilizes the SimPowerSystems toolbox of MATLAB Simulink to design the aforementioned motor-pump systems. In each case, a 3-phase, 4-pole, 415V, 3HP induction motor is used, where the supply voltage is varied and the corresponding values of the input power, output power, and hence efficiency is found. After a considerable number of simulations, the voltage-power curves have been obtained, which gives an idea of the amount of power that can be saved when the motor operates at lower-than-rated voltages.

II. The Role of VFD in Low-Voltage Conditions

The squirrel-cage induction motor is the most widely used motor in industry due to its simple construction and rugged design. The fact that it does not require a commutator, slip-rings or brushes makes it easy to maintain. Fig. 1 shows the equivalent circuit of the induction motor.

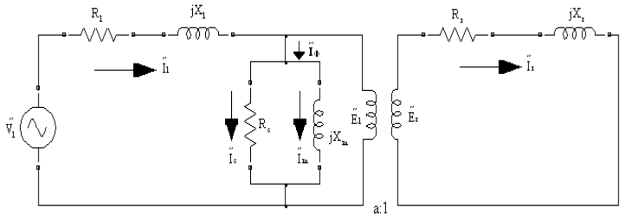

Figure 1. Per-Phase equivalent circuit of an induction motor.

A. *Effect of Low Stator-Voltage in an Induction Motor*

The torque-speed curve of an induction motor is shown in Fig. 2. If the voltage across the stator is lower, the operating point shifts to the left, giving rise to a wider range of operating speed. However, at this low voltage, the current drawn by the motor will be higher because it has to support the same rotating flux within the machine. This means that for a fixed load, the I^2R losses will be greater and, as a result, the efficiency will drop.

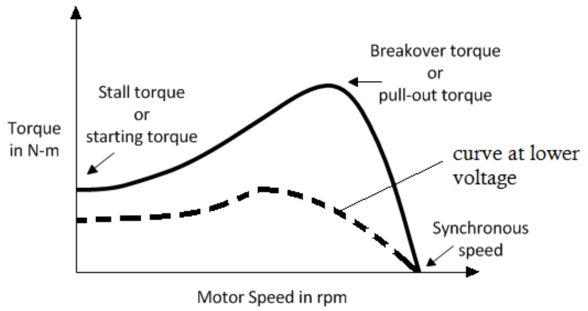

Figure 2. Typical speed-torque characteristic for a three-phase induction motor

B. *How the VFD Helps to Maintain High Motor Efficiency*

In the equivalent circuit shown above, if we neglect the leakage reactance drop and the winding resistance drop, essentially the voltage applied across the stator is given as follows.

$$V_s = jX_m \times I_m \tag{1}$$

In the above equation, X_m is the magnetizing reactance and I_m is the magnetizing current. Therefore, if we want to keep I_m constant, then the ratio V_s/X_m must be constant. X_m can be expressed as follows.

$$X_m = 2\pi f L_m \tag{2}$$

here, f is the supply frequency and L_m is the magnetizing inductance. The only variable in the right-hand side of the above equation is f. Therefore, the ratio of V_s/X_m can be kept constant by changing only the frequency in response to any changes in the stator voltage. Hence, the efficiency of the system is also preserved. Since constant flux is provided, this means that the torque at any voltage will also be constant. The speed torque characteristic of a motor using VFD at different stator voltages is shown in Fig. 3.

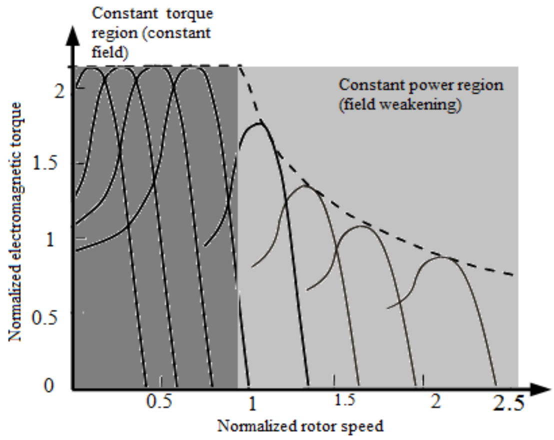

Figure 3. Speed-Torque characteristics of a motor using VFD at various voltages.

III. System Design in Simulink

A. *Motor-Pump System without VFD*

The first system is composed of a three phase, star configured voltage source connected to a squirrel cage induction motor, as shown in Fig. 4. Using the bus selector block, the stator current for one of the phases is chosen to be viewed on the scope, along with the rotor speed and electromagnetic torque. Assuming a centrifugal pump as the load, we can use (3) to (7) in order to describe the relationships between various motor parameters [12]. For a fan or pump type load, the torque is proportional to the square of speed, as shown in (3).

$$T = k \times \omega^2 \tag{3}$$

In (3) above, T is the electromagnetic torque produced by the motor, ω is the speed of the rotor and k is a constant of proportionality. Since supply frequency is 50Hz, the synchronous speed for the 4 pole machine is found using equation (4).

$$N_s = \frac{120 f}{p} \tag{4}$$

here N_s is the synchronous speed of the motor, f is the frequency of the supply voltage and p is the number of poles. Thus the synchronous speed is 1500rpm, or 157.08rad/s. We can now calculate the nominal torque of the motor as shown in (5) below. This yields a value of 14.25Nm for the 3HP motor.

$$T_n = \frac{P_n}{\omega_n} \tag{5}$$

here T_n is the nominal torque, P_n is the horsepower rating and ω_n is the synchronous speed of the motor. Hence, the value of k in (3) is found to be 5.77×10^{-4}Nms^2. This value of k is multiplied with the square of the rotor speed and fed back to the torque input of the motor, thus creating a model for a centrifugal pump type load.

The total input power, P_{in}, at each voltage is calculated by summing the power delivered at each individual phase, as shown in (6). The output power, P_{out}, is found from the product of load torque, T_{load}, and rotor speed, ω_r, as shown in (7).

$$P_{in} = V_{ph(a)} I_{ph(a)} + V_{ph(b)} I_{ph(b)} + V_{ph(c)} I_{ph(c)} \tag{6}$$

$$P_{out} = T_{load} \times \omega_r \tag{7}$$

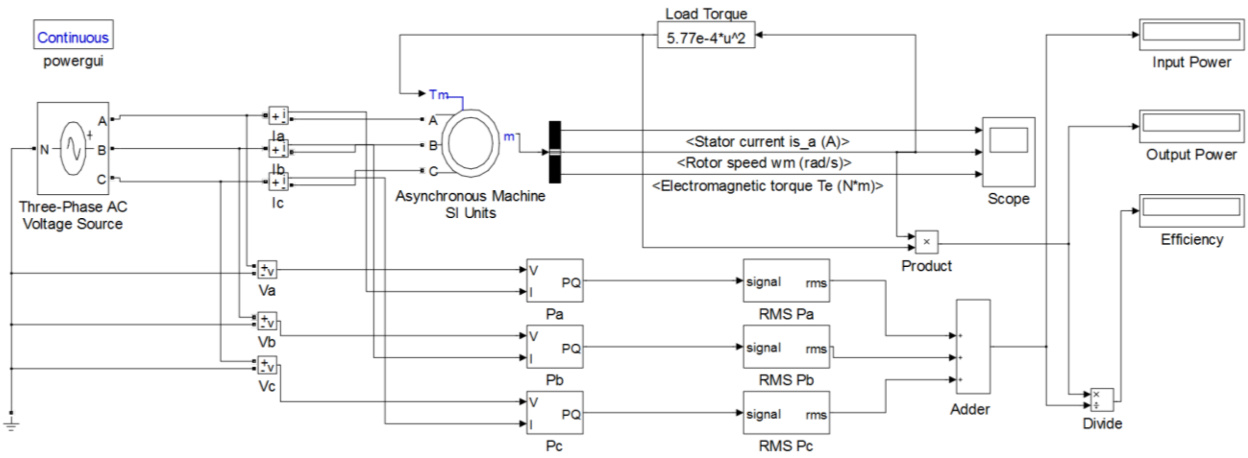

Figure 4. Model representation of a conventional motor-pump system in Simulink.

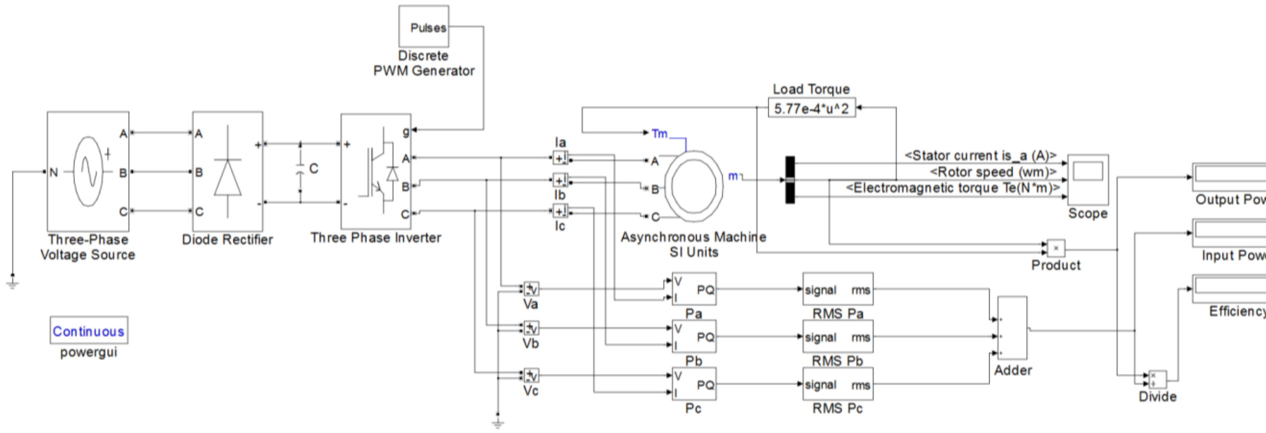

Figure 5. Model representation of a VFD motor-pump system in Simulink.

B. VFD Controlled Motor-Pump System

The second system, shown in Fig. 5, incorporates a VFD between the supply and the induction motor. The fundamental components of a VFD are the rectifier, DC link and inverter. The rectifier converts supply AC voltage to DC voltage. A bank of electrolytic capacitors constitutes the DC link, which stores electrical energy for the inverter to draw against and function properly. Finally the inverter converts the DC link voltage back into AC voltage whose frequency and magnitude can be changed according to system requirements.

Since the loading of the motor in this system is identical to that of Fig. 4, (3) to (7) are applicable for this system as well. However, the percentage of rated voltage applied to the motor is varied using the modulation index, m, of the pulse width modulated (PWM) inverter according to (8).

$$V_{rms\,line} = \frac{m}{2} \times \sqrt{\frac{3}{2}} V_{DC} \tag{8}$$

The value of V_{DC} is kept constant while calculating the modulation index for each value of percentage rated voltage. For the purpose of investigation, the percentage of rated voltage is varied keeping the Volts/Hertz ratio constant. At rated condition, line voltage is 415V and frequency is 50Hz. Consequently, the frequency is varied using (9). Finally, the efficiency, η, is calculated using (10).

$$f = \frac{3}{11} \times V_{rms\,line} \tag{9}$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\ \% \tag{10}$$

IV. Configuring the Solver

For the sake of demonstrating the effects of voltage changes on the power input and output, a significantly large number of simulations had been run for each system. In such a case, the time required for each simulation becomes an unavoidable issue. Especially when the VFD system is considered, the high switching frequency of each Insulated Gate Bipolar Transistor (IGBT) delays the runtime even further. The end result is a compromise between accuracy and simulation speed. The key is to set the relative tolerance to a value which reduces runtime considerably while having very little effect on the accuracy of the waveforms. Choosing a fixed step solver helps reduce the runtime to a certain degree. Discretizing the electric circuit is another alternative. A larger sample time can be used, provided that it is a multiple of the smallest sample time [13].

The systems under investigation, however, contain Signal-to-RMS converter blocks, which require variable step solvers. Hence, ode-23tb was selected with a relative tolerance of 10^{-4}. In addition, the models were run in accelerator mode. The accelerator mode works with any model, but performance decreases if a model contains blocks that do not support acceleration [14]. The number of scopes and displays used in each model were also kept small, since these are also causes of prolonged runtime.

TABLE I. Results for Normal Motor-Pump System

% of Rated Voltage	Input Power/W	Output Power/W	Efficiency (%)
45.45	1050	295	28.10
47.73	1174	370.4	31.55
50	1304	461.6	35.40
52.27	1439	569.3	39.56
54.55	1571	691.2	44.00
56.82	1694	820.6	48.44
59.09	1801	948.2	52.65
61.36	1890	1066	56.40
63.64	1962	1171	59.68
65.91	2020	1263	62.52
68.18	2067	1342	64.93
70.45	2105	1411	67.03
72.73	2138	1471	68.80
75	2165	1542	71.22
77.27	2189	1571	71.77
79.55	2209	1613	73.02
81.82	2227	1651	74.14
84.09	2242	1685	75.16
86.36	2256	1716	76.06
88.64	2269	1744	76.86
90.91	2280	1770	77.63
93.18	2290	1793	78.30
95.45	2300	1815	78.91
97.73	2308	1835	79.51
100	2316	1854	80.05

TABLE II. Results for VFD Motor-Pump System

% of Rated Voltage	Modulation Index	% of Rated Frequency	Input Power/W	Output Power/W	Efficiency (%)
45.45	0.4082	45.45	254.6	192.3	75.53
47.73	0.4287	47.73	290.8	221.7	76.24
50	0.4491	50	330.2	254	76.92
52.27	0.4695	52.27	373.3	289.1	77.44
54.55	0.4899	54.55	420	327.2	77.90
56.82	0.5103	56.82	470.4	368.4	78.32
59.09	0.5307	59.09	525	412.9	78.65
61.36	0.5511	61.36	583	460.5	78.99
63.64	0.5715	63.64	645.7	511.7	79.25
65.91	0.5920	65.91	712.5	566.3	79.48
68.18	0.6124	68.18	784.5	624.4	79.59
70.45	0.6328	70.45	859.7	686.2	79.82
72.73	0.6532	72.73	939.9	751.7	79.98
75	0.6736	75	1026	822	80.12
77.27	0.6940	77.27	1116	894.3	80.13
79.55	0.7144	79.55	1211	971.5	80.22
81.82	0.7348	81.82	1311	1053	80.32
84.09	0.7553	84.09	1418	1138	80.25
86.36	0.7757	86.36	1528	1228	80.37
88.64	0.7961	88.64	1645	1321	80.30
90.91	0.8165	90.91	1768	1419	80.26
93.18	0.8369	93.18	1896	1521	80.22
95.45	0.8573	95.45	2030	1628	80.20
97.73	0.8777	97.73	2170	1738	80.09
100	0.8981	100	2316	1865	80.53

V. Simulation Results and Discussion

By varying the fraction of rated voltage applied from 45.45% to 100% the power curves and efficiency curves of both systems were obtained. Table I shows the data obtained from the conventional system, where the percentage of the rated line voltage is varied. The results from the VFD system are presented in Table II. It can be noted that for the VFD system, the input voltage across the motor terminals was varied by changing only the frequency and modulation index of the PWM inverter, while the supply voltage was kept unaltered. Fig. 6 shows the power curves obtained from the data of Table I and Table II. A comparison of efficiencies of the two models is presented in Fig. 7.

It is quite apparent from Fig. 6 that at voltages lower than the rated voltage, the system containing VFD consumes much lower power than the conventional system. It is also worth mentioning that the gap between input and output power is much smaller, i.e. power loss is much lower, in the VFD system than the conventional one. As a result, the efficiency of the system using VFD is much higher and does not fall below 75%, as shown in Fig. 7. On the other hand, the efficiency of the conventional system can be as low as 28%.

These findings suggest that a VFD enables the motor-pump system to maintain its efficiency at a high level throughout a range of voltages lower than the rated voltage. Furthermore, it provides lower power to a system, when required, without having a significant impact on the efficiency of the system. It accomplishes this by proper Volts/Hz control of the induction motor. In contrast, if we attempt to provide lower output power using the conventional system by reducing the input voltage (for instance, with the help of a variac), it reduces the efficiency appreciably. It becomes dangerous to operate the motor at such low efficiencies, as the excessively high copper loss might overheat and burn the stator windings of the induction motor. Therefore, a conventional system is unable to adjust its power consumption according to system needs.

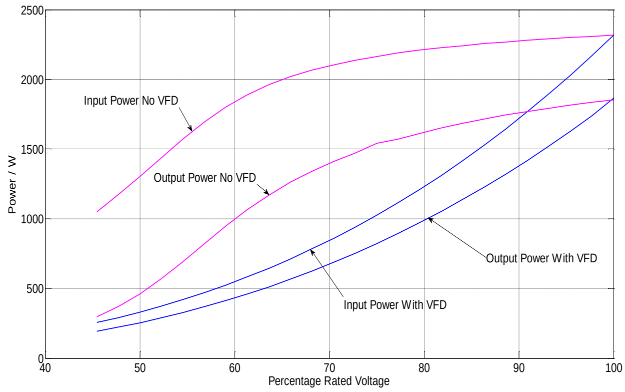

Figure 6. Speed-Torque characteristics of a motor using VFD at various voltages.

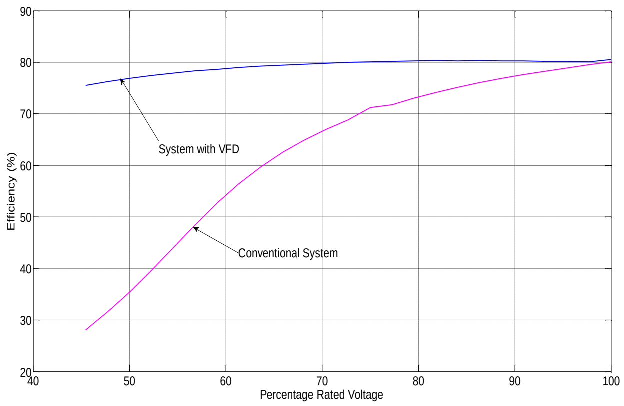

Figure 7. Comparison of efficiency with respect to voltage variations for conventional and VFD motor-pump system

VI. Conclusion

In this paper, the superior performance of a VFD motor-pump system in low-voltage conditions has been demonstrated in comparison to the conventional system. Two different motor-pump systems are designed using the SimPowerSystem utility of MATLAB Simulink, where they are subjected to a range of input voltages in order to determine its effect on the efficiencies of each system. It is found that using a VFD in a motor-pump system helps in preserving its efficiency at an almost constant value throughout the entire voltage range. On the other hand, an ordinary system exhibits a decline in efficiency at an increasing rate as the voltage is decreased. If VFD system is implemented in industrial applications all over Bangladesh, this will save a huge amount of energy in an annual basis. Given the current predicament this country is in as it relates to availability of energy, the widespread establishment of this scheme will definitely lend a much needed helping hand.

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