Speed Control of Induction Motor Using Genetic Algorithm-based PI Controller

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Abstract: In this paper, we present the design of a Proportional Integral (PI) controller using Genetic Algorithm (GA) to control the speed of an induction motor (IM) using indirect field-oriented control method (IFOC). The main advantage of this metaheuristic method (GA) is its simplicity. Based on a criterion defined using an objective function, it helps in the optimal calculation of the PI controller parameters. Several tests of tracking and control by PI-GA are analyzed and compared to the conventional PI controller. The simulation results obtained using Matlab/Simulink showed that the proposed controller had on one hand a good dynamic and static performance and on other hand had a better robustness compared to the conventional PI controller.

Keywords: induction motor; PI controller; IFOC; vector control; genetic algorithm

1 Introduction

Nowadays, as a consequence of the important progress in power electronics and micro-computing, the control of AC electric machines has seen considerable development and the possibility for application [1]. The induction motor, known for its robustness, relatively low cost, reliability and efficiency, is the object of several research works. However its control presents difficulties because of its high non-linearity and its highly coupled structure [2]. The technique known as vector control, first introduced by Blaschke and Hasse, has resulted in a large change in the field of electrical drives. This is because, with this type of control, the robust induction motor can be controlled with high performance.This control strategy can provide the same performance as achieved from a separately excited DC motor [3, 4]. The best known controller used in industry is the proportional-integral (PI) because of its simple structure and its robust performance in a wide range of operating conditions. This linear regulator is based on a very simple structure, whose functioning depends only on two parameters, namely the proportional gain (kp) and the integral gain (ki). Several methods of tuning a PI controller have been proposed in the literature; the most used are the poles assignment method and the Ziegler-Nichols method [5, 6]. However, the major inconvenience of these two is the necessity of the a priori knowledge of the various parameters of the induction motor. To surmount this inconvenience, we can use a procedure of optimization to better design this type of controller. Genetic Algorithm methods have been widely used in control applications. They are stochastic optimization methods based on the principles of natural biological evolution. The GA methods have been employed successfully to solve complex optimization problems. The use of GA methods in the determination of the different controller parameters is practical due to their fast convergence and reasonable accuracy [7]. The parameters of the PI controller are determined by the minimization of an objective function. The goal of this work is to show that by the optimization of the parameters of the PI controller, an optimization can be achieved. This can be seen by comparing the result of the genetic algorithm based PI controller and the conventional PI controller.

This paper is divided into six sections. The indirect field-oriented control of an induction motor is presented in Section 2, the optimization by GA method is summarized in Section 3, and the optimization of the PI controller parameters by the GA method is developed in Section 4. Simulation results are reported in Section 5. Section 6 concludes the paper.

2 Indirect Field-oriented Control of the IM

The dynamic model of the induction motor can be expressed in the d-q synchronously rotating frame as [8, 9].

$$\begin{cases} \dfrac{disd}{dt} = -(\dfrac{R_s L_r^2 + M^2 R_r}{\sigma L_s L_r^2}) i_{sd} + \omega_s i_{sq} + \dfrac{M R_r}{\sigma L_s L_r^2}\phi_{rd} + \dfrac{M}{\sigma L_s L_r}\omega\,\phi_{rq} + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = -(\dfrac{R_s L_r^2 + M^2 R_r}{\sigma L_s L_r^2}) i_{sq} - \omega_s i_{sd} - \dfrac{M}{\sigma L_s L_r^2}\omega\,\phi_{rq} - \dfrac{M}{\sigma L_s L_r}\omega\,\phi_{rd} + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d}{dt}\phi_{rd} = -R_r(\dfrac{\phi_{rd}}{L_r} - \dfrac{M}{L_r} i_{sd}) + \phi_{rq}(\omega_s - \omega) \\ \dfrac{d}{dt}\phi_{rq} = -R_r(\dfrac{\phi_{rq}}{L_r} - \dfrac{M}{L_r} i_{sq}) - \phi_{rd}(\omega_s - \omega) \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}(\dfrac{MP^2}{L_r}(\phi_{rd} i_{sq} - \phi_{rq} i_{sd) - PT_L} - f_c\omega) \end{cases} \tag{1}$$

$$\sigma = 1 - \frac{M^2}{L_s L_r} \tag{2}$$

where i, ϕ, v denote current ,flux linkage and voltage, respectively. Subscripts s and r stand for stator and rotor. ω is the rotor speed, d and q denote direct and quadratic components of the vectors with respect to the fixed stator reference frame, L and R are the auto-inductances and resistances, M is the mutual inductance, T_L is the load torque, P is the pole pairs, f_c is the viscous friction coefficient and σ is the coefficient of dispersion.

The vector control of the induction motor is a well-accepted method when high levels of performance of the system response are required. It is based on the decoupling of the magnetizing and torque-producing components of the stator current. Under this condition, the q-axis component of the rotor flux is set to zero, while the d-axis reaches the nominal value of the magnetizing flux, and it follows that [3]:

$$\phi_{rq} = \frac{d\phi_{rq}}{dt} = 0 \tag{3}$$

$$\phi_{rd} = \phi_r \tag{4}$$

Applying the results of (3) and (4), namely the field-oriented control, the torque equation becomes analogous to the DC machine and can be described as follows:

$$T_e = \frac{3}{2}\frac{P.M}{L_r}\phi_r.i_{sq} \tag{5}$$

And the slip frequency can be given as follows:

$$\omega_{sl} = \omega_s - \omega = \frac{M.R_r}{L_r.\phi_{rd}} i_{sq} \tag{6}$$

Consequently, the dynamic equations (1) become [10]:

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\left(\dfrac{R_r L_r^2 + M^2 R_r}{\sigma L_s L_r^2}\right) i_{sd} + \omega_s i_{sq} + \dfrac{MR_r}{\sigma L_s L_r^2}\phi_r + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = -\left(\dfrac{R_s L_r^2 + M^2 R_r}{\sigma L_s L_r^2}\right) i_{sq} - \omega_s i_{sd} - \dfrac{M}{\sigma L_s L_r}\omega\phi_r + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d}{dt}\phi_{rd} = \dfrac{MR_r}{L_r} i_{sd} - \dfrac{R_r}{L_r}\phi_r \\ \dfrac{d\omega}{dt} = \dfrac{P^2 M}{L_r J} i_{sd}\phi_r - \dfrac{f_c}{J}\omega - \dfrac{P}{J} T_L \end{cases} \tag{7}$$

According to the above analysis, the indirect field-oriented control of the induction motor with a current-regulated PMW drive system, and whose the speed is driven by a PI controller, can be presented by the block diagram shown in Fig. 1.

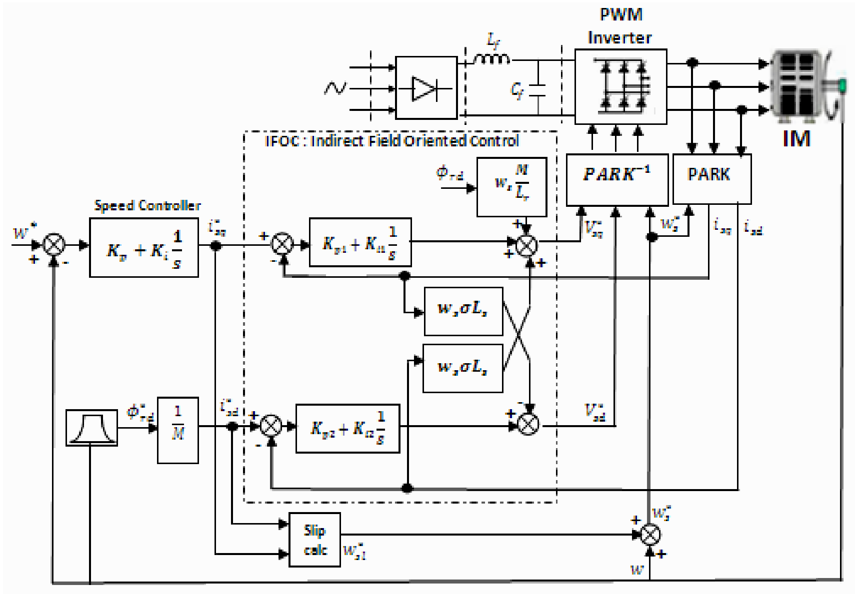

Figure 1
PI speed control structure

2.1 Tuning of the PI Speed Controller by Using the Conventional Approach

The dynamic model of the speed induction motor drive is significantly simplified, and can be reasonably represented by the block diagram shown in Fig. 2.

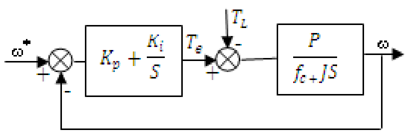

Figure 2
Block diagram of speed system controller

If $T_L = 0$, the transfer function in closed buckle is as follows (8):

$$G(s) = \frac{(K_p s + K_i)\frac{P}{J}}{s^2 + \frac{f_c + K_p}{L_r} s + \frac{K_i}{J}} \tag{8}$$

The characteristic equation is given as follows:

$$P(s) = s^2 + \frac{f_c + K_p P}{J} s + \frac{K_i P}{J} = 0 \tag{9}$$

By the imposition of two poles complex combined with real part negative, $s_{1,2} = \rho(-1 \pm j)$, we obtain the expression for K_p and K_i of the PI controller.

$$\begin{cases} K_i = \dfrac{2J\rho^2}{P} \\ K_p = \dfrac{2\rho J - f_c}{P} \end{cases} \tag{10}$$

where ρ is a positive constant.

PI gain values are given below in Table 1.

Table 1

PI: Controller values

Gain Coeff	K_p	K_i
Values	0.588	11.191

3 Genetic Algorithm

GA is a stochastic global adaptive search optimization technique based on the mechanisms of natural selection [11]. GA was first suggested by John Holland and his colleagues in 1975. GA has been recognized as an effective and efficient technique to solve optimization problems. Compared with other optimization techniques, such as simulating annealing and random search method techniques, GA is superior in avoiding local minima, which is a significant issue in the case of nonlinear systems [12]. GA starts with an initial population containing a number of chromosomes where each one represents a solution of the problem, the performance of which is evaluated by a fitness function. Basically, GA consists of three main stages: Selection, Crossover and Mutation. The application of these three basic operations allows the creation of new individuals, which may be better than their parents. This algorithm is repeated for many generations and finally stops when reaching individuals that represent the optimum solution to the problem. The GA architecture is shown in Fig. 3 [11, 13].

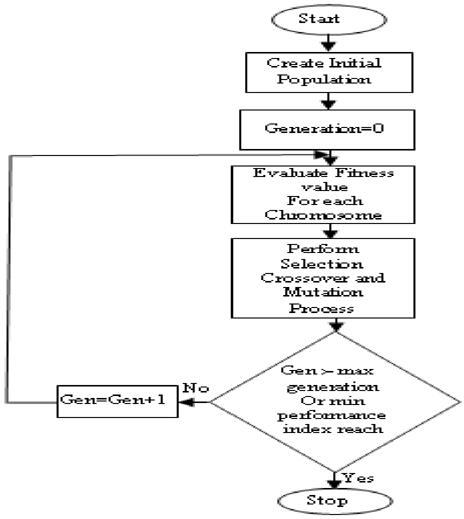

Figure 3
Genetic Algorithm Architecture

3.1 Genetic Operators

In each generation, the genetic operators are applied to selected individuals from the current population in order to create a new population. Generally, the three main genetic operators of reproduction, crossover and mutation are employed. By using different probabilities for applying these operators, the speed of convergence can be controlled. Crossover and mutation operators must be carefully designed, since their choice greatly contributes to the performance of the whole genetic algorithm [14].

3.1.1 Reproduction

A part of the new population can be created by simply copying without change selected individuals from the present population. Also the new population has the possibility of selection by already developed solutions [14].

They are a number of other selection methods available and it is up to the user to select the appropriate one for each process. All selection methods are based on the same principal, i.e giving fitter chromosomes a larger probability of selection.

Four common methods for selection are:

1 Roulette Wheel selection

2 Stochastic Universal sampling

3 Normalized geometric selection

4 Tournament selection

3.1.2 Crossovor

The crossover operator is the main operator and is used to produce offspring that are different from their parents but which inherit a portion of their parents' genetic material. Under this operator, a selected chromosome is split into two parts and recombines with another selected chromosome which has been split at the same crossover point. Typically this operator is applied at a rate of 60% to 80% of the population, and the crossover point and each pair is randomly selected [7].

3.1.3 Mutation

The mutation operator plays a secondary role in the evolution .It helps to keep diversity in the population by discovering new or restoring lost genetic materials by searching the neighbourhood solution space. Despite the fact that mutation can serve a vital role in a genetic algorithm, it should be noted that it occurs with a small probability rate of 0.1% to 10% of the entire population [7].

4 Tuning of the PI Speed Controller Using the Genetic Algorithm Approach

GA can be applied in the tuning of the PI speed controller's gains (K_p, K_i) to ensure optimal control performance at nominal condition for the induction motor. The block diagram for the entire system is given below:

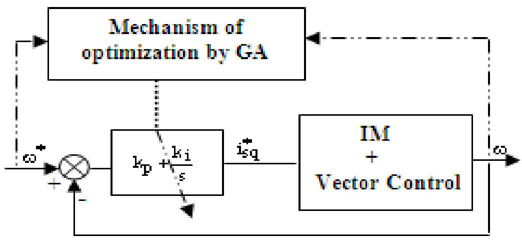

Figure 4

Structure of the technique of optimization of the PI controller by GA

Where:

ω^* is the speed reference

ω is the real speed of the induction motor

The objective function used is the following one [15]:

$$\text{Fitness}=\int_0^{t_{sim}} e^2(t).dt=\int_0^{t_{sim}} (\omega^*(t)-\omega(t))^2.dt \quad (11)$$

In this case, the block of the objective function is used to estimate the performances of the PI controller by minimizing this function.

The genetic algorithm parameters chosen for the tuning purpose are shown below.

Table 2
Parameters of GA

GA property	Value
Population size	60
Maximum number of generations	100
Crossover probability	0.8
Mutation probability	0.1
Tolerance	10^{-6}

After giving the above parameters to GA, the PI controller can be easily tuned and thus system performance can be improved. The parameters of the PI speed controller obtained according to the procedure of optimization by the technique of the GA are given below in Table 3.

Table 3
PI controller gain values

Gain Coeff	K_p	K_i
Values	0.90	9.75

5 Simulation Results and Interpretation

In order to verify the validity of the proposed controller, the computer simulation results for a 1.5 KW induction motor using a PI controller optimized by the GA technique is compared to a conventional PI controller whose parameters are determined by pole assignment method. The parameters of the test motor are given in the appendix.

A simulation program is designed to compare the stable and dynamic performances. Figs. 5 and 6 show the speed curve when the motor speed is at 150 rad/s. Fig. 5 is the result of the conventional PI controller, and Fig. 6 is the speed of the GA-based PI controller.

Fig. 5 shows that the conventional PI control has bigger overshoot. And Fig. 6 shows that the GA based PI controller has less overshoot and more stable performance.

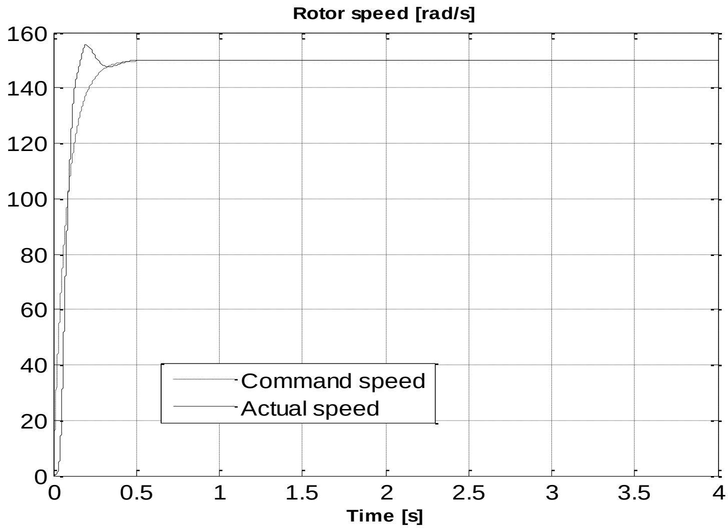

Figure 5

Rotate speed simulation curve when adopting conventional PI regulating strategy

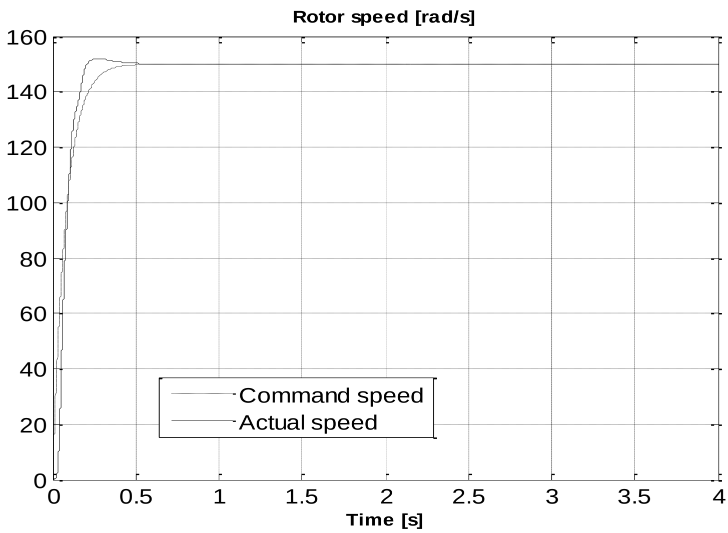

Figure 6

Rotate speed simulation curve when adopting PI controller based on GA

The next simulation, Figs. 7 and 8, were carried out to examine the disturbance rejection of each controller when the motor is fully loaded and operated at 150 rad/s and a load disturbance torque (10 N.m) is suddenly applied first at 1.5 s and at 3s. Figs. 7 and 8 show that the GA-based PI controller rejects the load disturbance very quickly, while the conventional PI controller takes longer to return to speed command.

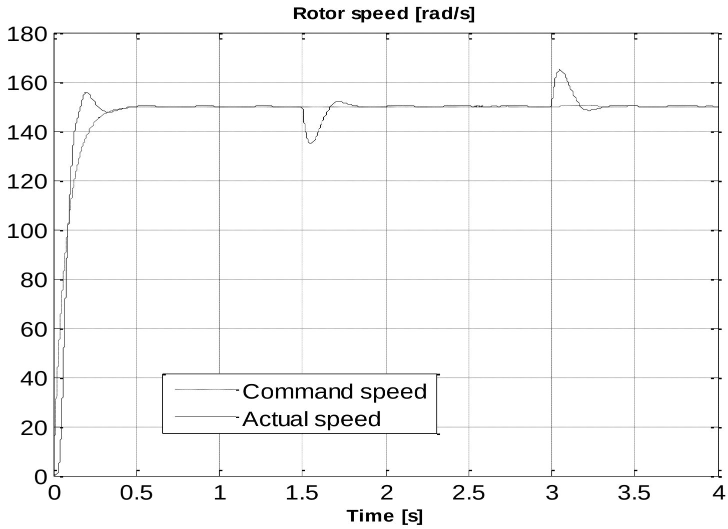

Figure 7
Rotate speed simulation curve using PI controller when load changes

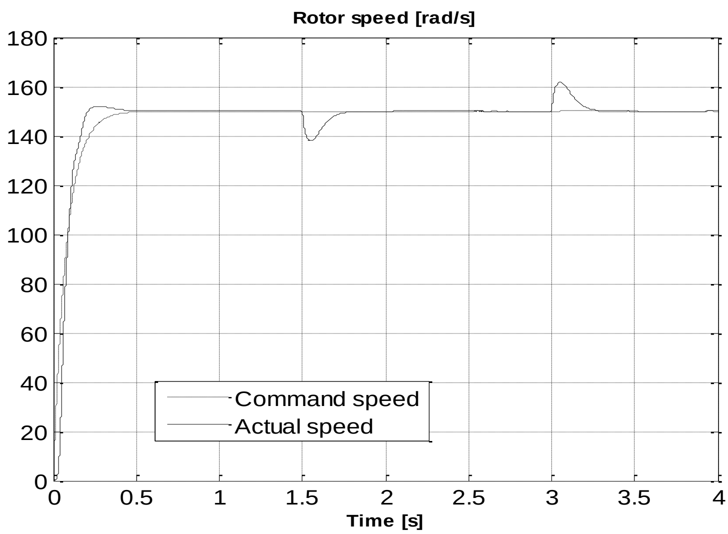

Figure 8
Rotate speed simulation curve using PI controller based on GA when load changes

Figs. 9 and 10 show clearly the comparison of both controllers in the presence of load disturbance. The GA-based PI controller returns the speed to the command speed within 0.37 s with a maximum drop of 12 rad/s. The conventional PI controller takes about 0.49 s to return the speed to 150 rad/s with a maximum drop of 15 rad/s.

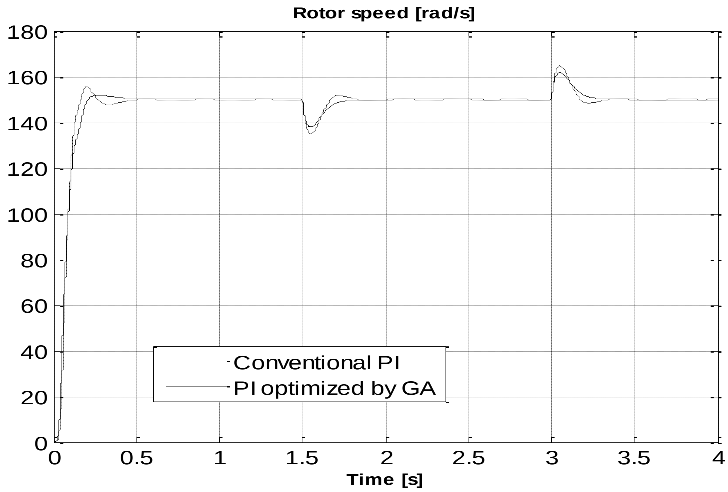

Figure 9

Comparison between the regulation of the IM by conventional PI and a PI optimized by GA when load changes

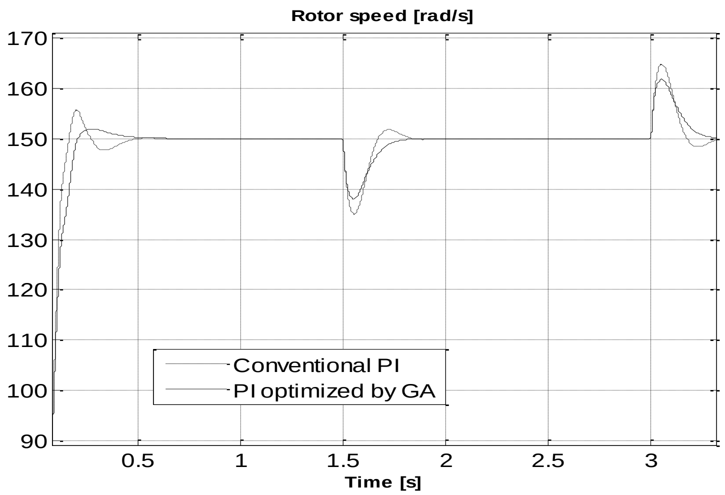

Figure 10

Comparison between the regulation of the IM by conventional PI and a PI optimized by GA when load changes (zoomed response)

Conclusion

The conventional PI controller gave satisfactory results. The major disadvantage of PI controllers resides in the determination of their parameters. Several design techniques of PI controllers were mentioned in literature. The most used are the poles assignment method and the Ziegler-Nichols method, but their disadvantages lie in the required prior knowledge of the various parameters of the IM. In our work we have chosen the GA optimization technique for the determination of the optimal parameters of the used PI controller.

The simulation results showed that the introduction of the GA led to an improvement in the speed regulation of the IM, which leads us to say that optimization by GA gives us the possibility of designing a powerful PI controller by optimizing its parameters.

Appendix

Induction motor parameters:

$P_n[KW]$	1.5	$R_s[\Omega]$	4.85	$f_n[Hz]$	50
$V_n[V]$	220	$R_r[\Omega]$	3.805	$J_n[Kg.m^2]$	0.031
η	0.78	$L_r[H]$	0.274	$f_c[N.m.s/rd]$	0.00114
$\cos\phi_n$	0.8	$L_s[H]$	0.274	P	2
$\omega_n[\min^{-1}]$	1428	$M[H]$	0.258		

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