Optimal Fuzzy Controller Tuned by TV-PSO for Induction Motor Speed Control

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***Abstract*—This paper reports an automated procedure for the design of an optimal fuzzy logic controller to be used as an induction motor speed controller. The procedure consists of selection of a suitable well known fuzzy logic controller and tuning via particle swarm optimization optimal for the selected criteria. In this way the time required for tuning of the controller is significantly reduced in comparison with trial and error methods. As a benchmark a proportional-integral (PI) controller is used. The PI controller is tuned via the symmetrical optimum procedure, the standard procedure for tuning a speed controller of an induction motor. Simulation results are obtained via a mathematical model developed in Matlab/Simulink. Experimental verification is carried out with a laboratory model based on the DS1104 digital control card. To minimize iron losses and to provide better motor performance for low loads, flux is reduced from nominal and speed is kept below nominal. Results are presented in tables and graphics. The optimal fuzzy logic controller provides a slight practical advantage.**

***Index Terms*—fuzzy logic, speed control, proportional-integral controller, swarm particle optimization, induction motor**

I. INTRODUCTION

Indirect field oriented control (IFOC) of induction motors (IM) is widely used in industrial drives. IFOC provides high dynamic performance for a wide range of applications. Depending on application there are up to six control loops in the IFOC scheme. The dynamic performance achieved is highly dependent on controller design [1, 2].

This paper is organized into six sections presenting theoretical and practical analysis of advanced techniques in speed controller design. Section I is a brief introduction to the subject, and lays out the significance of the contributions of the paper. Section II presents a theoretical background of IFOC. In Section III, time varying particle swarm optimization is discussed. Section IV presents advanced speed controller design. Section V describes the laboratory model in detail. Section VI reports experimental results, and finally Section VII presents our conclusions.

The two most common modes of operation in practical alternating current (AC) drive applications are: speed and torque modes. In the speed mode the challenge is to keep speed constant while torque varies, and vice versa in the torque mode.

The design of simple and robust speed controllers is a challenging task of great practical importance. The design effort must be economically justified and the dynamic performance gained must be at a high level. In the past decade, a significant number of scientific papers have been published which acknowledge significance of this area of research and its practical importance.

The design process of fuzzy logic controllers (FLC), which includes: formulation of the knowledge base, the number of linguistic variables, the type of membership functions and their parameters, and the division of input-output space in general; are not uniquely defined. The traditional heuristic trial and error procedure used to determine optimal fuzzy structure is a time consuming process with no guarantee of success [3]. The purpose of this report is to propose an automated design process which will provide good FLC performance. A known FLC is used [4], and chosen parameters are tuned via a time varying particle swarm optimization (TV-PSO) algorithm [5, 6]. Tuning parameters are weights of input and output of FLC. TV-PSO is used because of fast convergence and simple implementation. This approach simplifies the FLC design procedure and provides good performance.

As a benchmark, a proportional-integral (PI) speed controller is used. The PI controller is tuned via a symmetrical optimum (SO) procedure which is a standard benchmark for this kind of application [7].

It is very important to compare the FLC with an adequately tuned PID controller, not only to show one implementation, as in [8], or to use a purely tuned PID, as in [9], or tuning via the Zeigler-Nichols method [10, 11] and making a generalized conclusion, or to claim that FLC have the potential to replace PI controllers [12] based on weak foundations. Results presented in this way leave a lot of unanswered questions and do not give a clear picture of achieved performance. Generalized conclusions based on a particular case could be very misleading and dangerous. Caution is strongly recommended when different controller types are compared. The comparison must be as fair as possible and include a sufficient number of various tests [13]. This report presents a comparative analysis of well tuned PI and fuzzy speed controllers in an IFOC scheme. This investigation does not attempt to answer the question of which type is best in general.

The design of controllers is performed utilizing a mathematical model in Matlab/Simulink and verification is carried out in a laboratory model based on the dSPACE DS1104 digital control card. Laboratory tests are conducted using field weakening. To provide generally better induction motor (IM) work at reduced load and to reduce iron losses, flux is set to a sub nominal value and speed is maintained in the sub nominal range to protect the IM from mechanical faults.

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II. Rotor Flux Oriented Control of a Voltage-Fed Induction Motor

Because the concept of impressed currents in current source inverters (CSI) becomes impractical in the field weakening speed range, a voltage source inverter (VSI) with pulse width modulation (PWM) is used. Equations (1) to (3) describe the interactions between field-oriented stator voltages and currents, which with others [1] form the mathematical model of voltage-fed induction motor in field coordinates:

$$\underline{u}_S(t)e^{-j\rho} = u_{Sd} + ju_{Sq}, \quad (1)$$

$$\sigma T_S \frac{di_{Sd}}{dt} + i_{Sd} = \frac{u_{Sd}}{R_s} - (1-\sigma)T_S \frac{di_{mR}}{dt} + \sigma T_S \omega_{mR} i_{Sq}, \quad (2)$$

$$\sigma T_S \frac{di_{Sq}}{dt} + i_{Sq} = \frac{u_{Sq}}{R_s} - (1-\sigma)T_S \omega_{mR} i_{mR} - \sigma T_S \omega_{mR} i_{Sq}. \quad (3)$$

Of practical importance is the transformation from field-oriented into the fixed stator coordinate system

$$\underline{u}_{S\mathrm{Ref}} = (u_{Sd} + ju_{Sq})_{\mathrm{Ref}}\, e^{j\rho'}, \quad (4)$$

where are: ρ'-angle of the fundamental flux wave, σ-leakage factor, i_{Sd}, i_{Sq}-direct and quadrate components of stator current, i_m- magnetizing current representing rotor flux, u_{Sd}, u_{Sq}-direct and quadrate components of stator voltage, R_S-stator resistance, T_S-time constant [1]. Microcomputer control of the induction motor with a voltage source PWM inverter is shown in figure 1. In this report, speed control is tested for reduced flux in the sub nominal speed range. In this case, if IM works with lower shaft loads than nominal, iron losses are reduced and smoother and better work from the IM is obtained. The existence of practical applications led to consideration of IM operation at reduced flux value.

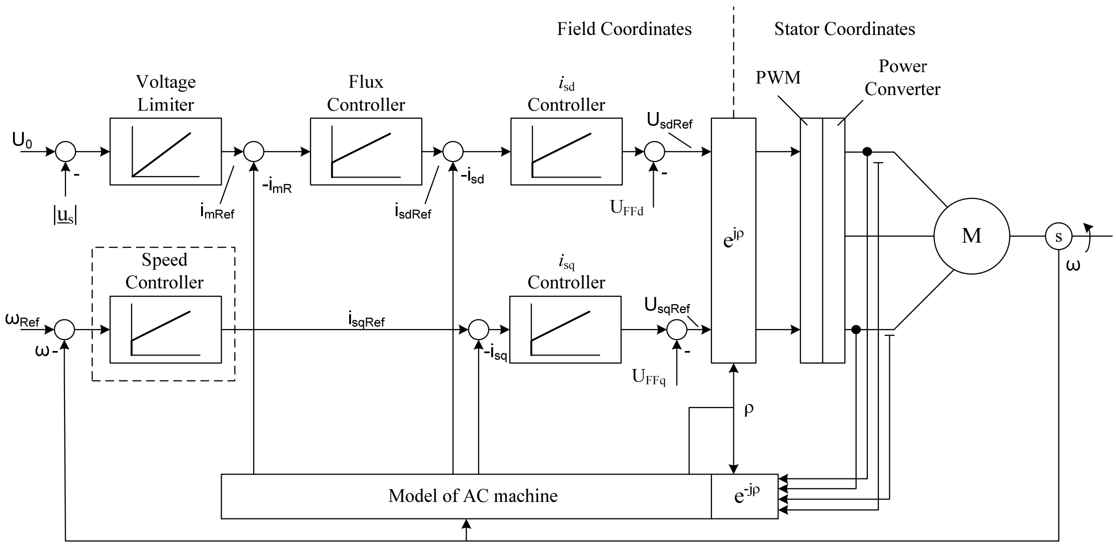


Figure 1. Microcomputer control of induction motor with a voltage source PWM inverter

III. Time Varying Particle Swarm Optimization

Particle swarm optimization (PSO) was introduced by Eberhart and Kennedy in the mid 1990's [5]. It was an attempt to mimic simplified behavior of flock motion. It is a global optimization technique suitable for solving complex, multidimensional problems. Flock or swarm is defined as a set of particles. Each particle is characterized by its position *(x)* and velocity *(v)*. The position of each particle is a candidate solution, each particle remembers its personal best position. The flock as whole remembers the best achieved position. In the each iteration position and velocity of all particles are updated in the following way:

$$v(k) = w(k)\cdot v(k-1) + cp(k)\cdot rp(k)\cdot (p(k)-x(k)) + cg(k)\cdot rg(k)\cdot (g(k)-x(k)), \quad (5)$$

$$x(k+1) = x(k) + v(k), \quad (6)$$

where w, cp, cg are parameters of the algorithm, rp and rg are random numbers in range [0, 1].

In reference [6] the authors proposed a new set of PSO parameters. Parameters like: "acceleration constriction", ξ, and "acceleration ratio", η, are introduced:

$$cp(k) + cg(k) = 4\xi(1 + w(k)), \quad (7)$$

$$cg(k) = \eta(k)\cdot cp(k). \quad (8)$$

Benefits are simplified convergence and direct control over the diversity of the swarm. When the initial population is displaced from the global optimum, the modified PSO algorithm performs significantly better than others [6].

IV. Induction Motor Speed Controller Design

The main challenge in speed control is to keep speed constant or at a defined complex trajectory with satisfactory dynamic performance and good load and noise disturbance rejection. The IM is a very robust machine but it is not primarily used for highly precise operations. The primary applications are pumps, fans and different robust industrial machines where the IM works in a sub-synchronous speed range where its linear characteristic is dominant.

A. PI speed controller design

The PI controller is the most common type of controller in industrial applications, employed in 95% of control loops [14]. Simple structure and well developed theory make PI controllers very powerful for practical implementation. Today the PI controller is primarily used in IFOC industrial drives. Transfer function of PI controller is:

$$G_c(s) = k_\omega \frac{1 + sT_\omega}{sT_\omega}. \quad (9)$$

Where: k_ω – static gain, T_ω – integration time of speed controller, s – complex variable. There are various procedures that can be used for speed controller tuning [14].

In this paper the SO procedure is used because it is one of the most common for speed control drive applications. It is an optimization procedure which gives speed controller parameters k_ω and T_ω and satisfies the conditions:

$$\begin{aligned} &|F_w(j\omega)| \cong 1, \omega < \omega_c \\ &|F_w(j\omega)| \cong 0, \omega > \omega_c \end{aligned} \tag{10}$$

Where: F_w is transfer function of the feedback speed control loop, ω_c is critical frequency. The main idea of SO is to design a low-pass filter that would preserve the original signal up to some critical frequency, and to repress signals above it. For speed control loops, ω_c has values of several dozen Hz.

Anti-windup technique [15] prevents agglomeration of the error integral and will be applied here. The output of the speed controller must be limited and filtered. In this particular case parameters of the PI speed controller are calculated based on a second order model [16]:

$$T_\omega = 4T_e,\ k_\omega = \frac{2T_m}{k_m T_\omega}. \tag{11}$$

Values of speed controller parameters are: k_ω=59.26 and T_ω=20ms. Speed loop parameters are: k_m=0.135, T_e=5ms, T_m=80ms.

In table 1 performance indexes of the SO tuned PI controller are given. Where: M_s – maximum complementary sensitivity, M_p – maximum sensitivity, M_n – maximum noise sensitivity, and MAE – mean absolute error.

TABLE 1. SO TUNED PI CONTROLLER PERFORMANCE INDEXES

Rise time	Settling time	Overshoot	Ph. margin
0.0152 sec.	0.0422 sec.	4.32%	65.5 deg.
M_s	M_p	M_n	MAE [p.u]
1.27	1	75.1	0.0795

In figure 2 the step response of the tuned speed control loop is shown. From table 1 and figure 2 it may be seen that good dynamic performance is achieved with reasonably small overshoot, good phase margin and sensitivity parameters, and no steady state error. Different procedures for tuning PI controllers can be found in [17].

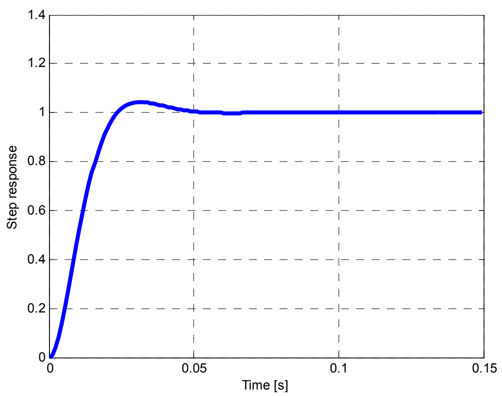


Figure 2. Step response of tuned speed control loop

B. *Fuzzy speed controller design*

Fuzzy logic is a very powerful tool which incorporates expert knowledge in controller structure. Different approaches and designs of FLC speed controllers can be found in the literature. Two basic designs are: (i) FLC for online tuning of a PI controller [18, 19], (ii) FLC standalone speed controller [20]. With expert knowledge of the system and robust design, consideration of FLC speed controllers as a candidate for the standard speed controller in IFOC schemes is justified.

In this report, a Mamdami type FLC is designed with 64 rules, two inputs and one incremental output. Input signals are error and change of error, and the output signal is change of control signal. Each signal is represented via eight linguistic variables. Fuzzy sets uniformly cover input-output domain. In table 2 the knowledge base is shown, where: NL-negative large, NM-negative medium, NS-negative small, NZ-negative near zero, PZ-positive near zero, PS-positive small, PM-positive medium, PL-positive large value, e-error, and Δe-change of error. Other properties of the FLC design are: and method: min, or method: max, implication: min, aggregation: max, defuzzification: largest absolute value of maximum. Intervals for input signals are in range [-1, 1], output signal is in range [-1, 1]. This is a well known FLC structure and can be found in reference [4]. The structure shown in figure 3 replaces the speed controller, marked with dashed line in figure 1. Optimization of FLC can be done in several ways: optimization of knowledge base, of membership function parameters and input-output weight optimization. The first two approaches have a large number of parameters that are involved in the optimization process. Due to simplicity and the small number of tuning parameters, optimization of FLC input-output weights (a, b, c), figure 3, was selected. In this case the optimization problem is three dimensional.

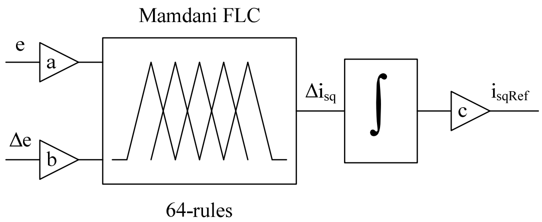


Figure 3. FLC structure and input-output weights

Figure 4 gives an overview of the generated FLC control surface. The surface is a graphical representation of the implemented fuzzy control law. Based on figs. 1, 3, and table 2, and adopted linguistic variables, the control surface (fig. 4) is designed. It sets the post-defuzzification numerical relationship between fuzzy inputs: e, Δe and output: Δi_{sq}, in other words, it describes the nature of the implemented control law. If inputs have values close to zero the output of the FLC is near zero and control output does not change. If the error has negative value and the change of error has also negative value, then the FLC generates negative output (marked with blue color in figure 4), with decreasing value of i_{sq}. An analog mechanism is used for contrary situations. The control surface is nonlinear due to the interdependent nature of signals e, Δe and Δi_{sq}, throughout the complete interval of operation modes. This represents FLC controller adaptivity to present operation conditions.

TABLE 2. FLC KNOWLEDGE BASE

ΔE E	NL	NM	NS	NZ	PZ	PS	PM	PL
NL	NL	NL	NL	NL	NL	NM	NS	PZ
NM	NL	NL	NL	NM	NM	NS	PZ	PS
NM	NL	NL	NM	NS	NS	PZ	PS	PM
NZ	NL	NM	NS	NZ	PZ	PS	PM	PL
PZ	NL	NM	NS	NZ	PZ	PS	PM	PL
PS	NM	NS	NZ	PS	PS	PM	PL	PL
PM	NS	NZ	PS	PM	PM	PL	PL	PL
PL	NZ	PS	PM	PM	PL	PL	PL	PL

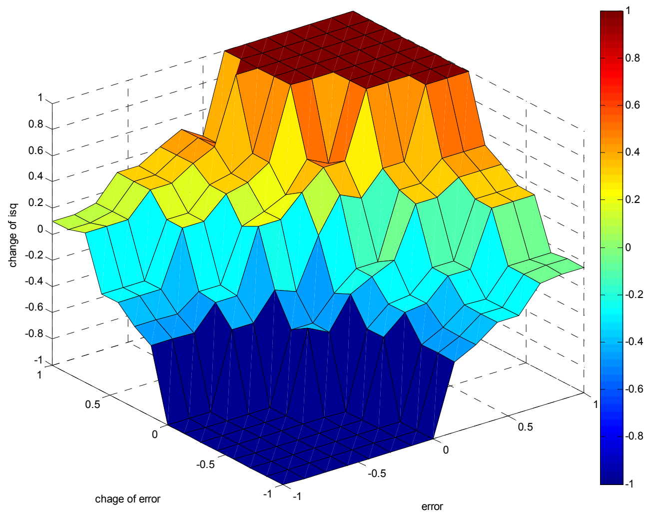


Figure 4. Generated FLC control surface

An adopted optimization criterion that considers error and control signals is:

$$J = \int_0^t (e^2(\tau) + u^2(\tau))\, d\tau \,, \qquad (12)$$

where: e(τ) – error signal, u(τ) - control signal. The optimization process is performed via a TV-PSO algorithm, due to its benefits. It is elegant in concept, simple to implement and has few parameters requiriing adjustment [6]. Each particle is represented by a three dimensional vector [*a, b, c*], where: *a* is scale factor of error signal, *b* is scale factor of change of error signal, and *c* is scale factor of control signal. Optimization of the FLC speed controller is performed in 20 iterations for selected minimizing criteria (12). Optimal scale factors are: *a*=10.5; b=0.15; c=1.7.

V. EXPERIMENTAL MODEL

Experiments were carried out on a prototype model based on a dSPACE DS1104 digital control card and two induction motors. The first, a two pole machine, is in drive mode and the second, a four pole machine, is load. Control algorithms are developed via the ACE1104 system. The DS1104 control card is based on the PowerPC603e micro processor.

The drive machine is driven by a current regulated voltage inverter based on IGBT (insulated gate bipolar transistor) Semikron SKM150GB123D modules. Maximal voltage for these modules is declared as 1200V, and maximum current is 50A. The experimental model is shown in figure. 5.

Transfer of control signals generated by control card DS1104 is carried out by optical link. The optical link system consists of optical transmitter HFBR 1524, receivers HFBR 2524 and multi-mode optical conductors OKE 1000 (Agilent Technologies). Power supply currents are measured by LEM LA 55P sensors with measuring ratio 1:1000. Measuring signals are amplified via LM741 and filtered by a low pass filter with cut off frequency 2kHz. For measurment of rotor angular speed on motor shaft, optical encoder Omron E6C3 – CWZ3XH was used with 3600 impulses per rotation.

Figure 5. Experimental model

VI. EXPERIMENTAL RESULTS

Experiments were conducted with the experimental model described in Section V. PI and fuzzy speed controllers described in Section IV are employed.

In the first experiment, complex reference speed trajectories are defined, no active shaft load is present, and the task for speed controllers is to minimize speed error. Flux value is decreased from nominal to a sub-nominal value of 0,6Vm, which is 70% of nominal. IM is protected from working at speed above nominal to prevent mechanical damage. Three different speed reference trajectories are defined T1, T2, and T3. The same parameters for soft-start function are used in all cases. An example of one test is shown in figure 6.

Three performance indexes are measured: mean absolute error (MAE), mean square error (MSE), and maximal error (MAXE). Performance obtained is given in table 3. From table 3 and figure 6 it is readily seen that generally good performance is obtained in all cases. Both controllers successfully tracked reference speed with no significant overshoot or steady-state error, with good noise suppression.

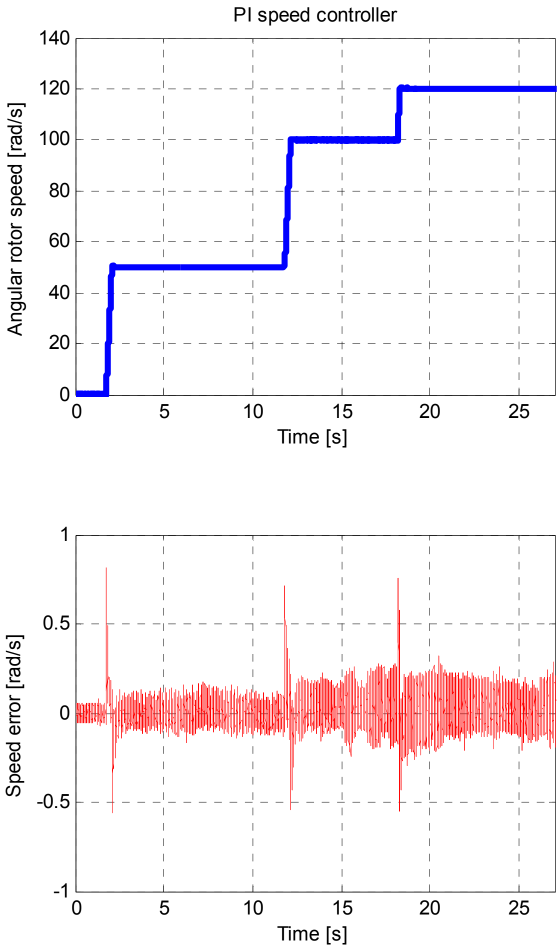
A slight advantage goes to the FLC controller if MAE and MSE are of interest (up to 20%) and to the PI controller if MAXE is considered (up to 28%). Percentage values are significant but in absolute units differences in achieved performance are relatively small. In the majority of practical applications this difference is insignificant.

TABLE 3. PERFORMANCE COMPARISON OF SPEED CONTROLLERS

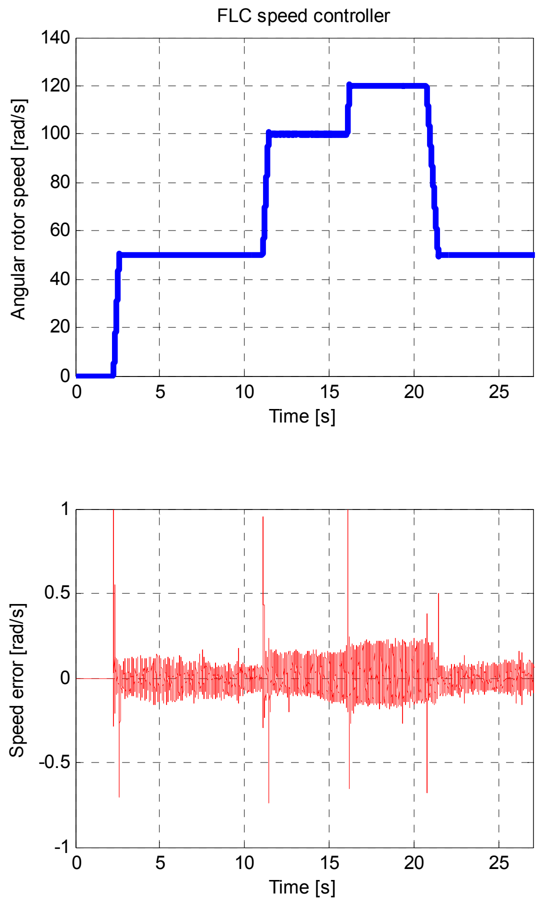
	MAE [p.u]	MSE [p.u]	MAXE [p.u]
PI T1	0.0637	0.0082	0.8185
Fuzzy T1	0.051	0.0067	1.1426
PI T2	0.0799	0.0111	0.7587
Fuzzy T2	0.0678	0.0095	0.7925
PI T3	0.0768	0.0115	0.8592
Fuzzy T3	0.0729	0.0109	0.9542

In the second test the IM is loaded and unloaded with 50% of nominal shaft load. In the first case the PI speed controller is used and in second case the FLC controller. Comparative load disturbance responses are given in fig. 7.

It can be seen that good load response is achieved in each case. At a speed of 50 rad/s the decrease is about 8 rad/s or 16% of reference value, at 100 rad/s speed decrease is 5%. Settling time is less than 1 sec, with no significant overshoot or steady-state error. A slight advantage goes to the FLC controller but observed performance differences have little practical importance.



a) PI speed controller response



b) FLC speed controller response

Figure 6. Comparison of PI and fuzzy speed control in field weakening region

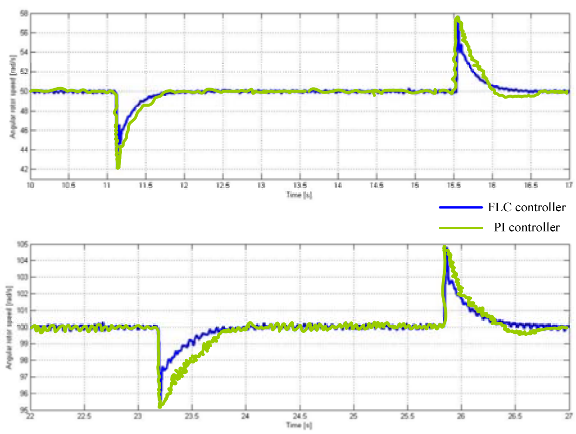


Figure 7. Load disturbance system response

VII. CONCLUSION

This report provides insight into the design of an automated and simplified procedure for tuning an FLC controller. A known FLC structure is used, tuning of input-output weights is done via a time-varying particle swarm optimization algorithm for selected optimal criteria. This approach simplifies the fuzzy logic controller tuning procedure, reduces the amount of time needed for speed controller design and provides good system performance.

The PI controller is one of the oldest control laws and in widest use at present. Simple structure and developed mathematical tools make it suitable and easy for practical applications. Because of the importance of the PI controller, the performance of the designed FLC is compared with a well tuned PI controller.

The FLC controller has slightly better performance in the case of rapid changes of disturbance and reference in comparison with the PI controller.

The main benefit of the proposed procedure is reduction of FLC design time with no negative consequences in respect to controller performance.

APPENDIX A

A. Load induction machine:

Type: ZK 90 L4, P=1.5 kW, ω_n=1405 rpm, R_s=5.25 Ω, R_r=3.17 Ω, $L_{\gamma s}$=0,0242 H, $L_{\gamma r}$=0,01 H, L_s=0,2992 H, L_r=0,285 H, L_m =0,275 H, T_r=90 ms, J=0,00332 kgm^2, i_{sd} (rated)=2,83 A, i_{sq} (rated)= 4,6 A.

B. Controlled induction machine:

Type: ZK 80 L2, P=2.2 kW, ω_n=2885 r/min, I_n=5,2 A, V_n=380 V.

C. Inverter:

Switching frequency: 8 kHz, V_{max}=1200 V, I_{max}=50 A, Dead time: 3.25 μs.

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