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Self-Tuning Speed Controller of the Induction Motor Drive

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***Abstract*–Induction motors are characterized by non-linear, complex and time-varying dynamics therefore conventional controllers cannot ensure speed step response specifications in all speed range. This paper presents hybrid fuzzy and proportional-integral-derivative (PID) controller to improve speed control of the induction motor. Proposed Fuzzy logic controller is used to tune each gain of PID controller separately. The simulation results are presented and discussed in the study. Simulink based model of induction motor drive is used for analysis of developed electromagnetic torque and speed response. Motor performance is thereby evaluated for speed control.**

***Index Terms*–Induction motor, fuzzy control, closed loop, Matlab Simulink.**

I. INTRODUCTION

Induction motors are mostly used for variable speed applications motors in industry [1]. In modern control theory, the induction motor is described by differential mathematical models, suitable to the employed control method [2].

There are fundamental analogue and digital strategies for induction motor control. Analogue control is based on direct measurement of the motor parameters (mainly the rotor speed), which is compared with the reference signal in the closed loop control system. Digital control because of its advantages is used for estimation of the motor parameters in the sensorless control, based on the mathematical models of motor, employing slip frequency calculation method, various speed and flux estimation methods. Also it is used for vector control, direct control of torque and flux.

Usually scalar control method (*Volts*-per-*Hertz* control) is used to control the induction motors, operating in the systems without strict speed specifications. Fuzzy logic control (FLC) is widely applied in different control systems, as speed and position tracking of induction motors [3], Fuzzy adaptive sensorless induction motor drives [4], where the model reference adaptive system was designed and described and Fuzzy direct torque control systems [5] as well as in many other control systems.

The adjustable speed drive with induction motor is non-linear system with continuously varying parameters with the rotor position, such as mutual inductance between rotor and stator windings, inductances, varying because saturation of magnetic material at great starting currents.

The conventional PID controller is linear and can operate properly only in a certain point of all operating range. Developed and investigated scalar controlled sensorless induction motor drive simulation model with composite PID and fuzzy logic controllers. Such synthesis allows to control non-linear system and to tune gains of PID controller according to changing nonlinearity. Paper deals with simulation results of rotor speed and electromagnetic torque produced by motor are presented and discussed.

II. STRATEGIES OF INDUCTION MOTOR MODELLING

An important problem related to modelling of the three phase induction machine with cage rotor is the non-linearity of the equations that describe its operation. This phenomenon appears in the voltage equations and the electromagnetic torque relation as well, due to the products between the state variables [6]. When a control system with induction machine is designed, it is very useful to linearize the machine equations. Mathematical models of induction motors can be classified as shown in Fig. 1.

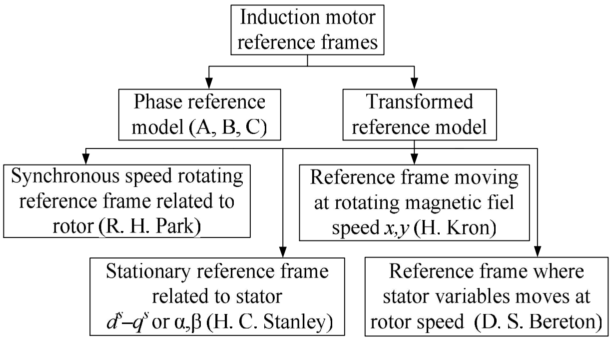

Fig. 1. Models of induction motors.

There could be used a lot of modifications in terms of mathematical parameters of induction motors [7]–[9] and everyone finds its area of application, for example, heat-exchanger units, driven machines. The motor model is elaborated in synchronous rotating reference frame $d^e - q^e$, where d and q presents ordinate and abscissa axis respectively, and e stands for synchronous rotating reference frame.

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III. PRINCIPLES OF SCALAR CONTROL

Usually scalar control method, which is also known as *Volts*-per-*Hertz* control (*V*/*Hz*), is used to control an induction motors.

If the ratio *V*/*Hz* remains constant with the change of frequency, then the maximum torque in speed-torque steady state characteristic remains constant. In actual implementation, the ratio between the magnitude and frequency of the stator voltage is usually based on the rated values of these variables, or motor ratings. However, when the frequency and also the voltage are low, the voltage drop across the stator resistance cannot be neglected and must be compensated. At frequencies higher than the rated value, the constant *V*/*Hz* ratio should not be applied to avoid insulation break-down, because the stator velocity should not to exceed its rated value.

Both open and closed-loop speed control of induction motor can be realized by applying the *V*/*Hz* control method. When error of speed response is not a concern, open-loop speed control is used, for example, in the heating systems, ventilation and air conditioning, fan or blower applications. In this case, the supply frequency is determined according to the desired speed and the assumption that the motor will roughly follow its synchronous speed. The error in speed resulted from slip of the motor is considered acceptable. When accuracy in speed response is a concern, closed-loop speed control can be implemented with speed feedback, as illustrated in Fig. 3, where a hybrid PID fuzzy controller is employed to regulate and to keep the motor speed at its set value [10], [11].

IV. FUZZY LOGIC CONTROL

Modelling of most real systems is difficult and sometimes impossible because of their nonlinearities and complexity of unknown relationships between its elements.

Fuzzy modelling can be applied when systems cannot be described by mathematical and electrical laws such as Ohm’s, Kirchhoff’s, Newton’s and so on. On the other hand, if the system is described by the physical laws, the total drive system comprises controller, which parameters should be defined. Widely used PID controller can be tuned by more than one hundred methods, but its operation in nonlinear system remains not rather effective as in linear ones.

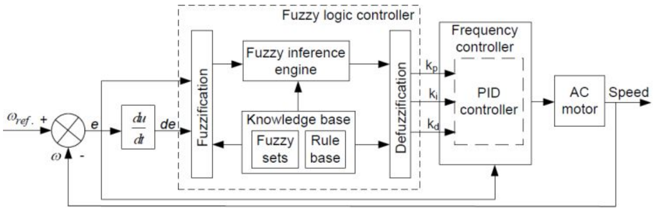

Fig. 2. Structure of the self-tuning fuzzy PID controller.

Therefore many researchers began to combine PID control strategies with fuzzy logic concepts. Proposed fuzzy auto-tuning of PID controller is used to find the fuzzy logic relationship between three gains k_p, k_i and k_d of PID controller according to speed error *e* and its change *de*. Such synthesis of the fuzzy logic and PID controller is able to control nonlinear system and make the controlled induction motor attain desired dynamic and static performance. Composite fuzzy-PID controller is designed in a manner, that object under control or system would be stable, overshoots, oscillations, response time and steady state error should be as small as possible [12], [13].

The developed model of induction motor with fuzzy logic and PID controllers is presented in Fig. 2.

Created fuzzy controller is a system with two inputs and three outputs. Error *e* and its change *de* are input variables, described as:

$$e(t) = \mu_{ref} - y(t), \qquad (1)$$

$$de = \frac{d}{dt}(\mu_{ref} - y(t)), \qquad (2)$$

where μ_{ref} is speed reference signal, *e(t)* – speed signal error, *y(t)* is output signal and *de* is change of the error signal and k_p is proportional gain, k_i is coefficient of integral action and k_d is coefficient of differential action [14], [15]. Figure 3–Fig. 5 shows each gain k_p, k_i and k_d control surface of the hybrid fuzzy logic controller according to speed error *e* and its change *de*. These figures are obtained in Matlab Simulink.

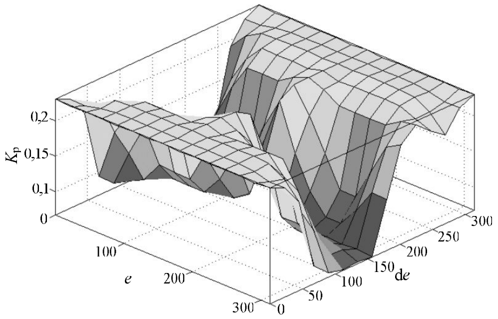

Fig. 3. Control surface of proportional integral derivative controller K_p gain.

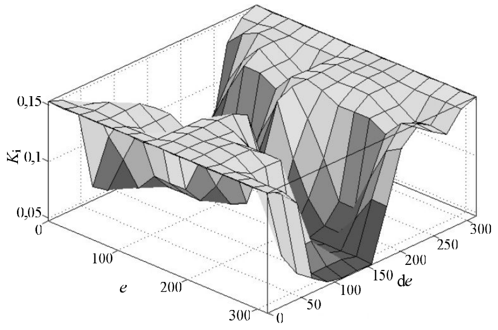

Fig. 4. Control surface of proportional integral derivative controller K_i gain.

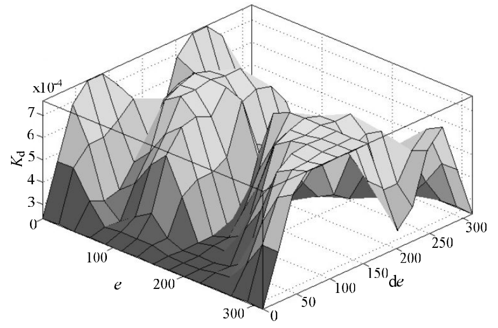

Fig. 5. Control surface of proportional integral derivative controller K_d gain.

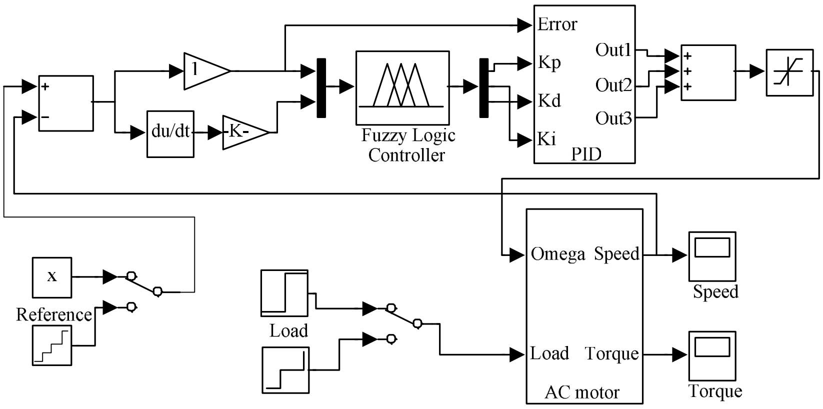

Fig. 6. Simulink model of the adjustable speed drive with fuzzy control in synchronous rotating reference frame.

It is clear, that control surfaces are nonlinear. It means, that fuzzy logic controller automatically and separately calculates each gain of PID controller. Such tuning of gains enables to control nonlinear system in all speed range up to synchronous speed. Figure 3–Fig. 5 are valid in all motor speed control range from 1 *rad*/*s* up to 314 *rad*/*s* and applying load up to 13 *N*·*m*.

V. SIMULATION RESULTS

The conventional PID controller in nonlinear system can ensure desired transients specifications only in a certain point of all operating range. The self-tuning fuzzy PID speed controller is created to solve this problem. Proposed controller can work in all working speed range from 1 rad/s up to synchronous speed. Model of induction motor with synthesis of fuzzy logic and PID controllers is presented in Fig. 6.

Figure 7 shows comparison of the induction motor speed reference and speed response signals. Speed reference is changed at 5th, 15th and 25th seconds.

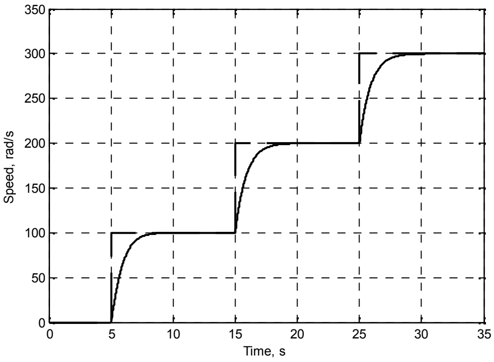

Fig. 7. Transients of the reference speed (dashed) signal and motor response signal.

It is obvious, that speed controller based on fuzzy logic with auto-tuning capability controls motor speed without steady state error. It takes about 3 seconds to reach steady state after the speed reference was changed by 100 *rad*/*s*. Figure 7 indicates no speed overshoot or oscillations.

Figure 8 shows starting speed transients of induction motor at reference signal 150 *rad*/*s*. When the motor reaches steady state, it is loaded by 5 *N*·*m* at time 8 *s*. It is seen, that speed transient with fuzzy PID controlled system reaches steady-state value in 3 *s* with no overshoot and oscillations.

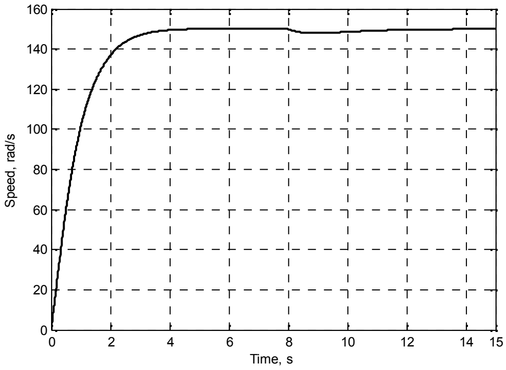

Fig. 8. Speed transient of induction motor.

Figure 9 presents torque response of induction motor at starting and applying the load.

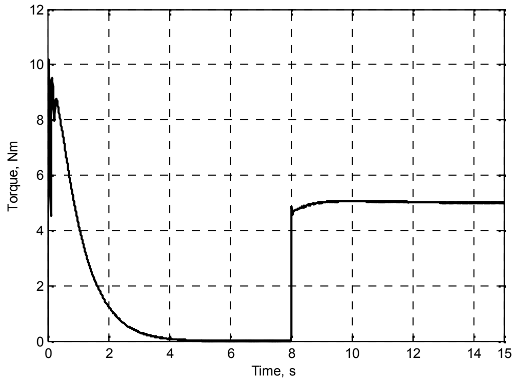

Fig. 9. Torque response of induction motor.

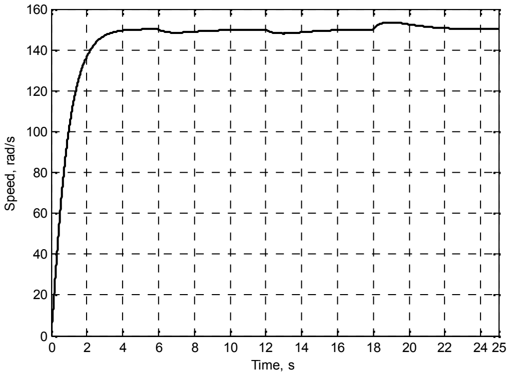

Fig. 10. Speed transient of induction motor when motor load is on and off.

When the 5 *N*·*m* load is turned on, motor speed decreases by 4 %, but it took less than 3 seconds to restore it to set up value. The transients indicate that speed control system with proposed fuzzy PID controller operates smoothly.

Figure 10 shows the speed transient with periodical increasing of load at time instants 6 seconds and 12 seconds correspondingly to 4 and 8 *N·m*, afterwards, at time instant 18 seconds load is set equal to zero.

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Figure 10 shows the speed transient with periodical increasing of load at time instants 6 seconds and 12 seconds correspondingly to 4 and 8 *N·m*, afterwards, at time instant 18 seconds load is set equal to zero.

Figure 10 indicates that motor speed comes back to the set up value despite the load is increased or turned off without any error. The settling time depends on motor inertia and does not exceed 3 *s*.

Figure 11 shows motor torque transient at motor starting without load, 4 *N·m* load is applied after 6 *s*, later, at time 12 *s* the load is increased to 8 *N·m* and at time 18 *s* the load is turned off. As it is seen, the transients react to the applied changes smoothly, that shows the precise operation of the elaborated controller.

From Fig. 12 we can see, that 5 *N·m* load is on at time 8 *s* and 10 *N·m* load is on at time 22 *s*. No overshoots or oscillations are observed.

In all previous simulation results we have no any overshoots, because controller is adjusted to have smooth motor start transients. However, if we have smooth start, we need more time to reach reference signal after the load is applied. In order to have fast speed recover we can increase gains inside the fuzzy controller.

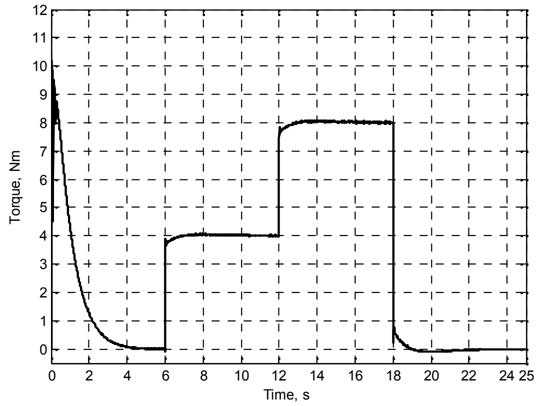

Fig. 11. Torque response of induction motor when load is applied twice and turned off.

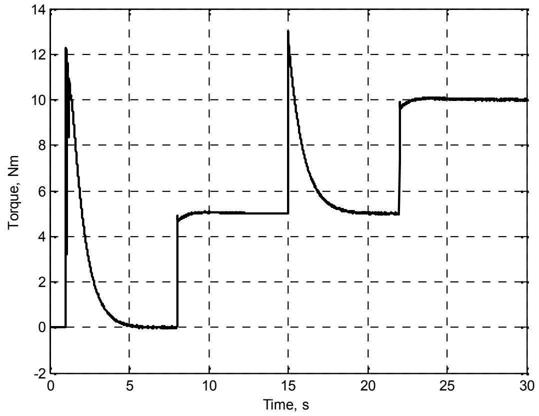

Fig. 12. Torque transient of induction motor when load is changing.

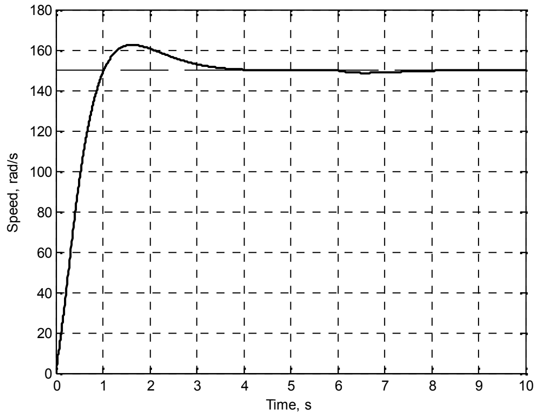

Fig. 13. Speed transient with increased gain.

Overshoot of 9 % is indicated in Fig. 13. Comparison of speed recovery, presented in Fig. 8 shows that settling time, required to reach reference signal after the load is applied is 50 % shorter.

VI. CONCLUSIONS

Conventional PID operates only at one point of all speed range its gains should be recalculated.

Elaborated speed control system simulation model with auto tuning fuzzy PID controller operates in all speed range from 1 *rad*/*s* up to synchronous speed 314 *rad*/*s* with steady state error ±0.05 %– ±5 %.

Parameters of PID controller are tuned automatically by fuzzy controller according to speed error *e* and change of the error *de*.

After the motor is loaded the speed drops down, but it took less than 5 *s* to adjust it to reference signal with smaller than 1 % error.

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