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# Design and Experimental Application of an Improved Cascade Controller Optimized via Genetic Algorithm for Cascade Systems

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**Abstract:** A single-loop conventional controller will not initiate corrective action for disturbances unless the output variable moves away from the set point. In this case, the cascade control strategy can be benefitted to obtain better control system performance, especially in the existence of strong disturbances. Proportional-Integral-Derivative (PID) type controllers are usually preferred in both loops of a classical cascade control structure. However, if the outer loop transfer function of cascade control has an unstable pole or an integrator, then its performance may not be as good as desired due to the limitations of PID controllers. In this study, a new improvement in the outer loop of the cascade control structure incorporating a PI-PD controller is been proposed. To obtain, optimal parameters of controllers in the proposed improved cascade control scheme have been simultaneously used Genetic Algorithm (GA). The superiority of the proposed improved cascade control structure over some cascade control schemes suggested in the literature has been shown by simulation examples. Also, a real-time DC PM motor speed control application on the DIGIAC 1750 process control set has been performed to illustrate the validity of the proposed improved cascade control structure.

**Keywords:** Cascade control, optimal control, PID, PI-PD, DC PM Motor

## 1. Introduction

In the case of strong disturbances and long-time delays, a classical single-loop controller does not provide enough performance for them. Cascade control loops have been commonly used in the process control industries for the control of temperature, flow, and pressure loops. Franks and Worley were the first to propose a cascade control (CC) structure that can be used to enhance the closed-loop performance of a system, particularly in processes with disturbances [1]. A single-loop conventional controller does not initiate corrective action for disturbances unless the output variable moves away from the set point. The response of the closed-loop system can be improved by using a second measurement point and a secondary controller, Gc2, in cascade to the main controller, Gc1, as illustrated in Figure 1.

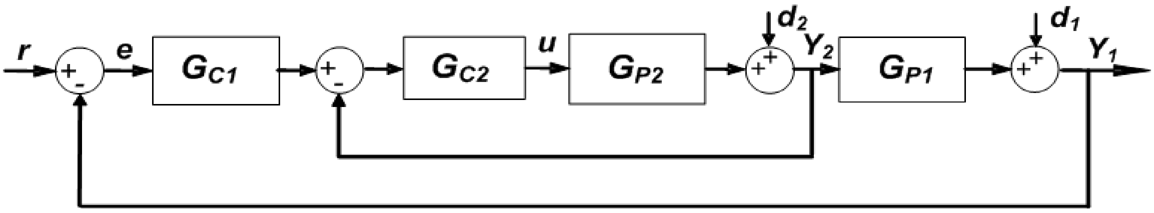


**Figure 1.** Block diagram of a system with a cascade controller

Different design methods have been investigated for tuning PID controllers in classical cascade control schemes, such as the ones given in [2, 3, 4, 5, 6]. Later improved cascade control structures

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have been suggested by many researchers to succeed in better closed-loop performances. For controlling open-loop stable processes, Kaya [7] used a cascade control configuration in conjunction with a Smith predictor scheme [8] in the outer loop led to improved system performance compared to some existing PID controllers. Lee et al. [9] suggested an enhanced control with a general cascade control structure. Kaya et al. [10] proposed a modified cascade control scheme, which incorporates the internal model controller (IMC) principles [11] in the inner loop and a Smith predictor scheme in the outer loop for controlling open-loop stable processes. Kaya and Atherton [12] gave an enhanced cascade control structure to control unstable and integrating processes. Enhanced cascade control schemes using IMC principles in the inner loop and a Smith predictor scheme in the outer loop were later given in [13, 14, 15] as well. Cakiroglu et al. gave an improved cascade control using a Smith predictor in each loop to compensate for time delay [16]. The design method of Lee et al. [9] cannot usually result in satisfactory closed-loop responses. Other design structures given in [7, 10, 12, 13, 14, 15] incorporate a Smith predictor scheme, which needs a model of the plant, in the outer loop. In addition, apart from the study of Kaya [7] and Cakiroglu et al. [16], above cited other studies use IMC principles for the inner-loop controller design. These may lead to the following difficulty. The inner loop is designed based on IMC principles so that a desired closed-loop transfer function is achieved and then the inner loop is enlarged with the outer loop process model to obtain a low-order apparent model. However, this model may not be as accurate as desired since Pade or Taylor's approximation is used to derive the required inner loop controller tuning parameters. As a result, the apparent model for the outer loop may involve large modelling errors. This may affect the closed-loop performance of the cascade control, as the outer loop includes the Smith predictor scheme and it is well known that the Smith predictor configuration is sensitive to modelling errors, especially to errors in the time delay.

The general procedure to design controllers in the inner and outer loop of a cascade control system involves first tuning the inner loop controller by setting the outer loop controller on a manual mode. The outer loop controller is then tuned while the inner loop controller is in the loop. This approach is time-consuming as it requires at least two runs of the process test. Therefore, more recently published works have concentrated on the simultaneous tuning of a cascade controller [17, 18]. The advantage of these studies is being independent of the availability of process models. However, in these studies, classical cascade control structures with PID controllers in both loops are used. It has been shown [19] that PID controllers may result in poor closed-loop responses for open-loop unstable or integrating processes and processes having poorly located poles. Therefore, methods given in [17, 18] may result in poor closed-loop performances if the process transfer function involves an unstable pole, an integrator, or poorly located poles.

To eliminate those shortcomings related to cascade control designs existing in the literature improved cascade control scheme shown in Fig. 2 has been proposed in this study. Proposed this structure, in contrast to enhanced cascade control structures proposed in the literature, is much simpler and does not alter the classical cascade control configuration much. In Figure 2, Gc2 is the inner loop PI controller, and Gc1 and Gc3 are the outer loop PI and PD controllers, respectively. This scheme uses a PI-PD controller in the outer loop. Hence, much better closed-loop system performances can be achieved for process transfer functions involving an unstable pole, an integrator, or poorly located poles as it was shown that PI-PD controllers can provide superior performances for those cases [19 - 21]. In the literature, the design methods for PID controllers in the classical and/or enhanced cascade control schemes usually require a model of the system. The modelling of cascade systems may be more cumbersome than the single-input single-output control system. Besides, unavoidable errors due to modelling and model reductions for existing design methods, such as the ones given in references [7, 10, 12, 13, 14, 15, 16], will inversely affect the system performance. Hence, in this paper design of controllers in each loop is performed without requiring a model of the inner and outer loops separately. Although design methods do not depend on the availability of a model of the process that can be found in the literature, they are proposed for the basic cascade control systems and thus for process transfer functions involving an unstable pole, an integrator, or poorly located poles satisfactory performances may not be achieved [17, 18]. Finally, another improvement of the paper is the simultaneous calculation of tuning parameters of controllers in each loop for the proposed improved cascade control. Tuning parameters of the inner and outer loop controllers are obtained so that the Integral of the Absolute value of the Error (IAE) is a minimum when both the reference input and disturbance exist in the control system. The Genetic Algorithm (GA) is used to adjust the controller parameters to give the minimum error value [22]. For this purpose, in the closed-loop responses, tuning parameters resulting in the minimum value of the IAE have been investigated.

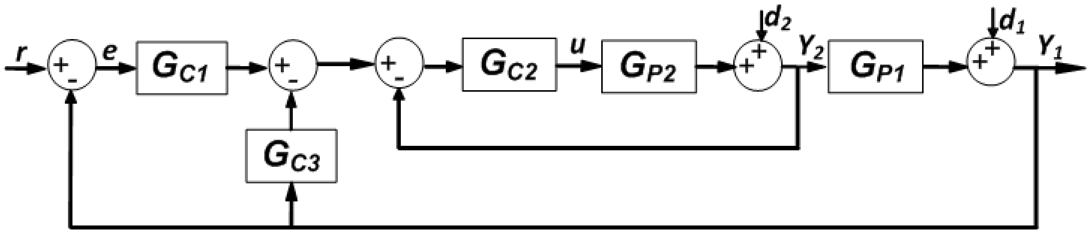


**Figure 2.** Proposed improved cascade controller structure

The rest of the paper is arranged as follows. A brief review of cascade control systems and a brief explanation of why a cascade control scheme leads to better closed-loop responses than the classical control systems with a single loop are presented in section 2. GA, which is used to identify tuning parameters of the controllers used in the proposed improved cascade control system, is shortly introduced in section 3. This section also explains how GA is used to identify tuning parameters of the proposed improved cascade control structure. Section 4 gives simulation results. Section 5 presents an application of the improved cascade control on a real-time plant. Finally, conclusions are presented in section 6.

## 2. Cascade Control

Temperature control is one of the fields where cascade control is the most frequently used. In the furnace temperature control schematic diagram in Figure 3-a, TT stands for temperature transmitter and TC for temperature controller. Figure 3-b shows a furnace temperature control block diagram. A change in oil flow rate will change the hot oil temperature, and immediate corrective action will be taken by the conventional control Gc1 with a single loop system shown in Figure 3-b. On the other hand, no control action to a change in the fuel flow will be performed until this is detected by the temperature measurement device. This causes a significant delay in correcting a fuel flow change, which then leads to a slow response. As a result, the control performance will decrease depending on the delay time of the furnace process GP1.

Figure 4 shows the schematic and block diagrams of a furnace temperature control. In Figure 4-a, FT stands for flow transmitter while FC stands for fuel flow controller. When using the cascade control structure shown in Figure 4, the change in the fuel flow is promptly noticed by the fuel flow measurement device and the required corrective action is taken by the fuel flow controller, and the control performance can be increased. There are three advantages of cascade control systems when compared to conventional control systems with a single loop [23]. First, the inner loop controller Gc2 can eliminate the effects of inner loop disturbances before it affects the controlled variable as seen in Figure 4-b. Second, also changes in the parameters of the inner loop dynamics can be better tolerated by the inner controller Gc2. Finally, any phase lag existing in Gp2 can be decreased by the inner controller Gc2. These can help to improve the performance of the main control loop. Therefore, if there is a secondary measurable variable, cascade control may be used to improve the closed-loop response. However, for a cascade control to result in better performances, the inner loop must be responding faster than the outer loop and the majority of disturbances must be happening in the inner loop.

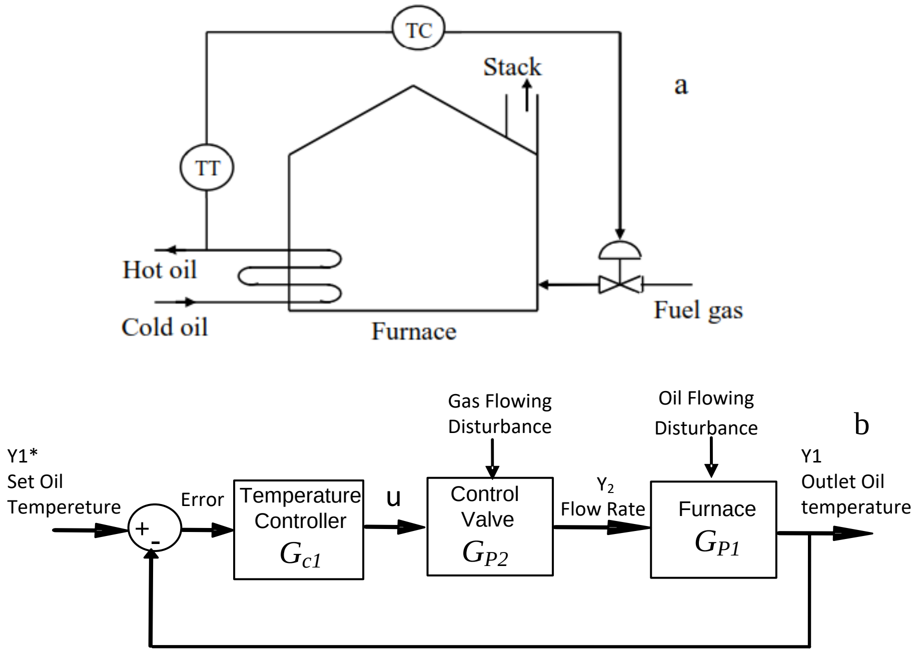


**Figure 3.** a) The schematic drawing of the furnace temperature control with single loops
b) The block diagram of the furnace temperature control with single loops

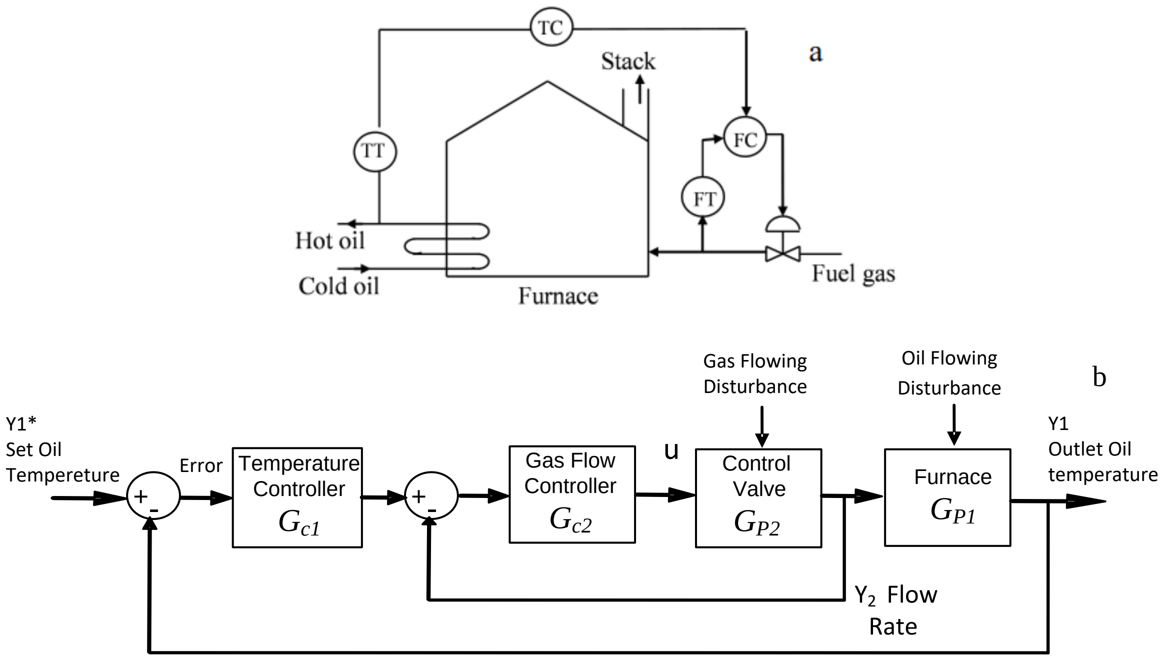


**Figure 4.** a) The schematic drawing of the furnace temperature control with dual loops
b) The block diagram of the furnace temperature control with dual loops

## 3. Genetic Algorithm

The genetic algorithm is a global optimization technique that is based on observed natural selection and genetic coding in the inflow events of life and was first proposed by Holland [24] in 1975. Since then, a lot of Genetic Algorithms (Gas) have been suggested to investigate different problems involving many engineering and optimization problems [25-28]. GAs use genetic-based mechanisms to produce new solutions from current solutions. Some or all individuals in the current solutions are used to produce newly produced individuals. As the process progresses, new solutions are expected to converge to the best solution.

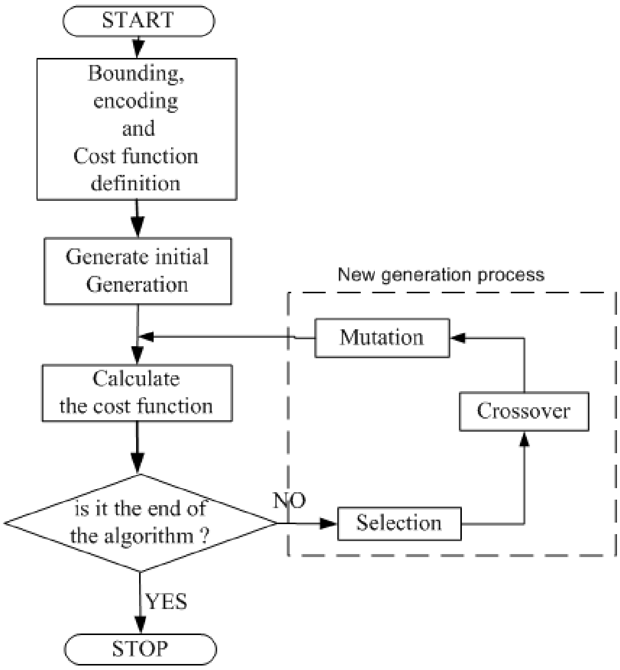


**Figure 5.** The basic scheme of the evolutionary algorithms

In an evolution algorithm, as shown in a simple GAs flow chart in Figure 5, first, bounds for a search space are determined. The fitness function is defined to decide the suitability of the individuals of the current generation to the solution and the parameters to be optimized. After that, the fitness values of all individuals in the generation are calculated by using the fitness function. In the next step, the algorithm generates a new population by performing treatments of selection and mutation for individuals. In different applications, for creating individuals of regeneration, different selection and mutation operators may be used. However, three standard operators are generally used for creating regenerations [29]:

• **Selection:** The process is established in a way to give more chances to individuals with a high fitness value than individuals with a low fitness value to pass on to the next generation.

• **Crossover:** It is the process of creating individuals of a new generation from individuals obtained in the selection duration. After the selection process, it is aimed to create a new generation dominated by genes of individuals with high fitness values. It causes genetic representations of each pair to inherit by individuals of regeneration.

• **Mutation:** It causes individual genetic representations to be exchanged according to some probabilistic rule. Therefore, using a mutation operator is getting ahead of the concentration of all individuals of the generation in a narrow area.

In this study, the fitness function has been related to the closed-loop performance based on the minimum value of Integral Absolute Error IAE criteria.

$$f = \frac{1}{1 + IAE} \tag{1}$$

Here, $f$ stands for the fitness function. IAE is given by

$$IAE = \int |e(\text{t})| dt \tag{2}$$

Here for obtaining the minimum value of IAE, it should be pointed out that the simulation must be executed until the closed-loop system response reaches the steady-state or simulation parameters reach extreme values, and then it is stopped. This can easily be performed by observing several simulations. A PI-PD controller has been chosen in the outer loop having ideal PI and PD controller structures:

$$G_{c1}(s) = K_o(1 + \frac{1}{T_o s}) \tag{3}$$

$$G_{c3}(s) = K_f(1 + T_f s) \tag{4}$$

In the proposed improved cascade control system, the inner loop controller is an ideal PI controller given by

$$G_{c2}(s) = K_i(1 + \frac{1}{T_i s}) \tag{5}$$

Depending on selected bounds, randomly produced individuals (controller tuning parameters) in the first population are used to control the system. The IAE value is obtained from the simulation results assuming that both the setpoint and disturbance inputs exist in the system. The best suitable parameters are searched by attending to both situations' results. Here, it would be appropriate to state that all points, having six tuning parameters, taken from decision space cannot always guarantee a stable closed-loop response. If the error signal reaches an excessively large value while running the GA program for setpoint tracking and distortion rejection, the simulation is stopped and is assigned a high number to the individual's IAE to reduce the chance of gene transfer. Otherwise, the obtained error signal is used to calculate the IAE value given by (2), and the calculated IAE value is then used in (1) for determining the fitness function. The next population is generated by running the algorithm shown in figure 5 until the last generation is produced or the desired criterion has been met.

The result of GAs depends on the parameters used in the algorithm such as the generation number, the population size, mutation rate, and crossover rate, and it is a quite difficult task how to select those parameters [30]. But several recommendations can be found in the literature about selecting mentioned parameters [31, 32]. If the population size is a large value such as 100, then 0.6 for the crossover rate and 0.001 for the mutation rate are recommended [32]. If the population size is a small value such as 30, Then 0.9 for the crossover rate and 0.01 for the mutation rate are recommended [32]. In the present study for GA parameters, it is appointed that 0.9 for crossover rate, 0.09 for mutation rate, 40 for population size, and 200 for the number of generations.

## 4. Simulation Examples

In this section, the successfulness of the proposed control structure and controllers design approach has been presented through two simulation examples. The first example considers the case where the outer loop process transfer function is open-loop unstable. The proposed approach is compared with studies given in [12, 14], as they have suggested modified cascade control schemes too. In the second example, an integrating outer loop process transfer function is considered. For this example, comparisons are made with studies of [9, 12].

**Table 1.** The decision space bounds and optimized PID parameters for example 1

| Parameters | | | Optimal value | Lower bound | Upper bound |
|---|---|---|---|---|---|
| Example1 | Outer Loop | $K_o$ | 0.8500 | 0.1 | 1 |
| | | $T_o$ | 30 | 1 | 30 |
| | | $K_f$ | 1.2715 | 0.1 | 3 |
| | | $T_f$ | 3.3368 | 0.1 | 5 |
| | Inner Loop | $K_i$ | 0.5631 | 0.1 | 3 |
| | | $T_i$ | 1.9850 | 0.1 | 5 |
| Example2 | Outer Loop | $K_o$ | 0.1279 | 0.01 | 1 |
| | | $T_o$ | 604.8757 | 400 | 1000 |
| | | $K_f$ | 0.001 | 0.00001 | 3 |
| | | $T_f$ | 120.004 | 100 | 200 |
| | Inner Loop | $K_i$ | 0.3733 | 0.1 | 1 |
| | | $T_i$ | 1.1020 | 0.1 | 2 |

**Example 1:** In this example, it is assumed that the outer and inner loop transfer functions are Gp1(s) = e−3s / (10s − 1) and Gp2(s) =2e−2s / (s + 1), respectively. The proposed design method is compared with the design methods suggested in [12, 14, 33]. Kaya and Atherton [12] used the controller Gc2(s )= (s+ 1) / (2s + 2), which was obtained using Internal Model Control (IMC) principles. They used a PI-PD controller in conjunction with Smith Predictor configuration in the outer loop. The outer loop tuning parameters were obtained as Kc = 0.5, Ti = 0.1, Kf = 14.25, Tf = 5.58. In addition, Kaya and Atherton used [12] a PD controller having tuning parameters of Kd = 1.00, Td = 1.414 to reject disturbances. Padhan and Majhi used a setpoint tracking controller responsible for overall servo performance [14]. They have got two PID controllers in series with first/second-order lead/lag compensators for the inner and outer loop. The inner loop controller parameters were provided as $K_{c2}$ = 0.0015, $T_{i2}$ = 0.8409, $T_{d2}$ =0.5, $a_{f1}$ = 449.5502, $b_{f1}$ = 0.8409. The outer loop controller parameters were given to be $K_{c1}$ = 0.0914, $T_{i1}$ = 3.3333, $T_{d1}$ = 1.25, $c_{f1}$ = 36.2409, $c_{f2}$ = 35.2409, $d_{f1}$ = 1.7273, $d_{f2}$ = 2.2519. Yin et al. [33] used three controllers together with a set filter for controlling this process. They used a controller $G_{c2}(s) = (s + 1) / (3s + 2)$ obtained by IMC principles for the inner loop and, also for the outer loop, two controllers for a setpoint tracking and a disturbance rejection. Both controllers have a PID with a lead-lag compensator filter based on a modified Smith Predictor control structure. Tuning parameters of the setpoint controller $K_{cS}$ = 1.8228, $T_{iS}$ = 46.522, $T_{dS}$ = 1.4649, in series with the filter $F_S(s) = (2.5s + 1) / (1.2846s + 1)$. Tuning parameters of the disturbance rejection controller $K_{cD}$ = 1.6431, $T_{iD}$ = 63.873, $T_{dS}$ = 1.502 in series with the filter $F_D(s) = (2.5s + 1) / (0.1715s + 1)$. In addition, they used a serial filter $F_R(s) =1/(68.152s2 + 46.522s + 1)$ for the reference signal. For the proposed improved control scheme, the upper and lower bounds of decision space and the optimal values of controller tuning parameters determined by GAs are given in Table 1. Fig. 6 illustrates responses for all cascade control structures to a unit step input and a disturbance d2 with a magnitude of -1 entering the system at time $t$ = 100 s.

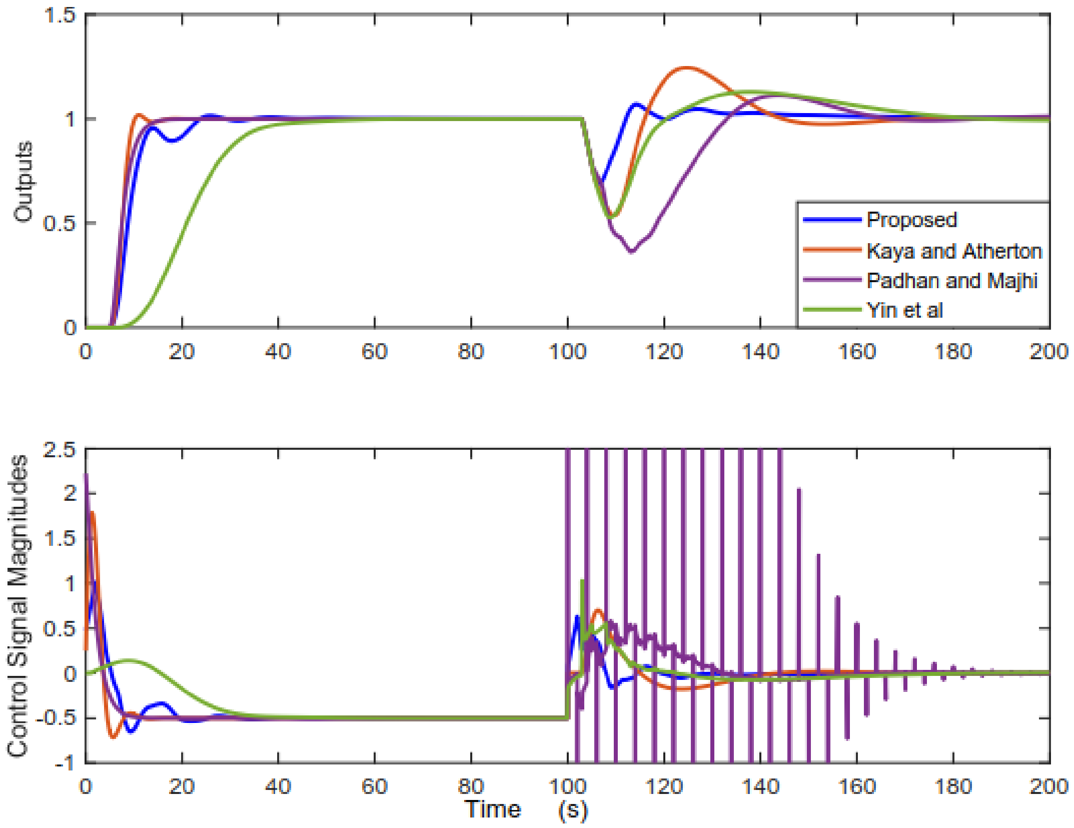


**Figure 6.** Output and control signal magnitude responses for a unit step input and disturbance $d_2$ with a magnitude of -1 for example 1

Data corresponding to the closed-loop performances for all design methods are shown in Table 2. The highest performance values are indicated as bold numbers in Table 2. It can be seen from Figure 6 and Table 2 the proposed improved cascade controller results in a longer rise time and settling time than the two methods for set-point tracking, but it is faster than another method. In point of overshoot, all design methods give almost similar responses. On the other hand, if the disturbance rejection capability is considered alone or the setpoint tracking plus disturbance rejection performance are taken together, much better closed-loop performances are achieved with the proposed control structure and our design method. However, it should be kept in mind that the proposed improved cascade control configuration has a much simpler structure than the other three schemes. In addition, tuning parameters of the inner and outer loop controllers of our proposed control system are calculated simultaneously while tuning parameters of the other three design methods are obtained in two steps (first the inner loop and then the outer loop is tuned). Fig. 6 also illustrates control signal magnitudes for all design methods. Here it is evident that the proposed control structure generally exhibits much more performance. Note that the control signal of the design method suggested by Padhan and Majhi [14] is so large that gets out of bounds of the given figure. The length of the axis showing the control signal magnitude is kept small to offer a clearer illustration. Figure 6 shows that the control signal for the method of Yin et al. [33] is the smallest, but its control performance is the poorest too. As it can be seen from Table 2, though the proposed method presents approximately %30 lower IAE performances than the best performing method for setpoint response, it has a %154 better IAE performance for disturbance rejection response and a %19.5 in totally IAE performance. Hence, it can be concluded that the overall performance of our proposed improved cascade control configuration is much superior.

**Example 2:** The outer and inner loop transfer functions are, respectively, assumed to be $G_{p1}(s) = 2e^{-2s}/s$ and $G_{p2}(s) = 4e^{-s} / (s+1)$. In this example, design methods of [12, 9] are used for comparison. Kaya and Atherton [12] obtained the inner loop of the controller $G_{c2}(s) = (s + 1) / (2s + 4)$ by using IMC principles. As stated in example 1, they used a PI-PD controller in conjunction with Smith Predictor configuration in the outer loop of the cascade control scheme. Tuning parameters for the outer loop controller were calculated to be $K_c = 0.1$, $T_i = 4.0$, $K_f = 0.606$, $T_f = -0.205$. Disturbance rejection controller tuning parameters were found to be $K_d$=0.083 and $T_d$=0.5. Lee et al. [9] used a PID controller having tuning parameters of $K_c = 0.22$, $T_i = 1.33$ ve $T_d = 0.25$ in series with a filter for the outer loop. For the inner loop, they again used a PID controller having tuning parameters of $K_c = 10.95$, $T_i = 1.23$ and $T_d = 1.68$, in series with the filter $q_{f2}(s) = 1/(0.91s+1)$.

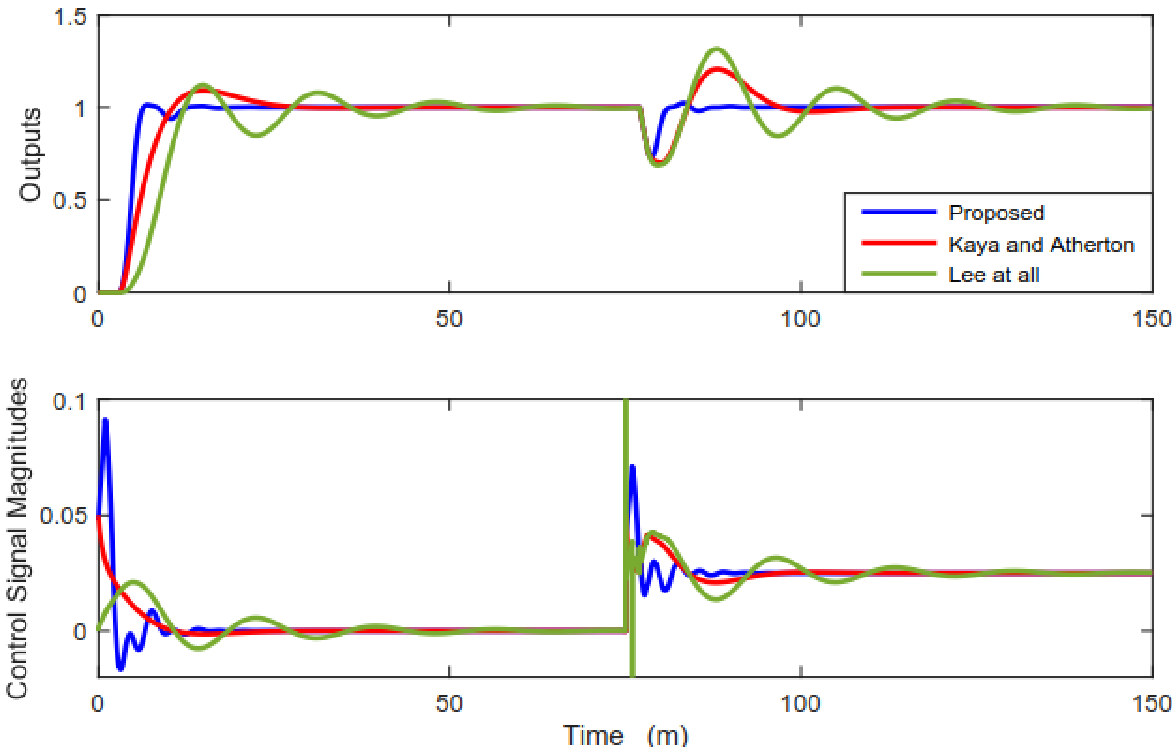


**Figure 7.** Output and control signal magnitude responses for unit step input and disturbance $d_2$ with a magnitude of -0.1 for example 2

The upper and lower bounds of decision space and optimal values of controller parameters obtained by using GA are presented for the proposed improved control scheme in Table 1. During a unit step input and for a disturbance with a magnitude of d2 = -0.1 at the 75th second, closed-loop responses and control signals of all controller methods are shown in Figure 7. As in example 1, the length of the axis showing control signal magnitude was preferred to be small to provide a clearer representation. IAE, rise time, settling time, and maximum overshoot values obtained from closed-loop responses are presented for all design methods in Table 2. The set-point tracking and disturbance rejection of the proposed improved cascade control is much better than the other two design methods. Design method suggested by Lee et al. [9] results in large control signal magnitudes. The proposed method has a superior performance compared to other methods in terms of set point response, disturbance rejection response, rising time, maximum overshoot and settling time. These conclusions can be driven from Table 2 as well.

**Table 2.** Closed-loop performances for all design methods

| | Method | IAE | | | Rise Time (s) | | Overshoot (%) | | Settling Time (s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Step | Dist. | Total | Step | Dist. | Step | Dist. | Step | Dist. |
| Example 1 | Proposed | 9.9769 | **3.1494** | **13.1263** | 23.77 | **12.01** | 1.5 | **29.7** | 22.76 | **46.2** |
| | Kaya and Atherton | **7.7067** | 7.9840 | 15.6907 | **10.24** | 16 | 1.8 | 46.34 | **9.907** | 58.8 |
| | Padhan and Majhi | 8.0000 | 12.7869 | 20.7869 | 18.86 | 33.2 | **0** | 63.85 | 13.76 | 61.8 |
| | Yin at al | 18.83 | 8.4393 | 27.269 | 42.0 | 18.1 | **0** | 47.32 | 42.5 | 74.0 |
| Example 2 | Proposed | **4.8974** | **0.7115** | **5.5088** | **6.42** | **6.45** | **1.4** | **26.75** | **11.79** | **8.7** |
| | Kaya et al. | 7.1339 | 3.1083 | 10.2421 | 10.6 | 8.86 | 9.3 | 29.83 | 23.85 | 20.84 |
| | Lee et al. | 10.8851 | 5.3248 | 16.2099 | 12.27 | 8.78 | 25.08 | 31.2 | 50.31 | 49.8 |

## 5. Experimental Setup and Results

The experimental setup shown in Figure 8 was used to observe the practical performance of the proposed control structure and design method. The experimental setup mainly consists of a DIGIAC 1750 process control set, a data acquisition card, a personal computer, and the MATLAB/Simulink software installed on the computer. The process control set includes a Direct Current Permanent Magnet (DC PM) motor, a tacho generator connected to its shaft for measuring the motor speed, and a current sensor for measuring the electrical current of the motor. DIGIAC 1750 process control set has a power amplifier for driving the DC PM motor. Power amplifier voltage range is limited between –10 V to +10 V. The electrical and mechanical equations of the DC PM motor for the electromechanical plant are given by equations as follows:

$$v_a(\mathrm{t}) = \mathrm{L}_m \frac{d}{dt} i_a(\mathrm{t}) + \mathrm{R}_m\, i_a(\mathrm{t}) + K_b \omega_m(\mathrm{t}) \tag{6}$$

$$J_m \frac{d\omega_m(\mathrm{t})}{dt} = T_m(\mathrm{t}) - \mathrm{T}_L(\mathrm{t}) - B_m \omega_m(\mathrm{t}) \tag{7}$$

$$T_m(\mathrm{t}) = \mathrm{K}_t\, I_a(\mathrm{t}) \tag{8}$$

In the above equations, $L_m$ is the motor winding inductance, $R_m$ is the motor winding resistance, $K_b$ is the back emf constant of the motor, $J_m$ is the rotor inertia, and $K_t$ is the torque constant of the motor, and $B_m$ is the mechanical damping factor. $T_m$ is the electrical torque, $T_L$ is the load torque and $\omega_m$ is the rotational speed of the motor, $v_a$ is the motor armature voltage, $i_a$ is the armature current. DC PM motor parameters for DIGIAC 1750 process control set were calculated by Alkaya and Eker [34]. These values, which are provided in Table 3, are used in this experiment as well. A data acquisition card (NI PCI-6229, 250 kHz, and 16 bits) is used to communicate between the experiment set and the computer. PCLD-8710 wiring terminal board is used for connecting the experiment set to DAQ. The computer has a Core 2 Quad CPU used, a 2.5-GHz microprocessor, and 3 GB of RAM.

Equations (6) and (7) describe the electrical dynamics of the motor, which is an electromechanical system, and equation (8) defines its mechanical dynamics. As can be seen from Figure 9 and the above equations showing the block diagram of the DC PM motor, there is feedback between the inner loop model transfer function of the electrical dynamics and the outer loop model transfer function of the mechanical dynamics. Therefore, the cascade controller design for the DC PM motor must be performed using a controller design method that does not require separate modelling of the inner and outer loop transfer functions.

**Figure 8.** A Scene from Experimental Setup

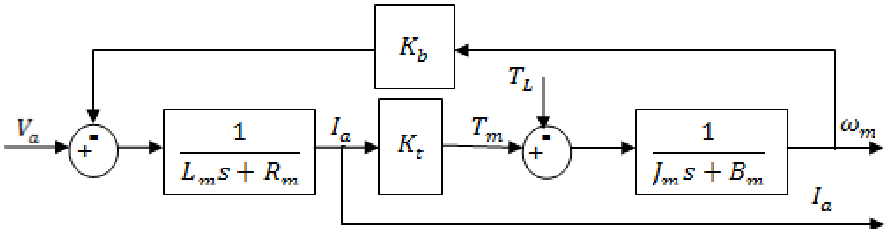


**Figure 9.** Block diagram of the DC PM motor

The voltages rated to the DC PM motor speed and armature current are measured from the tacho-generator and the current sensor, respectively. Figure 10 shows a diagram of the experimental setup that carried out the proposed improved cascade control structure installed in MATLAB SIMULINK software [35] and transferred the measurements to the PC through DAQ. By using measured current and speed, a control signal (armature voltage) has been produced, which is sent to the power amplifier through DAQ. The sampling period of 1 ms is used for all experimental tests.

**Table 3.** Parameters of the DC PM motor

| Parameter | Value |
|---|---|
| $R_m$ *(Ω)* | 2.4021 |
| $L_m$ *(H)* | 0.0197991 |
| $K_b$ *(Vs)* | 1.04 |
| $K_t$ *(NmA$^{-1}$)* | 1.04 |
| $J_m$ *(kgm$^2$)* | 0.076058 |
| $B_m$ *(Nm s$^{-1}$)* | 0.069858 |

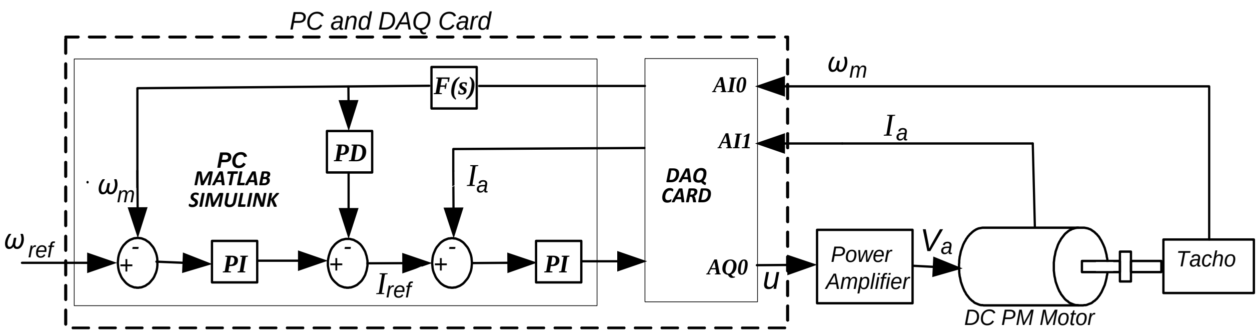


**Figure 10.** Diagram of the experimental setup

In this study, an offline optimization of cascade controller parameters by using the GA has been preferred to avoid damaging the experimental setup. GAs has used to obtain optimum values of both the inner and the outer loop controllers' tuning parameters simultaneously. The inner loop PI controller and the outer loop PI – PD controller tuning parameters are simultaneously determined as offline using the Simulink of MATLAB. For this purpose, optimization was carried out over the fitness values calculated using the IAE values obtained by applying a 5 V step test to the proposed cascade-controlled system. The maximum and minimum values of a range of the decision space for controllers tuning parameters and optimal values of tuning parameters obtained by GA are given in Table 4.

**Table 4** Decision space and optimized parameters for experimental setup

| *Parameters* | | *Optimal value* | *Lower bound* | *Upper bound* |
|---|---|---|---|---|
| *Outer Loop* | $K_o$ | 5.0 | 0.1 | 5.0 |
| | $T_o$ | 0.8907 | 0.001 | 20 |
| | $K_f$ | 0.0296 | 0.01 | 1.0 |
| | $T_f$ | 0.225 | 0.005 | 1.0 |
| *Inner Loop* | $K_i$ | 4.0 | 0.1 | 4.0 |
| | $T_i$ | 213.0 | 0.01 | 1000 |

As shown in Figure 10, a control signal based on the optimal tuning parameters obtained in the Simulink environment is generated and then applied to the real system via DAQ. Note that F (s) is a pre-filter block for measuring the speed used to eliminate excessive noise due to a tacho-generator with a permanent magnet. The performance of the proposed improved cascade controller is compared with the performance of a classical PID controller. For comparison, PID controller parameters ($K_c$ = 8, $T_i$ = 0.035, and $T_d$ = 0.009) obtained by using the Ziegler-Nichols method are taken from [36]. Transfer function of the pre-filter is given by $F(s)$ = 90/(s + 90).

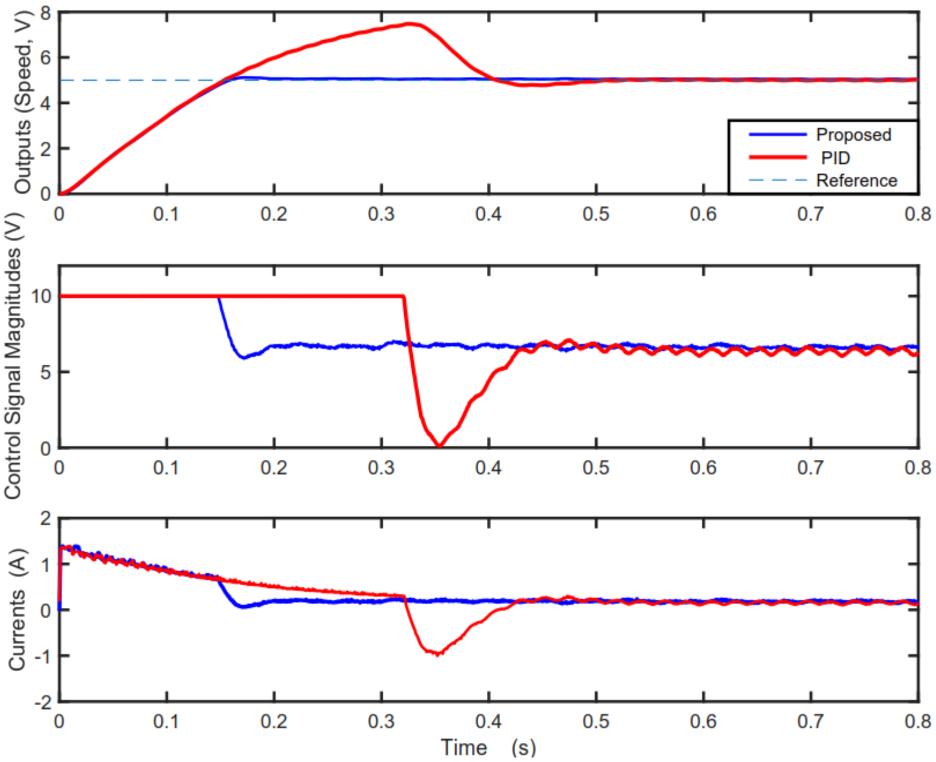


**Figure 11.** Responses for the outputs, control signal magnitudes and currents

Fig. 11 shows the closed-loop performances are the improved cascade control system and a classical single PID controller for a step input with a magnitude of 5 V, corresponding to a speed of 1300 rpm [37]. Figure 12 shows closed-loop control responses of both classical PID and the proposed cascade controller method for reference input ranging from 5 V to 6 V, corresponding to speeds of 1300 to 1550 rpm, respectively. Figure 11 shows that the proposed cascade control through the internal controller Gc1 reduces the control signal magnitude and motor current much earlier than when using a PID controller. Therefore, the improved cascade control has presented much satisfying performance. Much better closed-loop performance of the proposed improved cascade control structure is evident from Figs. 11 and 12.

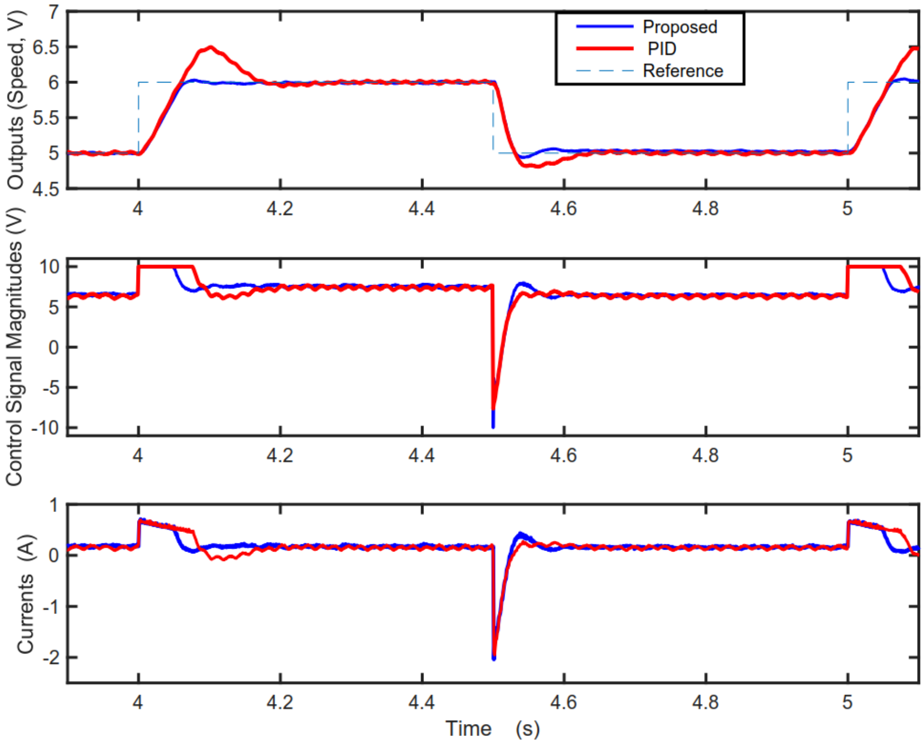


**Figure 12.** Responses when the reference input varies between 5 V to 6 V, corresponding to speeds of 1300 to 1550 rpm, respectively

## 6. Conclusions

In the classical cascade control design, generally, two steps approach for tuning controllers in both loops is followed. Additionally, usually, PID controllers are chosen to control the above-cited processes. However, PID controllers yield poor performances in controlling unstable and integrating processes. Therefore, an enhanced cascade control configuration using a PI-PD controller in its outer loop has been suggested to obtain much more satisfactory closed-loop performances. Also, GA is used for simultaneously evaluating parameters of controllers in both loops of the proposed enhanced cascade control scheme, under the assumption of the simultaneous existence of the setpoint and disturbance inputs. Moreover, the proposed design method does not depend on the availability of the inner and loop model transfer functions. Simulation results proved the much more improved performance of the offered cascade control configuration, compared to other modified cascade control design approaches. A real-time DC PM motor speed control application of the improved cascade control structure on the DIGIAC 1750 process control set has also been provided.

## Authors' Contributions

MN and İK decided to study together. MN carried out the simulations, the optimization processing with GA to obtain optimal controller parameters, and experimental studies. İK contributed to the study by supervising and interpreting in addition to writing the initial draft. All authors read and approved the final version of the paper

## Conflict of Interests

The authors declare that they have no conflict of interest.

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