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Investigate to Substitute Large Inertia by a Combination of Very Small Inertia Driven by v/f Controlled Drive

M. V. Palandurkar, J. P. Modak, S. G Tarnekar

Abstract — Process machines for fluctuating load torque use large flywheels with high moment of inertia. They suffer from the disadvantages of bulky systems prone to reduced acceleration. As a result these are harder to start and are likely to have frequent mechanical breakdowns. A method is suggested here to effectively work with much smaller flywheels. Suitably monitored VVVf drives and low moment of inertia offer a much better alternative. The system behavior is drastically improved. This paper deals with effective energy transactions in conventional systems to compare the same in case of the proposed system. The method is verified here with MATLAB simulation, based on which it is reported that good choice of frequency to suit the nature of load torque fluctuations resulted into optimum system performance

Index Terms— Process Machine, Flywheel, Demand Torque, Induction motor, ***V/f*** Control, moment of inertia, Modeling, simulation.

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1 INTRODUCTION

Generally there are two types of process machines, Type I and Type II. In Type I process machine, input motion is completely rotary and output motion is also rotary at uniform speed. In such process machine, demand torque does not vary cyclically, but varies with the load. Type II process machine makes use of link mechanism or cam mechanism or combination of linkage, cam and gears. For such process unit, at every instant, demand torque changes with respect to time. The arbitrary demand torque characteristics of any process machine can be estimated based on cycle time of operation, process resistance and inertia resistance [1], [2]. Hence, this variation is cyclic and cycle time is commensurate with rpm of process unit. But, usually, induction motor cannot generate closely matching torque characteristics. Hence, the flywheel is required to make up for the difference of the torque in different time intervals. Fig.1 describes an arbitrary demand torque characteristic of a process machine, where, T_d is demand torque and T_s is average of the electromagnetic torque generated. This can be estimated based on cycle time of operation, process resistance and inertia resistance. These can be detailed based on intended operation and proposed details of partial mechanical design [1, 2]. It is evident from Fig. 1 that crank speed of input shaft of the process machine should be 20 rpm.
Time for complete cycle of operation of the process unit should be 3000 msecond which gets completed in one rotation of the input link of the process machine.

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Fig. 1 shows that demand torque has fast variation with time, which the motor cannot cope up with this. Hence, the flywheel is required to make up for the difference of the torque in all sections of time axis. It is known that flywheel will decelerate during intervals AB & CD when load torque is greater than average electromagnetic motor torque whereas it will gain speed during intervals O'A, BC, DE sections of time axis when load torque is less than average electromagnetic torque.
Fig. 2 describes the schematics of an arbitrary process unit P along with usual mechanical power transmission system for torque amplification and speed reduction. Pulley D2 is a flywheel cum power transmission pulley, pulley D1 is driving pulley wchich receives power from the Induction motor M. The portion of the system between D2 and process unit is subjected to severe torsional vibrations. Hence, presence of flywheel with high moment of inertia J in the process machine increases power rating of the main drive, reduced acceleration, increased weight of engine, harder to start and fatigue in the component of power transmission system [3]. Therefore, it is desirable to eliminate flywheel from the design of any process machine in general. It is felt that by properly designing power electronic circuitry using VVVf drive having low moment of inertia, this may be possible. Hence, in the present paper, among different control schemes, a constant volt per hertz, principle is chosen to drive three phase induction motor as

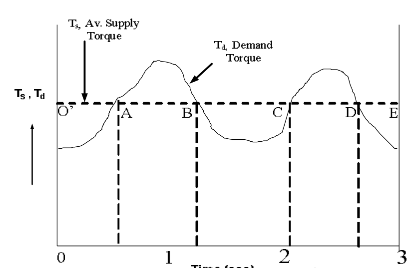

Fig.1. Arbitrary Demand Torque Characteristics.

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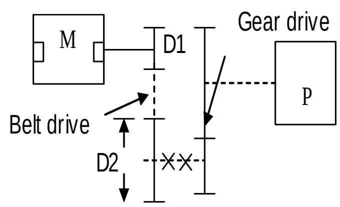

Fig. 2. Schematics of an Arbitrary Process Unit, Mechanical Power Transmission & 3 phase Induction Motor.

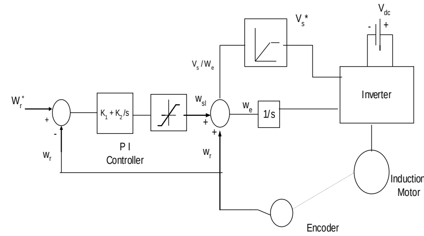

Fig. 3. Induction Motor Drive with Closed Loop Volts / Hertz Control.

shown in Fig. 3. In this technique, a dynamic model of three phase induction machine is derived from two phase machine. [4], [5]

The equivalence between three phase and two phase machine is based on the equality of the mmf produced by two phase winding and by three phase. The stator and rotor variables are transformed to a synchronously rotating reference frame that moves with the rotating magnetic fields. Finally, a dynamic machine model in synchronously rotating and stationary reference frame is developed in per unit by defining the base variables both in $a-b-c$ and $d-q-o$ variables. Authors have already reported [9], that the above method can be analyzed. It uses VVVf based induction motor drive by controlling input side frequency for better performance, with much smaller system inertia. According to change in demand torque, varying cyclically with respect to time, the requirement of input frequencies to the main drive during different time intervals also changes in order to generate electromagnetic torque characteristics matching with demand torque characteristics. Hence problems occurring due to the presence of large flywheel between induction motor and process machine are eliminated.

Generating electromagnetic torque to match demand torque characteristics of the process machine by the above method is not only a task to fulfill but it is also necessary to find how much energy is transacted from motor side when demand load torque sudden changes low to peak value. Hence, the present paper compares the effective energy transaction in conventional system having large flywheel with VVVf based induction motor drive of low moment of inertia of much smaller flywheel.

Induction motor coupled with conventional flywheel having large moment of inertia is run at constant frequency without applying any control technique whereas, in lateral case, induction motor is chosen to have low moment of inertia and is controlled by input side frequency using VVVf technique. The effective energy is calculated in both the case by using kinetic energy formula.

If rotor is moving at mechanical speed w_m with moment of inertia J , the kinetic energy produced is given by the formula,

$$K.E = \frac{1}{2} J\, w_m{}^2 \qquad (1)$$

Differentiating with respect to time, we get power, i.e.

$$\frac{d(K.E.)}{dt} = J\, w_m \frac{dw_m}{dt} \qquad (2)$$

Equation (2) enables us to calculate the energy transacted for a particular case. This has been the basis of comparing energy delivered by the rotating masses to the shaft during first dip in speed. This enables to conclude about the proposed scheme.

2 Close Loop Induction Motor Drive With Constant Volts Per Hertz Control Strategy

An implementation of the constant volts / hertz control strategy for the PWM inverter fed induction motor with suitable value of moment of inertia in per unit basis is simulated in MATLAB simulink software is shown in Fig. 4 [6]. The major blocks consist of PWM inverter, induction motor with mechanical load [7], [8] [12]. In this scheme mechanical load varying cyclically in an assumed pattern as shown in Fig. 5. As the load torque increases, the speed loop error generates the slip speed command w_{sl} through proportional-integral controller and limiter. The slip is added to the speed feedback signal w_o to generate the slip frequency command w_e .The slip frequency command generates the voltage command, V through a volts/hertz function generator. A step increase in slip fre-

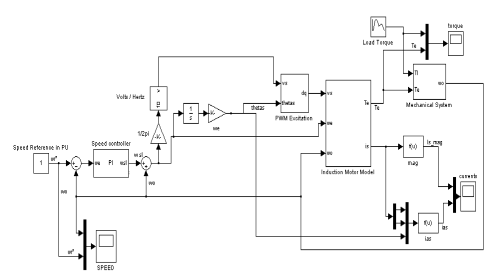

Fig. 4. Complete Induction Motor Model with PWM Excitation and Mechanical System along with v/f control scheme in MATLAB SIMULINK.

quency command produces a positive speed error and the slip speed is set at the maximum value. The drive accelerates due to changes in the frequency and current, producing the torque, matching with demand torque characteristics. The drives finally settle at a speed for which motor torque equals the load torque. Hence, for varying load torque with respect to time,

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the drive generates similar electromagnetic torque which matches with demand torque of the process machine.

3 CASE STUDY

A process machine under consideration comprises of a linkage mechanism as a main processor. On account of non linear kinematics of the mechanical hardware, demand torque characteristics of the process machine are time-variant. In an attempt to simplify the analysis, and tests the proposed system, using standard logics in control system engineering, the demand torque variation is as shown in Fig. 5. At t= 1.5 sec, the torque suddenly rises by a step. Sudden rise in torque needs extra kinetic energy to be fed to the shaft. Deceleration is the result. And first dip in speed contributes maximum to counter the sudden rise in torque. Therefore, first dip is expected to be most crucial for energy calculations. Here speed of the process machine is chosen to be 20 rpm, hence the total cycle time is 3000 msec. The induction motor rating is 3 phase, 415 V, 1 HP with a synchronous speed as 1500 rpm. In this case, the average angular velocity of the input crank of the process unit must be 20 rpm. This gives torque amplification from motor shaft to the process unit input shaft of the order of 75. This induction motor generates average supply torque of 5.96 N-m (with given torque formula [4]) or 0.596 Kgf m. Thus the supply torque at the process unit input shaft is 0.596 X 75 = 44.7 Kgf-m. Hence, the hp demand of the process unit with a given formula is,

$$hp = \frac{2 \cdot \pi \cdot N \cdot T}{4500}$$
$$= \frac{2 \cdot \pi \cdot 20 \cdot (0.596 \times 75)}{4500}$$
$$\approx 1.248$$

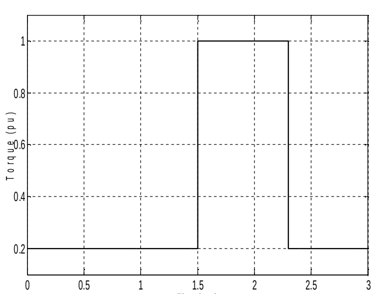

Fig. 5. Demand Torque characteristic of a specific Process Machine.

4 SIMULATION AND RESULT

In order to get the results, induction motor with two different moments of inertia is considered for simulation. In first case

TABLE 1
INDUCTION MOTOR DATA

HP	1 = 0.75 kW
Rated Voltage	415 V, ± 10% tolerance
Winding Connection	Star
Rated Frequency	50Hz
Pair of poles	2
Rated speed	1500 rpm
Stator Resistance	12.5487 Ω
Rotor Resistance	12 Ω
Stator Leakage Inductance	144.67 mH
Rotor Leakage Inductance	144.67 mH
Mutual Inductance	545.78 mH
Moment of Inertia	0.0018 kg m2
Friction Factor	0.01

induction motor with high moment of inertia is chosen to drive it at constant frequency. In second case induction motor with low moment of inertia is considered by controlling input side frequency using close loop VVVf drive. Here, all parameters of induction motor model are converted into per unit basis [5] and the main drive is simulated for one complete cycle of rotation of 3000 m sec to get the results.

After simulation of operation at constant frequency and with high moment of inertia, it is observed that induction motor generates similar nature of electromagnetic torque with respect to demand torque. Motor torque matches its load torque characteristics as shown in Fig. 6. Fig. 7 shows the simulation of induction motor by monitoring its input frequency using VVVf drive with low moment of inertia. This simulation shows that the electromagnetic torque is almost matching with demand torque characteristics requiring less starting period as compared to previous case. [9] When load torque suddenly increases to high value, generated electromagnetic torque is less than load torque during transient period hence, speed decreases. But when load torque decreases to low value, generated torque is greater than load torque in transient period hence, speed increases. Fig. 6.1 and Fig. 6.2 show decrease and increase of speed when load torque increases to peak value i.e. 1 pu and decreases to 0.2 pu respectively. Drop in speed with constant input frequency and with high moment of inertia of J = 0.018 kg-m2 is 0.9174 pu ie. 144.10 rad/sec with settling time of 0.35 sec. and increase in speed is 0.9974 pu i.e. 156.67 rad/sec with settling time of 0.3 sec. Here, base mechanical speed is considered as 157.079 rad/sec. The amount of effective energy is required to generate similar type of demand torque of process machine is 321.71 Joules.

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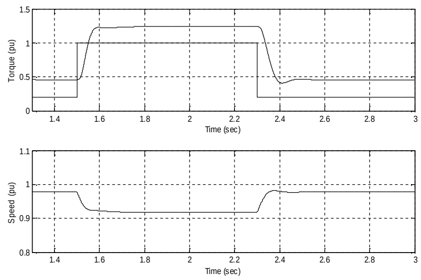

Fig. 6. Electromagnetic torque and speed of induction motor for load torque without VVVf with high value of J =0. 018 kg-m^2

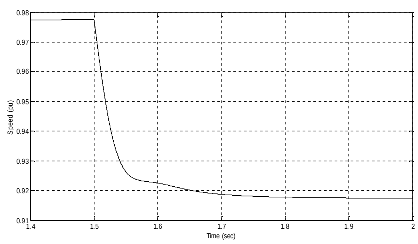

Fig. 6.1. Drop in speed for increase peak value of torque of J = 0.018 kg-m2.

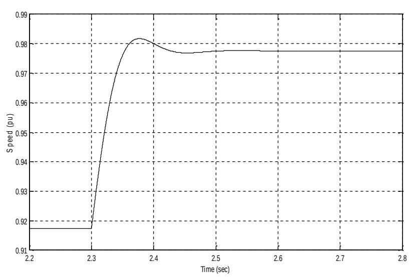

Fig. 6.2. Rise in speed for decrease of torque of J = 0.018 kg-m^2

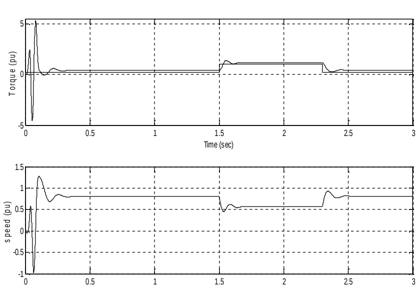

Fig. 7. Electromagnetic torque and speed of induction motor for load torque VVVf with low value of J =0. 0018 kg-m^2

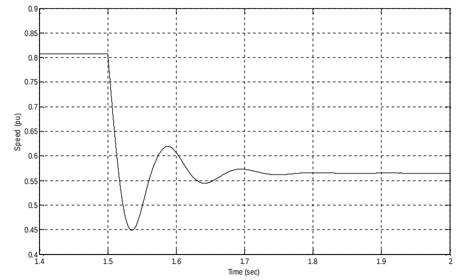

Fig. 7.1. Drop in speed for increase peak value of torque of J = 0.0018 kg-m^2.

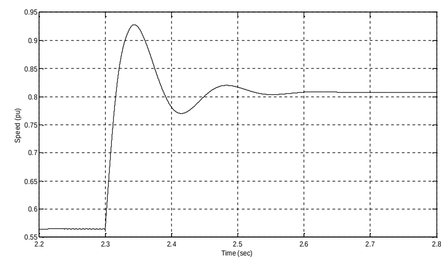

Fig. 7.2. Rise in speed for decrease of torque of J = 0.0018 kg-m^2.

In second case, by controlling input frequency of using VVVf drive with low moment of inertia of J = 0.0018 kg-m^2, electromagnetic torque is generated at reduced frequency 32.61 Hz to match the demand torque characteristics with less error . The drop in speed due to sudden increase in torque is more as compared to first case and it is observed as 0.565 pu i.e. 88.75 rad. /sec with same settling time i.e. 0.34 sec. as shown in Fig. 7.1 The increase in speed due to decrease of torque is 0.8075 pu i.e. 126.84 rad. /sec. with settling time 0.35 sec. as shown in Fig. 7.2. The required energy to produce similar type of load torque is 243.40 Joules which is less than that in previous case. Table 2 shows the calculation of energy due to sudden drop in speed when torque changes from low to high value.

5 CONCLUSION

In order to generate electromagnetic torque matching with demand torque characteristic of the process machine with less energy transaction, it is possible to run induction motor with much smaller flywheel using VVVf drive suitably controlling its input frequency. Hence, larger flywheel with high moment of inertia can be replaced with smaller one. From the result, it is clear that require energy for sudden change of load torque to peak value is more during transient period when speed drops drastically in conventional system with larger flywheel when motor runs at constant frequency. Opposite to previous case, require effective energy transaction from rotational masses to shaft of the motor to match the change of load torque to peak value is less when drive is controlled from input side frequency with low moment of inertia using VVVf technique, electromagnetic torque almost matches the demand torque at reduced frequency and acceleration of induction motor is also improved. Variation in speed is more oscillatory

TABLE 2
CALCULATION OF POWER FOR TWO DIFFERENT VALUES OF MOMENT OF INERTIA, J, BASE MECHANICAL SPEED, WM =157.079 RAD./SEC

Sr. No.	J (kg-m^2)	Fre-quency (Hz)	Time span (sec)		dt (sec)	Speed Range (pu)		$d(W_m)$ (pu)	$d(W_m)$ rad/sec)	$\frac{d(W_m)}{dt}$	W_m (pu)	W_m (rad/ sec)	$J*W_m*\frac{d(W_m)}{dt}$ (Joules)
1	0.018	50	1.5	1.57	0.07	0.977	0.923	0.054	8.482	121.176	0.939	147.49	321.71
2	0.0018	32.61	1.5	1.537	0.037	0.806	0.449	0.357	56.077	151.61	0.568	89.22	**243.40**

and settling time of fall in speed from transient period to steady state is same for both the cases. Hence, depending on torque fluctuation and the inertia, the optimum frequency which resulting into extracting energy from rotational masses is work out and found that drives with low moment of inertia suitably monitored offer a much better alternative to large flywheel to generate same load torque variation. Behavior of system is drastically improved.

6 SCOPE OF FUTURE WORK

Having reported the basic confirmation (using MATLAB) of the proposal to eliminate the bulky flywheel, following aspects can be investigated in future work

1. Estimation of necessary moment of inertia in view of some difference in the required demand torque characteristics and obtained generated demand torque characteristics.
2. Estimation of initial additional investment by incorporation of electronic circuitry and corresponding mechanical transmission. Estimate in both ways in terms of initial investment and operational cost.

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