

A TOOL FOR MULTI-LOOP OPTIMIZATION APPLIED TO POWER PLANT CONTROL

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Abstract

A platform in Matlab environment was developed addressing the problem of multi-loop control simulation and optimization. This platform offers an easy-to-use tool for optimization of several controllers simultaneously. This could be very beneficial in cases where process loops controlled by these several controllers are strongly coupled and any change in one controller affects other control loops as well. The platform was successfully applied to power plant steam temperature control. A unified approach is implemented for multi-loop control optimization problem. It consists of three main steps: Step 1: Define optimization problem. Step 2: Optimize controllers, Step 3: Check results.

1 Introduction

Power plant control systems (as well as many other industrial process control systems) are made up of multiple interacting control loops. The interaction between loops means that control action applied in one loop affects in some way also other loops. This poses problem not only to dynamic control but also to controller design, tuning, and optimization. Standard PID and other controller tuning methods suggest to optimize controller by controller starting at the bottom of the control loop hierarchy and working upward. For example, in cascade of PID controllers inner controller is tuned first and external controller computing set-point for the inner loop is tuned afterward.

An optimization tool was developed addressing the tuning problem of interacting multi-loop control system. The goal was to tune (optimize) several interacting controllers simultaneously while ensuring control performances for all controlled loops. Standard optimization algorithms were considered for the development. Additionally, the tool was meant for users without experience with these optimization algorithms. The procedure of multi-loop control tuning was divided into three steps: Step 1: Define optimization problem. Step 2: Optimize controllers, Step 3: Check result. However the procedure is not straightforward. After working through all three steps it can be necessary to return into Step 1 in order to adjust some ill-specified performance or setting and reiterate the entire procedure. Thus the procedure of optimization can be repeated several times before obtaining a satisfactory results.

The most complex part of the optimization process is Step 1. Here we define control performance specifications (rise time, settling time, max. overshoot,...), optimization algorithm parameters (objectives, constraints, algorithm specific parameters), and process model and control loop structure. In the platform this complex task is simplified as much as possible using clear structuring of data and implementing Matlab user graphical interface. Process model and control loops are defined and simulated in Matlab environment using Simlink.

Step 2 performs the actual optimization. The tool incorporates several different global optimization techniques: genetic algorithm, pattern search, simulated annealing [1,2]. Global optimization feature of these techniques means, that they are able to reach global optimum if run sufficiently long enough. In any time, user can stop the optimization to check actual best result and restart later to continue the optimization with actual best solution as starting point.

For results check in step 3, process responses are displayed in graphs and compared to initial and previous responses. Corresponding performance criteria are evaluated and displayed for each response as well.

2 Defining optimization problem of multi-loop control tuning

Structuring of data defining optimization problem is presented in this section. Three main data sets has to be defined to perform multi-loop control optimization using a process model (defined in Simulink):

- Optimization objectives. Desired process and control performance indicators have to be defined such as set-point tracking, robustness, disturbance rejection.
- Optimization options - select algorithm, algorithm options, and optimized controller parameters are defined.
- Optimized function settings - parameters concerning optimized criterion function(s) are defined. Optimization does not optimize directly the defined objectives. In single-objective optimization case it optimizes one criterion function, in multi-objective optimization case multiple objectives defined by multiple criterion functions.

Optimization objectives comprise a set of process and control performance specifications, such as rise time, settling time, etc. The performance specifications are evaluated for a specific simulation run. Each simulation run is defined by a) actual operational point, and b) actual set of process set-point signals - set-point scenario. Considering this fact, optimization objectives (performance specifications) are structured as follows:

Operational point 1

Set-point scenario 1

Performance specification 1

Performance specification 2

...

Example of optimization objectives

Operational point 1 - low load 0MW

Set-point scenario 1 - 10MW load set-point step, pressure, oxygen, and drum level set-point is constant

Specification 1 - Rise time on load process value

Specification 2 - Maximum overshoot on pressure process value

Specification 3 - Maximum overshoot on drum level process value

Set-point scenario 2 - 10MW load set-point ramp, pressure, oxygen and drum level set-point is constant values

Specification 1 - Settling time on load process value

Specification 2 - Maximum overshoot on pressure process value

Specification 3 - Maximum overshoot on drum level process value

Operational point 2 - high load 250MW

...

There are two approaches how to optimize a set of objectives:

- Multi-objective optimization. In the case of multi-objective optimization all defined performance specifications are optimized simultaneously. Each optimization objective is defined as criterion function. A set of criterion functions is then optimized. User can additionally define some scaling factor or normalization for each criterion function, see Optimized function settings.
- Single-objective optimization. In the case of single-objective optimization user must choose function which will produce one-value out of multiple specifications. This one function is

called criterion function. Typically, weighted sum of specifications is defined as the criterion function.

Example of multi-objective criterion functions:

Consider that user has defined objectives as shown in the example. Optimized criterion functions has then the following forms:

- $J_1(X) = (\text{Scaling factor 1}) * (\text{O.P.1:Scenario 1: Specification 1 - Rise time on load process value})$
- $J_2(X) = (\text{Scaling factor 2}) * (\text{O.P.1:Scenario 1: Specification 2 - Maximum overshoot on pressure process value})$
- ...

Example of single-objective criterion function:

$$J(X) = J_1(X) + J_2(X) + \dots$$

Objectives are defined by the following parameters:

- Number of operational points. One operational point is defined by:
 - Simulink model file.
 - Initial m-file for the model file (optional, it is useful if one model is used for all operational points). The m-file initializes Simulink process model for the defined operational point.
 - Number NSP of set-point scenarios. One scenario is defined by: Initial m-file of the scenario. The file initializes Simulink process model for the defined scenario, performance specifications.

Operational point is defined first, set-point scenarios next. One operational point can have several set-point scenarios. For each scenario multiple control performance specifications can be defined. They can be defined as an objective or a constraint. In the case of constraint a desired value of the specification is entered. The following types of performance specifications are considered:

- Rise time
- Settling time
- Maximum set-point error
- Integral of squared signal amplitude
- Maximum overshoot
- User in-model-defined performance

Optimization options cover the following information:

- Selection of optimization algorithm: Genetic algorithm, Pattern search, Simulated annealing
- Set of optimization algorithm options. To simplify use of algorithms two pre-specified sets have been defined for user: Quick-result optimization set, Full-scale optimization set.
- Display options during optimization run. Information to be displayed after each iteration step. Simple choice of display options is: Simple display, Best result display.
- Vector of optimized parameters. All optimized parameters (controller coefficients) are defined. For each parameter we define: variable name in Simulink model, range of values for optimized parameter., initial value.
- **Optimized function setting.** Objective function is defined in the case of single-objective optimization. In the case of multi-objective optimization scaling and normalization of objectives is defined. Common properties to be defined are:

- Type of optimization function: Multi-objective function or single-objective processing function. Only weighted sum of specifications is considered.
- Scaling factors. For single-objective optimization, scaling factors are multiplied with the performance specifications which forms objective function. In the case of multi-objective optimization, scaling factors multiply defined performance specifications.
- Bounds on optimized parameter value. Behavior of objective function if some optimized parameter is outside of specified range. Possibilities are
 - None - no reaction.
 - Reject with high value - Reject solution with very high value in the objective function.
 - Constraint - All solutions are restricted to remain within the defined limits.
- Monte Carlo options. User can define via Monte Carlo options random behavior of the process model and processing of this feature by optimization. The following parameters are defined:
 - Number of simulation runs. This value defines how many Monte Carlo simulation runs will be executed to obtain one objective value. With Monte Carlo options switched off only one simulation is executed to obtain one objective value.
 - Initial model files. Initial m-files for Simulink model are defined here one for each simulation run. If no files are defined, Monte Carlo runs are executed without a specific initialization. In this case it is supposed that initialization of model random behavior is implemented directly inside the Simulink model.
 - Evaluation function. A function producing one objective value out of multiple values obtained from the multiple simulation runs. The following functions are considered: Maximum value, Mean value.
- Criterion normalization function for each criterion function. The normalization function transform any criterion value into interval between 0 and 1.

3 Optimization procedure step by step using optimization tool

The procedure of optimization is an iterative procedure repeating the sequence of these three steps:

- Step 1 - (Re-)Define optimization problem.
- Step2 - Search for optimum (optimization run)
- Step3 - Evaluate obtained results

Step 1 is the most complex part of the optimization task from the user point of view. What data needs to be specified in Step 1 was shown in the previous section. Graphical user interface was used to facilitate this task, see Figure 1. From the main window of the tool user calls windows for editing data defining optimization problem:

- Optimization Objectives Window
- Optimization Options Window
- Optimized Function Parameters Window

Step 2 means for user to run an automated searching engine based on preselected optimization algorithm. Actual step simple or best result display is printed into Matlab command line. At any time user can stop optimization by pressing Stop button which is displayed after launching searching engine. Actual best result is kept in memory space for result display or for eventual searching, if needed.

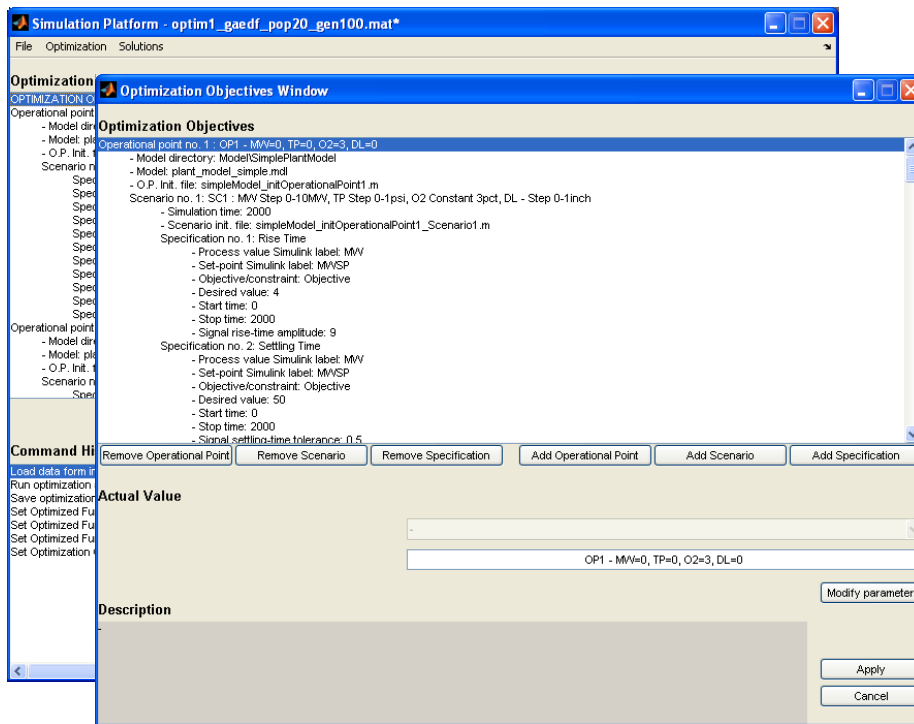


Figure 1: Window for performance objectives specification in front of main window of the optimization platform.

In Step 3, obtained results are displayed. Optimization results are obtained control performances and obtained controller parameters.

In the optimization platform we can choose to display

- Only best obtained result
- The best obtained result with respect to initial control
- The best three results with respect to initial control

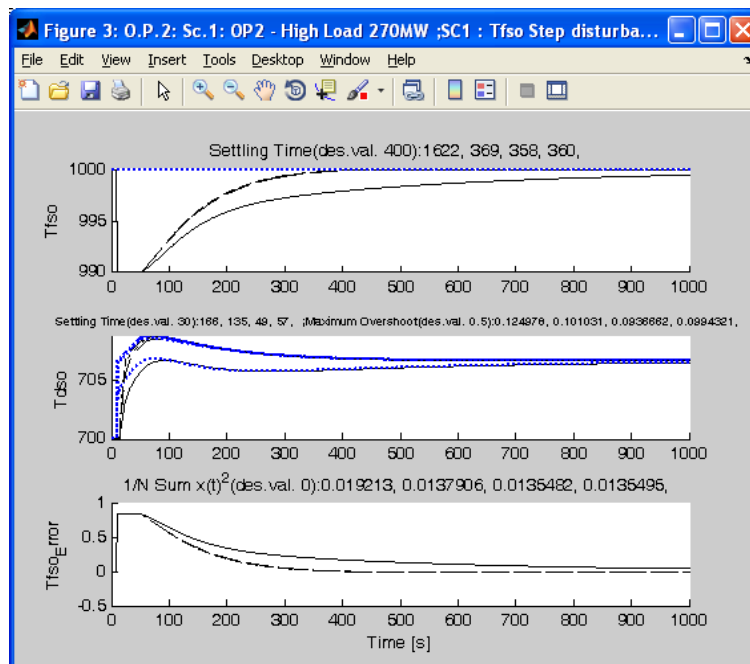


Figure 2: Display of obtained best three control performance (dotted and dashed black lines) with respect to initial control (solid black line) and set-point (dotted blue line).

4 Example of optimization using tool

Process power plant model used in this example is the one used in [2]. It is simplified Simulink model of the power output, throttle pressure, excess oxygen, and drum level dynamics and corresponding control loops, see Figure 3. Model was adapted for use in the optimization platform. “To Workspace” blocks are connected to the process value signals needed for evaluation of control performances (optimization objectives). The following process values are considered:

- Power output “MW”
- Power output set-point “MWSP”
- Throttle pressure “TP”
- Throttle pressure set-point “TPSP”
- Excess oxygen “O2”
- Excess oxygen set-point “O2SP”
- Drum level “DL”
- Drum level set-point “DLSP”
- Turbine valve position “TurbineValvePosition”
- Firing rate demand “FiringRateDemand”
- Fan damper demand “FanDamperDemand”
- Feed-water valve position “FeedwaterValvePosition”

The following operational point and set-point scenarios are defined:

- Operational point 1 - low load (initial power output value is 0)
 - Scenario 1 - Step 10MW
 - Scenario 2 - Ramp 10MW

The following controller coefficients are optimized:

- PID1 -, power output controller, coefficients k11, k12
- PID2 - throttle pressure controller, coefficients k21, k22, k23
- PID3 - excess oxygen cascade inner loop controller, coefficients k31, k32
- PID4 - excess oxygen cascade outer loop controller, coefficients k41, k42
- PID5 - drum level cascade outer loop controller, coefficients k51, k52
- PID6 - drum level cascade inner loop controller, coefficients k61, k62

Objectives are defined according to following desired performance definition. Try to make loops respond as fast as possible while limiting the overshoot to a step response to less than about 5% but more than 0%. The MW control should be quite fast using the turbine valves while the throttle pressure control can be much slower using the fuel control. To limit the actuator motion somewhat, in fact the actuator should not overshoot its final position by more than 50% in response to a closed loop set-point step test. Two scenarios are needed, one for a MW step change and one for a MW ramp change.

Based on the previous definition, optimization objectives (values to minimize) defined in the platform has the following form:

Operational point no. 1 : MW=0, TP=0, O2=3, DL=0

Scenario no. 1: Load step 10MW

Specification no. 1: Rise Time MW

Specification no. 2: Settling Time MW

- Specification no. 3: Maximum Overshoot MW
- Specification no. 4: Maximum Set-point Error TP
- Specification no. 5: Maximum Set-point Error O2
- Specification no. 6: Maximum Set-point Error DL
- Specification no. 7: Maximum Overshoot TurbineValvePosition
- Specification no. 8: Maximum Overshoot FiringRateDemand
- Specification no. 9: Maximum Overshoot FanDamperDemand
- Specification no. 10: Maximum Overshoot FeedwaterValvePosition

Scenario no. 2: Load ramp 10MW

- Specification no. 1: Settling Time MW
- Specification no. 2: Maximum Set-point Error MW
- Specification no. 3: Maximum Set-point Error TP
- Specification no. 4: Maximum Set-point Error O2
- Specification no. 5: Maximum Set-point Error DL
- Specification no. 6: Maximum Overshoot TurbineValvePosition
- Specification no. 7: Maximum Overshoot FiringRateDemand
- Specification no. 8: Maximum Overshoot FanDamperDemand
- Specification no. 9: Maximum Overshoot FeedwaterValvePosition

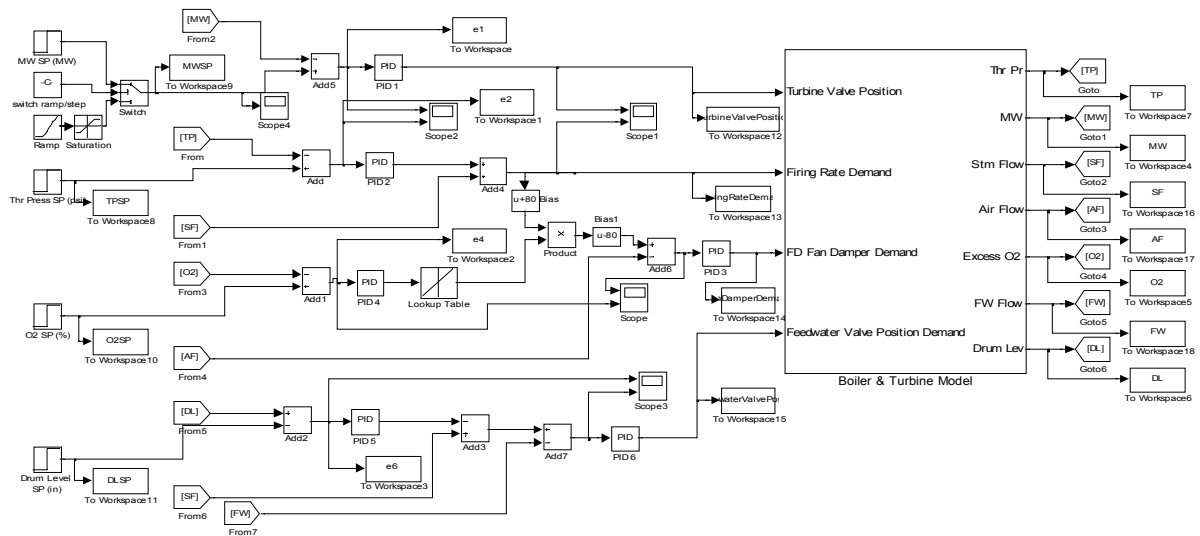


Figure 3: Power plant process model.

Optimization options are defined as follows. We choose specifically developed multi-objective genetic algorithm and quick-result optimization. Display mode is simple. Optimized coefficients has initial values $k_{11}=1$, $k_{12}=0.1$, $k_{21}=0.05$, $k_{22}=1e-5$, $k_{23}=2$, $k_{31}=4$, $k_{32}=0.1$, $k_{41}=4$, $k_{42}=0.4$, $k_{51}=1$, $k_{52}=0.0001$, $k_{61}=20$, $k_{62}=0.6$. Range is the same for all coefficients values from 0 to 100.

Optimized function settings are as follows:

- Multi-objective optimization is defined,
- optimized parameter bounds are processed as a constraint,
- no Monte Carlo simulation is set

- All scaling factors are 1 except the rising time of power output, which is 10
- no normalization is defined

Global optimization is started with the previously described input data. Not all performance specifications are satisfactory at first. Scaling factors and/or specifications are therefore changed and optimization is run again. This process is repeated several times. A sequence of optimizations and corresponding input data modifications is presented below. Performance specification values for each optimization are shown in the Table 1.

- Optimization 1
 - Input data: Initial data as described above
 - Performance evaluation: O2 loop is oscillating, control action overshoots are lower but they remain above desired level except feed-water valve position.
- Optimization 2
 - Input data: Settling-time specifications on O2 and TP are added for both scenarios to avoid its oscillations.
 - Performance evaluation: O2 loop is not oscillating, control action overshoots are higher except feed-water valve position, TP is oscillating but with smaller amplitude.
- Optimization 3
 - Input data: Scaling factors for control action overshoots is increased from 1 to 2 to reduce the overshoots. Scaling factor for MW-Settling time is increased from 1 to 10 for both scenarios to accentuate control of MW otherwise the optimization could completely eliminate MW controller.
 - Performance evaluation: TP is oscillating, first amplitude is high but it settles faster on set-point. Control actions has lower overshoots, but still above desired level.
- Optimization 4
 - Input data: Control action overshoot specifications for MW-ramp scenario are removed since they do not pose any difficulty if satisfied for MW-step scenario. Scaling factor for Maximum set-point error on TP is increased from 1 to 3. Scaling factors for remaining control-action overshoot specifications are increased from 1 to 3.
 - Performance evaluation: TP is oscillating the same way as previously. Control actions has low overshoots below desired levels except for Turbine Valve Position.

References

- [1] *Global Optimization Toolbox 3 User's Guide*, Mathworks 2010.
- [2] Bentsman J. *Assessment of Global Optimizers: Particle Swarm Optimization, Simulated Annealing, and Genetic Algorithms in Local Simultaneous Multi-loop Tuning of PID Gains*, EPRI Internal report, 2009.

Table 1: COMPARISON OF OBTAINED CONTROL PERFORMANCES

Oper. point	Scenario	Performance specification	Initial value 1	Optim. 1 value	New specif. initial value	Optim. 2 value	Optim. 3 value	Optim. 4 value
1	1	1 Specification no. 1 on M00 - Rise Time	5.00	4.00		4	5	5.00
1	1	1 Specification no. 2 on M00 - Settling Time	10.00	21.00		62	9	9.00
1	1	1 Specification no. 3 on M00 - Maximum Overshoot	1.88	3.25		2.71	1.21	1.21
1	1	1 Specification no. 4 on TP - Maximum Set-point Error	27.55	23.66		22.97	40.77	43.08
1	1	1 Specification no. 5 on O2 - Maximum Set-point Error	0.69	0.96		0.64	0.4	0.39
1	1	1 Specification no. 6 on DL - Maximum Set-point Error	0.31	0.23		0.19	0.27	0.10
1	1	1 Specification no. 7 on TurbineValvePosition - Maximum Overshoot	10.00	13.75		13.37	9.43	9.41
1	1	1 Specification no. 8 on FiringRateDemand - Maximum Overshoot	11.54	6.48		68.09	2.38	0.42
1	1	1 Specification no. 9 on FanDamperDemand - Maximum Overshoot	53.63	29.68		76.37	26.88	0.35
1	1	1 Specification no. 10 on FeedwaterValvePosition - Maximum Overshoot	11.24	2.00		0.08	4.5	0.02
1	1	1 Specification no. 11 on TP - Settling time	-	-	1407	422	729	773.00
1	1	1 Specification no. 12 on O2 - Settling time	-	-	411	122	33	133.00
1	1	2 Specification no. 1 on M00 - Settling Time	0.00	0.00		118	0	0.00
1	1	2 Specification no. 2 on M00 - Maximum Set-point Error	0.39	0.49		0.89	0.5	0.50
1	1	2 Specification no. 3 on TP - Maximum Set-point Error	27.16	15.60		19.69	40.44	42.76
1	1	2 Specification no. 4 on O2 - Maximum Set-point Error	0.15	0.20		0.13	0.07	0.16
1	1	2 Specification no. 5 on DL - Maximum Set-point Error	0.23	0.20		0.14	0.19	0.08
1	1	2 Specification no. 6 on TurbineValvePosition - Maximum Overshoot	1.44	1.36		1.22	1.72	-
1	1	2 Specification no. 7 on FiringRateDemand - Maximum Overshoot	1.17	3.52		1.18	0.46	-
1	1	2 Specification no. 8 on FanDamperDemand - Maximum Overshoot	0.17	0.43		0.08	0.1	-
1	1	2 Specification no. 9 on FeedwaterValvePosition - Maximum Overshoot	0.05	0.05		0.08	0.06	-
1	1	2 Specification no. 10 on TP - Settling time	-	-	1467	472	781	825.00
1	1	2 Specification no. 11 on O2 - Settling time	-	-	447	115	112	195.00