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A modified hybrid differential evolution for short-term scheduling of hydrothermal power systems with cascaded reservoirs

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ABSTRACT

This paper presents a new approach for short-term hydrothermal scheduling of cascaded reservoirs using a modified hybrid differential evolution (MHDE) algorithm. Hydrothermal scheduling involves optimization of a non-linear objective function with a set of system and hydraulic constraints. In this paper the hybrid differential algorithm is modified in order to handle the equality constraints especially reservoir end volume and power balance constraints. The hybrid differential evolution in combination with a novel equality constraint handling mechanism provides better solution at a lesser computational effort. To show the efficiency of the proposed algorithm different case studies are carried out considering valve-point effects, prohibited discharge zones, multiple thermal units and transmission losses. The results of the proposed approach are compared with those of dynamic programming, non-linear programming, genetic algorithm, evolutionary programming and particle swarm optimization techniques. The results of the proposed algorithm are compared with differential evolution (DE) and its variants. From the numerical results it is found that the MHDE based approach is able to provide better solution at a relatively lesser computational effort.

1. Introduction

Hydrothermal scheduling is an important aspect for the optimal utilization of the available hydro resources in order to achieve maximum economy. The short-term hydrothermal scheduling involves the hour-by-hour scheduling of all generations on a system to achieve minimum cost for a known scheduling horizon. The objective is to plan the usage of water available for hydroelectric generation in order to reduce the production cost of the thermal plants, with a set of starting conditions such as reservoir levels. A hydro unit has reservoir dynamics and constraints coupling the hourly generation across time. Hydraulic and thermal constraints may include generation, load power balance, operating capacity of the hydro and thermal units, water discharge rate, upper and lower bounds on reservoir volumes, water spillage and hydraulic continuity restrictions. Operating in certain regions may not be permitted for security or efficiency reasons, resulting in discontinuous regions or even discrete generation levels. Also the reservoir storage at the end of the planning horizon must be commensurable with future operation. In cascaded reservoirs, the generation of an upstream unit affects the reservoir levels of the downstream units. Therefore, hydrothermal scheduling is a complicated non-linear optimization problem with constraints such as limited water discharge rate, hydraulic continuity and final reservoir volume restrictions.

Several optimization techniques have been developed for solving the hydrothermal scheduling problems [1–4]. Mathematical and stochastic optimization techniques employ approximations of system models that may lead to sub optimal solution resulting in huge loss of revenue over the period of time. Hydrothermal scheduling problems therefore require the use of efficient, simple and robust optimization technique.

Evolutionary algorithms, powerful optimization techniques based on the principle of natural selection, are widely employed for the hydrothermal scheduling problems. These algorithms are easy to implement and have the capability to converge to global or near global optimum at a relatively lesser computational effort. These techniques are very efficient in solving highly non-linear hydrothermal scheduling problems since they do not place any restrictions on the shape of the cost curves and other system non-linearities.

Among the evolutionary computation approaches, genetic algorithm [5–8], evolutionary programming [9–11] and particle swarm optimization [12] have been used for solving the hydrothermal scheduling problems. Hydrothermal scheduling encounters linear as well as non-linear constraints of both equality and inequality constraints. In these algorithms constraints are handled by using

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a penalty function where infeasible solutions are penalized depending on the amount of constraint violation. The selection of an appropriate penalty parameter, an essential element for a successful simulation, normally requires a lot of fine-tuning.

Orero and Irving [6] had employed multiple resolution, multiple time step GA for the optimal scheduling of a multi-reservoir cascaded hydroelectric system. They had treated the desired final reservoir levels as soft constraints that can be either violated or relaxed. A penalty function approach has been employed for handling the constraints. The computational results reported in their work were the best of satisfaction of final reservoir storage levels and the cost of thermal generation. They have reported that improvement in scheduling cost was observed with a slight improvement in meeting the end volume constraints. This improvement was however accompanied by almost eighty percent increase in computation effort.

In order to satisfy the final reservoir levels Sinha et al. [10] had proposed a method of computing the hydro discharges of a randomly chosen dependent time interval using the initial and final reservoir volumes and hydro discharges of independent time interval. This method also does not guarantee that the computed discharges are within their limits. Therefore, a robust technique is needed to handle the reservoir final level constraints in scheduling of hydrothermal systems, which eliminates the need for penalty parameters. In this paper an efficient equality constraint handling mechanism is developed and combined with hybrid differential evolution.

Differential evolution (DE) developed by Storn and Price, is a numerical optimization approach that is simple, easy to implement and robust. This method is a promising candidate for solving real-valued optimization problems [13]. The success rate, a best measure for the performance of the technique, is defined as the ratio of the total number of times the optimal solution is found to the total number of test runs. DE is found to have one hundred percent success rate. However, in DE population size depends on the number of variables (dimension). It is usually preferred in the order of five to ten times the dimension to avoid premature convergence [14].

Hybrid differential evolution (HDE) has overcome the usage of large population, which results in lesser computation time. It employs two additional operations, acceleration operation that improves the fitness from one generation to another and migration operation to upgrade the exploration of the search space. The acceleration phase is used to accelerate convergence while the migration phase helps to escape the local optimum point since the new individuals are regenerated on the basis of the best individual at the current generation. Correspondingly, the diversity can still be retained by such a regeneration procedure [15].

In this paper emphasis is given to the equality constraint of satisfying the reservoir end volume for hydro reservoirs and the power balance constraint since they have significant bearing on the cost of the overall schedule. This paper focuses on the integration of HDE algorithm with a problem specific constraint handling mechanism thereby making it efficient and effective for the hydrothermal scheduling. To prove the effectiveness of the proposed modified hybrid differential evolution (MHDE), different case studies have been conducted with valve-point effects, prohibited discharge zones and multiple thermal units including transmission losses.

2. Hydrothermal scheduling problem

The optimal scheduling of hydrothermal plant constitutes a non-linear optimization problem involving objective function and a set of linear, non-linear and dynamic constraints.

2.1. Objective function

The objective of the hydrothermal scheduling is to provide optimal utilization of hydro resources in order to minimize the thermal cost over a scheduling period T and it is expressed as

$$\text{Minimize } F = \sum_{t=1}^{T}\sum_{i=1}^{N_s} f_i(P_s(i,t)) \tag{1}$$

where N_s is number of thermal units and P_s represents thermal generation in MW.

2.2. Load balance constraint

At each time interval the total active power generation should meet the power demand and the system transmission losses, expressed as

$$\sum_{i=1}^{N_s} P_s(i,t) + \sum_{i=1}^{N_h} P_h(i,t) = P_D(t) + P_L(t) \tag{2}$$

where N_h is the number of hydro units, P_h is the generation of hydro units in MW, P_D is the power demand in MW and P_L is the total transmission loss in MW. The hydro generator power output is expressed as a function of the rate of water discharge and reservoir water head and is expressed as

$$\begin{aligned} P_h(i,t) = {} & C_{1,i}V_h(i,t)^2 + C_{2,i}Q_h(i,t)^2 + C_{3,i}V_h(i,t)Q_h(i,t) \\ & + C_{4,i}V_h(i,t) + C_{5,i}Q_h(i,t) + C_{6,i} \end{aligned} \tag{3}$$

where Q_h is the water discharge rate in m^3, V_h is the storage volume of reservoir in m^3 and C represents hydropower generation coefficient.

2.3. Generator capacity constraints

The generator capacity constraints are expressed as

$$P_s(i)^{\min} \leqslant P_s(i,t) \leqslant P_s(i)^{\max} \tag{4}$$

$$P_h(i)^{\min} \leqslant P_h(i,t) \leqslant P_h(i)^{\max} \tag{5}$$

2.4. Hydraulic network constraints

The continuity equation neglecting spillage is given by

$$V_h(i,t+1) = V_h(i,t) + I_h(i,t) - Q_h(i,t) + \sum_{m=1}^{R_u}\sum_{t=1}^{T} Q_h(m,t-\tau) \tag{6}$$

where I_h is the inflow rate the reservoir, R_u is the number of upstream plants and τ is the time delay to immediate downstream plant in hours. Physical limitations on reservoir storage volumes are given by

$$V_h(i)^{\min} \leqslant V_h(i,t) \leqslant V_h(i)^{\max} \tag{7}$$

The water discharge rate limits are given by

$$Q_h(i)^{\min} \leqslant Q_h(i,t) \leqslant Q_h(i)^{\max} \tag{8}$$

The initial and final reservoir storage volumes are given by

$$V_h(i,t)|^{t=0} = V_h(i)^{\text{begin}} \tag{9}$$

$$V_h(i,t)|^{t=T} = V_h(i)^{\text{end}} \tag{10}$$

where $V_h(i)^{\text{begin}}$and $V_h(i)^{\text{end}}$ are initial and final reservoir volumes respectively.