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Article

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Optimization of a drum boiler startup using dynamic simulation and a micro-genetic algorithm

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Abstract

In order to develop thermal power plants operational capabilities to face the new operational challenges of electrical power, in this paper we propose an approach to design operational procedures on a drum boiler of a thermal power plant. The proposed approach uses a coupled system of a simulation model and a metaheuristic optimization algorithm. The simulation model is developed in the modeling and simulation environment OpenModelica and the metaheuristic optimization algorithm is a micro-genetic algorithm (mGA). The results show that optimized operating profiles minimize the startup time to reach the drum boiler goal state by at least 35 percent and generate control valves operating sequences that must be carry out to achieve the desired profile.

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Keywords: Startup optimization; Drum boiler; Modelica; Micro genetic algorithm; Thermal power plants

1. Introduction

In globalized energy systems, operational flexibility plays a key role for the transition from centralized energy systems to liberalized energy markets. As shown by Alizadeh et al. [1], new energy markets must be able to efficiently integrate on a large-scale the energy generated by variable renewable energy sources, such as wind energy and solar energy.

Considering the operational capabilities of electrical power systems, it possible to improve electricity-generation flexibility by means of better operational strategies at the power plant level. In this regard, previous work such as that reported by Gonzalez-Salazar et al. [2], Hentschel and Spliethoff [3] and Kubik et al. [4] quantified and evaluated the operational flexibility of conventional power plants to deal with growth of renewable energy sources. Results of these works suggest that gas fired, combined cycle and coal fired power plants can be more competitive

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Nomenclature

ρ_l	Density of water
ρ_v	Density of steam
σ_D	Thermal stress in the thick-walled
C_p	Metal specific heat capacity
h_l	Water and steam enthalpy
h_v	Steam enthalpy
k	Thermal conductivity
l_l	Water level inside the drum
p	Pressure inside the drum
p_{sat}	Saturation pressure in the drum boiler
p_{goal}	Goal pressure
\dot{Q}_{flow}	Stream mass flow outside the drum
q_l	Feedwater flow
q_{goal}	Goal steam mass flow
q_v	Steam flow rate extracted from the drum
t	Time
t_0	Initial time
t_f	Final time
T_D	Inner temperature in the drum
V_l	Water volume in the drum
V_{lv}	Mixture volume (water-steam) in the drum
V_v	Steam volume in the drum
V1	Heat supplied combination
V2	Position of the steam flow control valve
w_n	Weight factor

if their operation becomes more efficient and faster with flexible operation capabilities. Likewise, they conclude that the development trend of these power plants includes: the increasing of power ramp rates, the decreasing of minimum power load, advances in cyclic operational capabilities and reduction of emissions.

In the same way, it is widely known that an essential system to enhance operational flexibility of a thermal power plant is the steam generator. The reason is that the steam quality and steam flowrate that influence the generation of energy in the steam turbine are managed by the steam generator. Therefore, recent research focuses on the development of advanced simulation, control and optimization techniques that aim at minimizing startup times and improving water level control in drum boilers as show [5–8].

Despite their focus is on startup-time reduction, current approaches fail short and can only obtain startup curves but cannot identify the corresponding control actions (operations) and their sequence. The present work aims at designing the operation sequence that minimizes the drum boiler startup times so as to satisfy the steam demand required by the power plant. Specifically, we propose an approach a simulation-based approach that incorporates a micro genetic algorithm.

This paper is structured as follows: In Section 2 the proposed approach is presented. Next, the case of study is described in Section 3. Then, Section 4 the experiments and results are presented. Finally, Section 5 presents the conclusions and future work.

2. Proposed approach

In the proposed approach, the problem consists of finding the sequences of control valves that minimize the time needed to take the system from an initial state to a goal state. This problem is formulated as a dynamic optimization

problem, involving a dynamic simulation model with variables whose values change in time. In order to solve this problem, we present a methodology that couples a dynamic simulation model with an optimization algorithm.

2.1. Simulation model

The simulation model is based on the model by Åström and Bell [9]. The simulation model consists of a feedwater system, heat supply, drum water level PI control and a system to regulate saturated steam that must be extracted from the drum. For simplicity, the model assumes thermodynamic equilibrium between water and steam inside the drum. Feedwater from the condenser enters to drum and saturated steam is extracted. Behavior of the boiler furnace in a coal fired power plant or exhaust gases of a gas turbine are modeled by means of a heat supply system to heat and evaporate the water in the rising tubes.

The mass balance in the drum boiler is shown in Eq. (1):

$$\left(\frac{\partial \rho_l}{\partial p} V_l(l_l) + \frac{\partial \rho_v}{\partial p} V_v \right) \frac{dp}{dt} + (\rho_l - \rho_v) \frac{dV_l(l_l)}{dt} = q_l - q_v \quad (1)$$

where V_l is the water volume in the drum, V_v the steam volume in the drum, ρ_l and ρ_v the density of water and steam, l_l the water level inside the drum, p the pressure inside the drum, q_l feedwater flow y q_v the steam flow rate extracted from the drum.

Drum boiler energy balance is formulated by Eq. (2):

$$\left(V_{lv} \left(h_v \frac{\partial \rho_v}{\partial p} + \rho_s \frac{\partial h_v}{\partial p} \right) + V_l \left(h_l \frac{\partial \rho_l}{\partial p} + \rho_l \frac{\partial h_l}{\partial p} \right) - V + m C_p \frac{\partial T_v}{\partial p} \right) \left(\frac{dp}{dt} \right) + (\rho_l h_l + \rho_v h_v) \frac{dV_l}{dt} = \dot{Q} + (q_l h_l - q_v h_v) \quad (2)$$

where \dot{Q} is the heat flow, V the water-steam volume in the drum, h_l y h_v are the water and steam enthalpies, while C_p denotes the specific heat capacity of steam.

According Franke et al. [10] thermal stresses occurs in the thick-walled drum if there are spatial temperature differences. Thus, thermal stress is determined proportionately to the time derivative of the metal temperature, considering that the metal temperature is equivalent to the water saturation temperature inside the drum, as given in Eq. (3):

$$\sigma_D = k \frac{dT_D}{dt} \quad (3)$$

where σ_D is the thermal stress in the thick-walled, k the thermal conductivity of the wall and $T_D = T_{sat}(p)$ the inner temperature in the drum.

2.2. Optimization algorithm

The optimization algorithm is responsible for finding the valve sequences that minimize the startup time. In order to do so, it has to interact with the simulation model explained above. Like a traditional genetic algorithm (GA), micro genetic algorithms (mGA) [11] solve optimization problems with or without constraints, using small populations of individuals (solutions) based on a natural selection process that emulate biological evolution. The proposed micro-genetic algorithm (mGA) uses variable length chromosomes. The operation diagram of the mGA is shown in Fig. 1.

In the proposed mGA algorithm, each individual is represented as an ordered list of operations. Each operation is composed of an action, action duration, and a repetition parameter. Each action is a vector that consists of two valve openings: one that regulates the heat fed into the system and another that regulates the steam flow at the outlet of the drum boiler. The action duration is the duration in seconds for which both valve openings are kept unchanged. The repetition parameter shows the number of times that an action is carried out. Both the valve openings and the action duration are discretized. An indexed list has been creating containing the possible combinations between valve openings and action durations. Each individual is represented by three chromosomes. The first chromosome contains the sequence of actions, the second one contains the action durations and the third one contains the repetition parameters.

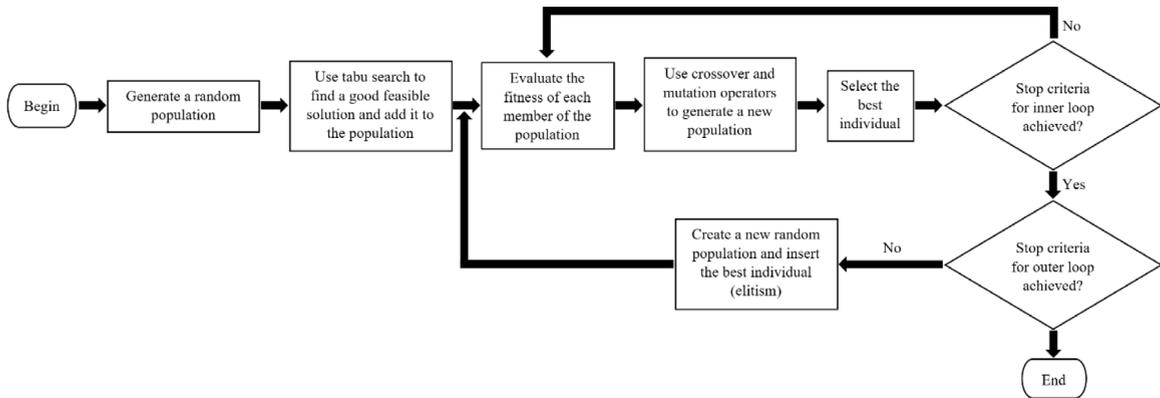


Fig. 1. Operation diagram of the mGA.

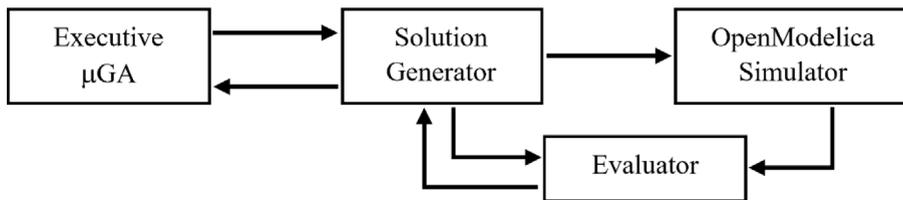


Fig. 2. Implementation of the mGA.

The implementation of the mGA has four components: *Executive*, *Solution Generator*, *Extended Simulator* and *Solver* (Fig. 2). The *Executive* executes the micro-genetic algorithm and requests solutions from the solution generator. The main role of *Solution Generator* is to find new solutions based on previous ones. For each solution, the *Solution Generator* runs a simulation using OpenModelica. After every simulation in OpenModelica, the *Evaluator* calculates the objective function and evaluates the constraints. This information is then passed to the *Solution Generator*.

3. Case study

The proposed approach is illustrated with a case study that focuses on the generation of operation profiles and their sequences of control valve operations in a drum boiler of a thermal power plant. A simulation model was developed modeling and simulation environment OpenModelica [12]. Fig. 3 shows the drum boiler model in the OpenModelica OMEdit graphic environment.

The drum boiler model was validated by executing the startup sequence published by Belkhir et al. [13] and comparing pressure, temperature, thermal stress, heat supplied, steam flow and steam flow regulation profiles. Fig. 4a and b, show the results reported by Belkhir et al. [13] and those obtained with our model implementation, respectively. From the comparison of these profiles, it can be concluded that the simulation of the implemented model with OpenModelica is validated.

The optimization problem focuses on the design of an optimal drum boiler startup profile with its corresponding control-valve operation sequence. The objective is to achieve a given state in terms of steam temperature and pressure in the shortest time possible. Based on the work of Belkhir et al. [13] and Franke et al. [10] we formulate the optimization problem in terms of the drum-boiler internal pressure and the output steam mass-flowrate of the drum boiler. Therefore, optimization problem for generating drum boiler startup operating procedure can be written as follows:

Objective function:

$$\min \sum_{t_0}^{t_f} w_1 (p(t_f) - p_{goal})^2 + w_2 (q(t_f) - q_{goal})^2 dt \tag{4}$$

flowrate of the steam that is extracted from the drum boiler:

$$0 \leq \dot{Q} \leq 500 \text{ MW} \quad (5)$$

$$0 \leq PV_{valve} \leq 1 \quad (6)$$

where \dot{Q} is the input heat flow and PV_{valve} is the percent of valve opening of the steam output valve.

In order to avoid sudden changes in the state variables, heat flow rate is constrained as follows:

$$-24 \frac{\text{MW}}{\text{min}} \leq \frac{d\dot{Q}}{dt} \leq 24 \frac{\text{MW}}{\text{min}} \quad (7)$$

Finally, an output constraint is introduced in order to avoid large thermal stresses in the drum boiler thick wall.

$$-10 \text{ MPa} \leq \sigma_D \leq 10 \text{ MPa} \quad (8)$$

4. Experiments and results

To solve the optimization problem, the micro genetic algorithm (mGA) was implemented together with an interface that connects to the drum boiler simulation model in OpenModelica. Both the algorithm and the interface were implemented in C# code.

The experiments considered three action durations (60, 120, and 180 s) and eight different actions were obtained, resulting from the combination of three valve positions for the two valves (the case of both valves closed was not considered). The repetition parameter was allowed to take integer values from 0 to 10. The mGA configuration parameters used in the numerical experiments were 10% for mutation and 20% for crossover. The population of the mGA consisted of 5 individuals and the termination criteria were set a maximum of 40 generations and 20 epochs respectively. All the experiments were carried out on a 3.4 GHz Intel Xeon E3-1245 V2 computer with 16 GB of RAM and Windows 10 pro.

The results of the optimized startup of the drum boiler are shown in Fig. 5. Fig. 5a compares the process (state) trajectories. The respective operation profiles of these trajectories are shown in Fig. 5b.

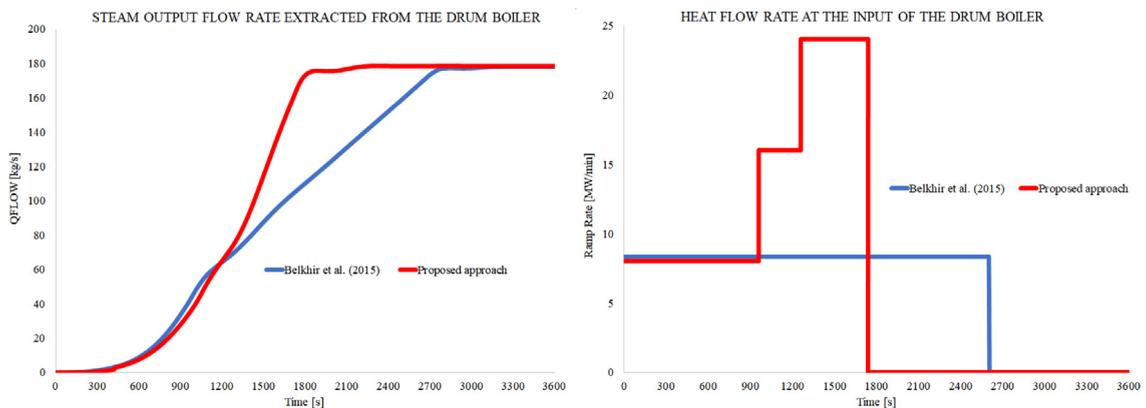


Fig. 5. Results comparison between the curve reported by Belkhir et al. [13] (blue line) and the proposed approach (red line). (a) output flowrate of the steam that is extracted from the drum boiler; (b) heat flow supplied to the system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions and future work

An approach to optimize the startup of a drum boiler was presented. This approach involves optimal response times and its sequences of operations to supply steam demands as required by the power plant. The approach was developed using a simulator in the OpenModelica environment coupled with a micro genetic algorithm.

By formulating the problem as a dynamic optimization problem, steam production reached its goal in 35% shorter time compared to the baseline start-up strategy.

As a future work, we will investigate an optimization approach based on exergy or entropy. Likewise, this approach will be tested using a combined cycle power plant simulator coupled with mGA.

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