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An Approach Towards Enhancement of Operational Reliability of a Low Cost Automation Device Energised by Human Powered Flywheel Motor by Designing a Linear Electronic Circuit Based Controller

KEYWORDS: Finger Type Clutch, HPFM, Process Unit

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ABSTRACT *For the benefit of the third world people and to run a post carbon society with all comforts of modern life, pedal powered technology has to be adopted. Based on this theme ,the bicycle can be used to generate power for many rural based low cost manufacturing process machines, which is called as HPFM (Human Powered Flywheel motor).These are basically developed by Modak and his associates. In the present research a Linear Electronic Circuit Based controller has been developed for one of the models of a phenomenon. The same phenomenon can be modeled and controlled in different ways. Depending upon the operational reliability of these models one can design a Linear Electronic Circuit Based Controller which would reduce the loss of production to an entrepreneur operating a small capacity factory.*

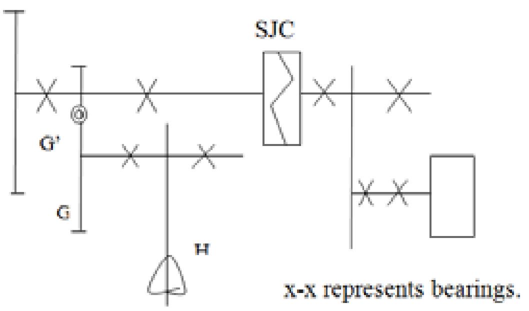
1. INTRODUCTION

1.1 HPFM Energized Process Machine:

Modak and his associates [1 &2] have developed a HPFM energized process machines for various applications [3&4] which are rural based and necessary to improve the life of the people of the third world. The machine consists of three subsystems namely, HPFM (Human Powered Flywheel Motor), comprising of a flywheel F, speeded up through speed amplification gears G' and a conventional bicycle operated by a human operator, Spiral jaw clutch SJC and torque amplification gear G & Process unit. The schematic arrangement of the machine in its plan view is as described in the Fig 1.

1.2 Machine parameters, Operation & Operational Characteristics:

A flywheel is arranged (1 m rim Φ & 10 cm rim width, 2cm rim thickness) in which a man pumps the energy at a rate convenient to him (human power approximately 0.13 hp continuous duty) for about a minute's time by operating a pedaling mechanism through a speed rise gear pair having speed ratio equal to 4.5:1. At the end of a minute's duration, flywheel is accelerated to about 700-800 rpm speed. Then the pedaling is stopped, spiral jaw clutch is engaged and the kinetic energy stored in the flywheel is communicated to a process unit through a pair of torque amplification gear [G = 4.1].



Fig(1):Schematic Arrangement of the machine

Process unit exhausts the energy stored in the flywheel during a very small time 3-10 seconds (Process HP up to 3) depending on the resistance of the process unit. Thus the processes which could be of an intermittent nature and needing power far in excess of human capacity can be energized manually by such machine concept. The concept is tried for various applications such as water lifting, wood turning, wood strip cutting, potter's wheel, brick making, algae formation etc.

1.3 The need for development of Torsionally Flexible Clutches:

During the period of clutch engagement the mechanical system is subjected to severe shock due to instantaneous momentum exchange. On account of this, spiral jaw clutch is subjected to unpredictable malfunction. This is one of the serious drawbacks of this system.

The basic reason for the spiral jaw clutch failure is, it does not have torsional flexibility very much needed in this situation. A clutch with torsional flexibility will permit momentum exchange at a slow rate. The exhaustive literature survey [5&6] shows that clutches with torsional flexibility are not developed excepting the attempts of Modak and his research scholars[7 to 10]. These types of clutches permit momentum exchange at a a fairly slow rate. Though literature indicates development of plate clutches with axial flexibility [5&6] these are not useful for the present purpose.

The present research addresses to the generation of design data through the development of generalized experimental model for a finger tip load and subsequent vibrations of fingers in a finger type torsionally flexible clutch.It also details inclusion of LEC based [14] controller for getting operational velocity of process unit.

2.FINGER TYPE TORSIONALLY FLEXIBLE CLUTCHES

2.1 Construction:

Clutch comprises of two members. Member I is connected to the flywheel shaft through splines. Multiple numbers of fingers 3, 4, 6 are provided integral with the hub of the member I. Fingers have rectangular section as shown. Member II is carrying jaws J (3, 4, 6, depending on the number of fingers provided, but no. of jaws equals no. of fingers). Member II is integral with the jaw which provides drive to the process unit.

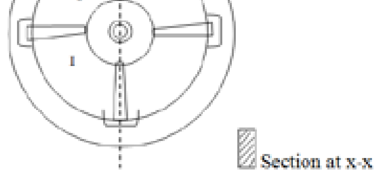


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Fig (2): Schematic of Finger Type Clutch

2.2 Working:
When the flywheel F of the main machine is being accelerated, member I is so located on the flywheel shaft that fingers F do not have contact with jaws J and the clutch is in disengaged position. After getting the desired flywheel speed, peddling is stopped, member I is axially slided over flywheel shaft. The moment when fingers dash on jaws J, the process of momentum transfer from flywheel shaft to load shaft commences. Fingers F, structurally behave as short cantilever having spring like action because of its elasticity. Thus the fingers provide relative angular displacement between load shaft and the flywheel shaft during the period of clutch engagement. This is how torsional flexibility is provided by this type of clutch.

3.DYNAMICS OF THE CLUTCH
Clutch engagement duration is defined to be the time interval in which the flywheel shaft and the load shaft attain the identical speeds after first contact of fingers with the jaws. During this period, flywheel shaft speed $\dot{\theta}_F$ & load shaft speed $\dot{\theta}_L$ are different. Applying De-Alembert's formulation, the general equations of motion for the flywheel shaft and the load shaft respectively can be derived as –

$$-I_F\ddot{\theta}_F - b_F\dot{\theta}_F - K\alpha t = 0 \qquad \text{(I)}$$

$$K\alpha t - I_L\ddot{\theta}_L - b_L\dot{\theta}_L - T_L = 0 \qquad \text{(II)}$$

In equations (I) & (II) IF and IL are moment of inertia's of flywheel and load shaft. bF and bL are bearing friction torque constants of flywheel and load shaft respectively. TL= Load Torque on the load shaft as imposed by the process resistance. K= Stiffness of the fingers, αt = instantaneous slope of the finger at its fixed end. Careful examination of Equas (I) & (II) shows that these equations are not solvable unless experimental feedback of the behavior of the system is known. Hence, it amounts to establishing the generalized experimental data based models for $\dot{\theta}_F$ & $\dot{\theta}_L$ or eventually of finger tip load and finger vibrations which can be considered to be a function of $\dot{\theta}_F$ & $\dot{\theta}_L$.

4. DESIGN OF EXPERIMENTATION
Generalized experimental models for W & S (maximum stress induced in the fingers due to finger load and vibrations) are established adopting methodology of experimentation [13].

As per this methodology all independent parameters and/or physical quantities are varied over widest possible range. Huge response data is collected. Based on this entire data Generalized models are formed. The detailed steps are (1) Establishing the dimensional equations of the mechanics of a clutch (2) Test envelopes, Test points and Test sequence (3) Design and building up of an experimental set up ,(4) Performing experimentation (5) Publication of Experimental Data (6) Establishing the exact mathematical function of the dimensional equation based on Experimental Data.

4.1 Dimensional Equations:

Applying Buckingham-II theorem and a Raleigh's method [13],the dimensional equations for (WD/TL) & (SD3/TL) are formulated as under:

$$\frac{WD}{T_L} = f\left[\begin{matrix}\left(\frac{I_F}{T_L{*}t^2}\right).\left(\frac{I_L}{T_L{*}t^2}\right)\left(\frac{b_F}{T_L{*}t}\right)\left(\frac{b_L}{T_L{*}t}\right).\\ \left(\frac{R}{D}\right).\left(\frac{W}{D}\right).\left(\frac{d}{D}\right).\left(\frac{ED^3}{T_L}\right).(U).(N).\left(\frac{gt^2}{D}\right)\end{matrix}\right] \qquad \text{-----(III)}$$

$$\frac{SD^3}{T_L} = f\left[\begin{matrix}\left(\frac{I_F}{T_L{*}t^2}\right).\left(\frac{I_L}{T_L{*}t^2}\right)\left(\frac{b_F}{T_L{*}t}\right)\left(\frac{b_L}{T_L{*}t}\right).\\ \left(\frac{R}{D}\right).\left(\frac{W}{D}\right).\left(\frac{d}{D}\right).\left(\frac{ED^3}{T_L}\right).(U).(N).\left(\frac{gt^2}{D}\right)\end{matrix}\right] \qquad \text{-----(IV)}$$

Where
I_F=Moment of Inertia of Flywheel Shaft

I_L=Moment of Inertia of Load Shaft
T_L=Load Torque on Load Shaft
R= Radius of the finger tip measured from centre O
D= Diameter of the finger
W= Width of the finger
d= Depth of the finger
E=Modulus of Elasticity of Finger Material
t=Time
g= Acceleration due to gravity

4.2 Test Planning:
Keeping in view the functional response obtained in previous investigations [1,2,7 to 10] & in view of cost, time and computational accuracy constraints the test planning is decided as described in Table 1.

∏ Term	Test Envelope
WD/TL	-34.5 21.7
IF. TL/t2	-107.29 42916.8
IL TL/ t2	-0.909 363.7

IF is held constant. IL is varied over TL. For some π terms the test planning could not be done as time (t) gets associated with the π term.

4.3Experimental Set Up:
Fig 3 describes the experimental set up having the provision of varying all independent π terms of equations III & IV.

A band brake (BB) is arranged to vary TL. Encoders EF and EL put on flywheel shaft and load shaft respectively generate signals representing $\dot{\theta}_F$ & $\dot{\theta}_L$. $\dot{\theta}_F$ & $\dot{\theta}_L$ are further processed through frequency- voltage transducer using IC's and voltage output is fed to the PC using A-D converter. PC gives graphic display of $\dot{\theta}_F$ & $\dot{\theta}_L$ verses time. A representative variation is depicted in Fig 4.

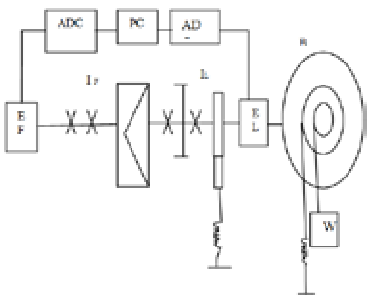

Fig 3: Experimental Set up

4.4Generalised Models:

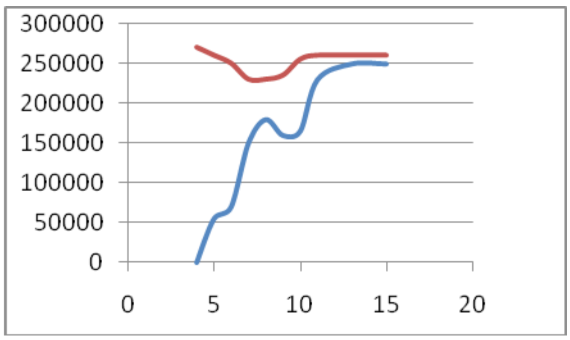

Fig 4 Dynamic Response

Using the principle of (I) force balance & (II) energy balance

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variation of W verses time is established as depicted in Fig 5 by the curves (a) & (b) respectively corresponding to the experimental data of Fig 4.

Fig 5 shows erratic variation of W. This appears to be because of unpredictable bearing friction torque. This situation may be perhaps due to much more severe loading on the flywheel shaft & load shaft. Hence hereafter the anticipated finger tip load based on force balance concept is no more considered. The vibration response is evaluated approximating the finger as a single degree of freedom spring-mass-damper system.' ζ ' is assumed to be 0.9 in view of the fact that the system damping is due to the friction between the finger and the jaws due to axial siding of fingers under severe tip load during the period of engagement is not reflected in Equations I &II . To account for this ζ is assumed to be very high and of the order of 0.9.

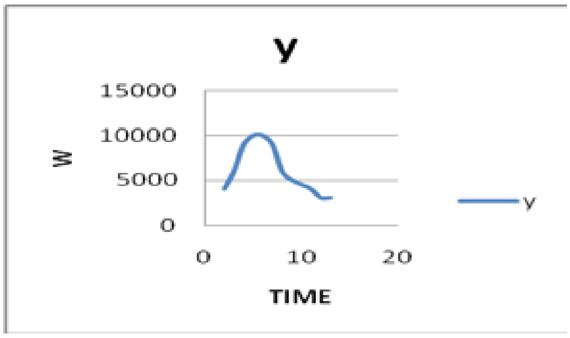


Fig 5 (a):Variation of load (W) with time (t)

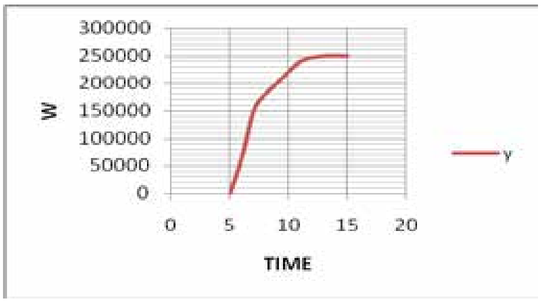


Fig 5(b): Variation of maximum stress vs Time

Fig 5 (a) shows the variation of W vs time for the variation of maximum stress vs time as shown in fig5 (b) respectively. The above variations are obtained for the entire experimental information gathered in this work. Based on this research, exact mathematical form of dimensional Equations (I&II) are obtained after performing necessary mathematical operations & are reproduced below.

$WD/T_L = -0.063\ [(I_F/T_L t^2)^{1.569} (I_L/T_L t^2)^{-0.07} (RwdN/D^2)^{0.031} (ED^3/T_L)^{-0.237} (gt^2/D)^{1.512}]$ -------(V)

$SD^3/T_L = -0.1438\ [(IF/T_L t^2)^{0.0027} (IL/T_L t^2)^{0.0289} (RwdN/D^2)^{0.2356} (ED^3/T_L)^{0.8438} (gt^2/D)^{-4.128}]$ (VI)

5.DISCUSSION ON RESULTS

In this section it is proposed to discuss the mechanics of energy transfer from flywheel shaft to the load shaft through this finger type clutch.

Fig 4 shows that in the early part of clutch engagement there is a drop in flywheel speed but afterwards it keeps on increasing right from t=t3 $\dot{\theta}_F = \dot{\theta}_L$. $\dot{\theta}_L$ however keeps on increasing right from t = t1 till t = t3 with some spells of time in which $\dot{\theta}_L$ is reducing. Similar behavior is observed for entire variation of independent quantities.

This indicates that immediately upon colliding of fingers on the jaws considerable energy is stored in the finger in the form of elastic strain energy. Maximum energy should be stored during δt=t2-t1 . In fact this gets confirmed from subsequent calculations of estimation of finger tip load W.

Curve of Fig5(b) shows maximum W at t=t2 when $\dot{\theta}_F$ is minimum .As W is maximum at t=t2 tip load determination is maximum at t=t2 , hence is the maximum storage of strain energy. Interestingly, it is observed that δt=t2 - t1 varies with system independent variables. Infact, generalized experimental model should be formulated for δt which will reveal the influence of independent quantities on δt & hence on impact phenomenon.

Further interesting observation is at times $\dot{\theta}_L$ is increasing and at times reducing during δt=t3 – t2.This solidly confirms that load shaft at times demands energy from fingers and at times pumps the energy in the fingers. This should cause severe superimposed oscillation over and above that caused by variation of W vs time. Finger vibrations during δt=t3 –t2 and also during δt=t2 - t1 as W is rising with steep gradient, fingers are subjected to transient vibrations . On the whole therefore fingers are subjected to vibrations which need estimation of stress under vibrations.

Curve a of Fig 5 shows higher value of W as compared to those of curve b. This is obvious because frictional energy loss is not assumed for information presented by curve a. Bearing friction phenomenon appears to be pretty erratic because curve b shows W=0 for some instants. This is because at those instants frictional resistance itself is enough to impose necessary retardation even if not reaching to limiting value of friction.

The experimental set up may need additional instrumentation to solidify ascertain the influence of friction.

In the estimation of vibration response over simplifying assumptions are made which are as under (1) Entire finger mass is assumed to be at the tip. (2) Finger elasticity is assumed to be linear. In fact it may be non-linear leading to the sever finger oscillations.(3) ζ is assumed to be 0.9 , a very high value without which stress under vibrations could not have been a practically acceptable figure. ζ =0.9 may be justified because considerable axial frictional rub or the fingers during

δt = t3 – t1 is not modeled. Of course this will be only possible by sophisticated instrumentation like telemetry.

VI. FORMULATION OF THE PROPOSED MODEL:

Equation(VI) can be rearranged to deduce necessary number of fingers for the specified TL and specified material of the fingers . However since the reliability of estimation of clutch performance based on equation (VI) being not adequate it is necessary to change the mathematical form of the model. What follows is this change in the form of the model.

$S=f(I_F,I_L,T_L,t,g,E,R,w,d,N,D)$ (VII)

In Equation (VII)

I_F= Moment of Inertia of Flywheel Shaft

I_L=Moment of Inertia of Load Shaft

The most compact form of the dimensional equation for equation (VII), could be as under as per Raleigh's Method.

$SD^3/TL= f\ ((IF.R.w.d.N.E.g.t^2) / (I_L.T_L.D))$ (VIII)

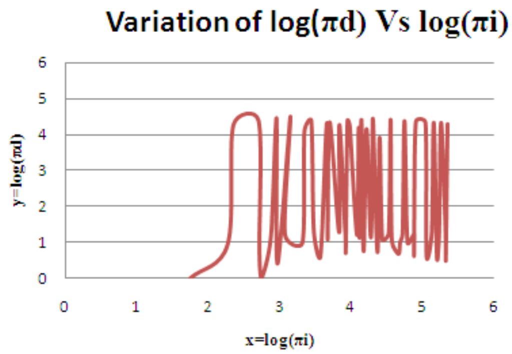
Let Equation (VIII) be written in the form

$\pi_d=f(\pi_i)$ (VIII-A)

Based on the experimental data, the variation log(πd) Vs log(πi) is as shown in the Fig 6.

Figure (6) indicates that the variation of log (πd) Vs log (πi) is having several peaks and crusts. Hence, the most appropriate form of model could be either the higher order polynomial form or the sinusoidal form. The polynomial form of model deduced is as under:

Y=1.0e+006*(0.0002x9-0.0479x8+0.1244x7-2.2663x6+3.6081x5-1.7813x4+1.6889x3 -1.6133x2+0.3033x-0.0162) (IX)



Fig(6)Variation of log(πi) Vs log(πd)

This form is having better reliability as compared to the reliability of the model depicted in Equation (VI). Further, this form of the model is more convenient from the point of view of designing controller based on linear electronic circuits [14].

VII. LEC BASED CONTROLLER

Equations (IX) simulate operation of the system under consideration.

Now as and when, the operating conditions change i.e. inputs change, it becomes inevitable that responses also change. But, it is necessary to maintain responses within certain limits.

For example in this case the load torque TL changes say increases, it will increases the finger tip load (W) and in turn it will increase induced stress (S). But S should not increase beyond a certain limit allowable stress in bending. Only way, to do this in this case will be to change (i) either cross section of fingers (ii) increase D (iii) change the material of the fingers (iv) change IF or IL (v) change no. of fingers, N.

Amongst these alternatives easiest is to change the number of fingers N. This amounts to provision of more than one clutch. So one may provide three clutches with N=3, 4 and 6.

Further, there has to be a provision of (i) measuring TL (ii) comparing measured T_L with designed T_L (iii) if T_L actual is more than designed then, there has to be a provision of measuring how much in excess is T_L. Then subsequently there has to be a provision to decide a clutch with number of N to be engaged. Finally, a necessary physical system is to be provided to shift energy flow from flywheel F to process unit through a proper clutch.

Entire system including a controller schematically is shown in Figure 7. This schematic represents (i) main system to be controlled and (ii) the Linear Electronic Circuit Based controller. This controller comprises of TM the torque meter, A/D converter, Linear Electronic Circuit calculating necessary number of fingers in a clutch corresponding to load torque TL , selection of motors M1, M2, M3, corresponding linkages converting rotary motion into rectilinear motion of slider of dog clutches DC1, DC2, DC3. It is obvious that A/D converter,LEC based mini computer estimating necessary number of fingers ,N and selector of M1, M2, M3, could be on one chip denoted here as LEC BASED CONTROLLER.

VIII . MODEL

According to equation (VIII-A) ,i.e.

$SD^3/T_L= f((I_F.R.w.d.N.E.g.t^2) / (I_L.T_L.D))$ (VIII-A)

Now put $y=SD^3/T_L$ and $x= (I_F.R.w.d.N.E.g.t^2) / (I_L.T_L.D)$ in equation(VIII-A), then Equation(VIII-A) changes to

$y= f(x)$ (XI)

Plotting y and x on ordinate and abscissa respectively, one gets graphic plot of variation of y as x varies. This graphic plot is converted into polynomial form of model as under

$Y=A_0+ A_1x+ A_2x^2+ A_3x^3+$.................. (XII)

CASE (i):

Now only considering second term of the model i.e .Equation (XII), one gets

$y=A_1x$ (XII-A)

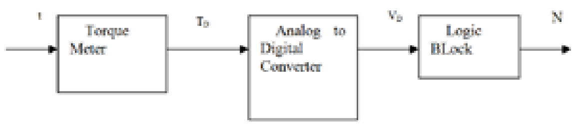
Substituting in Equation (XII-A) and substituting for original variables for y and x, equation (XII-A) takes the following form

$SD^3/T_L= A_1((I_F.R.w.d.N.E.g.t^2) / (I_L.T_L.D))$

$N=(1/A_1). (SD^3/T_L). ((I_L.T_L.D)/ (I_F.R.w.d.E.g.t^2))$

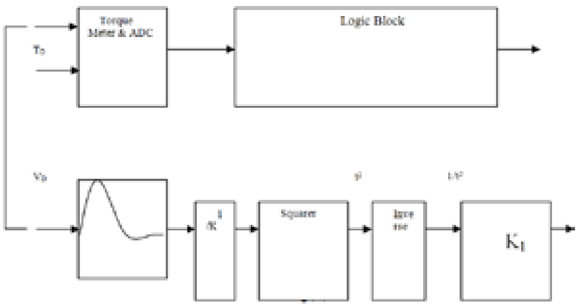
$N=(1/A_1). (SD^3). ((I_L.D)/ (I_F.R.w.d.E.g.t^2))$ (XII.B)

Here't' is a specific time instant during the period of clutch engagement. However, from the point of view of the physics of the system, it is T_L which in fact decides N for specified material of the finger i.e. the parameters S and E .In fact instead of't', V_D (digital voltage)as detailed below should be substituted for 't'.



Fig(8).

Perhaps it could be as under



Fig(9):

In the above block

$K_1=(SD^3.I_L.D)/(A_1.I_F.R.w.d.g.E)$ (XII.C)

CASE (ii):

Now only considering third term of the model i.Equation (XII), and let us denote this contribution to total y as y'' , then

$y''= A_2x^2$ (XIII)

Upon substituting for $y''=SD^3/T_L$ and

$x== (I_F.R.w.d.N.E.g.t^2) / (I_L.T_L.D)$

Equation (XIII) would take the form

$SD^3/T_L= A_2 ((I_F.R.w.d.N.E.g.t^2) / (I_L.T_L.D))^2$

$N^2= (1/A_2). (SD^3/T_L). ((I_L.T_L.D)/ (I_F.R.w.d.E.g.t^2))^2$

$N=[(S.D^5T_LI_L^2)/A_2(I_FR.w.d.g.t^2.E)^2]^{1/2}$ (XIII.A)

Here also 't' is a specific time instant during the period of clutch engagement. However from the point of view of the

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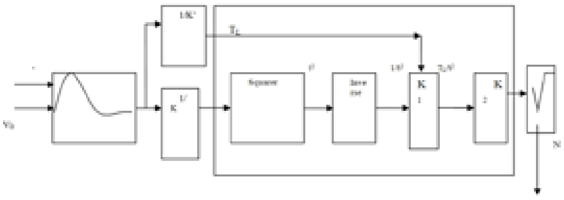
physics of the system .it is T_L which in fact decides N for specified material of the finger i.e. the parameters S and E .In fact instead of't', V_D (digital voltage) as detailed below should be substituted for 't'.



Fig(10):

Let $K_2=(SD^5I_L)/(A_2I_F(Rwd) .g.E\ )$

Similarly for 3^{rd} ,4^{th} ,5^{th} -------9^{th} component of polynomial form one should develop complete block diagram. [Refer Figure(11)]

VIII. CONCLUSION

This paper initially emphasizes on adoption of human powered flywheel motor energized rural and interior civilization based process units manufacturing items of daily needs of normal rural life. The most vital component of this production system is in general a positive clutch, a finger type clutch in particular. Experimental data based model is proposed to be formulated because of instantaneous momentum exchange from the flywheel to process unit. There are chances of malfunctioning of the clutch resulting into inadequate reliability of operation of the main processor. However adequate reliability can be achieved by introducing LEC based controller with the main system.The main emphasis of the paper is to 1) Get more reliable experimental data based model depicting behavior of the clutch and 2) to develop corresponding LEC based controller.

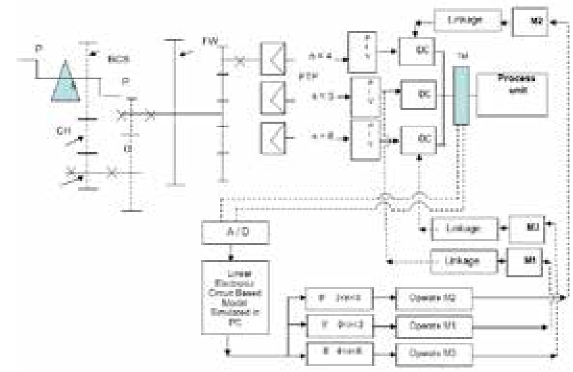
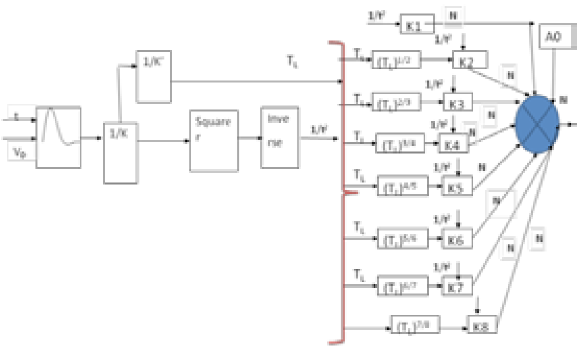


Figure7: Schematics of LEC Based Controller



Fig(11):

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