QUASI-EXTREMUM SCALAR CONTROL FOR INDUCTION TRACTION MOTORS: RESULTS OF SIMULATION

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Abstract: The paper is based on the possibility to reduce the induction motor losses by partial load, choosing the "optimal slip". For the railway traction applications, the operation by partial load is very frequent and for a long-time period.
The authors present the results of simulation for two superposed systems: speed control system and extremum-searching system with test signal. The advantages of the extremum-search control system, implemented in a cheap and accessible version, are demonstrated.

Keywords: induction motors, railway traction, extremum-search control

1. INTRODUCTION

The theory and the operation of the induction machines prove that a certain mechanical power may be delivered for infinity of pairs: stator voltage – stator frequency. Each pair determines the flux level.
It is possible to define various optimum criteria ("maximum efficiency") available by the minimization of the machine losses. In accord to (Festila, 2005), an "active" method of optimization is based on the electrical power measurement for a known mechanical load and on the search for the optimum slip (Festila, 2005; Kouns, 2001). The equation of the motor losses as function of the slip is a nonlinear one, with extremum (minimum). In order to maintain the operating point of the machine on the extremum, it is necessary to apply an extremum-searching system. If, for small power electrical drives – robotics, machine-tools, etc. – the mechanical load changes frequently, in electrical traction systems arise operations at high power and for long time at constant mechanical power, very often, partial loads.
With the development of the high power electrical inverters and of the dedicated DSP's, it is possible to overlap two control loops: a classical speed (or torque) loop and an extremum-search control loop.
The contribution is based on simplified models of the inverter and of the induction machine in order to determine the motor torque and the electrical power. If a steady state of the operation can be found, an extremum-search control system is enabled, until the electrical power reaches the minimum. It is used an external, periodical test signal – triangular shape wave – which determines the increases or the decreases of the additional voltage control signal. Once the extremum point was reached, the system operates in this new steady state, until a change in the mechanical power is detected.

2. SIMPLIFIED MODELS FOR INDUCTION MOTOR AND INVERTER

Based on the equivalent / phase circuit, figure 1 (Kouns, 2001; Tulbure, 2003), for a pair: stator voltage, stator frequency (V_1, ω_1), the motor torque is given by the equation (1):

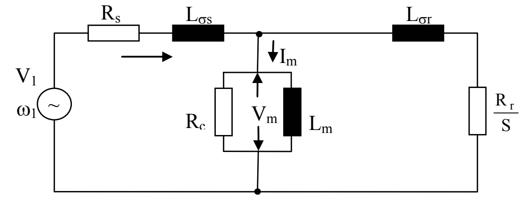


Figure 1. Per phase equivalent circuit

$$T_m = \frac{3 \cdot V_1^2 \cdot R_r / S}{\omega_1 \left[\left(R_s + \frac{R_r}{S} \right)^2 + \omega_1^2 (L_{\sigma s} + L_{\sigma r})^2 \right]} \tag{1}$$

where (R_s, R_r, $L_{\sigma s}$, $L_{\sigma r}$) are the “classical” motor parameters (Festila, 2005; Fransua, 1986; Tulbure, 2003),(S) is the slip:

$$S = \frac{\omega_1 - \Omega_m}{\omega_1} \tag{2}$$

and (Ω_m) is the rotor mechanical angular speed. For the motor is supposed one pole-pair.

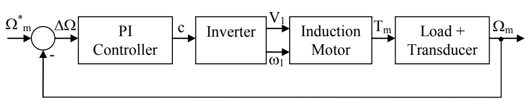


Figure 2. Speed control system topology

In the speed control loop, figure 2, it is used a power inverter and a PI speed controller. The following equations govern the whole speed control system:

- for controller:

$$c(s) = k_P \Delta\Omega(s) + \frac{k_I}{s} \Delta\Omega(s) \tag{3}$$

- angular frequency set-point:

$$\omega_1^* = k_\omega c \tag{4}$$

- voltage set point:

$$V_1^* = k_u \omega_1 + \beta \left(\omega_1^* - \omega_{1N} \right)^2 \tag{5}$$

- motor voltage and frequency are given by:

$$V_1(s) = \frac{V_1^*}{1 + T_{inv} s}; \qquad \omega_1(s) = \frac{\omega_1^*(s)}{1 + T_{inv} s} \tag{6}$$

- “mechanical” drive equation:

$$\Omega_m(s) = \frac{T_m(s) - T_L(s)}{Js + B} \tag{7}$$

and

- the load torque is supposed:

$$T_L = T_{L0} + k_T \Omega_m \tag{8}$$

Here: -(k_P) and (k_I) are the proportional and integral coefficients;

-(ω_{1N}) is the rated angular speed (ω_{1N}=314rad/sec);

-(T_{inv}) is the inverter equivalent time-constant;

-(J) is the moment of inertia and (B) is the friction coefficient;

-(k_ω; k_u; β; k_T) are conventional coefficients (Festila, 2005; Kouns, 2001).

In (Kouns, 2001; Tulbure 2003) is proved that the equation (5) ensures a constant level for the motor flux, at the rated value $\Phi = \Phi_{rated}$. The equations (1)÷(8) allows the analysis of the behaviors of the control system under scalar strategy (V/f=const=ct).
The motor losses are:

$$P_{l,m} = R_s I_s^2 + R_r I_r^2 + V_m^2 / R_c \tag{9}$$

given by the stator cooper losses, rotor cooper losses and core losses. In (Kours, 2001) is given the equation:

$$P_{l,m} \cong S(T_m \Omega_m) \left[1 + \frac{R_s}{R_r} + \frac{1}{S^2} \frac{R_r}{R_c} + \frac{\Omega_m^2 L_{\sigma r}^2}{R_r R_c} \right] \tag{10}$$

The estimation of the inverter losses is a difficult task one. Using the results from (Festila, 2005),

$$P_{l,inv} \approx k_1 (T_m \Omega_m) + k_2 S$$

The total electrical power is given by the equation:

$$P_{el} = T_m \Omega_m \left\{ 1 + k_1 + S \left[1 + k_2 + \frac{R_s}{R_r} + \frac{1}{S^2} \frac{R_r}{R_c} + \frac{\Omega_m^2 L_{\sigma r}^2}{R_r R_c} \right] \right\} \tag{11}$$

3. EXTREMUM CONTROL SYSTEM

By partial load, the induction motor losses ($P_{l,m}$) as function of the slip (S) exhibits an extremum (minimum) (Festila, 2005; Kouns, 2001). For instance, in the case of equation (10), the “optimal slip” (S) is given by:

$$S^* = \frac{R_r}{\sqrt{R_c (R_s + R_r) + \Omega_m^2 L_{\sigma r}^2}} \tag{12}$$

In the scalar control strategy, the extremum-search use as manipulated variable the voltage (α_1) and as test signal the triangular voltage (α_2), in order to change the stator voltage (V_1):

$$V_{1total} = V_1 + \alpha_1 + \alpha_2$$

Based on the simplified equations (Fransua, 1986):

$$\text{a)}\quad T_{mM} \sim k_M (V_1)^2 \qquad (13.1)$$

$$\text{b)}\quad T_m = \frac{2T_{mM}}{\frac{S}{S_k} + \frac{S_k}{S}} \approx \frac{2T_{mM}}{\frac{S_k}{S}} = \frac{2ST_{mM}}{S_k} = \frac{2k_M}{S_k}\left(V_1^2 S\right) \qquad (13.2)$$

results the dependence:

$$S = \frac{S_k T_m}{2k_M} \frac{1}{(V_1)^2} \approx \frac{1}{(V_1)^2}.$$

If the test signal $\alpha_2(t)$ is a triangular wave with the amplitude $(\Delta V_1)_M = \alpha_{1M}$, and the period ($T_t$), the position of the current operating point (1, 2 or 3 in figure 3) relative to the extremum can be determined by the variation ($\Delta P_{l,m}$) due to the test signal ($+\alpha_{2M} = +(\Delta V_1)_M$), in the first half period ($T_t/2$), so that :

- if ($\Delta P_{l,m} > 0$), the current slip is $S < S^*$ (point 1)
- if ($\Delta P_{l,m} < 0$), the current slip is $S > S^*$ (point3), and
- if ($\Delta P_{l,m} \approx 0$), the slip is optimal $S = S^*$.

In order to force the induction motor to operate close to extremum (choosing the manipulated variable a ramp $\alpha_1 = d \cdot t$):

- a negative manipulated variable (α_1) must be added so that

$$\Delta V_1 = \alpha_2(t) - \alpha_1(t) = \alpha_2(t) - d \cdot t = \alpha(t), \qquad (14)$$

if ($\Delta P_{l,m} > 0$),

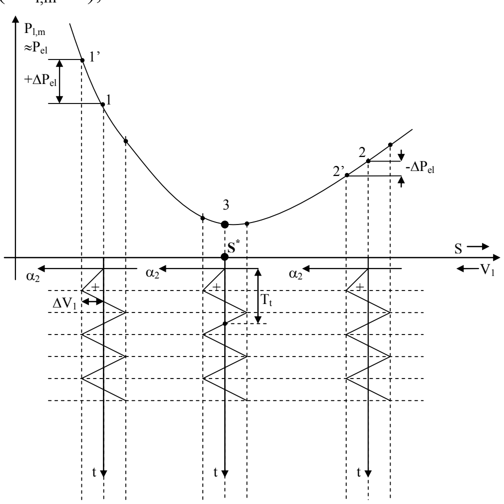


Figure 3. Principle of operation of the extremum control system

- a positive manipulated variable (α_1) must be added so that

$$\Delta V1 = \alpha_2(t) + \alpha_1(t) = \alpha_2(t) + d \cdot t = \alpha(t), \qquad (15)$$

if ($\Delta P_{l,m} < 0$),

- $\alpha_1(t) = 0$ if ($\Delta P_{l,m} \approx 0$).

It is important to note that in this paper it is accepted the hypothesis that functions $P_{l,m} = f_1(S)$ and $P_{el} = f_2(S)$ have the same structure ("shape").

4. GLOBAL SIMULATION SCHEME

The both control systems (speed and extremum-search) where simulated using SIMULINK.

The global system topology is given in figure 4. The arithmetic unit (f_s) calculates the slip (S), equation (2), and the unit (f_p), calculates the total electric power P_{el}, equation (11).

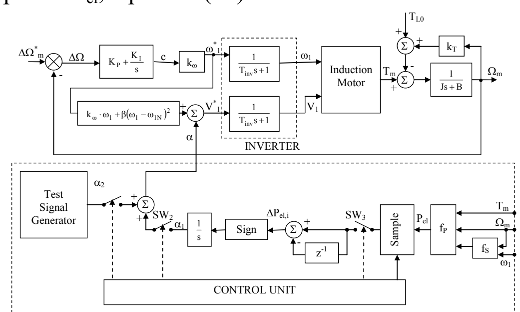


Figure 4. Global system topology

5. SIMULATION STRATEGY

In this paper a very simple simulation strategy is presented:

a. In the time interval ($0 \div t_1$):
   - the extremum-search control system (ECS) was disabled, ($\alpha(t) = 0$);
   - a ramp reference $\Omega^*_M(t) = \varepsilon \cdot t$ was imposed and the main variables $\Omega_m(t)$, $T_m(t)$, $V_1(t)$, $\omega_1(t)$, P_{el},… were registered.

b. In the time interval ($t_1 \div t_2$):
   - the ECS remains disabled ($\alpha(t) = 0$);
   - a constant reference $\Omega^*mM(t) = ct$ was applied in order to reach the steady state

c. In the time interval ($t_2 \div t_3$), the both systems are active. Based on the analysis of the effect of the test signal $\alpha_2(t)$, the manipulated variable $\alpha(t)$ reduces the supplied electrical power until the difference ($\Delta P_{el,k}$) is

$$|\Delta P_{el,k}| < \text{"threshold"};$$

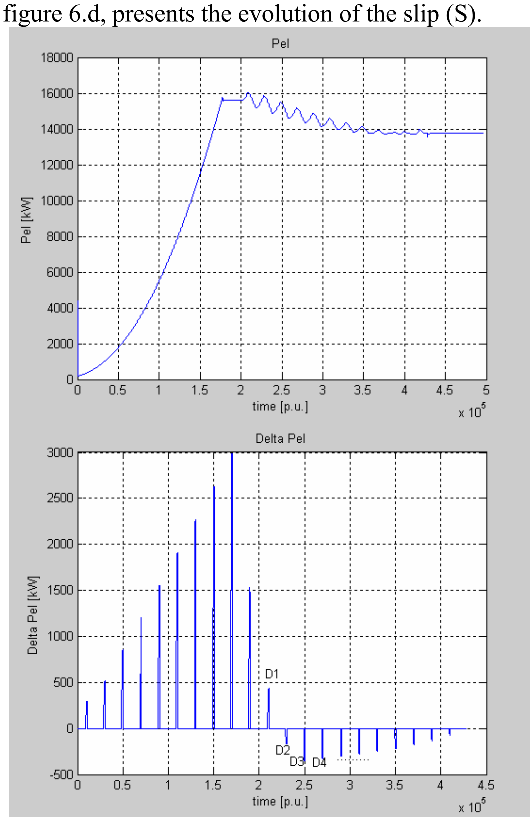
in that moment (t^*) the "quasi-extremum" was reached.

d. In the time interval ($t3 \div \infty$), the test signal $\alpha 2(t)$ is disabled (by SW1) and the whole system operates with the previous value $\alpha 1(t3)$=ct. (by SW3; d=0).

The electrical power is continuously measured. If any “significant” change is detected, the signal $\alpha(t)$ decreases in a certain time period and the machine flux increases to the value associated to the equation (5).

6. SIMULATION RESULTS

The general scheme in SIMULINK is given in figure 5, where: t_1=180 p.u.; t_2=220 p.u.; t_3=410 p.u.; P_N=30kN; V_{1N}=220V, K_P=10; $K_i=10^{-3}$; T_{inv}=2; K_w=2; $\beta=2.5\cdot 10^{-4}$; K_u=0.7; W_{1n}=314; J=1; B=0.05; T_{L0}=5; K_t=0.292; R_s=0.082; R_r=0.087; $L_{\sigma s}=1.28\cdot 10^{-3}$; $L_{\sigma r}=1.58\cdot 10^{-3}$. The results of the simulation are given in figure 6.
The evolution of the electrical power is given in figure 6a. The differences $\Delta P_{el,k} = (P_{el,k}-P_{el,k-1})$ are presented in figure 6.b: $\Delta P_{el,1} > 0$, which decides d<0; α_1= - d·t; the rest of the differences $\Delta P_{el,2}$,… are negative because $P_{el,k}$ decrease until the quasi-minimum value $P_{el,min} \approx$ 14.6 kW is reached. The figure 6.c. gives the manipulated variable $\alpha(t)$ and the figure 6.d, presents the evolution of the slip (S).



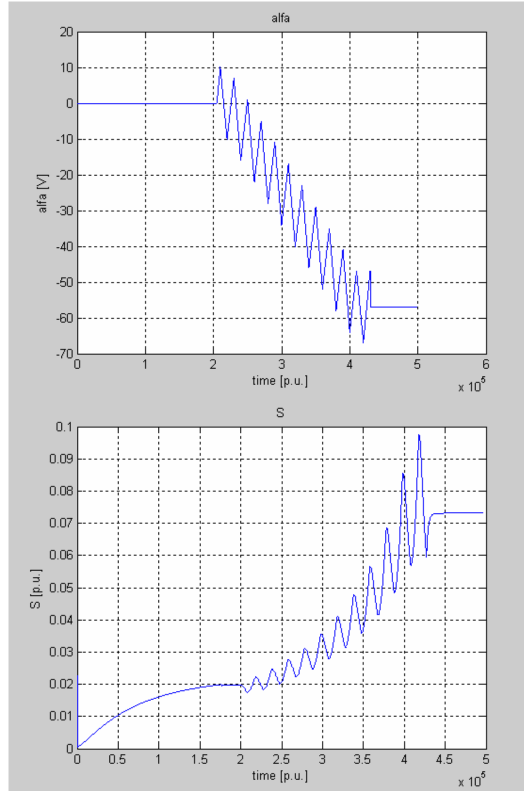


Figure 6. Simulation results

7. CONCLUSIONS

The actual paper demonstrates the utility of the extremum-search control system. For instance, for a rated motor power of 30 kW, at partial load (≈50%; ≈15kW), the electrical power given by the main line may be reduced from 15.8kW to 13.9kW, maintaining the motor mechanical speed practically unchanged.

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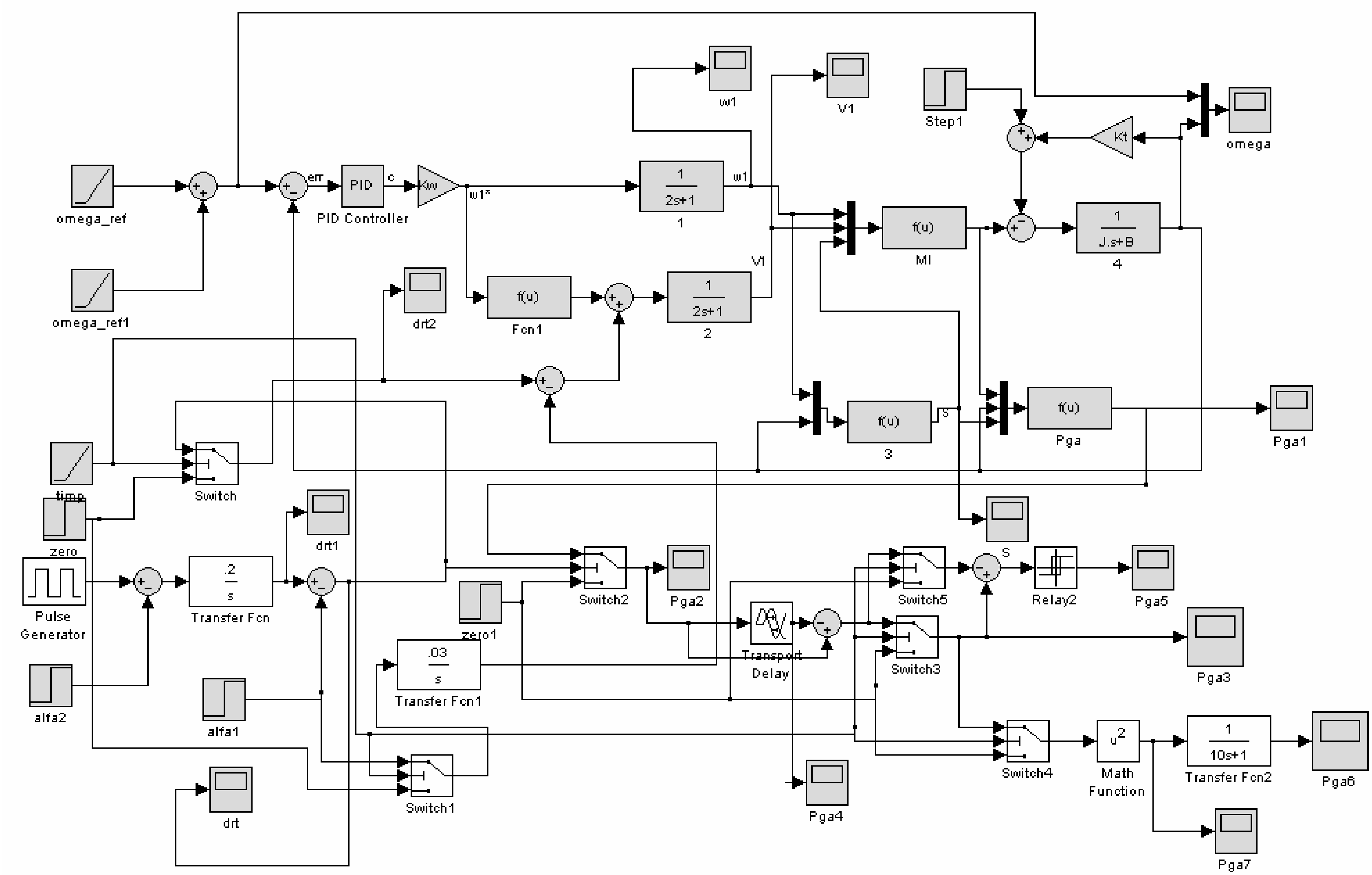

Figure 5. The general simulation scheme