ON THE DYNAMIC SIMULATION OF A MECHATRONIC VARIATOR

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Abstract: In a previous paper [1] it is proposed a mechatronic speed variator, which consists of a differential planetary unit and of two electrical machines: a *motor* and a *generator*. This paper presents a simplified dynamic model and simulates the dynamic response of a like variator equipped with DC machines.

1. INTRODUCTION

In the paper [1] it is proposed and analysed a conceptual solution of a mechatronic speed variator, whose scheme is given in Fig.1; in this scheme, the indexes *m*, *g* and *r* mean *motor*, *generator* and *resistant load* respectively. For a like variator, equipped with a differential planetary unit and with two DC machines (a *motor* and a *generator*), the paper presents a simplified dynamic model and simulates its dynamic response, for two given running cases.

2. THE DYNAMIC RESPONSE

In Fig.1 there are presented the scheme and notations used in the dynamic modelling, which relies on and the following premises:
a) the elements are rigid bodies;
b) the used DC motor runs on an *adjustable mechanical characteristic* and its angular speed is positive (ω_m>0, see Fig.1); the characteristic adjusting is accomplished by modifying the supplying voltage U: $U/U_n = \omega_{0m}/\omega_{0mn}$ (the index *n* refers to the *natural* characteristic);
c) the used DC generator runs only on its *natural mechanical characteristic*; its angular speed has the following features: $\omega_g<0$ and $|\omega_g| < |\omega_m|$ (see Fig.1);
d) the inertial effects from the planetary mechanism (considered lonely) are neglected;
e) the rubbing effect is considered by means of the efficiency: $\eta_0 = \eta^H_{13} = 0{,}975^2 = 0{,}95$;
According to Fig.1, the following correlations can be written using the *Newton-Euler's* method:

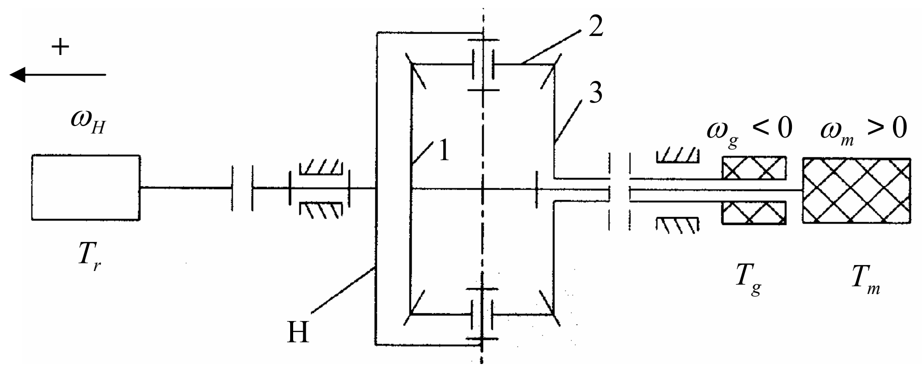


Fig. 1. *The conceptual scheme of the mechatronic planetary speed variator.*

$$\omega_H = 0{,}5 \cdot (\omega_m + \omega_g) \Leftrightarrow \varepsilon_H = 0{,}5 \cdot (\varepsilon_m + \varepsilon_g)$$
$$T_1 + T_3 + T_H = 0; T_1 \cdot i_0 \cdot \eta_0^w + T_3 = 0 \quad ; i_0 = i_{13}^H = -1; \; w = \operatorname{sgn} T_1(\omega_1 - \omega_H) = +1;$$
$$J_1\varepsilon_m = T_m - T_1 = T_m + \frac{1}{1+\eta_0} T_H; J_3\varepsilon_g = T_g - T_3 = T_g + \frac{\eta_0}{1+\eta_0} T_H; \quad (1)$$
$$J_H\varepsilon_H = -T_H + T_r \Rightarrow T_H = T_r - J_H\varepsilon_H.$$

The dynamic behaviour of the differential speed variator is described by two movement equations, which result from the system (1):

$$\varepsilon_m = (2.J_3T_r + AT_m - J_HT_g).B^{-1}; \varepsilon_g = (2.\eta_0 J_1 T_r - \eta_0 J_H T_m + C.T_g).B^{-1}, \quad (2)$$

in which:

$$A = \eta_0 J_H + 2.(1+\eta_0).J_3; B = A.J_1 + J_3.J_H; C = J_H + 2.(1+\eta_0)J_1. \quad (3)$$

The variator's dynamic model can be obtained by defining the outside torques T_g , T_m and T_r, which interfere in equations (2). For the next simulations, the output torque T_r is considered constant, while the generator torque (T_g) and the motor torque (T_m) are defined by the following expressions.

The generator running has two phases:

1) *The phase of the idle running*, in which $\omega_g = 0\ldots\ \omega_{0g}$ and $T_g = 0$;
2) *The phase of the load running*, in which $|\omega_g| \geq |\omega_{0g}|$ and

$$T_g = -\nu_g.\omega_g + \tau_g = -6{,}093.\omega_g - 1416{,}5[Nm], \quad (4)$$

The motor runs on a *artificial mechanical characteristic,* derived from the output sizes (T_r and ω_H), whose equation has the following expression:

$$T_m = -\nu_m\omega_m + \tau_m = -4{,}357.\omega_m + 4{,}357.\omega_{0m}[Nm], \quad \omega_{0m} = \omega_{0m}(T_r, \omega_H) \quad (5)$$

In the stationary regime (when $\varepsilon = 0$ and $T_r = T_H$, $T_1 = T_m$, $T_3 = T_g$), the angular speed $\omega_{0m} = \omega_{0m}(T_r, \omega_H)$ and the implicit voltage $U_m = U_m(T_r, \omega_H)$ can be calculated thus:

$$T_g = -\frac{\eta_0}{1+\eta_0} T_r; T_m = -\frac{\eta_0}{1+\eta_0} T_r;$$
$$\omega_g = \omega_{0g} - \frac{1}{\nu_g} T_g = \omega_{0g} + \frac{\eta_0}{\nu_g(1+\eta_0)} T_r;$$
$$\omega_m = 2\omega_H - \omega_g; \; \omega_{0m} = 2\omega_H - \omega_{0g} - \frac{T_r}{1+\eta_0}\left(\frac{\eta_0}{\nu_g} + \frac{1}{\nu_m}\right); U_m = U_{mn}\frac{\omega_{om}}{\omega_{0mn}}, \quad (6)$$

in which, for our simulations:

$\omega_H = +20{,}944$ [s^{-1}], TH= -400; -1000 [Nm], $U_{mn} = 460$ [V] and $\omega_{0mn} = 418{,}88$ [s^{-1}].

First, by means of the previous mechanical characteristics, the sizes ω_m, ω_g and ε_m, ε_g can be established from the equations (2),…,(6). Then, on the basis of these solutions, can be obtained the other parameters (with respect of time), which interfere in the dynamic response of the variator:

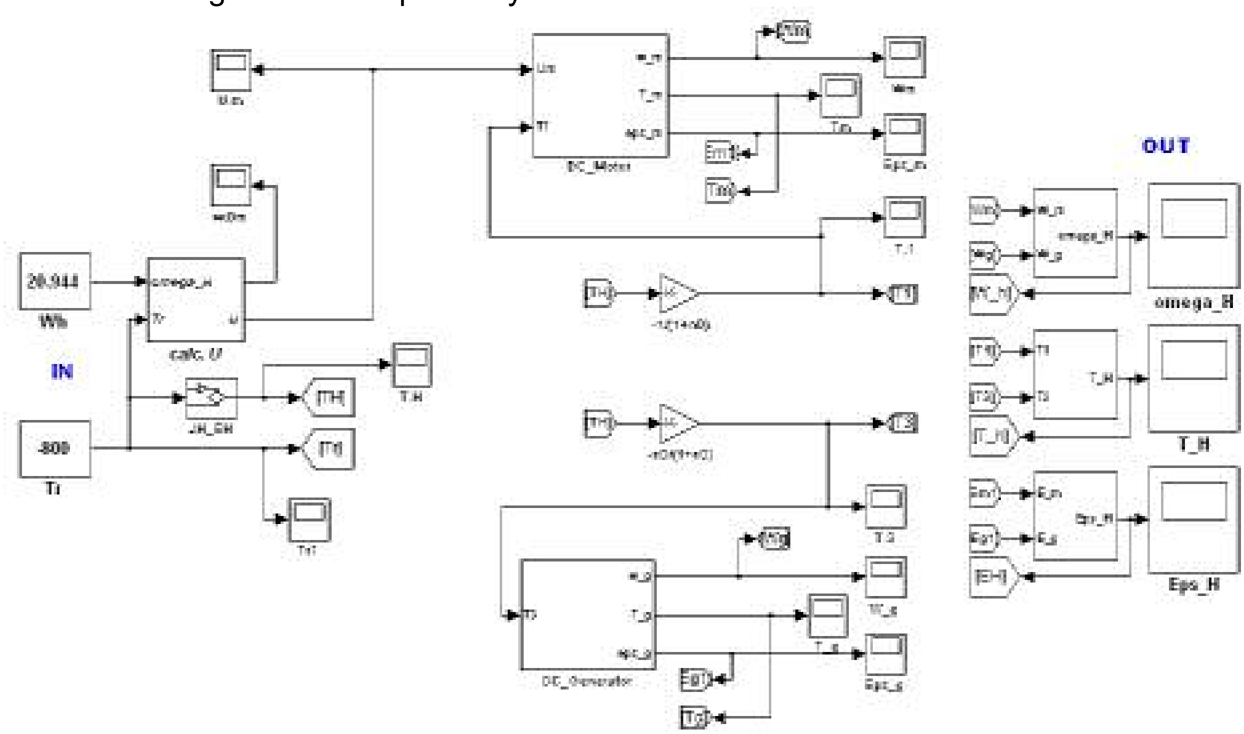
$$\varepsilon_H = 0{,}5(\varepsilon_m + \varepsilon_g) \Rightarrow \omega_H = 0{,}5(\omega_m + \omega_g);$$
$$T_m = \nu_m(\omega_{0m} - \omega_m); T_g = \nu_g(\omega_{0g} - \omega_g); \quad (7)$$
$$T_1 = T_m - J_1\varepsilon_m; T_3 = T_g - J_3\varepsilon_g; T_H = -(T_1 + T_3); T_r = T_H + J_H\varepsilon_H.$$

On the basis of relations (2),…,(7) and of the Matlab-Simulink programming medium, a calculating program was elaborated, whose schemes are illustrate in Fig.2,a,…,d.

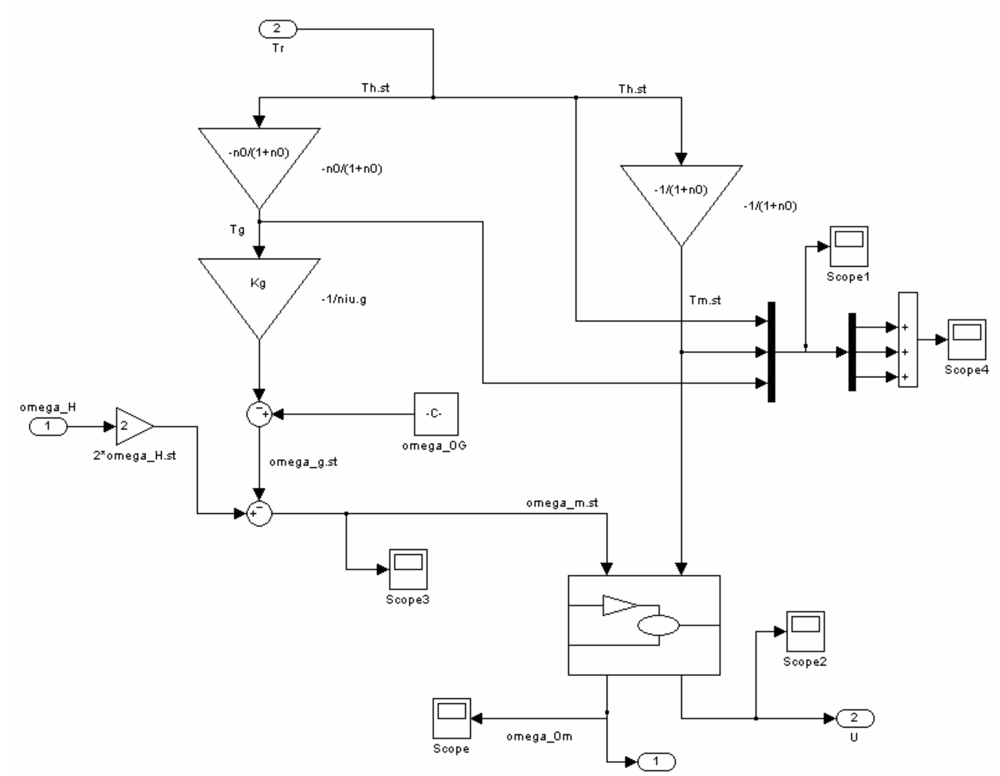
According to Fig.2,a, in which the overall programming scheme is represented, the simulations start from the values of the output sizes T_r and ω_H.

First, by means of these values and of the relations (6), there are determined the stationary generator's torque (T_g) and the stationary motor's torque (T_m). Then, on the basis of the generator's mechanical characteristic there are established the generator's stationary angular speed (ω_g) and the motor's stationary angular speed (ω_m) implicitly.

The values of the stationary sizes T_m and ω_m allow the determination of motor's artificial mechanical characteristic, by the idle motor speed ω_{0m} and by the supply voltage U_m. The Simulink block scheme, illustrated in Fig.2,b, establishes these parameters. Similarly, the Simulink blocks, illustrated in Fig.2,c and d, model the mechanical characteristics of the motor and of the generator respectively.



a)



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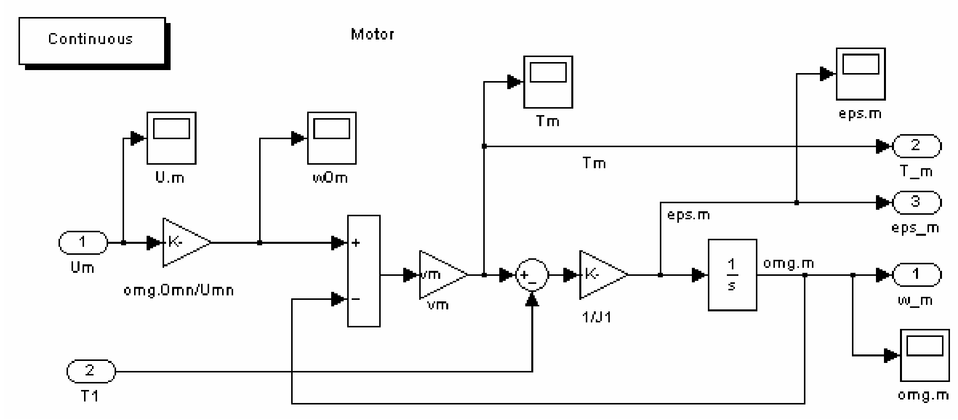
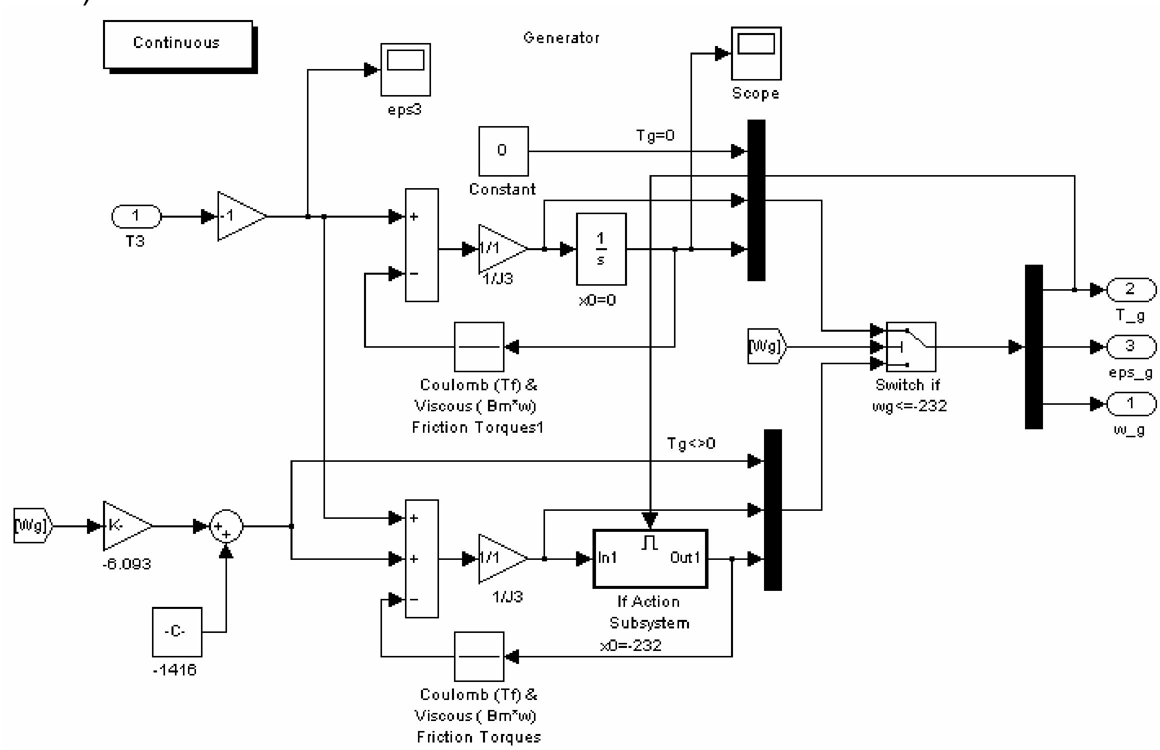


c)



d)

Fig. 2. *Simulink schemes of the running program: a) the overall scheme; b) partial scheme for the determination of the sizes T_g, ω_g, T_m, ω_{0m} and U_m; c, d) the motor and generator scheme.*

3. NUMERICAL SIMULATIONS

By means of the calculating program, illustrated in Fig.2, there are achieved numerical simulations of the variator's dynamic response, for the two stated values of the output torque T_r; as an example, the previous numerical data were used, completed with the following data:

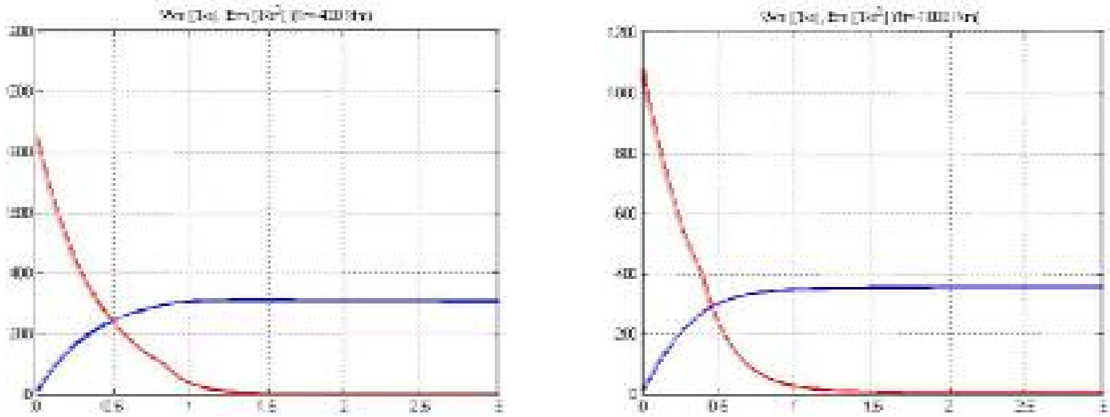
$J_1 = 1{,}1$ [kgm^2], $J_3 = 1$ [kgm^2], $J_H = 5$ [kgm^2], $\omega_H = +20{,}994$ [s^{-1}] .

The elaborated program offers the complete variations (with respect of time) of the parameters which describe the variator's dynamic response. Some of these variations are illustrated in the Fig.3 and 4.

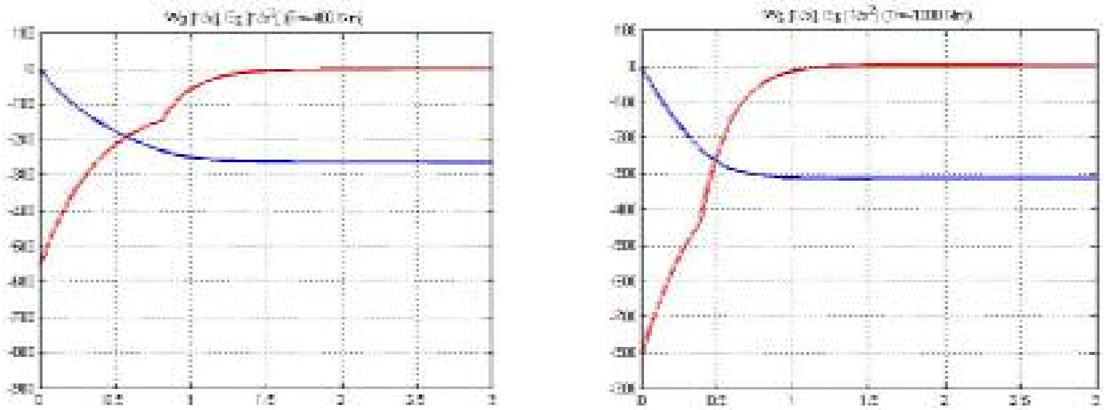
Two main parameters interfere in the variations of the previous sizes:

-the moment in which the generator goes from the idle in the load running: $t_{0g} = t(\omega_g = \omega_{0g})$ and

-the start time of the variator t_{start}, which represents lapse of time in which the angular speeds become constant and the angular accelerations become null implicitly (lapse of time in which the variator goes in the stationary regime).



a)



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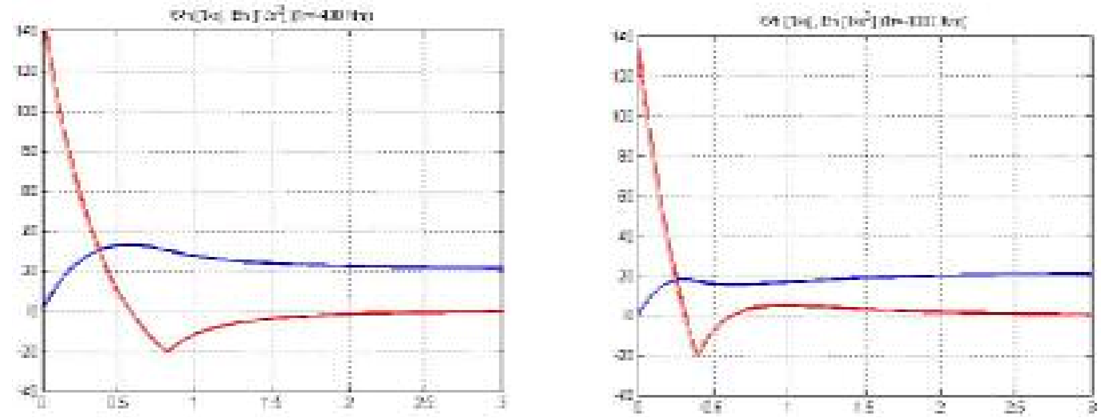
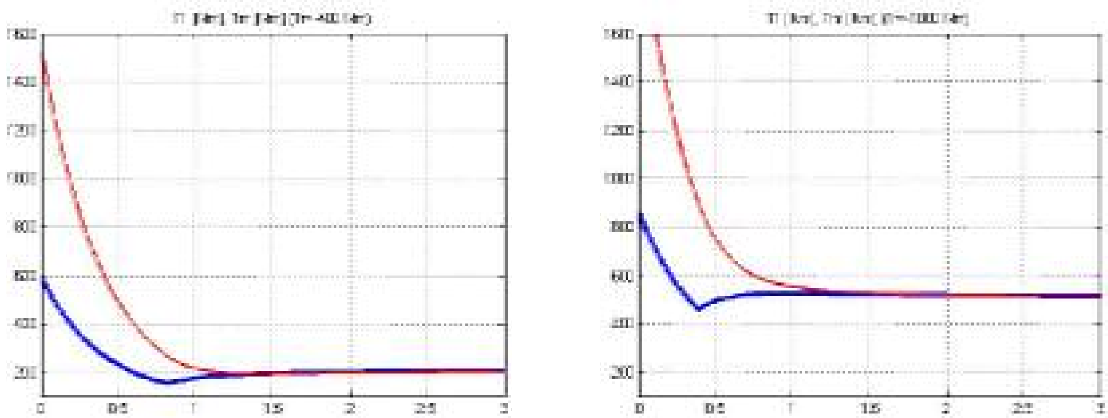


c)

Fig.3. *The shafts' speed [s^{-1}] and acceleration [s^{-2}] for the different loads T_r: a) the shaft m-1, b) the shaft g-3 and c) the shaft H-r.*



a)

b)

c)

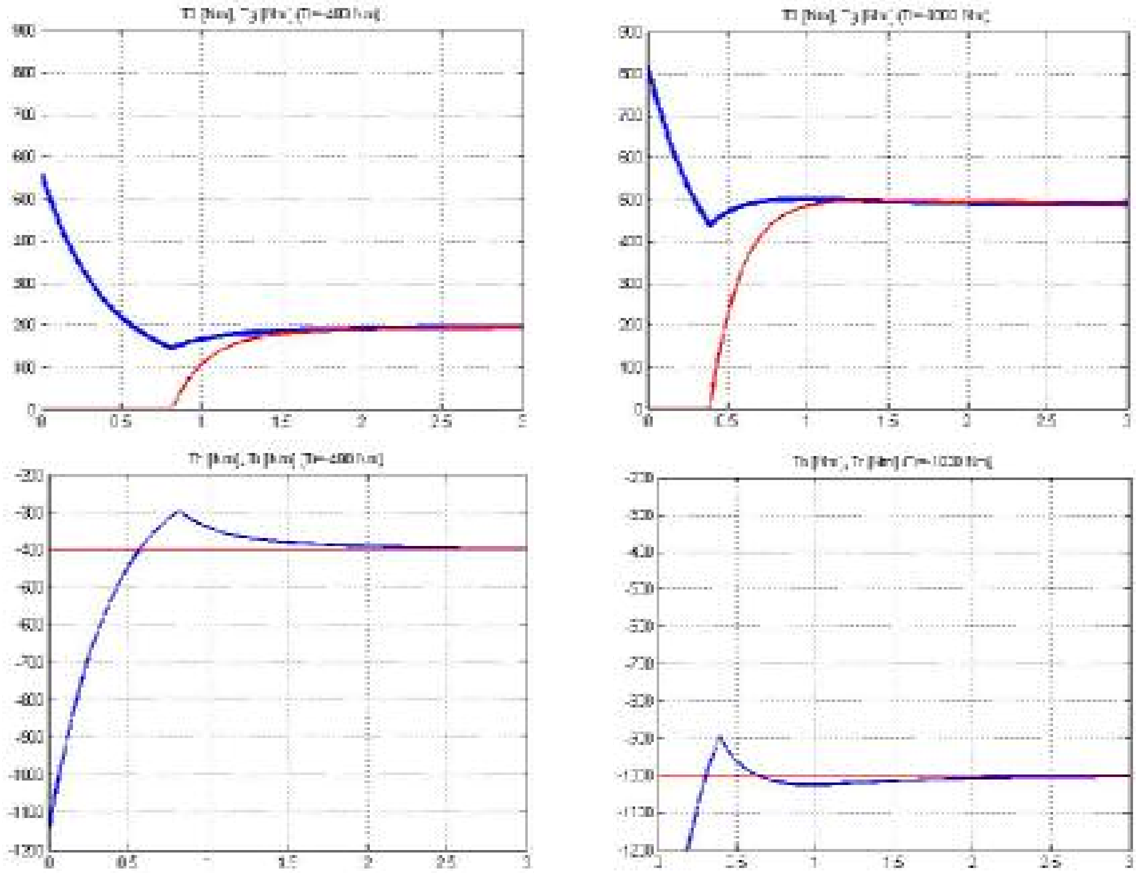


Fig.4. *The shafts' torsion torques [Nm] for the different loads T_r: a) the shaft m-1, b) the shaft g-3 and c) the shaft H-r.*

The analysis of these results makes evident the following relevant dynamic aspects:

1) During the first running phase (see Fig.1, 3 and 4), the generator's resistant torque is null ($T_g = 0$) and the motor's torque (which has a decreasing variation) assures both the own shaft acceleration (shaft *m-1*) and the generator's shaft acceleration (shaft *g-3*); because, at the beginning, the torque $T_H = T_1 + T_3$ is bigger than T_r (in the given numerical conditions), the motor accelerates also the output shaft H, by means of the inertia of the generator's shaft g-3.

Obviously, if J_3 becomes null, the torques T_1 , T_3 and T_H become null too and the output shaft H remains at rest implicitly; in this case, the shaft H begins to move when the generator's resistant torque assures the achievement of the condition: $T_H = T_1+T_3 > T_r$.

2) The first running phase (in which, the generator's torque is null: $T_g = 0$) is finished at the moment when (see Fig.3 and 4) $\omega_g = \omega_{0g} = -232{,}478$ [s^{-1}]. Since this moment, the generator produces resistant torque and the variation curves of the state parameters are modified implicitly.

3) The start stage is finished at the moment when the angular speeds become constant and the angular accelerations become null implicitly (see Fig.3 and 4).

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