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Computational Procedure to Replace a Bulky Flywheel by a Controlled Motor and a Smaller Flywheel

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ABSTRACT

Process machines with tougher duty cycles are subjected to wide fluctuations in load torque. These often need a bulky flywheel for torque equalization with disadvantages of torsional oscillations. This results into fatigue of mechanical power transmission elements leading subsequently to equipment failure causing prolonged and frequent down time which results into financial losses. A simpler acceptable alternative is proposed in this article. Suitably monitored VVVf drives and low moment of inertia offer a much better alternative, for improving the system behavior drastically. Controlling the power input to the main electric drive with VVVf technique can generate almost matching demand torque characteristics. A much smaller flywheel is able to improve the accuracy to have better torque matching. This paper deals with estimation of necessary moment of inertia of flywheel in view of minimizing the difference in the required demand torque characteristics and the generated supply torque characteristics. The calculations deal with the net energy transactions. Over one cycle of torque fluctuations, the net energy to/from flywheel should be zero.

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1. INTRODUCTION

Flywheel is a kinetic energy storage device. It stores energy during the period when the supply of energy is more than the requirement and releases it during the period when the requirement of energy is more than the energy which can be supplied. The main function of flywheel is to smoothen out variations in the speed of a shaft caused by torque fluctuations. Applications utilizing a flywheel for smoothening angular velocity fluctuations include an internal combustion engine, piston compressors, punch presses, rock crushers, etc. Figure 1 describes the schematics of an arbitrary process unit P along with usual mechanical power transmission system for torque amplification and speed reduction. In this figure, pulley D2 is a power transmission pulley which also acts as a flywheel. Pulley D1 is driving pulley which receives power from induction motor M. The process machine P makes use of link mechanism or cam mechanism or combination of linkage, cam and gears. For such process unit, 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. These can be detailed based on intended operation and proposed details of partial mechanical design [1, 2]. Hence, this variation is cyclic and cycle time is commensurate with rpm of process unit. Figure 2 describes an arbitrary demand torque characteristics of such process machine, where, T_d is demand torque and T_s is average of the electromagnetic torque generated. Here crank speed of input shaft of the process machine is chosen as 30 rpm. Therefore, time for complete cycle of operation should be 2000 msecond which gets completed in one rotation of the input link of the process machine. This figure shows that demand torque has a fast variation with time. The motor cannot cope up with this. Hence, the flywheel is required to make up for the difference of the torque in all time intervals marked in Figure 2. 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, and DE sections of time axis when load torque is less than average electromagnetic torque.

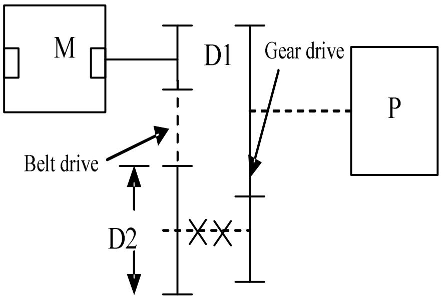

Figure 1. Schematics of an Arbitrary Process Unit, Mechanical Power Transmission & Three-phase Induction Motor

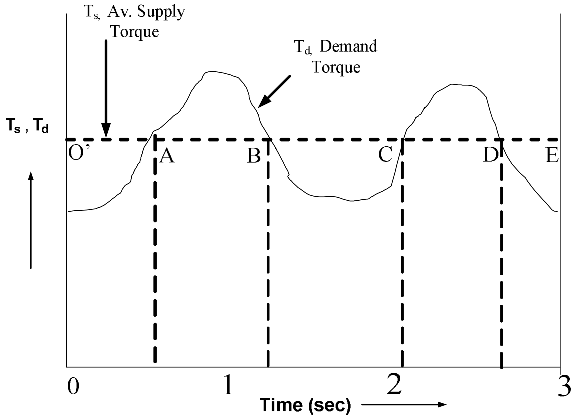

Figure 2. Arbitrary Demand Torque Characteristics

But, usually induction motor (Figure 1) cannot generate closely matching torque characteristics. Hence, a flywheel is required to make up for the difference of the torque in different time- intervals. The portion of the system between D2 and process unit is subjected to severe torsional vibrations. Also, presence of flywheel with high moment of inertia (J) in the process machine results into following disadvantages: increased power rating of main drive, increased weight, reduced acceleration, increased fatigue in the power transmission-components. These effects also lead to frequent functional failures [3]. Therefore, it is desirable to eliminate large flywheel from the design of any process machine, in general.

With the advent of electric drives and power-electronic circuitry using $VVVf$ method, proper energy monitoring is possible to control the power fed to induction motor with the system having low moment of inertia to generate supply torque closely matching with demand torque resulting in elimination of bulky flywheel.

In the present paper, among different control schemes, a constant volt per hertz principle is chosen to drive three phase induction motor as shown in Figure 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 winding. The stator and rotor variables are transformed to a synchronously rotating reference frame that rotate 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 the $d-q-o$ variables.

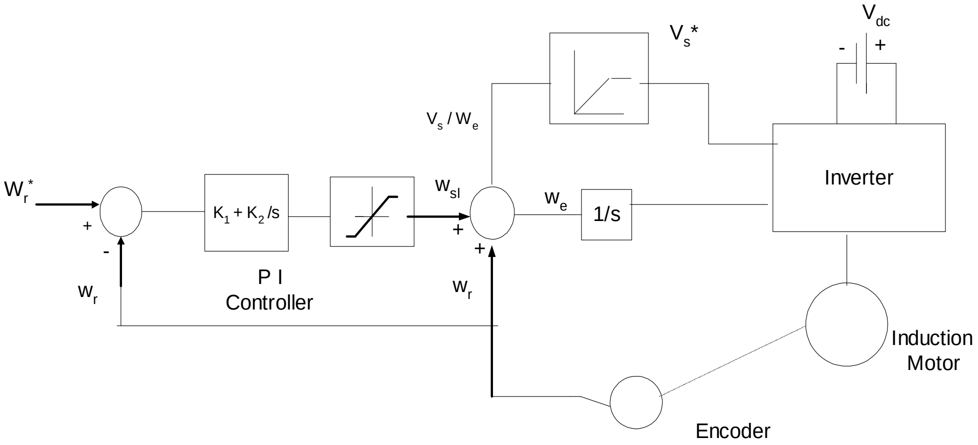

Figure 3. Induction Motor Drive with Closed Loop Volts / Hertz Control

Authors have already reported [9], that the above method can be analyzed for the proposed scheme. 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 can be changed in order to generate electromagnetic torque matching with demand torque. Hence problems occurring due to the presence of large flywheel between induction motor and process machine can be eliminated. It is observed that required effective energy transaction from rotational masses to shaft of the motor to match the change of load torque to peak value is also less when drive is controlled from input side by frequency control, using VVVf technique, with low moment of inertia [10]. At the same time, it is also observed that generated electromagnetic torque from the above method is not exactly matching with demand torque characteristics [9], therefore need of small size flywheel of suitable moment of inertia is necessary to connect between drive and process machine to match exact demand torque characteristics.

This paper deals with procedure to find out required moment of inertia of total rotating masses which would minimize the difference between the generated torque and demand torque. This can be done by calculating fluctuations in flywheel-energy. The flywheel releases its kinetic energy when generated torque is less than demand torque and stores the energy when generated torque is more than required demand torque. This can be done by calculating the difference of area between generated torque and demand torque in terms of N-m or kgf-m in comparison with total area of demand torque. Based on this, the hp demand of the process machine can also be calculated.

2. DYNAMIC MODEL OF INDUCTION MOTOR

For the two phase machine, the circuit equations represent both $d^s - q^s$ & $d^r - q^r$ and their variables can be converted in a synchronously rotating $d^e - q^e$ frame. The stator equations are [4], [6], [9], [13] as follows,

$$V_{qs} = R_s \, i_{qs} + \frac{d}{dt}(\Psi_{qs}) + w_e \, \Psi_{ds} \tag{1}$$

$$V_{qs} = R_s \, i_{qs} + \frac{d}{dt}(\Psi_{qs}) + w_e \, \Psi_{ds} \tag{2}$$

$$V_{qr} = R_r \, i_{qr} + \frac{d}{dt}(\Psi_{qr}) + (w_e - w_r)\Psi_{dr} \tag{3}$$

$$V_{dr} = R_r\, i_{dr} + \frac{d}{dt}(\Psi_{dr}) - (w_e - w_r)\Psi_{qr} \tag{4}$$

If rotor is moving at angular electrical speed w_r, the $d-q$ axes fixed on the rotor move at a speed, $(w_e - w_r)$ relative to the synchronously rotating frame. For a singly fed machine, such as a cage motor $V_{qr} = V_{dr} = 0$

The development of torque by the interaction of air gap flux and rotor mmf can be generally expressed in the vector form as,

$$T_e = \left(\frac{3}{2}\right)\frac{P}{2}\frac{1}{w_b}\left(\Psi_{ds}\, i_{qs} - \Psi_{qs}\, i_{ds}\right) \tag{5}$$

And the electromechanical dynamic equation is given by

$$T_e = J\,\frac{d(w_m)}{dt} + T_L + B\, w_m \tag{6}$$

The mechanical rotor speed is related with rotor electrical Speed given by, $w_m = \frac{2}{P} \times w_r$

where,

d : direct axis

q : quadrature axis,

$d^s - q^s$: stationary reference frame ,

$d^e - q^e$: synchronously rotating reference frame,

V_{ds}, V_{qs} : d and q axis stator voltages,

V_{dr}, V_{qr} : d and q axis rotor voltages,

Ψ_{ds}, Ψ_{qs} : d and q axis stator flux linkages,

Ψ_{dr}, Ψ_{qr} : d and q axis rotor flux linkages,

i_{ds}, i_{qs} : d and q axis stator currents,

i_{dr}, i_{qr} : d and q axis rotor currents

R_s : stator resistance

R_r : rotor resistance,

w_r : rotor angular electrical speed

w_e : stator angular electrical frequency,

w_m : rotor mechanical speed,

w_b : motor angular electrical base frequency,

T_e : electrical output torque,

T_L : load torque,

J : moment of inertia,

B : coefficient of friction of load,

P : number of poles.

2.1. Per Unit Model

The normalized model of the induction motor is derived by defining the base variables both in the $a-b-c$ and the $d-q-o$ variables [5], [9]. In the $a-b-c$ frames, let the rms values of the rated phase voltage and current form the base quantities, given as, Base Power, $P_b = 3V_{b3} I_{b3}$

where, V_{b3} and are three phase voltages and currents, respectively. Selecting the base quantities in $d-q$ frames denoted by V_b and I_b to be equal to the peak value of the phase voltage and current in $a-b-c$ frames, we get,

$$V_b = \sqrt{2} V_{b3} \qquad I_b = \sqrt{2}\, I_{b3}$$

Hence, the base power is defined as

$$P_b = 3V_{b3} I_{b3} = \frac{3}{2} V_b I_b$$

Base voltage, $V_b = Z_b I_b$ and

Base torque, $T_b = \dfrac{P}{2} \dfrac{P_b}{w_b}$ (7)

Substituting base voltage and base torque into above equation (1) to (4), and defining the normalized parameters and variables into per unit system, the above equation in per unit can be written in matrix form as,

$$\begin{bmatrix} V_{qsn} \\ V_{dsn} \\ V_{qrn} \\ V_{drn} \end{bmatrix} = \begin{bmatrix} R_{sn} + \frac{X_{sn}}{w_b} p & w_{en} X_{sn} & \frac{X_{mn}}{w_b} p & w_{en} X_{mn} \\ -w_{en} X_{sn} & R_{sn} + \frac{X_{sn}}{w_b} p & -w_{en} X_{mn} & \frac{X_{mn}}{w_b} p \\ \frac{X_{mn}}{w_b} p & (w_{en} - w_{rn}) X_{mn} & R_{rn} + \frac{X_{rn}}{w_b} p & (w_{en} - w_{rn}) X_{mn} \\ -(w_{en} - w_{rn}) X_{mn} & \frac{X_{mn}}{w_b} p & -(w_{en} - w_{rn}) X_{mn} & R_{rn} + \frac{X_{rn}}{w_b} p \end{bmatrix} \begin{bmatrix} i_{qsn} \\ i_{dsn} \\ i_{qrn} \\ i_{drn} \end{bmatrix} \quad (8)$$

Similarly, the normalized electromagnetic torque in per unit is obtained as,

$$T_{en} = \left(\Psi_{dsn}\, i_{qsn} - \Psi_{qsn}\, i_{dsn} \right) \text{ pu} \quad (9)$$

Normalized electromechanical dynamic equation using equation (6) in per unit yields,

$$T_{en} = 2H\, p\, w_{rn} + T_{Ln} + B_n\, w_{rn} \text{ pu} \quad (10)$$

where, $H = \dfrac{1}{2} \dfrac{J\, w_b^2}{\left(\left(\frac{P}{2} \right)^2 P_b \right)}$ and $B_n = \dfrac{B\, w_b^2}{\left(\left(\frac{P}{2} \right)^2 P_b \right)}$

3. CLOSED LOOP INDUCTION MOTOR DRIVE WITH CONSTANT VOLTS PER HERTZ CONTROL STRATEGY

Let Figure 4 describes an assumed demand torque characteristics of a process machine. In order to produce same demand torque, an implementation of the constant volts / hertz control strategy for the PWM inverter fed induction motor on per unit basis is simulated in MATLAB simulink software as shown in Figure 5 with given mechanical demand torque. In PWM inverter, the per unit voltage command through volts / hertz function generator is converted into three phase stationary reference frame variables $a-b-c$ which are further transformed into two phase stationary reference frame $d^s - q^s$ variables and then into synchronously rotating frame in $d^e - q^e$ variables. Major blocks consist of PWM inverter and induction motor with mechanical load [7], [8], [12]. In this scheme mechanical load is varying cyclically in an assumed pattern. 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 frequency command, w_e produces a positive speed error and the slip speed, w_{sl} is set at the maximum value. The drive accelerates due to changes in the frequency and current, producing the torque, matching with the demand torque. The drive-speed finally settles at a slip speed for which motor torque equals the load torque. Hence, for varying load torque with respect to time, the drive generates electromagnetic torque which almost matches with demand torque of the process machine.

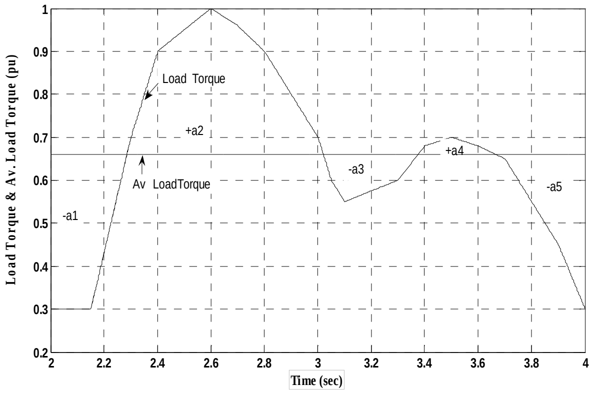

Figure 4. Demand Torque characteristic of a specific machine

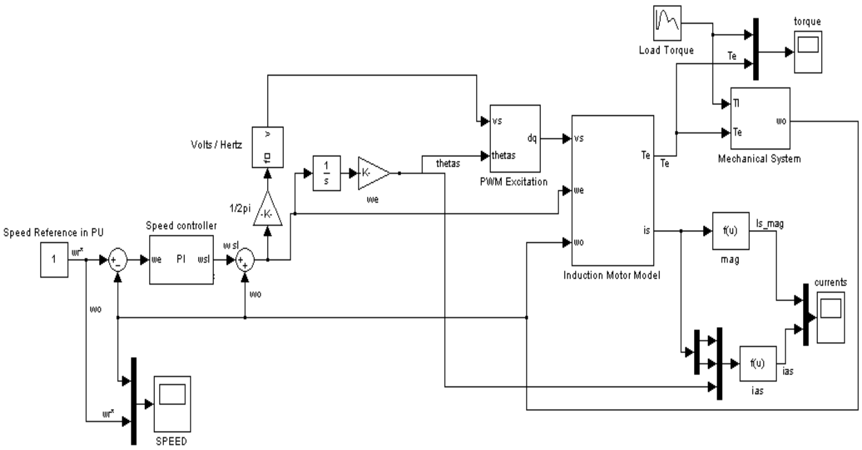

Figure 5. Complete Induction Motor Model with PWM Excitation and Mechanical System along with v/f control scheme in MATLAB software.

4. PROPOSED COMPUTATIONAL PROCEDURE

From Figure 6, let the kinetic energy, K.E. in the flywheel at 0, is E. Then K.E. at 1, $E - a_1$

K.E. at 2, $E - a_1 + a_2$

K.E. at 3, $E - a_1 + a_2 - a_3$

K.E. at 4, $E - a_1 + a_2 - a_3 + a_4$

And, K.E. at 5, $E - a_1 + a_2 - a_3 + a_4 - a_5$ = Kinetic Energy at 0 (i.e. cycle repeats after pt. 0)

Where, a_1, a_2, a_3, a_4, a_5 represent area between generated torque and demand torque or work done in cycle in N-m when flywheel releases or stores energy. [11]
Let us now suppose the greatest of these energies is at 2 and least at 4. Therefore,
Maximum kinetic energy in the flywheel = $E - a_1 + a_2$,
And, minimum kinetic energy in the flywheel = $E - a_1 + a_2 - a_3 + a_4$
Maximum fluctuation of energy, $\Delta E = (E - a_1 + a_2) - (E - a_1 + a_2 - a_3 + a_4) = a_3 - a_4$ (11)
Now, let W be the mass of the flywheel in kg, K_s is the coefficient of fluctuation of speed of the flywheel, I^o is the moment of inertia of the flywheel about its axis of rotation in kg-m sec^2 and W_{mean} is mean speed in rad/sec,
then, maximum fluctuation of energy, $\Delta E = I^o * K_s * (W_{mean})^2$ (12)
And, therefore, moment of inertia, $I = \frac{I^o}{g}$ kgf-m^2 (13)
This calculated moment of inertia decides the suitable size of flywheel to be inserted between VVVf controlled induction motor drive and process machine. The moment of inertia of flywheel estimated this way will be much smaller than adapting usual way of feeding power to the process machine.

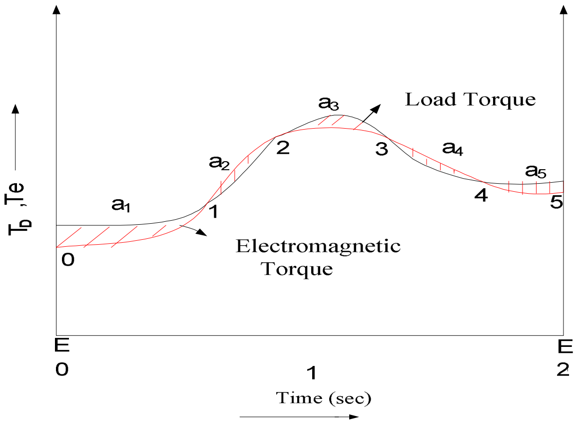

Figure 6. Electromagnetic torque Vs Demand torque

5. CASE STUDY

A process machine is selected which comprises of some linkage mechanism as a main processor. On account of non linear kinematics of the hardware, demand torque characteristics of the process machine are time variant as shown in Figure 4. The total cycle time of the process machine is 2000 msec. The induction motor rating is three phase, 415 V, 1hp with a synchronous speed of 1500 rpm. In this case, the average angular velocity of the input crank of the process unit must be 30 rpm. This gives torque amplification from motor shaft to the process unit input shaft of the order of $1500/30 = 50$. As induction motor generates average supply torque of 5.96 N-M (with given torque formula [4]). Thus the supply torque at the process unit input shaft is 0.596 X 50 = 29.8 kgf-m. Hence, the hp demand of the process unit with a given formula is

$$hp = \frac{2 \cdot \pi \cdot N \cdot T}{4500}$$
$$= \frac{2 \cdot \pi \cdot 30 \cdot (0.596 \times 50)}{4500}$$
$$\approx 1.248$$

Table 1. 1 Hp 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

6. COMPUTATIONAL PROCEDURE

Authors have already simulated [9] a closed loop v/f controlled induction motor drive in the synchronously rotating reference frame on per unit basis using MATLAB simulink [5] containing the simple load torque and complex load torque (Figure 4). The parameters of the induction motor are shown in Table 1.

After simulation, it is observed that induction motor generates similar type of electromagnetic torque with respect to demand torque as shown in Figure 7, by controlling frequency for the motor. As load torque goes on increasing, supply torque is little less than the load torque and hence the speed decreases. As soon as load torque becomes constant, supply torque characteristic follows the same path with respect to load torque to maintain constant speed. But as load torque goes on decreasing, supply torque is greater than load torque, therefore speed of induction motor goes on increasing which is clearly observed in the simulation results. Figure7 shows the characteristics of generated electromagnetic torque and speed with respect to load torque. Figure 8 shows the nature of stator current of induction motor with magnitude on upper portion after variation of load torque. It is observed that as load torque increases or decreases, stator current also increases or decreases to fulfill the requirement of load torque. Figure 9 show change in three phase AC voltages given to induction motor in per unit with respect to change in load torque to maintain v/f constant. Hence, chosen frequency in each time interval is different for the load torque changing cyclically during that time interval in order to generate electromagnetic torque characteristics matching with demand torque characteristics to eliminate large flywheel.

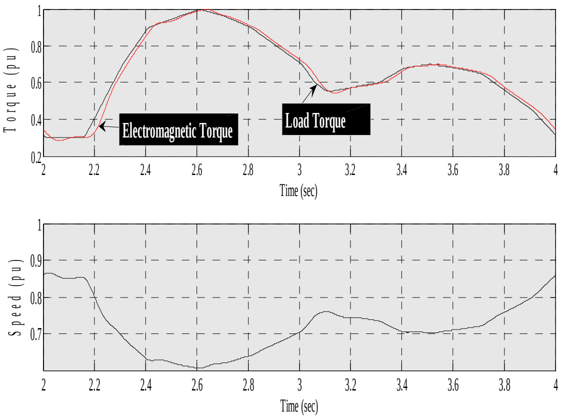

Figure 7. Electromagnetic torque and speed of induction motor for load torque shown in Figure 4

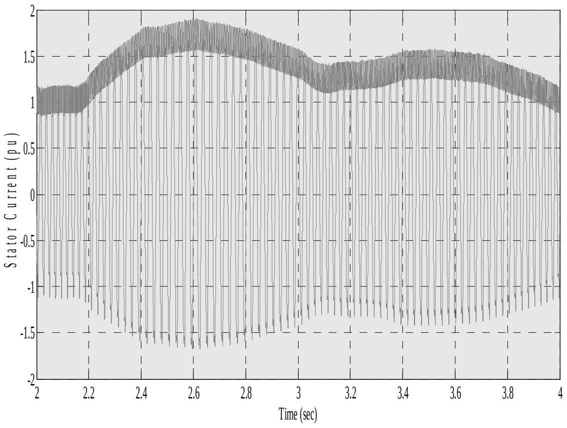

Figure 8. Stator current of induction motor for load torque shown in Figure 4

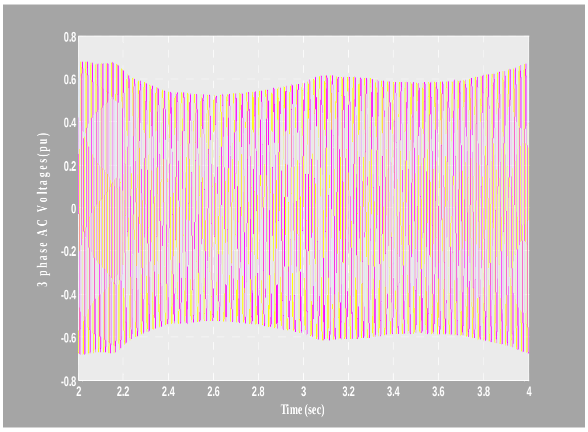

Figure 9. 3 phase AC voltages for load torque shown in Figure 4

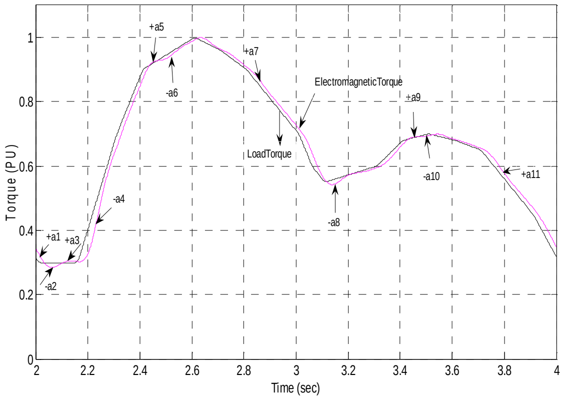

Figure 10. Load Torque vs Electromagnetic Torque for area calculation.

Figure 10 shows a close view of generated electromagnetic torque and the demand torque as functions of time. From this figure, it is observed that generated torque is not exactly matching with demand torque characteristics. Hence suitable small moment of inertia of flywheel is to be added to cater to the difference between generated torque and demand torque. In order to calculate the required moment of inertia of flywheel, one complete cycle of time variation of torque is divided into different zones based on change in position of electromagnetic torque with respect to demand torque shown in Figure 10. Then area of each zone is calculated in kgf-m to calculate maximum fluctuation of kinetic energy of flywheel.

Table 2 shows the area of each zone of Figure 10. Negative area means flywheel releases kinetic energy when drive produces less electromagnetic torque as compared to demand torque. Positive area results in to flywheel storing kinetic energy when generated torque is greater than demand torque. It also shows the calculation of fluctuation of kinetic energy based on maximum and minimum areas of this energy, over one cycle.

Table 2. Calculation of Maximum Fluctuation of Energy of Flywheel as Shown in Figure 10.

Area	(N-m)		(N-m)	(N-m)
a_1	0.01094	$E+a_1$	E+0.01094	
a_2	0.01301	$E+a_1-a_2$	E-0.00206	
a_3	0.00334	$E+a_1-a_2+a_3$	E+0.00127	
a_4	0.19636	$E+a_1-a_2+a_3-a_4$	E-0.19508	
a_5	0.00093	$E+a_1-a_2+a_3-a_4+a_5$	E-0.19415	
a_6	0.018655	$E+a_1-a_2+a_3-a_4+a_5-a_6$	E-0.21280 (minimum)	E-0.21280
a_7	0.13744	$E+a_1-a_2+a_3-a_4+a_5-a_6+a_7$	E-0.07535	
a_8	0.05549	$E+a_1-a_2+a_3-a_4+a_5-a_6+a_7-a_8$	E-0.13085	
a_9	0.00095	$E+a_1-a_2+a_3-a_4+a_5-a_6+a_7-a_8+a_9$	E-0.12989	
a_{10}	0.00338	$E+a_1-a_2+a_3-a_4+a_5-a_6+a_7-a_8+a_9-a_{10}$	E-0.13327	
a_{11}	0.16665	$E+a_1-a_2+a_3-a_4+a_5-a_6+a_7-a_8+a_9-a_{10}+a_{11}$	E+0.03338 (maximum)	E+0.03338
		Maximum Fluctuation of Kinetic Energy , ΔE = Maximum Energy-Minimum Energy		**0.24618 N-m**

From Table 2, total flywheel kinetic energy calculated is 0.24618 N-m or 0.024618 kgf-m

Hence, moment of inertia, I^o in kgf-m-sec^2

$$I^o = \frac{0.024618}{0.08 * \left(2\Pi * \frac{30}{60}\right)^2} = 0.03 \tag{14}$$

Hence, required moment of inertia

$$I = I^o \times g = 0.0312 \times 9.81 = 0.3058 \text{ kgf-m}^2 \tag{15}$$

Required weight of the each fly balls of having equal mass placed at equal distance is,

$$\begin{aligned} I^o &= 2 \times \left[\frac{W}{g} \times \left(\frac{1}{2}\right)^2\right] \\ W &= I^o \times 2g \\ W &= 0.0312 \times 2 \times 9.81 \\ W &= 0.612\, kg \ or \ 612\, gms \end{aligned} \tag{16}$$

The centrifugal force is balanced on these rotating fly balls by an equal and opposite radial force, known as controlling force. The variation of centrifugal force is inversely proportional to variation of load. As load torque increases, centrifugal force on the balls decreases. Hence governor speed decreases and vise versa. Hence, these fly balls are used to control the force for torque equalization of the process machine.

Table 3 shows the fluctuation of flywheel energy of demand torque and average torque when induction motor drive is not controlled by VVVf technique and a large flywheel is used in between drive and the process machine for torque equalization and speed variation to produce an exact demand torque characteristics of the process machine.

Table 3. Calculation of Maximum Fluctuation of Energy of Flywheel as Shown in Figure 4.

Area	(N-m)		(N-m)	(N-m)
a_1	0.49612	$E - a_1$	E-0.49612 (minimum)	E-0.49612
a_2	3.53514	$E - a_1 + a_2$	E+3.03900 (maximum)	E+3.03900
a_3	0.31394	$E - a_1 + a_2 - a_3$	E+2.72507	
a_4	0.12744	$E - a_1 + a_2 - a_3 + a_4$	E+2.85251	
a_5	0.50463	$E - a_1 + a_2 - a_3 + a_4 - a_5$	E+2.34788	
Maximum Fluctuation of Energy , ΔE = Maximum Energy-Minimum Energy				**2.54288 N-m**

From Table 3, total flywheel energy calculated is 2.54288 N-m or 0.254288 kgf-m

Hence, moment of inertia, I^o in kgf-m-sec^2

$$I^o = \frac{0.254288}{0.08 * \left(2\Pi * \frac{30}{60}\right)^2} = 0.322 \tag{17}$$

Hence, required moment of inertia in kgf-m^2 $I = I^o \times g = 0.322 \times 9.81 = 3.1626$ (18)

$$I^{o} = 2 \times \left[\frac{W}{g} \times \left(\frac{1}{2} \right)^{2} \right]$$

$$W = I^{o} \times 2\, g \tag{19}$$

$$W = 0.322 \times 2 \times 9.81$$

$$W = 6.317\ kg\ or\ 6317\ gms$$

7. COMPARISION: PREVALING SYSTEM-VS-PROPOSED SYSTEM

It is observed that, in the proposed system, moment of inertia of flywheel is very small i.e. 0.3058 kgf-m2 and weight of fly balls is only 612 gms when drive is controlled by VVVf technique, as compared to large flywheel of moment of inertia, 3.1626 kgf-m2 with constant frequency operation. Here, weight of fly balls under volts /hertz control scheme is one tenth of weight of fly balls of conventional large flywheel. Therefore, in order to produce supply-torque characteristics matching exactly with demand-torque-characteristics of the process machine, VVVf technique is a superior method to control the input side power of electric drive with small size of flywheel with less moment of inertia. Therefore, disadvantage of large flywheel is eliminated for better and smooth operation of the system.

8. CONCLUSION

In order to eliminate the conventional large flywheel from the process machine with wide fluctuations in demand torque, it is possible to control the input side of the main drive using VVVf technique by applying constant v / f scheme. Generated supply torque characteristics from induction motor almost matches with demand torque characteristics of the process machine. To produce exact supply torque with respect to demand torque, small size flywheel effect with less moment of inertia is required in between drive and process machine. Hence disadvantages of large flywheel are totally reduced with much less torsional vibrations and fatigue in the component of mechanical power transmission.

FUTURE SCOPE

To confirm the analytically obtained results, it is necessary to make a prototype industrial process machine. This will be driven by an induction motor with VVVf drive controlled as described in this article. This will give an experimental evidence of the proposed system.

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