Optimally tuned PI controller for V/f control of induction motor using Matlab/Simulink

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Abstract. Induction motors are widely used in the industry due to their high accountability and low price. This study presents the use of Matlab/Simulink for controlling the induction motors with PI controller. The choice of controller parameters is especially important stage from the designing of control systems from which their efficiency depends. The practice shows that additional controller tuning is needed when classical methods are used. In the paper is applied a optimization method for determining the controller parameters. In Matlab/Simulink, based on objective functions for minimum settling time and minimum overshoot is determined the controller parameters using a genetic algorithm. The simulation results show an accurate and fast response with relatively no oversoot and no steady state error.

1 Introduction

Induction motors (IM) are among the most commonly used motors in practice. V/f control is one method of controlling motor speed. [1].

PID controllers are highly popular in practical applications because they are straightforward to use yet highly effective at maintaining precise system control. The choice of controller parameters is especially important stage from the designing of control systems from which their efficiency depends. There are many methods in the literature to find the controller parameter values [2]. The practice shows that additional controller tuning is needed when classical methods are used. Some researchers have successfully employed genetic algorithms as an optimization tool to determine the optimal parameters for PID controllers. [3, 4].

The genetic algorithm (GA) is a stochastic optimization method capable of handling both constrained and unconstrained problems by mimicking the mechanics of natural selection and biological evolution. At each evolutionary step, the GA modifies a population of individual solutions by selectively advancing candidate designs from the current generation to populate the next. This selection process relies on one or more objective functions, which mathematically evaluate how closely each individual approaches the desired optimal solution.The rules, based on which the individuals are selected from the current population are: Selection rules; Crossover rules; Mutation rules [5, 6].

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The GA can be applied to solve various optimization problems.

In all of these applications the tuning is obtained around the operating point, where the model is considered to be linear. Currently, optimization techniques such evolution methods are necessary at tuning the PID controller while taking into account all nonlinearities in the system.

The GA is used for determining the parameters of the PID controller in speed control systems of induction motors by minimizing the integral square error or the integral of absolute error [3, 4, 5]. Of particular interest is the multi-criteria optimization of PID controller parameters to meet the conflicting requirements of minimum transient response time and minimum overshoot.

The purpose of this article is to determine the parameters of a PID controller for V/f speed control of an IM using a genetic algorithm based on the criteria of minimum settling time and minimum overshoot of the transient response.

To achieve the aim of the study is necessary to be realized the following stages of work:

- Modelling the control system of IM in Matlab/Simulink;
- Determination the PID controller parameters using a genetic algorithm;
- Analyzing the simulation results of system with PI controller tuned with GA.

2 Modelling the closed loop V/f control-based IM speed control in Matlab/ Simuling

The virtual test bench for speed control of IM using a PI controller was implemented using the MATLAB software and the Simulink and SimPowerSystem. Figure 1 illustrates the Simulink block diagram of a closed-loop speed control system for an IM utilizing the Space Vector Pulse Width Modulation (SVPWM) technique.

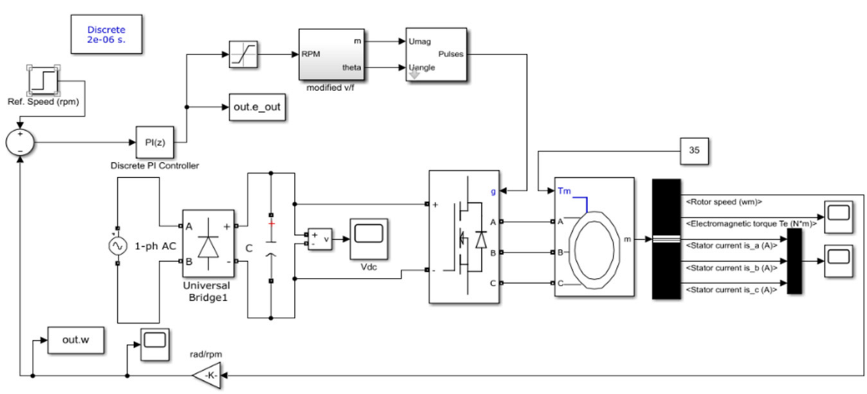

Fig. 1. Simulink model of the closed loop V/f control-based IM speed control.

Power Circuit Configuration: The IM is driven by a voltage source inverter connected to a DC power supply. In this simulation setup, the inverter is implemented using a Universal Bridge block configured with MOSFET switches, while the IM itself is represented by the standard Asynchronous Machine block. A constant mechanical load torque of 35 Nm is applied directly to the motor shaft.

Control Strategy and Feedback Loop: To achieve accurate speed regulation, a feedback loop monitors the actual rotor speed and compares it against the reference speed command. The resulting error signal is fed into a standard Proportional-Integral (PI) controller. This controller processes the error to generate a control signal, which serves as the input for the Volt-per-Hertz (V/F) control block that commands the SVPWM module.

Monitored Performance Metrics: The dynamic behavior and performance of the IM are evaluated using rotor speed, electromagnetic torque and stator current [7,].

The mathematical model of the embedded IM unit used in SimPowerSystem is:

$$U_{sd}= R_s \, . \, i_{sd}+(d\psi_{sd})/dt - \omega \, . \, \psi_{sq}; \tag{1}$$

$$U_{sq}= R_s \, . \, i_{sq}+(d\psi_{sq})/dt + \omega \, . \, \psi_{sd}; \tag{2}$$

$$U_{rd}'=R_r'. \, i_{rd}'+(d\psi_{rd}')/dt-(\omega-\omega_r). \, \psi_{rq}'; \tag{3}$$

$$U_{rq}'=R_r'. \, i_{rq}'+(d\psi_{rq}')/dt-(\omega-\omega_r). \, \psi_{rd}'; \tag{4}$$

the equation for the electromagnetic moment:

$$M=1,5p(\psi_{sd} \, . \, i_{sq}- \psi_{sq} \, . \, i_{sd}); \tag{5}$$

and the equation of motion of the drive:

$$J \, . \, d\omega/dt=M-M_s. \tag{6}$$

In the above equations are used the following designations: R_s, R_r' - active resistance of the stator and reduced rotor winding; U_{sd}, i_{sd}, U_{rd}',i_{rd}' and U_{sq}, i_{sq}, U_{rq}',i_{rq}' - the projections of the stator and rotor voltage and current onto the axes **d** и **q**; ψ_{sq}, ψ_{sd}, ψ_{rd}', ψ_{rq}'- the projections of the stator and rotor flux linkages on the axes **d** and **q**; ω and ω_r - synchronous and angular speed of the rotor; p - number of pole pairs; J – inertia moment; M_s – the applied to the rotor shaft resistance moment. To properly adjust the induction motor block, it is necessary to know, in addition to the nominal power, voltage and network frequency, and to be determined experimentally or analytically the stator resistance and induction, rotor resistance and induction and mutual inductance. The IM electrical parameters are shown in Table 1.

Table 1. IM Parameters.

Parameter	**Value**
Rated Power	4391.5 W
Rated Voltage	230 V
p	6
R_s	0.5 ohm
L_s	0.75 ohm
R_r	0.25 ohm
L_r	0.5 ohm
J	0.02 kg.m^2

The transfer function of discrete PI controller is

$$W(z)= K_P + K_I .Ts .1/(z-1) \tag{7}$$

where K_P is the proportionality coefficient of the controller, K_I is the integration coefficient, and Ts is sample time.

3 Determination the PI controller parameters using a genetic algorithm

Most often, the optimal PI controller settings in automatic control systems are determined by minimizing the objective functions of the integral square error or the integral of absolute error [3, 4, 5].

The use of criteria based only on the system's error signal would struggle to satisfy the conflicting requirements between steady-state accuracy and the system's dynamic performance - settling time and overshoot. Therefore, when solving optimization problems, it is increasingly common to use not just one but several criteria that take into account the specific characteristics and requirements of the task at hand. The relationship between the various criteria and the PI controller tuning parameters is nonlinear, which justifies the use of a genetic algorithm for its tuning [3]. The resulting vector optimization problem can be solved in Matlab using the **gamultiobj** command. In this work, the criterion ***minF=[F1 F2]*** is used, where the criteria ***F1*** and ***F2*** are settling time and overshoot in the system, respectively. The PI controller optimization problem is implemented using the MATLAB and Simulink environments. Within the Simulink closed-loop control model, the PI block is parameterized with variables K_P and K_I, and sample time $Ts=0.0001s$. The resulting plant output is exported directly to the MATLAB workspace. The objective function evaluating the optimization criterion is defined in an M-file (Figure 2), where K_P and K_I are declared as global variables, and the dynamic simulation is executed via the **sim** command. Finally, the optimization process is initiated by executing the genetic algorithm routine script detailed in Figure 3.

```
function F=eval_reg_PID(X);
global Kp Ki;
Kp=X(1);Ki=X(2);
warning off;
options = simset('SrcWorkspace', 'current', 'Solver', 'ode45');
simOut = sim('proposed_model_PI_2013b_last', [], options);
w = simOut.get('w');
s = stepinfo(w.Data,w.Time);
tp = s.SettlingTime;
ov = s.Overshoot;
F=[tp ov];
display(X);
return
```

Fig. 2. M-file for evaluating the objective function.

```
global Kp Ki;
options=gaoptimset('PopulationSize',30,'ParetoFraction',0.9,'PlotFcn',@gaplotpareto,...
'Generation',30,'TolFun',0.001);
[x fval]=gamultiobj(@eval_reg_PID,2,[],[],[],[],[0.8 3],[5 15],options);
```

Fig. 3. M-file for start-up of GA.

The **gaoptimset** command specifies the parameters of the optimization procedure. The vectors defining the lower and upper bounds of the optimization parameters K_P and K_I are set within ranges that include the values of the tuning parameters previously determined according to Zigler-Nichols [2]. The optimization procedure terminates upon reaching the specified tolerance when calculating the objective function (options.TolFun).
The transient response requirements for the induction motor speed control system specify a settling time of less than 1 second, zero overshoot, and zero steady-state error.

The Pareto line is shown in Figure 4.

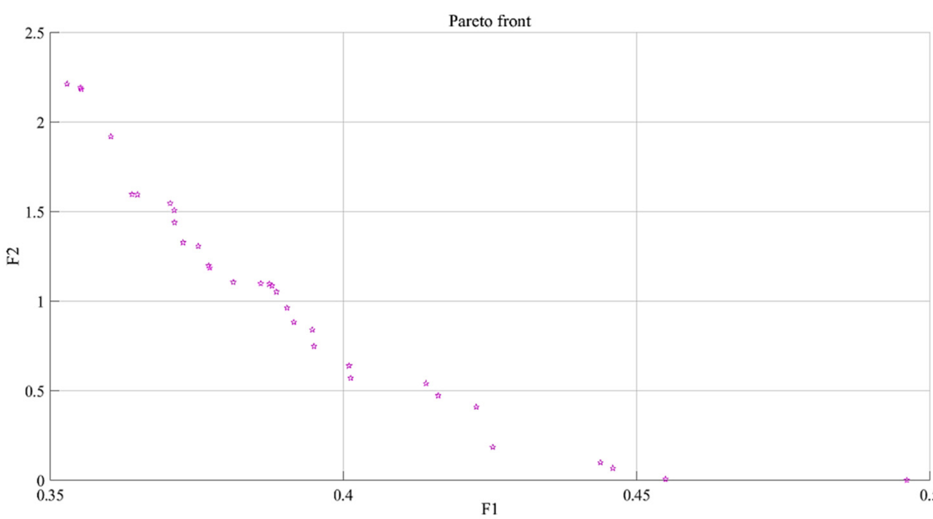

Fig. 4. Pareto line.

To optimize the transient process in the developed system with a PI controller for V/f control of an induction motor, a Pareto front has been plotted in the space defined by the criteria F1 (duration) and F2 (overshoot). The relationship between the two indicators is clearly conflicting. The left endpoint of the Pareto front defines the fastest-acting mode of the system, characterized by the greatest overshoot. The lower right endpoint corresponds to an aperiodic process without overshoot, in which the duration is greatest. This is the point that satisfies the requirements set for the controlled object.

4 Results of control system with PI controller tuned with GA

In Figure 5 is shown a transient process satisfying the set requirements – without oveshoot and with a duration of tp=0,492 s, and referance 920 min^{-1}. The parameters of the PI controller obtained from the optimization procedure, in this point of the Pareto line, are K_P=0,8558; K_I =9,7100.

Figures 6–8 show the speed transient, the variation in stator currents, and the electromagnetic torque of an induction motor controlled by a PI controller, whose parameters were determined through optimization using a genetic algorithm. To evaluate the dynamic characteristics and stability of the system, a step change in load was applied, with the load torque increasing from 3 Nm to 35 Nm during the first second of the simulation.

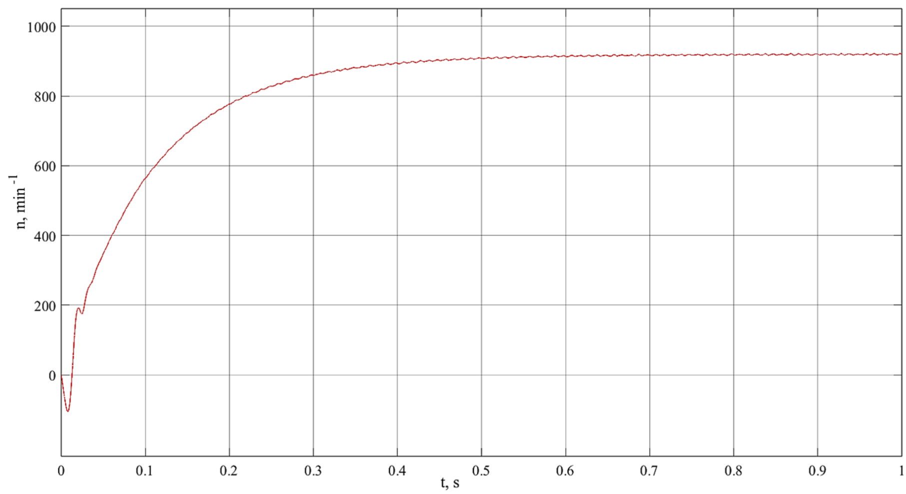

Fig. 5. Transient process in system with PI controller tuned with GA.

The speed graph (Figure 6) shows that, upon the sudden increase in load, there is a brief deviation of the speed from the setpoint, after which the PI controller quickly compensates for the disturbance. The transient process proceeds without significant fluctuations, and the system restores the setpoint speed in a short time, demonstrating good dynamic properties and high control accuracy.

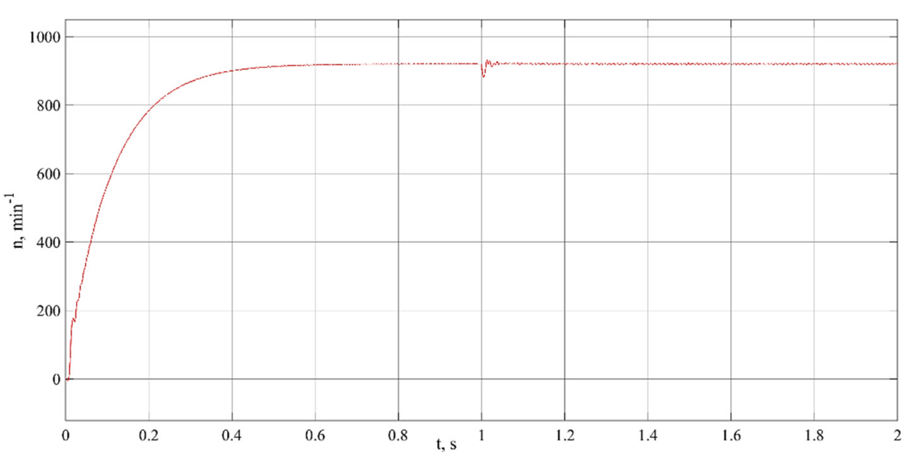

Fig. 6. Transient process in system with PI controller tuned with load torque 35 Nm.

Figure 7 shows the variation in the stator currents. At the moment the load torque increases, an increase in the amplitude of the stator currents is observed, which is necessary to provide a greater electromagnetic torque. After the transient process ends, the currents settle at a new steady-state level corresponding to the increased mechanical load, without significant fluctuations.

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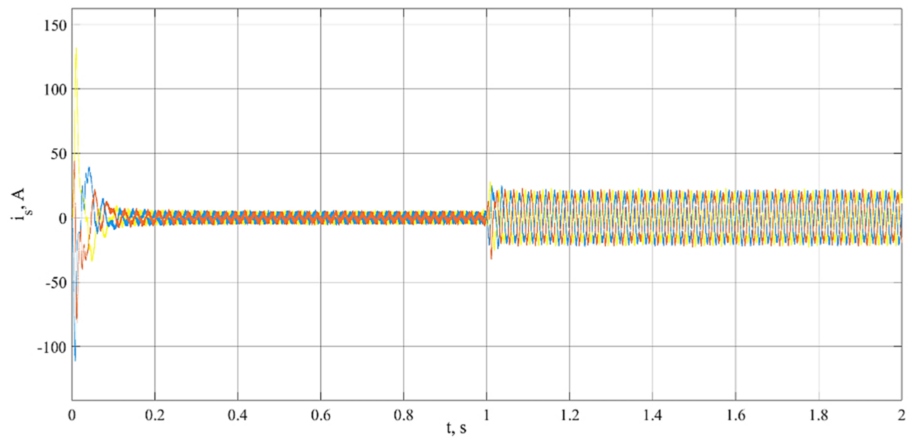

Fig. 7. Stator currents in the system with PI controller tuned with GA.

The electromagnetic torque, shown in Figure 8, responds immediately to changes in load. When the load torque increases, the motor's electromagnetic torque rises rapidly to compensate for the applied load and ensure that the set speed is maintained. Once the transient process is complete, the torque stabilizes at a value corresponding to the new operating conditions, without significant oscillations.

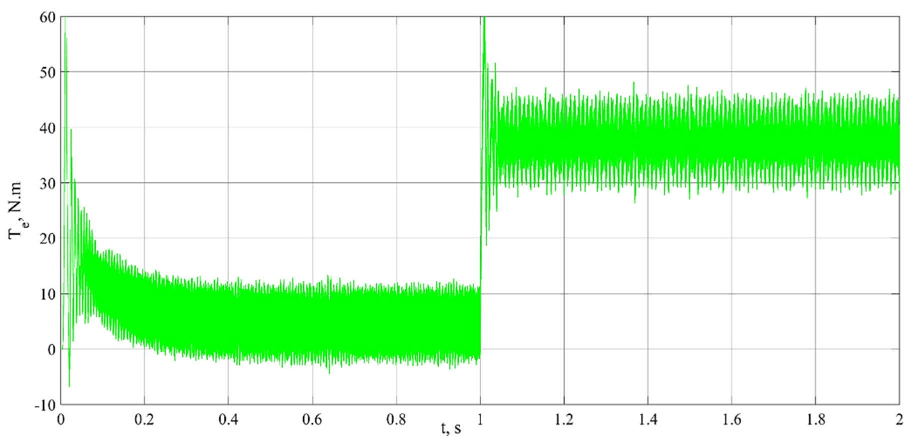

Fig. 8. Electromagnetic torque in the system with a PI controller tuned using GA.

The results show that the PI controller, tuned using a genetic algorithm, provides high control quality, good resistance to load changes, and effective suppression of transient processes. The system maintains its stability and sustains the set speed of the induction motor even during a sudden change in mechanical load, which confirms the effectiveness of the proposed method for optimizing the controller parameters.

5 Conclusion

The widespread use of the classic PI controller in V/f speed control of an induction motor is primarily due to the fact that it is relatively simple and can provide good control quality. Both general-purpose synthesis methods and specialized methods designed specifically for standard controllers can be used to determine its parameters. Practice shows that additional tuning is necessary when using classical methods. Therefore, this paper presents an optimization method for tuning the parameters of the PI controller. The parameters of the PI controller are determined using a genetic algorithm in Matlab/Simulink. The optimization criteria proposed to date are based on the system error signal and do not address the conflicting requirements between steady-state accuracy and dynamic system performance.

The article presents a multi-criteria optimization, based on objective functions for minimum settling time and minimum overshoot. The simulation results show an accurate and fast response with relatively no overshoot and no steady state error. The proposed simulation model can be used for multi-criteria optimization of the controller parameters as well as for investigating the operation of various induction motors.

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