A programmable dynamometer for motor testing using dc machine

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This paper presents a programmable dynamometer for motor testing. The transient and steady state characteristics under different load types can be obtained. With this dynamometer, the user can define a model reference of the steady state and inertial torque-speed characteristics of the desired load. The desired load characteristics can be obtained by selecting polynomial and inertia coefficients of the torque model reference; the output is used to control the torque of a separately excited dc generator connected with a half controlled single phase bridge and driven by the motor under test. The dynamometer is set to load the motor with constant, linear, quadratic, third order, and step-change loading. Simulation and experimental results show that the proposed dynamometer offers a good tracking for the de..ired torque speed characteristics of the load.

يتطلب اختبار المحركات تعرضها لحمل حقيقي حيث تتعرض محركات التسيير لتغيرات في الحمل تتوقف على ظروف التشغيل. ولذلك فإنه يصعب الحصول على مثل هذه الظروف الفعلية في المعمل باستخدام فرمله أو مولد تقليدى. في هذا البحث تم اقتراح نظام تحميل مرن يمكن التحكم فيه ليعطى التغييرات المطلوبة طبقا لحمل مرجعي تم إعداده مسبقا ليلائم ظروف الاختبار المطلوبة. والنظام المقترح يتكون من مولد تيار مستمر ذا تغذية ثابتة محكوم بقنطرة ثيرستور أحادية الوجه ومحمل بمقاومة بحيث يتم التحكم في تيار المولد لإعطاء العزم المطلوب لحظيا لتتبع العزم المرجعي. تم تحليل النظام واستنباط نموذج رياضي له بما في ذلك المتحكم المطلوب ومعادلة العزم المرجعي وذلك لاختبار محرك حثي ثلاثي الوجه يعمل من مصدر ذا جهد وتردد ثابتين.

Keywords: Motor testing, Dynamometer, DC machine

1. Introduction

Dynamometers are extensively used for testing rotating machines in the laboratory in order to determine their efficiency, to establish mechanical developed torque or/and to carry out full load temperature rise tests. This is to determine whether a motor is truly of energy conversion efficient type, or just claimed to be so.

Since, most actual motor loads are active, a simple brake or a generator cannot mimic a practical load. Normally, one load type is used at a time for motor testing. In both cases, however, the machine is loaded with constant inertia. Other type of testing uses an inertial load. For a high enough inertia, the rise time will be very long, and so the motor will be in a quasi-steady-state during acceleration. A number of machineless dynamometer schemes for motor temperature rise tests have been proposed; a list of references could be found in [1].

Recently, advanced motor controls for precise torque tracking have been developed. Those techniques can be applied to a dynamometer for tracking a desired torque-speed profile in real-time. The Motor Under Test (MUT) supplies the driving torque. Its control, if any, will be independent of the dynamometer control. The dynamometer is usually run in the generating mode, with excursions into the motoring mode during certain events, such as acceleration when the desired load inertia is less than that of the actual system. Alternative dynamometers depending on the previous method have also been proposed in [2-4] using indirect field orientation to control the three-phase induction motor. However, due to the complexity of field orientation, the study has been restricted to simulation [2, 3]. A dynamometer that can emulate a practical load characteristic requires control of the load torque on a continuous basis. This control is necessary in both steady state and transient conditions if the actual static and inertial loading characteristics are to be emulated.

In this paper, a separately excited dc machine is employed as a dynamometer machine (DM). The dc machine is chosen because it is inherently field oriented and has a stable and straightforward characteristics. It is also ideally suited for trajectory control applications [5]. From the point view of control systems, the dc machine can be considered as a Single Input Single Output (SISO) system, thereby eliminating the complications associated with a multi-input drive system [2-4].

The torque of the proposed dynamometer is controlled using a single-phase half-controlled bridge. The user can define the model reference for the desired steady state and inertial torque-speed characteristics. Its output is considered a torque reference for the dynamometer PI controller. A three-phase induction motor is used as the MUT. The dynamometer is set to load the motor with constant, linear, quadratic, third order, and step-change loading. The dynamometer may operate either in the generation or motoring modes. For generating mode, it can be used to simulate different loads while, for motoring mode, it can simulate the behavior of different prime-mover systems. Simulation and experimental results show that, the proposed dynamometer offers good tracking of the desired torque-speed characteristic for testing the MUT.

2. Concept of the proposed method

Usually, a dc generator is used for testing loaded motors, where the load can be adjusted by the generator output. The torque developed by a dc generator with fixed excitation is given by:

$$T_g = KI_a = \left(\frac{K}{R_L + r_a}\right)E_g = \left(\frac{K^2}{R_L + r_a}\right)\omega_m . \quad (1)$$

Thus, with constant R_L, the torque-speed relationship in the steady state is linear, where the system inertia is constant. With the proposed dynamometer, a controlled voltage source V_d is inserted in series with E_g feeding R_L. The voltage V_d is the output of a thyristor power converter whose firing angle is controlled according to the desired torque-speed profile. A simplified representation of the proposed dynamometer is shown in fig. 1.

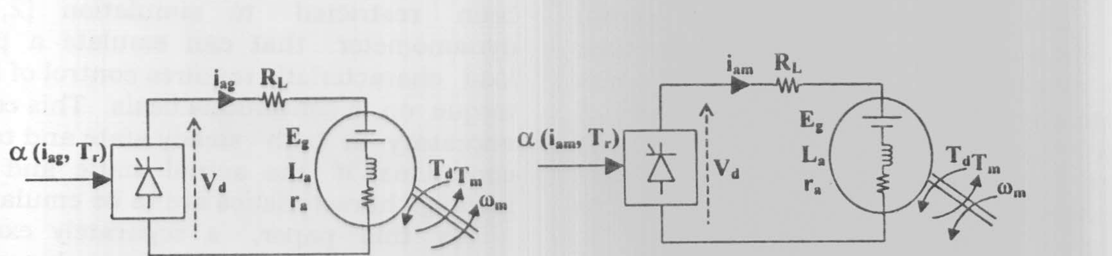
In normal operation, the MUT supplies the driving torque, as shown in fig. 1-a. In this case, the dynamometer current is given by:

$$I_{ag} = \frac{V_d + E_g}{R_L + r_a} . \quad (2)$$

When the DM operates in the motoring mode, fig 1-b, the corresponding current is given by:

$$I_{am} = \frac{V_d - E_g}{R_L + r_a} .$$

The half-controlled bridge gives voltage and current of the same polarity, always, e.g. one quadrant operation. Thus, in the generating mode of the DM, controlling the armature current I_a can be forced to track the desired load torque, e.g to simulate different loads such as compressors, fans, centrifugal pumps, hoists, and traction drives. Similarly in the motoring mode, controlling V_d, forces I_a to track a desired torque speed characteristic to test the MUT in the generating mode. The present work is focused on the DM generating mode, e.g. for motor testing.



a- generating mode b- motoring mode

Fig. 1. Simplified representation of the proposed dynamometer.

3. Dynamometer system

The motor/dynamometer combination will have transient behavior that depends on the MUT, the DM, and the coupling between them. The actual transient behavior which is often determined using the real load can be obtained using the proposed dynamometer. In general, the desired load torque can be expressed as:

$$T_r = a_0 + a_1\omega_m + a_2\omega_m^{\,2} + a_3\omega_m^{\,3} + J\frac{d\omega_m}{dt}. \quad (3)$$

The constant a_0, a_1, a_2, a_3, and J are specified to simulate the actual load. Accordingly, the control system will control the DM such that shaft torque tracks the desired characteristic, provided it is within the capabilities of the dynamometer. Thus, the MUT can be tested for any load type, simply by changing the constants. The control strategy presented in this paper, is quite general and can be applied to other applications of similar nature.

The complete system is shown in fig. 2. The transient behavior of the overall system is given by:

$$T_m - T_e = J_s\frac{d\omega_m}{dt} + \beta_s\omega_m , \quad (4)$$

where : $J_s = J_d + J_m$, and $\beta_s = \beta_d + \beta_m$.

The torque T_L which acts on the MUT is:

$$T_L = T_e + J_d\frac{d\omega_m}{dt} + \beta_d\omega_m . \quad (5)$$

Since T_L is the actual torque of the programmable dynamometer, the control system must force the DM to track the desired torque trajectory T_r as closely as possible.

3.1. The dynamometer realization

The dynamometer system is represented as shown in fig. 2; the block diagram is shown in fig. 3. The speed is measured and $\frac{d\omega_m}{dt}$ is determined via the model reference. These are manipulated using eq. (3), to determine the torque reference according to the desired torque-speed characteristics. The PI controller compares the torque reference with the torque feedback signal, and acts to minimize the error. However, the delay due to the PI controller can be neglected with respect to the mechanical time constant.

3.2. Mathematical model

From fig. 3, eq. (4) as well as the following electrical equation may describe the overall system:

$$V_a(s) = -k\ \omega_m(s) + R\ I_a(s) + s\,L_a\,I_a(s) \quad (6)$$

where: $R=R_L+R_a$, and the dc machine is in the generating mode supplying continuous dc current.

The single-phase half-controlled bridge controls the armature current, I_a. If the small time delay associated with the converter firing is neglected, the converter transfer function can be considered linear over the range from $\alpha = 30^\circ$ to 150°, then within this range:

$$\frac{V_d(s)}{V_c(s)} = G . \quad (7)$$

The mathematical model expressed by eqs. (3-7), the feedback gains, and the PI controller is represented by the block diagram of fig. 3. The proposed dynamometer can be modeled to give different load types as discussed below.

3.3. Torque control range

The torque control range of the proposed dynamometer in the linear range of thyristor bridge can be determined from eq. (2). The average output voltage of the half-controlled bridge in the continuous motor current mode is [6]:

$$V_d = \frac{V_m}{\pi}(1 + \cos\alpha) . \quad (8)$$

For a minimum reference torque, i.e. $\alpha \cong 150^\circ$, giving a minimum average voltage $V_{dmin}=0.042V_m$, yielding a minimum developed torque, and eqn (2) becomes:

$$T_{g\,min} = \frac{0.042\,K\,V_m}{R_L + r_a} + \frac{K\,E_g}{R_L + r_a} \cong \frac{K\,E_g}{R_L + r_a}. \quad (9)$$

While, for a maximum reference torque, i.e. $\alpha \cong 30^\circ$, giving $V_{dmax}=0.6V_m$, and:

$$T_{g\,max} = \frac{0.6\,K\,V_m}{R_L + r_a} + \frac{K\,E_g}{R_L + r_a}. \quad (10)$$

Eqs. (9) and (10), define the torque control range from T_{gmin} to T_{gmax}. For the induction motor as a MUT, E_g can be considered constant, assuming approximately constant speed motor. To increase the torque control range, R_L and V_m have been chosen sufficiently large but within the capabilities of DM current, i.e. such that:

$$\frac{0.6\,K\,V_m}{R_L + r_a} \geq 4\,\frac{K\,E_g}{R_L + r_a} \quad \text{or} \quad \frac{0.6\,K\,V_m}{R_L + r_a} \geq 4\,T_{g\,min}.$$

Accordingly, the developed DM torque can be varied from $T_{g\,min}$ to $T_{g\,max} = \frac{0.6\,K\,V_m}{R_L + r_a} + \frac{K\,E_g}{R_L + r_a} =$ $4T_{gmin} + T_{gmin} = 5\,T_{gmin}$. That gives 80% variation of the DM torque.

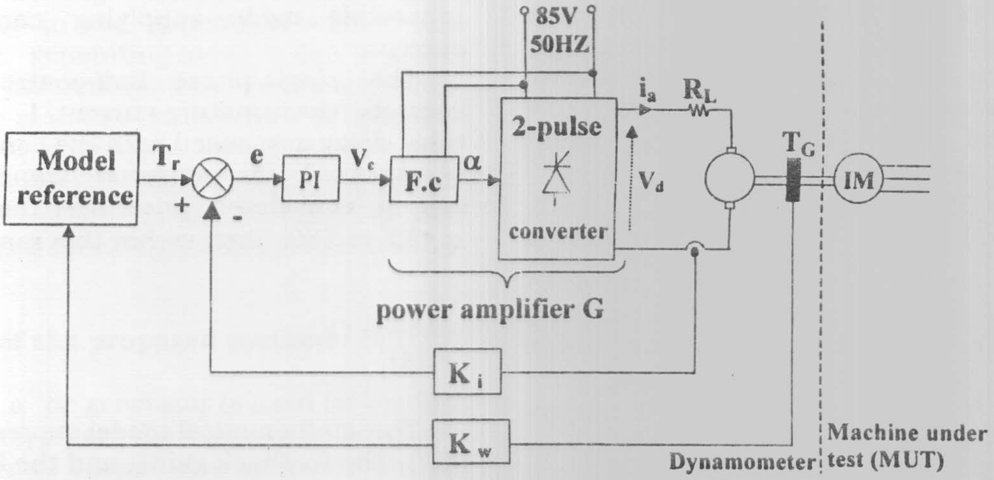


Fig. 2. The programmable dynamometer system.

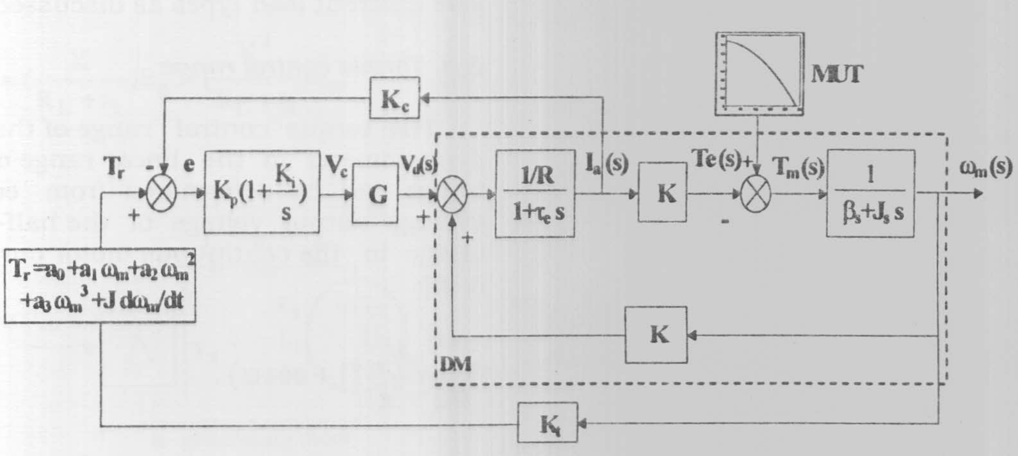


Fig. 3. Block diagram of the dynamometer system.

4. Applications

4.1. Constant torque operation

For constant torque operation, eq. (3) becomes:

$$T_r = a_0 + J\frac{d\omega_m}{dt}. \qquad (11)$$

Thus, from fig. 3, and for constant MUT torque, an expression for armature current change ΔI_a can be written in terms of the motor speed change $\Delta\omega_m$ as:

$$I_a(s) = \frac{1/R}{1+\tau}\left[k\omega_m(s) + (a_0(s) + Js\,\omega_m(s) - k_c\,I_a(s))\,G\,(k_p + \frac{k_i}{s})\right].$$

Rearranging the terms yields:

$$I_a(s) = \frac{1}{R\,\tau}\,\frac{[(JG\,k_i + k) + JGk_p\,s]\,s\omega_m(s) + a_0(s)\,G(s\,k_p + k_i)}{s^2 + \frac{R + k_c G\,k_p}{R\tau}s + \frac{k_i\,k_c G}{R\tau}}. \qquad (12)$$

From the above equation, for a step change in a_0 by $a_0(s) = \frac{\Delta a_0}{s}$, the corresponding change in I_a in the steady state using the final value theorem with eq. (12) is:

$$\Delta I_a = \operatorname{Lim}\ s\ \frac{1}{R\tau}\left.\frac{[(JG\,k_i + k) + JGk_p s]\,s\Delta\omega_m(s) + \frac{\Delta a_0}{s}G(s\,k_p + k_i)}{s^2 + \frac{R + k_c G\,k_p}{R\tau}s + \frac{k_i\,k_c G}{R\tau}}\right|_{s=0}$$

$$= \frac{\Delta a_0}{k_c}. \qquad (13)$$

It is obvious that the resulting steady state current (torque) is maintained unchanged regardless of the shaft speed.

4.2. Linear torque operation

For linear torque operation, eq. (3) becomes:

$$T_r = a_1\omega_m + J\frac{d\omega_m}{dt}. \qquad (14)$$

Thus, from fig. 3, and for constant MUT torque, an expression for armature current change ΔI_a can be written in terms of the motor speed change $\Delta\omega_m$ as:

$$R(1+\tau_e)I_a(s) = k\omega_m(s) + G(k_p + \frac{k_i}{s})\,[-k_c I_a(s) + a_1(s)(h + Js)\omega_m(s)].$$

Rearranging the terms yields:

$$\frac{I_a(s)}{\omega_m(s)} = \frac{1}{R\tau}\,\frac{JGk_p a_1(s)s^2 + (a_1(s)hGk_p + JGk_i a_1(s) + k)s + a_1(s)hGk_i}{s^2 + \frac{R + k_cG\,k_p}{R\tau}s + \frac{k_i\,k_c G}{R\tau}}. \qquad (15)$$

The variation of torque-speed characteristics for step change in a_1 by $a_1(s) = \frac{\Delta a_1}{s}$ can be obtained using eq. (15), which gives:

$$\Delta I_a = \frac{\Delta a_1 h}{k_c}\,\Delta\omega_m. \qquad (16)$$

It is clear that the slope of the steady state torque-speed characteristics for the dynamometer is linear and directly related to a_1, h, and k_c. Thus, using a_1, this slope can be adjusted to obtain the desired linear torque-speed characteristics.

4.3. Quadratic or higher order load torque

For a quadratic or fan-type load simulation, the coefficients a_0, a_1, and a_3 in eq. (3) are set to zero. The system becomes nonlinear, but, the action of the PI controller forces I_a to track the torque reference T_r in the steady state as in eqs. (13) and (16). This action is valid for linear and nonlinear systems. So, for the quadratic steady state load action:

$$T_r = a_2\,\omega_m^2 = k_c I_a \quad \text{and} \quad I_a = \frac{a_2}{k_c}\,\omega_m{}^2. \qquad (17)$$

This is also valid for higher order load torque characteristics, and so the third order load torque in the steady state becomes:

$$T_r = a_3\,\omega_m^3 = k_c I_a \quad \text{and} \quad I_a = \frac{a_3}{k_c}\,\omega_m{}^3 \qquad (18)$$

5. System simulation

The dynamometer system was simulated on Matlab software package to examine its operation. The DM is a separately excited dc machine which was used at 100V, 3A, 1300rpm, with inertia 0.005 N-m sec^2/rad, viscous friction of 0.0014N-m-sec/rad, armature resistance of 8Ω, back e.m.f constant of 0.17V-sec/rad, armature inductance of 0.17H (the employed dc motor is basically rated at 220-V, 1.25A, 1500rpm), load resistance of 30Ω and thyristor converter gain of 30. While, the MUT is 220V, 50Hz, I_{ph}=1.125A, 4-pole, and 1340rpm induction motor with inertia 0.011 N-m sec^2/rad, and viscous friction of 0.00075N-m sec/rad.

The experimental torque-speed characteristics of the MUT is fitted in the second-order polynomial:

$$T_m = -26*10^{-6}\,\omega_m^2 - 0.96*10^{-3}\,\omega_m + 1.471\,. \qquad (19)$$

This polynomial is used to simulate the MUT in the Matlab software program. According to the dynamic behavior of the system, parameters of the PI controller were chosen as K_p=2, and K_i=50sec^{-1}. The MUT was tested with *constant, linear, quadratic, third order* torque-speed characteristics and with *step change* in load torque.

For *constant load torque,* the dynamometer inputs were J=0.016 and three values were assigned to a_0 while the other model reference coefficients were set to zero. Results of this simulation are shown in fig. 4-a. These results show that the load torque T_L tracks well the reference T_r, except during starting of the MUT.

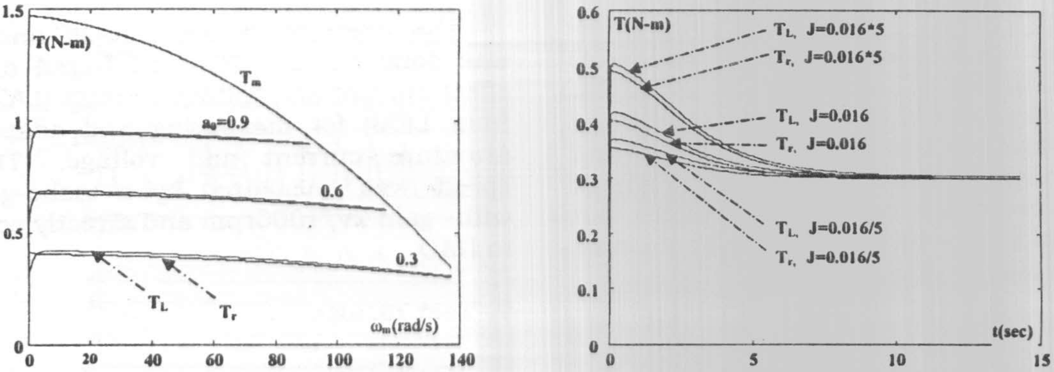
To investigate the effect of varying the inertia at constant load torque, the coefficient a_0 was set to 0.3 and J was given different values. The results are shown in fig. 4-b; both the steady state load and speed are the same, but the value of the inertia greatly affects the acceleration time. There is a good tracking of the load torque to reference.

For *linear load torque,* the coefficients were set to a0= a2= a3= 0, and J= 0.016, and a_1 was given different values to simulate different linear loads. Thus, the steady-state loads and the corresponding speeds are different for each coefficient a_1. The response of the dynamometer tracks closely the desired trajectories as shown in fig. 5-a. The coefficient a_1, which determine the slope of load line, greatly affect the acceleration time, as depicted in fig. 5-b. The higher the value of a_1, the higher the slope of load line and the smaller the acceleration times.

For a *quadratic load* simulation, the coefficients were set to a0= a1= a3= 0, J= 0.016, and a_2 was given different values for comparison of different fan loads. The results of this simulation are shown in fig. 6. These curves show the torque-speed characteristics for three different values of a_2. It can be observed that, the higher the value of a_2, the higher the slope of load line and the lower the acceleration. Also, the simulation results are shown in fig. 7 for *third order load* torque at different values of a_3.

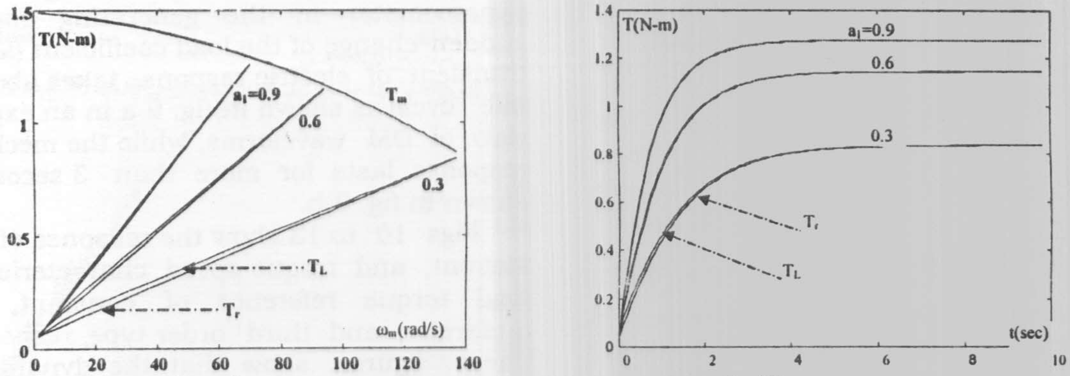
For a *step change,* the user inputs the step value of T_r to obtain the desired load torque. For example, suppose a centrifugal pump is cavitating and suddenly, the pump primes. The inertia will remain essentially constant but the coefficient a_2 will suddenly change. An example of this is shown in fig 8. The torque-speed characteristic used for simulation is:

$$T_r = \left[\; 0.05\,u(t) + 0.075\,u(t-15)\;\right]\omega_m{}^2 + 0.016\frac{d\omega_m}{dt}\,. \qquad (20)$$



a- Speed response at J=0.016 b- Time response at a_0=0.3

Fig. 4. Constant load torque.



a- Speed response b- Time response

Fig. 5. Linear load torque at J=0.016.

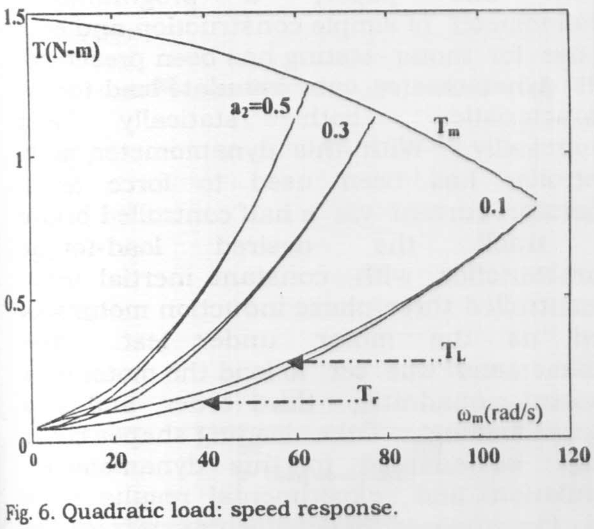


Fig. 6. Quadratic load: speed response.

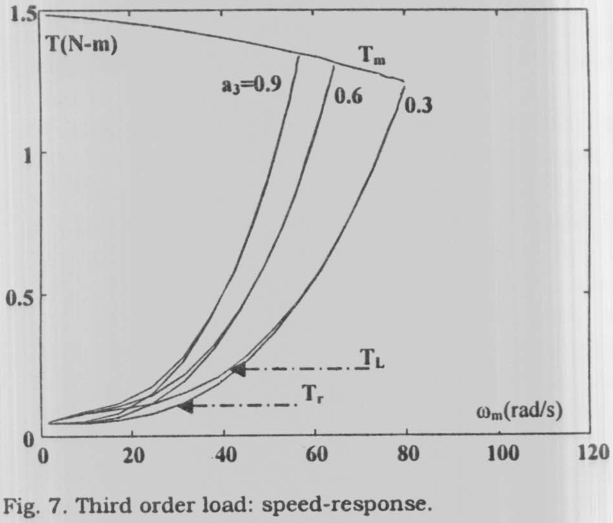


Fig. 7. Third order load: speed-response.

The actual and desired trajectories follow each other very closely. The PI controller controls T_e to track T_r not shaft torque T_L. So, T_L is always greater than T_r by the inertial and friction torque of DM according to eq. (5) and as shown in figs. 4 to 8. However, the largest departure occurs beyond the disturbance, but duration of this error is very short and can be ignored for testing purposes.

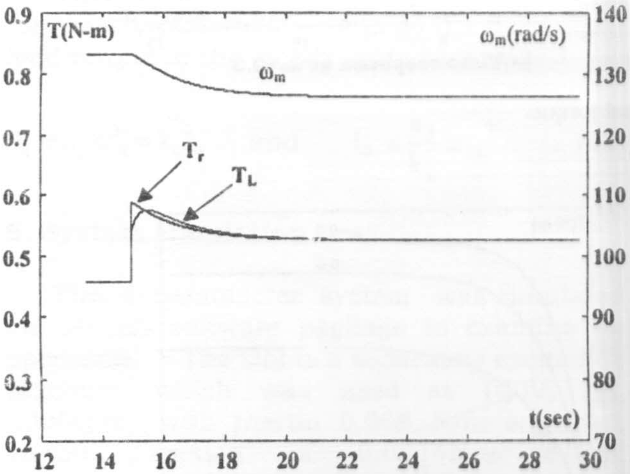


Fig. 8. Step change in quadratic load in a_2=0.05 to 0.075 after 15sec at J=0.005.

6. Laboratory setup

A laboratory dynamometer system having the structure shown in fig. 2 and the data given in section 5 was built with a PC computer to acquire the measurements. The functions of the PC are: on-line model reference control and on-line data acquisition. The model reference function is digitalized to be implemented using commercially available control-oriented software, e.g., "LabView" [7]. The real time measurements are entered via the DAQ card of type Lab-pc1200 analog I/O device 12bits from National Instruments [8]. The sampling rate was chosen 5KHz, i.e. much less than one-tenth of the system rise time (10ms) [9]. Parameters of the model reference were also modified to preserve the time response of the real dynamometer close to that of the analog one, eqs. (11-18). Based on the desired load type during every time interval, the model reference was executed and the on-line control signal was transmitted via the DAQ card as a torque reference (T_r).

The interface between the PC and the DM was done via an I/O card based on a Hall effect current and voltage sensors (LA25, LV25 from LEM) for measuring and adapting the armature current and voltage. The shaft speed was measured by a tacho-generator with gain 2v/1000rpm and directly connected to DAQ.

7. Test results

Several experimental tests were performed to examine the proposed dynamometer. The results presented in the following figures are acquired, displayed and plotted by the PC.

Fig. 9 shows the acquired signals of the dynamometer in the generating mode for sudden change of the load coefficient (a_0). The transient of electric response takes about one half cycle as shown in fig. 9-a in an expanded view of DM waveforms, while the mechanical response lasts for more than 3 seconds are shown in fig. 9-b.

Figs 10 to 13 show the response of speed, current, and torque-speed characteristics for load torque reference of constant, linear, quadratic, and third order type, respectively. These figures. show that the dynamometer precisely tracks the desired condition.

8. Conclusions

In this paper, a programmable dynamometer of simple construction and easy to use for motor testing has been presented. This dynamometer can simulate load-torque characteristics both statically and dynamically. With this dynamometer, a PI controller has been used to force a dc generator current via a half controlled bridge to track the desired load-torque characteristics with constant inertial term. Uncontrolled three-phase induction motor was used as the motor under test. The dynamometer was set to load the motor with constant, quadratic, third order, and step change loading. Other loading shapes could easily be adapted to this dynamometer. Simulation and experimental results show that the proposed dynamometer can track the desired response precisely.

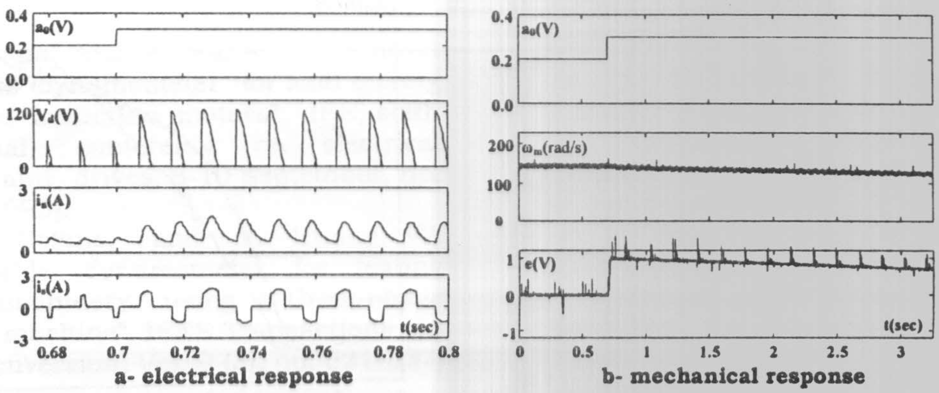


Fig. 9. Dynamometer time response for a sudden change of a_0.

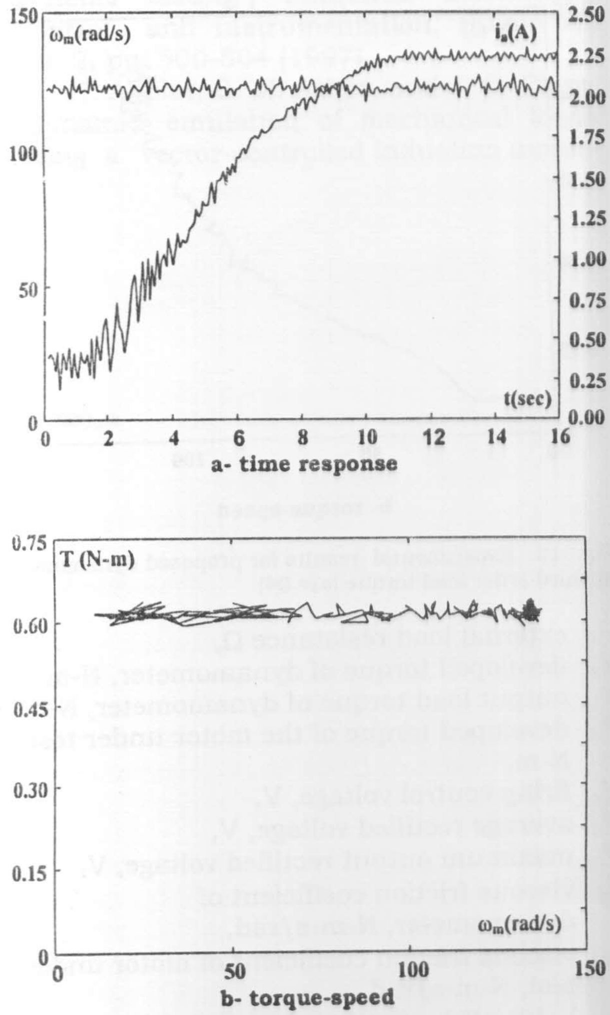


Fig. 10. Experimental results for proposed dynamometer at constant load torque (a_0=0.3).

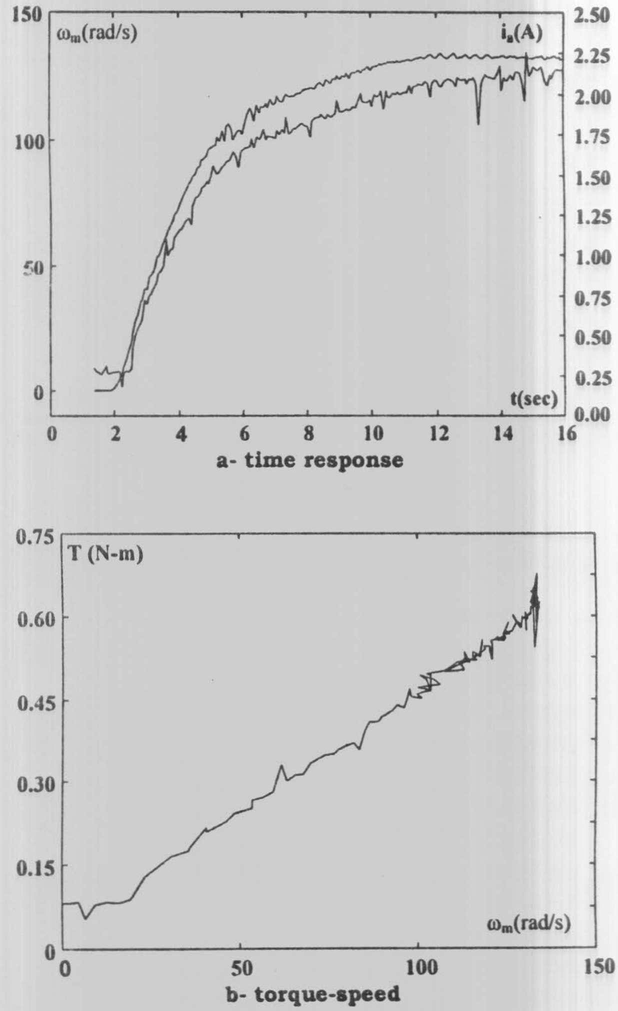


Fig. 11. Experimental results for proposed dynamometer at linear load torque (a_1=0.3).

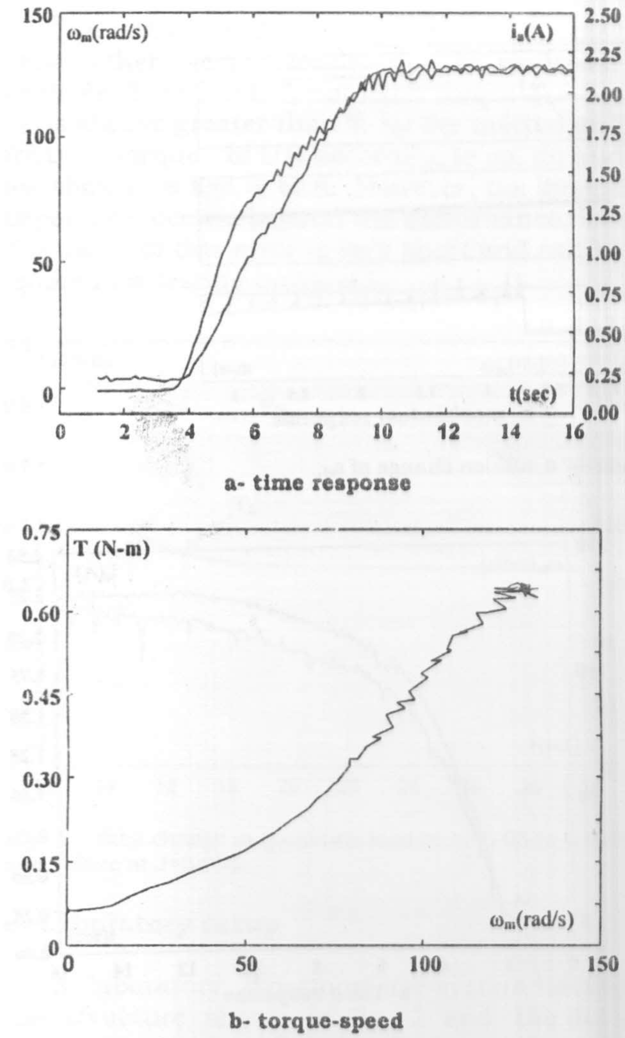


Fig. 12. Experimental results for proposed dynamometer at quadratic load torque(a_2=.02).

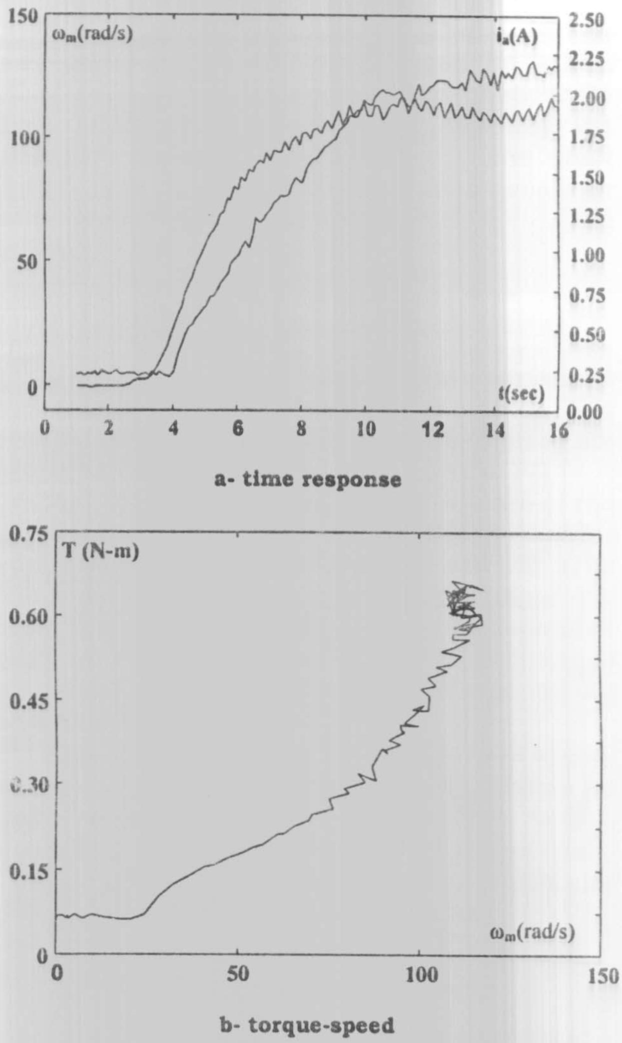


Fig. 13. Experimental results for proposed dynamometer at third order load torque (a_3=.04).

List of symbols

E_g e.m.f of dc machine, V,
h speed feedback gain, V/rad/s,
G power amplifier gain,
I_a average armature current, A,
J_d moment of inertia of dynamometer machine, N-m-sec^2/rad,
J_m moment of inertia of machine under test, N-m-sec^2/rad,
K back e.m.f (torque) constant, V-s/rad,
K_i current feedback gain, V/A,
K_{in} integral gain, s^{-1},
K_P proportional gain,
R_a, L_a armature resistance (Ω) and inductance (H), respectively,
R_L external load resistance Ω,
T_e developed torque of dynamometer, N-m,
T_L output load torque of dynamometer, N-m,
T_m developed torque of the motor under test, N-m,
V_c firing control voltage, V,
V_d average rectified voltage, V,
V_m maximum output rectified voltage, V,
β_d viscous friction coefficient of dynamometer, N-m-s/rad,
β_m viscous friction coefficient of motor under test, N-m-s/rad,
τ $L_a/(R_a+R_L)$, effective electrical time constant, s,
ω_m rotor speed, rad/s.

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