Research Journal of Applied Sciences 8 (1): 82-88, 2013
ISSN: 1815-932X

Multi-Objective Cascade Control Sytem Design with an Application to Level Control in Liquid Level Process

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Abstract: This study proposes a multi-objective cascade control approach to tune the various controllers employed in the cascade control loop. Most of the modern cascade loops require separate tuning of primary and secondary controllers and hence the design task becomes complicated. Non-dominated Sorting Genetic Algorithm (NSGA-II) and Non-dominated Sorting Particle Swarm Optimization algorithm (NSPSO) based multiobjective approaches are employed in the design to fine tune the controller parameters of both primary and secondary loop. Inner loop comprises of flow process and the outer loop comprises of level process. The process considered in this study is highly non-linear with varying time delay and provides a challenging test bed for most of the modern control problems. Experimental results confirm that a multi-objective, paretobased NSPSO search gives a better performance for regulatory process when compared to NSGA-II. Finally, multiobjective optimization using NSPSO for the level process are compared with NSGA-II and the former exhibit good disturbance rejection capability which is a primary factor considered in cascade control.

Key words: Multi-objective controller, NSPSO, NSGA-II, disturbance rejection, non dominated sorting, cascade control

INTRODUCTION

Control engineering problems are characterized by several multiple conflicting objectives which have to be satisfied simultaneously which inturn yields Pareto-optimal solutions. Lot of researchers have employed various techniques for cascade control of various processes. To improve overall control system performance where multiple loops are involved cascade control becomes important. Cascade loops are employed where disturbances acting on the secondary process have major impact on the primary process. The system can lower the effect of the disturbances entering the secondary variable on the primary output. The task of regulating the level in an process control system is a challenging problem. Disturbances arising in the secondary loop further complicate the dynamics of the control problem. Due to these reasons, level control is viewed as an benchmark for control of highly non linear processes. Earlier level control was performed using linear conventional controllers by employing cascade and feed forward controllers as proposed by Mcmillan. They suffer from the problems of robustness and load disturbances.

Cascade control has two objectives. First is to suppress the effects of disturbances on the primary process output via the action of a secondary or inner control loop around a secondary process measurement. The second is to reduce the sensitivity of a primary process variable to gain variations of the part of the process in the inner control loop. A robust fuzzy cascade control strategy is used with minimum number of rules for any number of inputs (Maffezzoni *et al*., 1990). In main steam temperature of a boiler cascade control is used which improves the static and dynamic performances (Wei *et al*., 2010). Cascade schemes of PI torque and speed controllers are presented to enhance the objectives of speed control in the system (Cheng *et al*., 2009).

Cascade control is used to reduce the effect of load disturbances to overcome the failure of traditional PID control (Homod *et al*., 2010). Cascade control uses PID and Fuzzy control logic to improve the dynamic characteristics of level control in horizontal tank (Tunyasrirut and Wangnipparnto, 2007). Simple relay feedback test is applied to the outer loop of the cascade control to identify both loop parameters (Song *et al*., 2002). An improvement is achieved over an existing

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feedback cascade temperature control system using new hybrid control approach (Modak *et al*., 2006). Using offline PID Selection Methods, Cascade Control Methods has been designed and simulation done on Matlab/Simulink (Honglian, 2011). Cascade control is designed to ensure enhanced robustness by minimizing the mutual influence among loops (Maffezzoni *et al*., 1990).

Effect of hydroviscous drive speed regulating start depends on control strategy, present control has many problems, the problem is resolved by fuzzy PID cascade control system, the fuzzy PID cascade control was simulated by Matlab/Simulink (Qing-Rui and You-Fu, 2011). Cascade control inner loop used for sliding control, outer loop uses PI control are designed and analysed for a boost converter (Chen *et al*., 2011). Cascade control configuration used in two degree of freedom design approach guarantees smooth control (Alfaro *et al*., 2008).

The multiobjective PID control problems are characterized in terms of Eigen value problem and it can be efficiently solved by the LMI toolbox in Matlab (Tseng and Chen, 2001). In cascade control arrangement the inner loop consists of multivariable control of three compressors which gives high performance compared to SISO scheme (Maciejowski *et al*., 1991). NSPSO combines the operation of both NSGA-II and multiobjective PSO with a single Particle Swarm Optimizer (PSO) and the obtained results are better than the two compared algorithms (Liu, 2008).

The multiobjective optimization problems solved by evolutionary algorithm NSGA and its performance is compared with other algorithms (Dias and de Vasconcelos, 2002). A new multiobjective optimization algorithm is introduced to design optimal PID controller by tissue P systems to satisfy objectives synchronously (Huang *et al*., 2008).

By minimizing overshoot, settling time and by smoothening of output curve, the optimal fuzzy controller designed using GA (Serra, 2003). GA are used inorder to find the fittest solutions because of their ability to discover solutions quickly for complex searching and optimization problems (Serra, 2003). A research on MOPs can be found on (Zhao and Tsu-Tianlee, 2003).

This study aims at designing a cascade control scheme for liquid level process based on multiobjective Optimization technique. Multiobjective Optimization based on NSGA-II and NSPSO are presented. Comparative Analysis of NSGA-II and NSPSO are performed and simulation results are analysed. Finally, hardware implementation of the results are presented.

MATERIALS AND METHODS

Cascade Control System: In industries, cascade control is employed in drum level boilers, distillation columns, evaporators and batch reactors. Cascade control is most advantageous on applications where the secondary closed loop can include the major disturbance and second order lag and the major lag is included in only the primary loop. The secondary loop should be established in an area where the major disturbance occurs. It is also important that the secondary variable respond to the disturbance. Figure 1 shows the block diagram of cascade control system employed.

The primary loop monitors the control variable and uses deviation from its set point to provide an output to secondary loop. The secondary loop receives its set point from primary loop and controls the reference variable accordingly. Multiobjective Evolutionary algorithms NSGA-II and NSPSO are used. The two objectives considered are steady state analysis and disturbance rejection.

Non-dominated Sorting Genetic Algorithm-II (NSGA-II): The primary reason for choosing EA is their ability to find multiple pareto-optimal solutions in a single run. The main criticism in NSGA was the high computational complexity of non-dominated sorting, lack of elitism and need for specifying the shared parameter. To overcome these, NSGA-II, a slight modification in NSGA approach is being used which has a better sorting algorithm (Fig. 2).

The population is initialized and sorted based on non-domination into each front. The first front being completely non-dominant set in the current population when compared to other higher fronts. Each individual in each front are assigned a rank (fitness value) based on front in which they belong to. The crowding distance is calculated for each individual which is based on how close an individual is to its neighbors. Large average crowding distance will result in better diversity in the population. An individual is selected in the rank is lesser

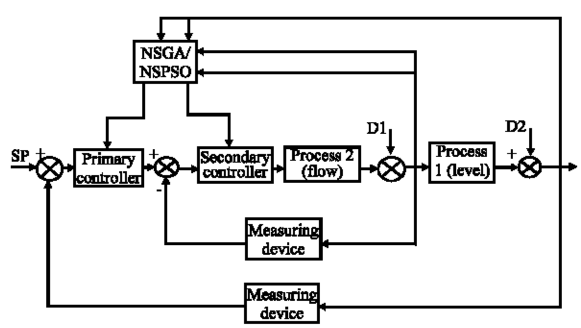

Fig. 1: Cascade Control System

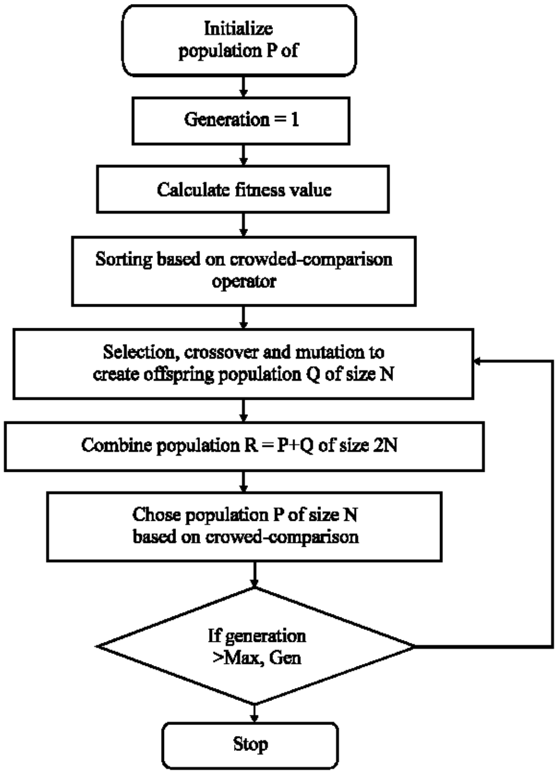

Fig. 2: Flow chart of NSGA-II

than the other or if the crowding distance is greater than the other. The selected population generates offspring's from crossover and mutation operators. This algorithm is same as adopted by Liu (2008).

Multi-objective Non-dominated Soting Particle Swarm Optimization (NSPSO): NSPSO is a modified form of PSO which is highly competitive with other evolutionary and multiobjective algorithms. In the entire population NSPSO compares the personal bests of all particles and their offspring's instead of comparison between single particle and its offspring. This approach yields more non-dominated solutions through dominant comparisons and sorts the entire population into different non-dominated levels as used in NSGA-II. This NSPSO based on PSO and NSGA-II thereby it combines the features of other algorithms such as crowding distance ranking, elitist strategy and selection and mutation operations with single objective PSO as adopted by Liu (2008).

Step 1: Generate an initial population P (Population size = N) and velocity for each individual (agent or particle) in a feasible space. Set the maximum speed v_i max (v_i max = its upper bound minus lower bound) for a variable.

Step 2: Sort the population based on the non-domination and crowding distance ranking.

Step 3: Do rank-based selection operator.

Step 4: Assign each individual a fitness (or rank) equal to its non-domination level (minimization of fitness is assumed).

Step 5: Randomly choose one individual as gbest for N times from the nondominated solutions and modify each searching point using previous PSO formula and the gbest:

$$v_i\ (k+1) = k\ [v_i^k + c_i \times rand\ ( ) \times (pbest_i - s_i^k) + c_2 \times rand\ ( ) \times (g)]$$

$$K = \frac{2}{\left|2-\varphi-\sqrt{\varphi^2-4\varphi}\right|},\quad \text{where } \varphi/ = c_1+c_2,\ \varphi > 4$$

$$S_i^{-k+1} = s_i^k + v_i^{-k+1}$$

where, rand ( ) is a random number between (0, 1). The constriction factor approach can generate higher quality solutions than the conventional PSO approach. If current position outside the boundaries then it takes the upper bound or lower bound and its velocity is generated randomly ($0 \le v_i^{k+1} \le v_i^{max}$) and multiplied by -1 so that it searches in the opposite direction.

Step 6: Do mutation operator.

Step 7: Combine the offspring and parent population to form extended population of size 2N.

Step 8: Sort the extended population based on nondomination and fill the new population of size N with individuals from the sorting fronts starting to the best.

Step 9: Modify the pbesti of each searching point: If current rank of the new individual (offspring) P_i^{K+1} is smaller than or equal to the previous one (parent) in R, replace the $pbest_i$ with current individual; otherwise keep the previous $pbest_i$.

Step 10: Perform steps (2-9) until the stopping criterion is met.

Mathematical modeling of flow and level process: Transfer function of level process is given by:

$$G_1(s) = \frac{1.03e^{-0.5s}}{49.5s+1}$$

Transfer function of flow process is given by:

$$G_2(s) = \frac{17.6336}{s}$$

Objective functions employed for the system
Steady state response:

$$f_1 = \sum_{i=1}^{n} |h_i - h_{ref}(i)| g(i)$$

where, g (i) = 1 if $|h_i - h_{ref}(i)| \le \sigma_0$, 0 otherwise. This index measures the absolute error only along segments of level response settling around the steady state. Parameter σ_0 defines settling band.

Disturbance rejection:

$$f_2 = |h(n) - h_{ref}(n)|$$

This index measures the absolute error in the last time sample. It is used to evaluate the ability to reject the change in load which is applied in the final part of simulation.

RESULTS AND DISCUSSION

System requirements:
PC: Intel Pentium, Dual core, software used: MATLAB 7.10.0 (R2010a). Multi-objective optimal level control of cascade control system tuned using NSGA-II is to be implemented in MATLAB/SIMULINK is shown in Fig. 3. Basic parameters employed in the system are listed in Table 1. Pareto optimal front obtained with NSGA-II is shown in the Fig. 4. From the different values of PI parameters the optimal value is chosen.

The Pareto optimal front and output level response obtained using NSGA-II with steady state response and disturbance rejection as objective functions is shown in Fig. 4 and 5. From the Pareto optimal front, samples are taken and from these samples, corresponding optimum K_p, K_i values are obtained as per the requirements of the user. Optimal values of the gains are (K_i = 2.1572 and K_p = 3.1544) for primary and (K_i = 1.0928 and K_p = 2.265) for secondary loop. Multi-objective optimal level control of cascade control system tuned using NSPSO is to be implemented in MATLAB/SIMULINK and the results are shown. Basic parameters employed in the system are listed in Table 2.

The Pareto optimal front obtained using NSPSO with steady state response and disturbance rejection as objective functions is shown in Fig. 6 and 7. From the Pareto optimal front, samples are taken and from these obtained as per the requirements of the user. Optimal samples, corresponding optimum K_p, K_i values are values of the gains are (K_i = 1.6917 and K_p = 2.1511) for primary and (K_i = 1.0567 and K_p = 1.6567) for secondary loop.

Table 1: Basic parameters of NSGA-II algorithm

Algorithm parameters	Values
Population (N)	20.00
Generations (G)	50.00
Pool size (N/2)	10.00
Tour size	2.00
Crossover probability	0.90
Mutation probability	0.33

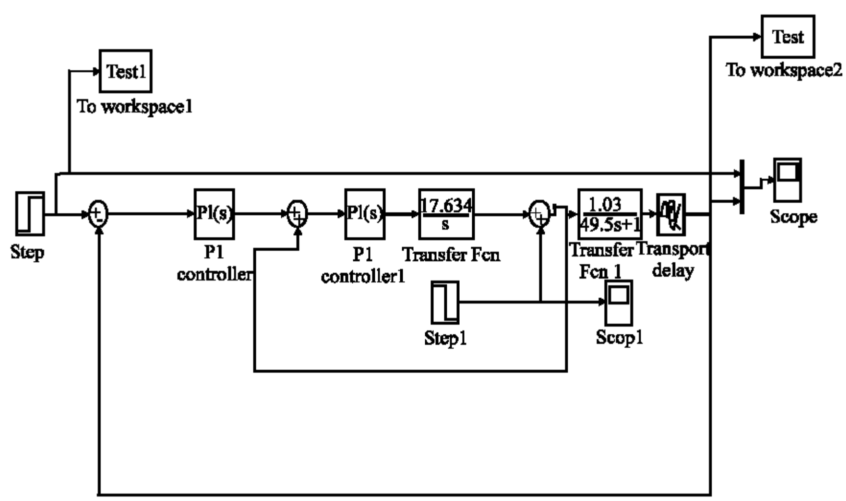

Fig. 3: Simulink diagram of Cascade Control System

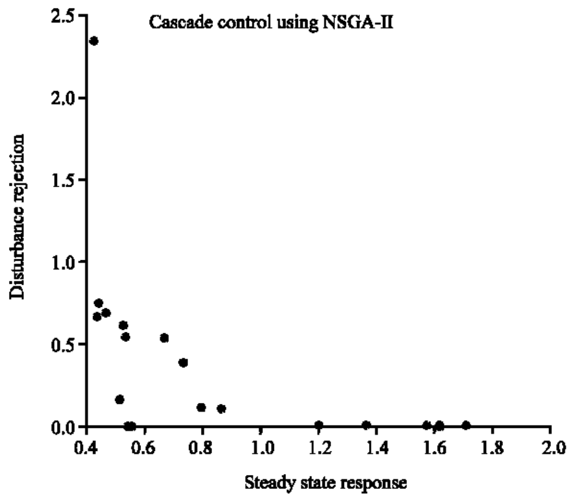

Fig. 4: Pareto optimal front with steady state response and disturbance rejection as objectives with NSGA-II

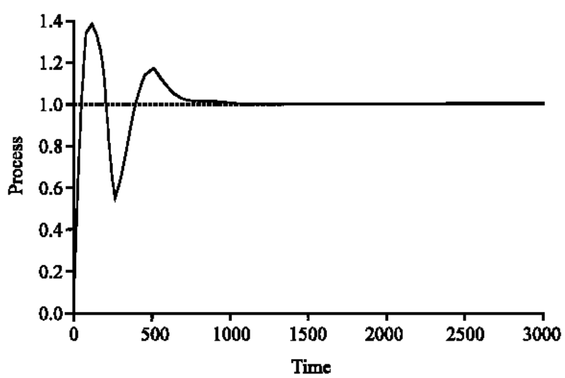

Fig. 5: Simulink output of cascade control tuned using NSGA-II

Table 2: Basic parameters of NSPSO algorithm

Algorithm parameters	Values
Population (N)	20.00
Generations (G)	10.00
Pool size (N/2)	10.00
Tour size	2.00
Crossover probability	0.90
Mutation probability	0.33

Comparative analysis (simulation mode): The optimum K_P, K_I, K_P1, K_I1 of level and flow controllers, respectively tuned using NSGA-II and NSPSO algorithm are shown in Table 3. The parameters obtained as a result of simulation show that NSPSO is better than NSGA-II. As the Table 3 shows that the rise time and settling time of cascade control of NSPSO is lower than the time needed for NSGA-II. Overshoot is higher in case of NSGA-II whereas it is also lower in NSPSO. Disturbance rejection is very faster in NSPSO than in NSGA-II.

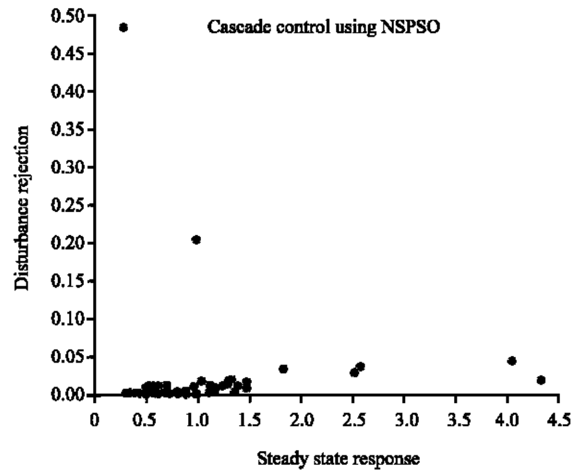

Fig. 6: Pareto front values with steady state response and disturbance rejection as objectives with NSPSO

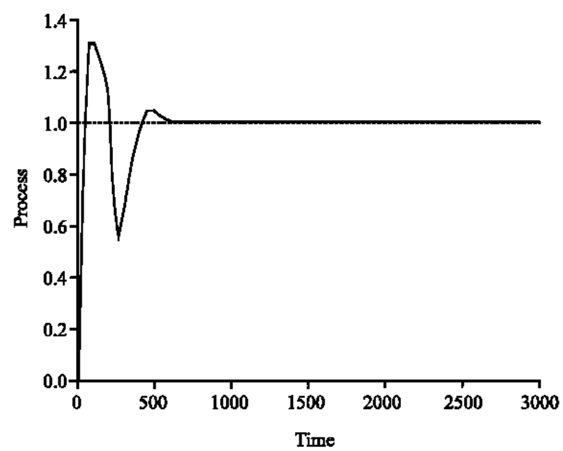

Fig. 7: Simulink output of cascade control tuned using NSPO

Table 3: Comparative analysis between NSGA-II and NSPSO

Parameters	NSGA-II	NSPSO
K_P	3.1544	2.1511
K_I	2.1572	1.6917
K_p1	2.265	1.6567
K_I1	1.0928	1.0567
Rise time	80 sec	70 sec
Settling time	1100 sec	600 sec
Overshoot	1.4	1.3

Figure 8 clearly shows that NSPSO has good disturbance rejection, less steady state error and less settling time than NSGA-II. Thus, two objectives are well-satisfied using NSPSO than NSGA-II.

Hardware implementation: Photograph of experimental setup is shown in Fig. 9.

Components and their specifications

I/P converter: Input is (4-20) mA, Output is (3-15) psi.

Air regulator: Max. Input Pressure is 18 kg/cm^2, Output pressure 2.1 kg/cm^2.

Level transmitter: Input is (0-25) cm, Output is (4-20) mA.

Rotameter: Range is (0-500) lph.

DPT: HART field communication protoco Range is (0-4000) mmwwc.

Flow transmitter: Wheel flow transmitter, Range is (0-600) lph, Output is (4-20) mA.

Control valve: Max. actuator pressure is 35 psi.

Pump: Variable speed, Discharge 800lph.

DAQ: VAD-104.

Table 4 shows the parameters of the process tank in which the level is to be controlled using NSGA-II and NSPSO.

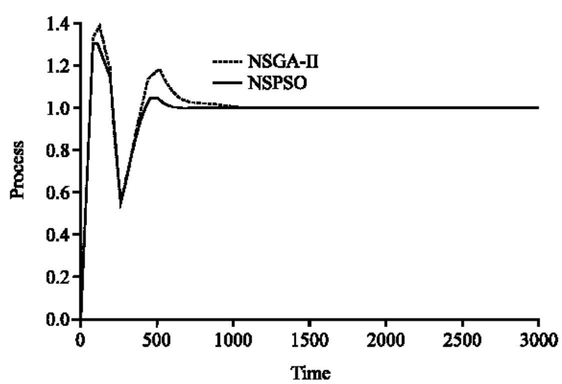

Fig. 8: Comparison of level responses between NSGA-II and NSPSO

Fig. 9: Photograph of experimental setup

Results obtained from real time experiments: The response obtained for the level control of cascade control system tuned using NSGA-II for K_p = 3.1544, K_i = 1.1572, K_p1 = 2.265, K_i1 = 1.9028 is shown in Fig. 10. The response obtained for the level control of Cascade Control System tuned using NSPSO for K_p = 2.1511, K_i = 1.6917, K_{p1} = 1.6567, K_{i1} = 1.0597 is shown in Fig. 11.

Table 5 shows the comparison between NSGA-II and NSPSO obtained in real time. From the comparative analysis, NSPSO provides better response compared to NSGA-II in terms of rise time, settling time and overshoot.

Table 4: Parameters of the process tank

Parameters	Values (cm)
Height	25.0
Diameter	11.0
Thickness	0.5

Table 5: Comparison between NSGA-II and NSPSO obtained in real time

Parameters	NSGA-II	NSPSO
K_P	3.1544	2.1511
K_I	2.1572	1.6917
K_p1	2.265	1.6567
K_I1	1.0928	1.0567
Rise time	34 sec	32 sec
Settling time	60 sec	50 sec
Overshoot	1.067	1.033

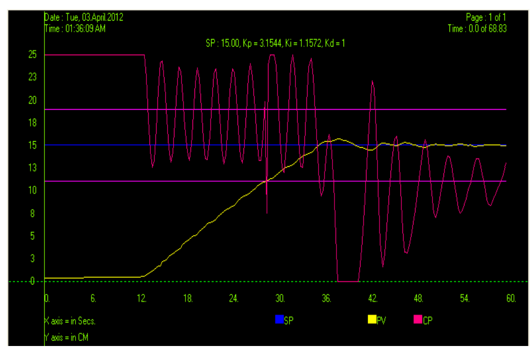

Fig. 10: NSGA-II output for cascade control in real time

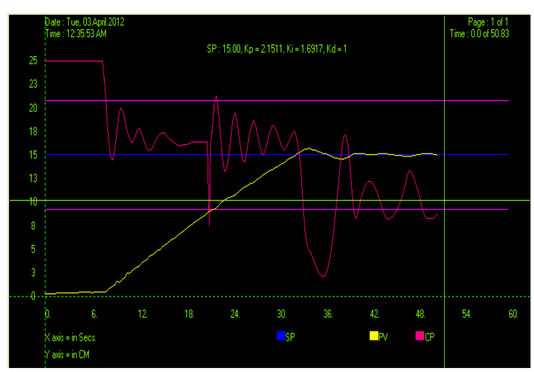

Fig. 11: NSPSO output for cascade control in real time

CONCLUSION

Multiobjective evolutionary algorithms NSGA-II and NSPSO are successfully implemented in cascade control loops for optimization of steady state responses and disturbance rejection. PI controllers are used for building the cascade controller inorder to control the level in the cylindrical tank. Mathematical modeling of cylindrical tank for level and flow process is developed. Overall system performance was realized using hardware for measurement and software tools like MATLAB. Simulation results show that NSPSO gives accurate pareto front values and good diversity as compared to NSGA-II. Simulation results of both the evolutionary algorithms NSGA-II and NSPSO are compared. Hardware Implementation of the same is performed and the results are compared. The comparative results prove that NSPSO provides better disturbance rejection and less overshoot than NSGA-II. Thus, NSPSO outperforms NSGA-II in cascade control of level process.

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