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Dynamic Analysis of Sensorless Controlled Industrial Pump Drive

K. Anil Kumar[1], M. Harshit[2], R. Raja Singh[3]

[1] Department of Electrical Engineering, MNIT Jaipur, Rajasthan, India
[2] Department of Electrical Engineering, Indian Institute of Technology Roorkee, Uttrakhand, India
[3] Avanced Drives Laboratory, Department of Energy and Power Electronics, Vellore Institute of Technology, India

Correspondance: hmohann@gmail.com

Abstract. Industrial pumps operating with variable speed provides numerous benefits including valve elimination, wide range of flow rate, single stage higher head and energy saving. The realization of variable speed pump operation is carried out using an induction motor, power electronic switches, current sensors and controller without speed feedback is known as sensorless variable speed control. This paper implements a field-oriented control based sensorless scheme on 150 kW induction motor drive system, which is integrated to centrifugal pump load in Matlab/ Simulink environment. The centrifugal pump is modelled mathematically in the same environment for obtaining the identical torque speed characteristics.

Keyword: Induction Motor, Industrial Pump Drive, Centrifugal Pump, Sensorless Control, Field Oriented Control, Energy Efficiency.

1. Introduction

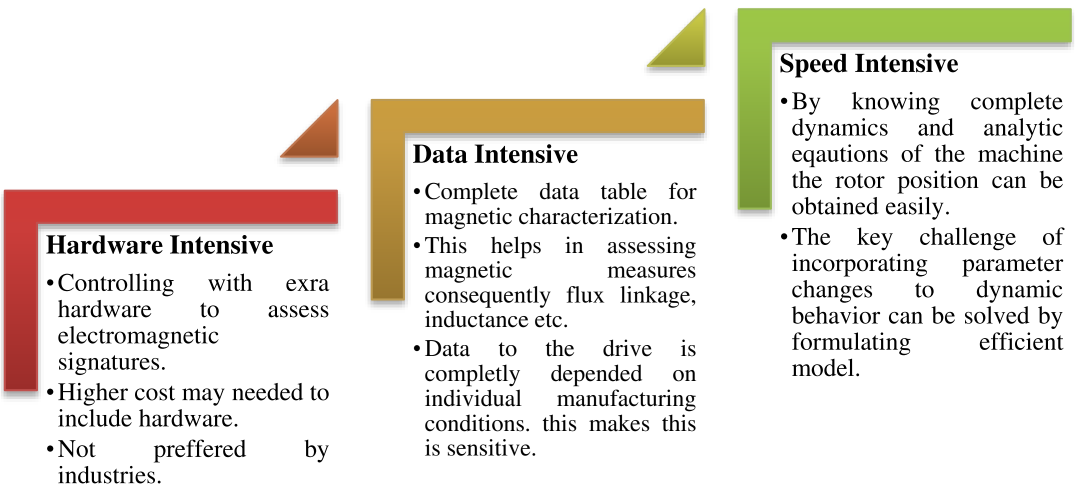

Figure 1 Categorisation of Sensorless Techniques

Continuous industrial process needs extensive research in the development of drives systems. In view of sustaining high harsh environments, decreasing cost and sometimes to increase system reliability, sensorless control of ac drives are preferred. The sensorless drives have no mechanical sensors for identifing the rotor position and speed without deteriorating its dynamic performance. Controlling of drives without sensors needs either extensive hardware or high data on drive properties with high-speed capability. These drives are broadly classified in to three types as shown in figure 1 and the adoption of various strategies on different machines and applications are reviewed in [1]. In most of the industrial applications, the induction motors are widely preferred due to its lower cost, higher performance, lesser parts with simplified design and reliability.similarly, pumps drives are widly notable in many industries[2], [3], [4]. Overall this paper organization are as follows, section 2 discuss the pumping applications in industries and the benefits of variable speed operation. Section 3 describes the operation of sensorless controlled pump drives implementation. Section 4 provides the detailed mathematical modelling of induction motor based pump vector control drive system woth speed and flux estimation and centrifugal pump. In section 5, the simulation of sensorless controlled pump drive is performed in Matlab Simulink environment and followed by the results are disused in detail. Finally, the paper concluded in section 6.

2. Industrial Pumping

Industrial pumps have significant role in industriual process such as handling the liquids under different pressure and transfering of liquids water, chemicals, petroleum, oil and semi solid products like sludge, food, etc., the maximum percentage of pumps used in industries are centrifugal and positive displacement pumps. Industrial pump applications have benefited from the use of different forms of variable speed. Over the last few decades, the electronic drives used with speed motors have improved their cost to performance ratio and are now considered the variable speed technology of choice for many pump applications. Due to the advantages of this speciality drive systems, use in process plant environments has increased. Benefits include pump performance flexibility, ability of a single pump to cover a broader range of flows and heads, higher allowable head per stage, energy savings, and possible throttling or bypass valve elimination. Beginning in the 1960s, electronic drives were developed for varying the speed of AC induction motors, the most commonly used industrial motors. These devices, commonly called variable frequency drives or VFDs, use solid-state semiconductors to transform fixed frequency AC power available from the electric utility into varying frequency power. This transformation allows variable speed motor operation and operation of motors at higher than the standard speed. The key to the advancement of VFDs has been the development of solid-state semiconductors of higher amperage and voltage levels. This technology is providing continued advancement in the most popular VFD style today, the pulse width modulated, or PWM, drive. The continued advancements of VFD technology have provided wide application possibilities. VFD usage today is widespread in several industrial applications. The fundamental variable speed pump-system interaction provides many significant benefits; they are;

2.1. Performance Flexibility

Centrifugal and positive displacement pumps can cover a broad range of hydraulic conditions, producing exactly the desired flow and head shown in figure 2. If a user is unsure of required flow and head at pump selection, time, variable speed can be used in the field to produce exactly the required conditions similarly [2], [3]. If a user needs for several pumps with similar but not identical duty points, identical pumps shall be used for part interchangeability and fine-tune their performance with speed. This flexibility also allows for changes in specific gravity and viscosity. From a pump manufacture's point of view, the use of this range ability can allow a reduction in the number of models stocked to cover a given hydraulic envelope.

2.2. Higher Head Per-Stage

Pumps with higher speed produce higher flow or in case of centrifugal pumping, higher head.Thus the employment of higher speed pumps can replace multiple stage pumps[4]. When pumps are operated at higher speeds, radial bearing and other loads can increase dramatically, often with the square of the speed. Net positive suction head of centrifugal pump also the increases with the square of the speed. Cavitation damage can be more severe. The variation in speed changes flow, hence valve can be eliminated. Hence, this saves capital cost, maintenance, the pressure drop across the valve (often 10 percent of the total required pressure rise) and valve stem leakage. For instance, the centrifugal pump can be operated to a noticeable lower flow if a valve or other form of restriction is placed within 5 feet of the pump discharge flange. However, the minimum allowable stable flow is reduced linearly with speed and thus, the lower flow may be available from a VFD operated pump with no valve than from a fixed speed pump with valve.

2.3. *Energy Savings*

The lack of throttling valve removes pressure drop hence loss of energy be compensated with larger flow or higher height [5]. The centrifugal pump curve as shown in figure 2b consists of a fixed speed pump using discharging throttling that would produce head H, at Q2 flow rate to deliver the desired H2 head at Q3 flow rate to the system. Alternatively, by using variable speed, only Q2 flow rate at H2 head need be produced if the proper speed is selected. Hydraulic horsepower saving from using variable speed for variable speed positive displacement pumps is in cases with large head changes and for positive displacement pumps in cases with large flow changes. To use these chart, locate the desired off-design point and read from the chart the percentage amount of energy saved when reaching an off-design point by a variable speed, rather than by discharge throttling or flow bypass. Any gearbox or other ancillary loads may vary with speed differently. Offsetting these saving are increased losses in the VFD and motor at lower speeds and loads.

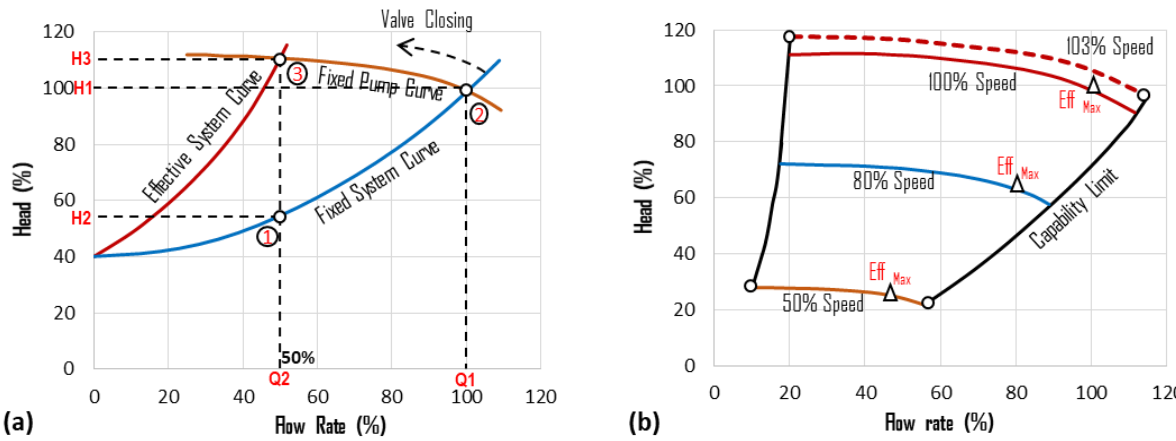

Figure 2. Centrifugal pump operation (a) variable speed and (b) fixed speed

2.4. *Determine Net Positive Suction Head (NPSH) and Efficiency Vs Speed*

Centrifugal pump NPSH is proportional to the square of the speed hence efficiency of the pump as shown in figure 3. Minimum and maximum efficiencies remain unchanged, but the flows at which they occur are shifted by the amount of the speed change. Pump selection depends on NPSH, flow and speed hence care must be taken while its selection Since NPSH, is increased at higher speed, inducers may be required to reduce NPSH, to available levels [6].

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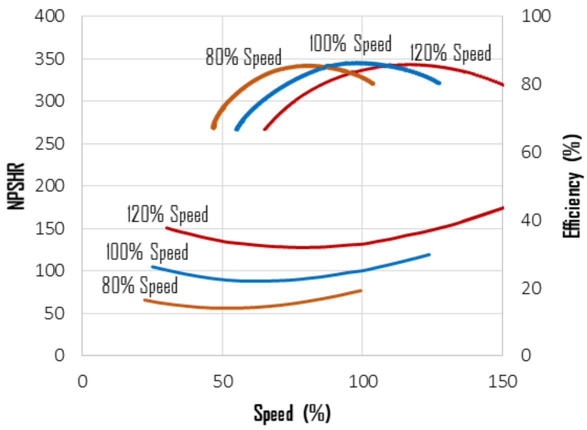

Figure 3. NPSHR – Efficiency Vs Speed

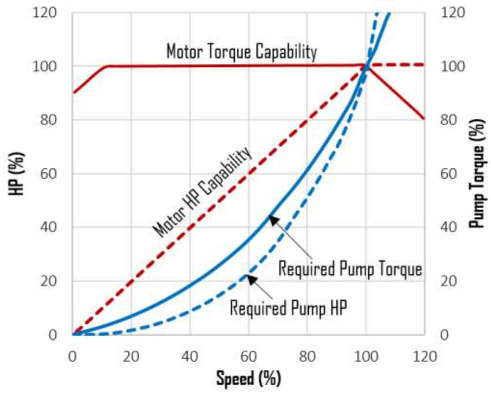

Figure 4. Pump capability curve

2.5. Match pump torque with motor torque

Available motor torque must exceed required pump torque at start-up and every speed. The motor torque capability remains constant as speed is lowered, while the centrifugal pump torque required always falls rapidly, its exact value being dependent upon the shape of the system curve. This relationship for the case of zero static lift is shown in figure 4. Starting torque for a centrifugal pump is generally small and easily provided for by a variable speed motor. On occasion though, some forms of centrifugal pumps with high suction pressures may have a high instantaneous breakaway torque required.

2.6. Avoidance of Lateral Critical Speed

The pump standard API 610 states that, depending on the unbalanced response amplification factor, a pump may not be operated between 85 percent and 105 percent of its predicted critical speed. Adherence to these rules can block out a large portion of the allowable performance envelope, as shown in figure 5. This potential problem indicates the need for careful application of variable speed technology with additional knowledge of the customer's system and desired duty points to ensure a careful matching of pump performance to the desired range of flow and head. Fortunately, most pumps are of a stiff staff design and will operate below their first lateral critical speed. However, if faced with this block out, a pump vendor may be able to change the mechanical design to raise or lower the critical to provide full range speed adjustment.

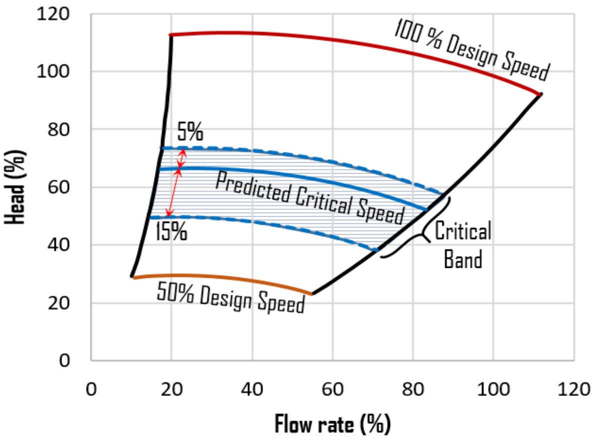

Figure 5. Critical speed band curve

2.7. Account for Torsional Critical Speeds

Torsional critical speeds are resonant frequencies at which motor and driven equipment shafts can begin to oscillate with angular displacement as a result of torsional excitation. VFDs can cause torsional excitation known as torque ripple. Typically, torque ripple is not a concern for units below 200 hp. In fixed speed systems, torsional excitation may occur at some multiple of fixed motor speed such as 2 x running speed due to coupling misalignment. If this excitation is at a torsional critical frequency, the equipment can suffer serious damag e depending on the amplitude of the excitation and the resulting stress on the system. Frequently, however, the pump design or coupling angular stiffness can be changed to avoid this fixed speed induced torsional problem. With variable speed, however, the situation is complicated considerably since the base speed changes and the VFD causes torque ripples due to electrical harmonics at multiples of base frequency or speed.

3. Sensorless Controlled Pump Drive

The annotations for the use of induction motors (IM) are lower cost, simplified design with fewer parts, good performance under high power application, higher reliability and less chance of raw material price fluctuations and shortages. For sensorless applications by using IM, several algorithms have been developed, where the most significant part is at zero frequency and hence near to zero frequency a lot of research presented in various papers [1,2]. In IM, the rotor position can be estimated with tracking changes in reluctance due to rotor slotting's. However, in general, IMs are designed to close slotting's and skewing's hence minimizing variations by having them [9]. Hence sufficient tracking of the IM necessities special design machine that shows significant variations to detect slotting's. Closing and skewing these slots may deteriorate direct-on-line staring behaviour. But with vector controlled power converters these deteriorations be avoided. Nevertheless, IMs are manufactured at low-profit margins, and there is a resistance to solutions that require specially designed machines [11]. Now the rotor position can be tracked by detecting changes in reluctance. This is different from zero excitation frequency injection method (ZEFIM) and gives better torque and flux control than earlier without any restrictions any even zero frequency[6]. In simple principle, specially designed machines are necessary unlike all common machines. Although an auxiliary observer is necessary to derive exact speed estimate, there are many full-torque zero-speed applications in which either a speed signal is not required or only required at low accuracy. These include pumping, traction and marine drives, dynamometers, self-locking and brake release drives, and many high-power industrial drives. Previous research into flux-position-tracking ZEFIM drives has focused mainly on the signal injection and signal processing techniques [10], [7], [8]. There has been relatively little research investigating the actual closed-loop sensorless performance.

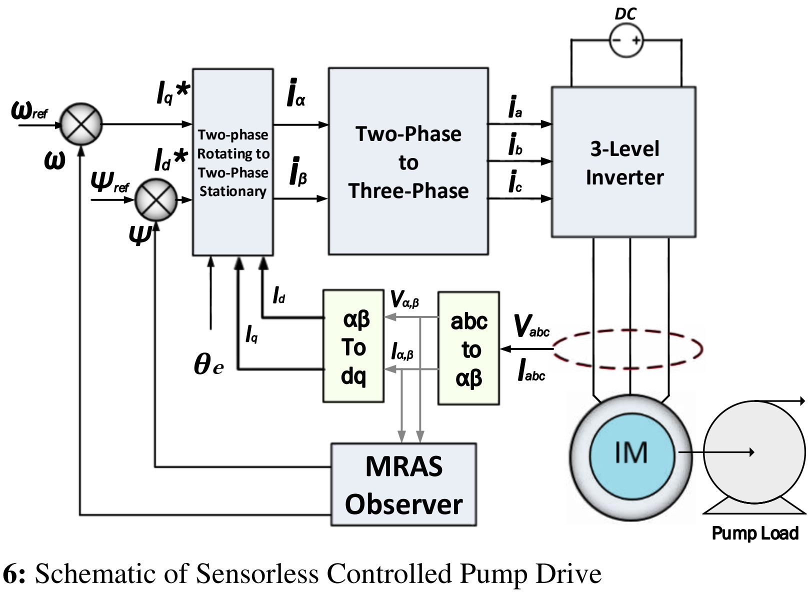

Figure 6: Schematic of Sensorless Controlled Pump Drive

4. Mathematical Modelling of Sensorless Controlled Pump Drive

4.1. Vector Control of Induction Machine

The proposed vector control scheme, the induction machine is modelled in a synchronously rotating reference frame known as rotor flux oriented frame of reference and hence denoted by "RF". The voltage equations of stator and rotor for the induction machine in this frame are;

$$\vec{v}_s^{RF} = r_s \vec{i}_s^{RF} + \frac{d\vec{\psi}_s^{RF}}{dt} + j\omega_{RF}\vec{\psi}_s^{RF} \tag{1}$$

$$\vec{v}_r^{RF} = r_r \vec{i}_r^{RF} + \frac{d\vec{\psi}_r^{RF}}{dt} + j(\omega_{RF} - \omega_M)\vec{\psi}_r^{RF} \tag{2}$$

Where, v, i and ψ denotes the voltage, current and flux respectively. The subscript s & r are for the stator and rotor and ω_M is the rotor mechanical speed. ω_{RF} represents the speed at which reference frame is rotating. The corresponding flux and torque equations can be written as;

$$\vec{\psi}_s^{RF} = L_s \vec{i}_s^{RF} + L_m \vec{i}_r^{RF} \tag{3}$$

$$\vec{\psi}_r^{RF} = L_r \vec{i}_r^{RF} + L_m \vec{i}_s^{RF} \tag{4}$$

$$J\frac{d\omega_M}{dt} = T_e - T_L = \frac{3}{2}.p.Re\,[j.\vec{\psi}_s^{RF}.\vec{i}_s^{RF}] - T_L \tag{5}$$

Where, J is the moment of inertia, T_e is the electromagnetic torque developed and T_L is the load torque. Since the decoupled control is required in vector control, hence the flux equations can be transformed in dq reference frame as;

$$\frac{d}{dt}\begin{bmatrix}\psi_{sd}^{RF}\\ \psi_{sq}^{RF}\\ \psi_{rd}^{RF}\\ \psi_{rq}^{RF}\end{bmatrix} = \begin{bmatrix} -r_s/\sigma L_s & \omega_{RF} & r_s L_m/\sigma L_s L_r & 0\\ -\omega_{RF} & -r_s/\sigma L_s & 0 & r_s L_m/\sigma L_s L_r\\ r_r L_m/\sigma L_s L_r & 0 & -r_r/\sigma L_r & \omega_{RF} - \omega_M\\ 0 & r_r L_m/\sigma L_s L_r & \omega_M - \omega_{RF} & -r_r/\sigma L_r \end{bmatrix}\begin{bmatrix}\psi_{sd}^{RF}\\ \psi_{sq}^{RF}\\ \psi_{rd}^{RF}\\ \psi_{rq}^{RF}\end{bmatrix} + \begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}v_{sd}^{RF}\\ v_{sq}^{RF}\end{bmatrix} \tag{6}$$

And the corresponding current equations will be;

$$i_{sd}^{RF} = \frac{1}{\sigma L_s}\psi_{sd}^{RF} - \frac{L_m}{\sigma L_s L_r}\psi_{rd}^{RF} \tag{7}$$

$$i_{sq}^{RF} = \frac{1}{\sigma L_s}\psi_{sq}^{RF} - \frac{L_m}{\sigma L_s L_r}\psi_{rq}^{RF} \tag{8}$$

$$i_{rd}^{RF} = \frac{1}{\sigma L_r}\psi_{rd}^{RF} - \frac{L_m}{\sigma L_s L_r}\psi_{sd}^{RF} \tag{9}$$

$$i_{rq}^{RF} = \frac{1}{\sigma L_r}\psi_{rq}^{RF} - \frac{L_m}{\sigma L_s L_r}\psi_{sq}^{RF} \tag{10}$$

Now by using the above equations the torque equation in dq reference frame can be assessed as;

$$J\frac{d\omega_M}{dt} = T_e - T_L = \frac{3}{2}\frac{L_M}{L_s}[\psi_{sd}^{RF} i_{rq}^{RF} - \psi_{sq}^{RF} i_{rd}^{RF}] - T_L \tag{11}$$

4.2. Speed and Flux Estimation

The Model Reference Adaptive System (MRAS) is used for the estimation of speed and flux. The reference system consists of the estimation of flux derivatives by using voltages, currents and machine parameters which is independent of speed as;

$$p\psi_{dr} = \frac{L_r}{L_m}(v_{ds} - r_s i_{ds} - \sigma L_s p i_{ds}) \tag{12}$$

$$p\psi_{qr} = \frac{L_r}{L_m}(v_{qs} - r_s i_{qs} - \sigma L_s p i_{qs}) \tag{13}$$

Whereas the adaptive system consists of the estimation of flux derivative by using currents and machine parameters which is dependent on speed as;

$$p\hat{\psi}_{dr} = -\hat{\omega}_r\hat{\psi}_{qr} - \frac{1}{T_r}\hat{\psi}_{dr} + \frac{L_m}{T_r}i_{ds} \tag{14}$$

$$p\hat{\psi}_{qr} = -\hat{\omega}_r\hat{\psi}_{dr} - \frac{1}{T_r}\hat{\psi}_{qr} + \frac{L_m}{T_r}i_{qs} \tag{15}$$

The error between these two is further used along with PI controller to estimate the speed. The corresponding equations are;

$$K = \psi_{qr}\hat{\psi}_{dr} - \psi_{dr}\hat{\psi}_{qr} \tag{16}$$

4.3. Centrifugal Pump

The loading characteristics for the centrifugal pumps are dissimilar from other loads. The centrifugal pump load torque T_L can be modelled by using the equations below as;

$$T_L = {}^{g}/_{\omega} \tag{17}$$

$$P_H = 1000 * QgH \tag{18}$$

$$Q = {}^{T\omega}/_{gH * 1000} \tag{19}$$

Where, the H is the head in meters, Q is the discharge rate in litre/sec, g is gravitational constant, P_H is the hydraulic power and ω is the speed in rad/sec.

5. Simulation of Sensorless Controlled Pump Drive

The figure 7a shows the illustration for the sensorless speed control of induction motor drive for the pumping application. The centrifugal pump model is used to generate the reference speed and torque commands as these are in proportion to each other. The figure 7b shows the Simulink representation for the vector control scheme, where the reference speed & torque commands of the centrifugal pumps used to generate the torque producing quadrature axis component of current and reference flux is used to generate the flux producing direct axis component of currents as shown. These components of currents

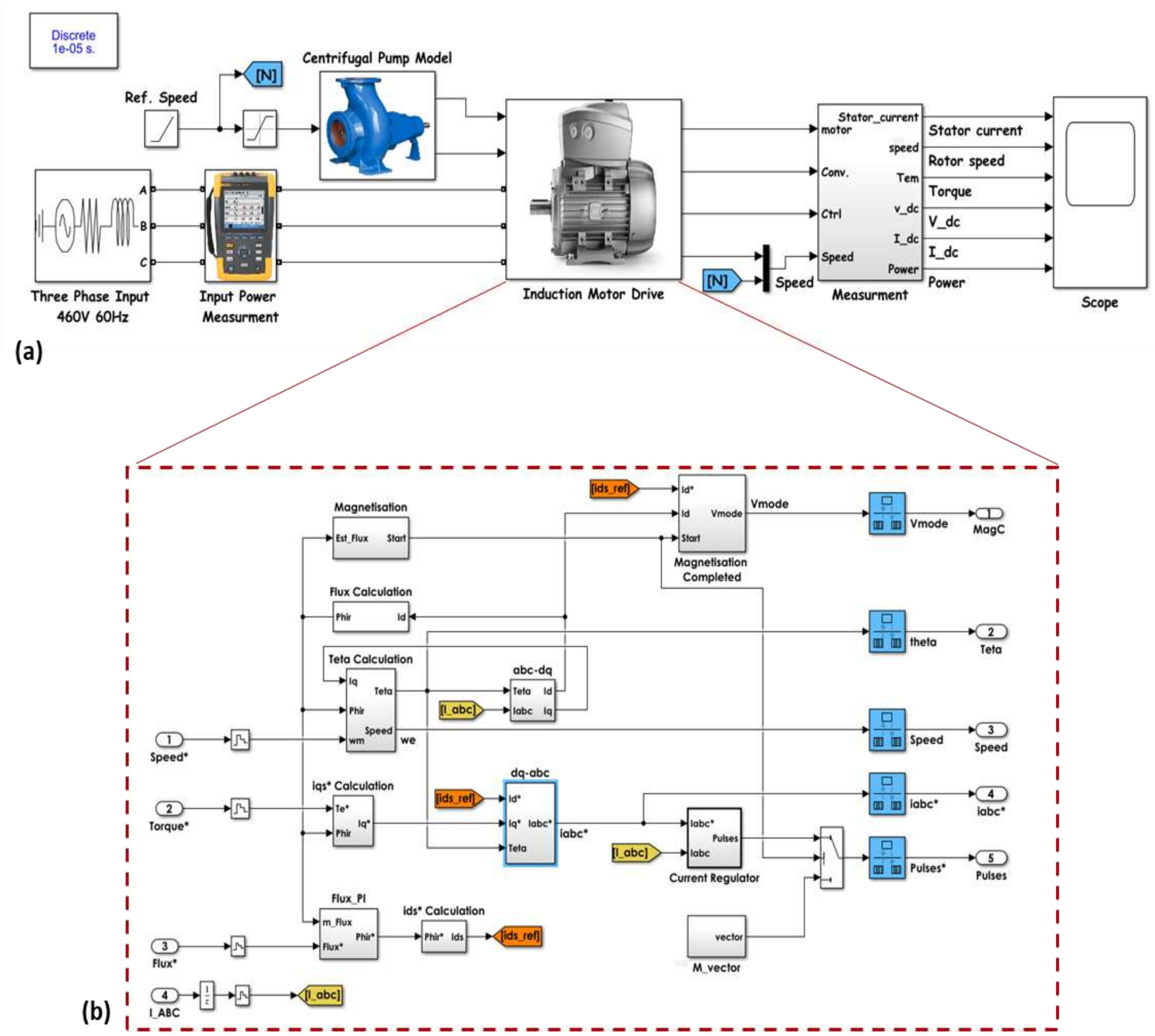

Figure 7: Simulation of Sensorless Controlled Drive with Centrifugal Pump Model
a) Overall simulation model b) Sensorless vector control of induction motor drive

are further transformed to the three phase systems, where by comparing with the actual three phase currents, the switching pulses are obtained. As the vector control is observed in rotor field oriented reference frame and corresponding to which the angle or rotation is calculated in theta calculation block. This makes the decoupled control for the torque and flux. In the next section, the simulation results for this scheme are observed and discussed.

5.1. Result and Discussion

To analyse the operating performance of the sensorless vector controlled induction motor drive based pumping system, the electrical and mechanical parameters are recorded under different operating conditions, shown in figure 8 for a 200Hp induction machine. The parameters including stator current, speed, torque, dc-link voltage, dc-link current and input power are taken into account for investigation. The centrifugal pump drive is considered for analysis where the torque is directly proportional to the square of the speed, and hence the speed is varied to observe the performance of the drive. Once the drive is energized, the reference speed (1800 RPM) is fed to the control scheme with the acceleration rate of 500 RPM per second, at t=0.5 sec. Thus the speed ramps up from zero speed to 1800 RPM in 3.6 sec, shown in figure 8b. Similarly, the speed reduction comment is provided to the controller at 4.5s, and thereby, the speed is deaccelerated from 1800 RPM to 1300 RPM in 0.2 sec.

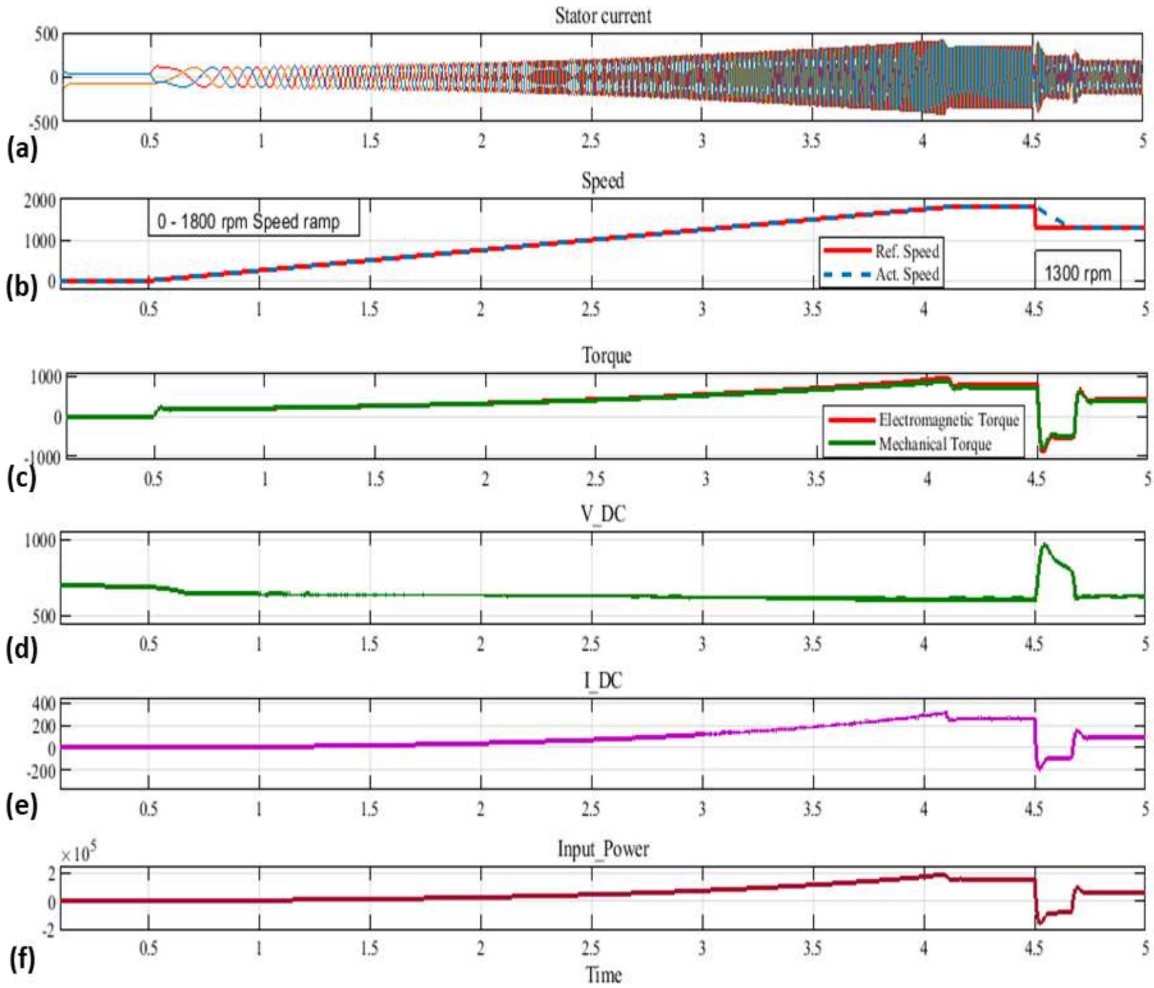

Figure 8: Simulated results of sensorless pump drive
(a) stator current, (b) reference speed and actual speed, (c) electrical torque and mechanical load torque, (d) converter dc-link voltage, (e) converter dc-link current and (f) input dc-link power

During this investigation, the stator current increases gradually as the reference speed is increased to its rated speed, up to time t=4.1 sec. Once the reference speed is achieved, the stator current settles to its corresponding loading current. Later at time t=4.5 sec, when reference speed is decreased, the stator current settles to a new lower value after transients as shown in figure 8a. As in the centrifugal pump, the torque varies in proportion with the speed, the developed electromagnetic torque increases for the first phase of speed transition to maintain the mechanical torque demand, which later at time t=4.5 sec decreases to a new value corresponding to the speed, shown in figure 8c. At time t=4.5 sec, the negative developed torque is observed as the reference speed reduces and hence this power is fed back to the system, which can be utilized for other system requirements. The key measures are dc-link voltage figure 8d and currents figure 8e, where the variation is observed following the loading and hence can be justified. The negative change in the dc-link current at time t=4.5 sec is because power is returned to the system as discussed. figure 8f shows the plot of incremental input power during the initial phase of attending the reference speed, which settles down to a constant value once reached. Later the input power requirement decreases as the reference speed is reduced and the transient at t=4.5 sec, shows the corresponding power back to the source.

6. Conclusion

Industrial pumps operating with variable speed drives offers several benefits including valve elimination, wide range of flow rate, single stage higher head, energy saving etc. The realization of variable speed operation is carried out using an induction motor, power electronic switches, current sensors and controller without speed feedback is known as sensorless variable speed control. A brief review for the VFD drives used in pumps and their speed control algorithms are discussed in this paper. Along with this in this paper an indirect field-oriented sensorless control scheme on 150 kW induction motor drive system is implemented, through centrifugal pump load. The Matlab/ Simulink is used to simulate the scheme and the various results for this type of pump loading are presented. Overall from the annotations it can be concluded that the use of variable speed drives for pumping applications offers advantages in terms of energy saving etc. however further research is supplementary such as finer low & wide ranging speed control, effective consumption of energy during regeneration etc.

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