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Solution to security constrained environmental/economic pumped-storage hydraulic unit scheduling problem by modified subgradient algorithm based on feasible values and pseudo water price

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ABSTRACT

Objective: A security constrained environmental/economic power dispatch problem for a lossy electric power system area including a pumped-storage (p-s) hydraulic unit is formulated. An iterative solution method, which is proposed by us and based on modified subgradient algorithm operating on feasible values (F-MSG) and pseudo water price for the p-s hydraulic unit, is used to solve it.
Method: The cost function is made up of weighted sum of total fuel cost and total emission cost of the thermal units in an operation cycle. In the proposed solution method, the F-MSG algorithm is used to solve the dispatch problem of each subinterval, while the pseudo water price is employed to adjust the net amount of water spent by the p-s hydraulic unit during the considered operation period. Since all equality and inequality constraints in our nonlinear optimization model are functions of bus voltage magnitudes and phase angles, the off-nominal tap settings of tap changing transformers and susceptances values of svar systems, they are taken as independent variables. Load flow equations are added into the model as equality constraints. Therefore, the *actual* transmission loss is used in solution of the considered dispatch problem. The unit generation constraints, transmission line capacity constraints, bus voltage magnitude constraints, off-nominal tap setting constraints and svar system susceptance value constraints are added into the optimization problem as inequality constraints. Since the F-MSG algorithm requires that all inequality constraints should be expressed in equality constraint form, all inequality constraints are converted into equality constraints by a method, which does *not* add any extra independent variable into the model, before application of the F-MSG algorithm to the optimization problem. Since the method does not add any extra independent variable into the model, the solution time of the optimization problem is reduced further.
Results: The proposed dispatch technique is demonstrated on an example power system. Pareto optimal solutions for the power system without any p-s unit are calculated first. Later on, the same Pareto optimal solutions for the power system with the p-s unit are recalculated, and the obtained savings in the sum of optimal total fuel cost and total emission cost, due to the employment of the p-s unit, are presented. We also applied the F-MSG method to the dispatch problem with p-s unit *directly*. We demonstrated that the proposed solution method, where the F-MSG method is employed to solve an interval's dispatch problem, gives less solution time than the one obtained from the direct application of the F-MSG method to the dispatch problem with the p-s unit although both methods give very close sum of total fuel and emission cost values.

Introduction

The main function of p–s hydraulic units in electric power systems is to store inexpensive surplus electric energy that is available during off-peak load levels as hydraulic potential energy. This is done by pumping water from the lower reservoir of a p–s unit into its upper reservoir. The stored hydraulic potential energy is then used to generate electric energy during peak load levels (peak shaving hydraulic units). p–s units are generally operated over daily or weekly periods. Operation of a p–s unit over a period can reduce the total cost in a power system.

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Dieu et al. used enhanced merit order and augmented Lagrange Hopfield network method for solving hydrothermal scheduling problem with pumped-storage units [1]. A complete methodology to define the dimensions of an autonomous electricity generation system based on the maximum available solar energy at minimum electricity generation cost is given by Kaldellis et al. in Ref. [2]. In this study, the most cost efficient energy storage means including pumped-storage unit is tried to be found. Loisel analyses the power storage options including pumped-storage unit to support the wind energy integration to a power system [3]. The French power system is taken as the case study in this paper. Parrilla et al. use an optimization method based on mixed linear integer programming in solution of large scale hydrothermal scheduling problem with pumped-storage hydro plant [4]. Some previous papers about p–s unit scheduling problem during 1960s can also be found in [5]. In our previous work, p–s hydraulic unit scheduling problem in a lossy electric power system is solved by using the pseudo spot price of electricity algorithm [6]. In this paper, some security constraints, such as bus voltage magnitude constraints and transmission line maximum transmission capability constraints, and emission costs of the thermal units are not considered. Gonzalez et al. investigated combined optimization of wind farm and p–s unit in a market environment [7]. The problem is modeled as two-stage stochastic programming problem that considers two random parameters: market price and wind generation. Kanakasabapathy analysis the effect of pumped storage energy trading on the social welfare of electricity market in [8].

We applied the F-MSG method into non-convex security constrained dispatch problem in Ref. [9]. We also used the same method in solution of security constrained non-convex dispatch problem of an electric power area that includes limited energy supply thermal units in Ref. [10]. In Refs. [9] and [10], the outperformance of the F-MSG method against some evolutionary solution methods in terms of both solution time and total cost values is demonstrated on the example power systems that are frequently used in the literature. Application of the dispatch technique based on the F-MSG method and pseudo water price into pumped-storage hydraulic unit scheduling problem is given in Ref. [11]. We applied a solution method based on the F-MSG method and pseudo scaling factor to environmental/economic dispatch problem of a power system area including limited energy supply thermal units in Ref. [12]. ② In our papers mentioned above, except the one given in [12], the F-MSG algorithm is applied to security constrained economic power dispatch problems where basically total fuel cost is taken into consideration (single objective problem). In the current paper, the F-MSG method is applied to an environmental/economic power dispatch problem of a power system with a p–s unit where combined total fuel and total emission costs are considered (multi objective problem). We demonstrated the proposed solution method on a test power system having five thermal units and a p–s hydraulic unit. For the purpose of comparison, we calculated Pareto optimal solutions of the test system where the p–s unit is not included first. Later on, the same Pareto optimal solutions are recalculated for the test system where the p–s unit is included in. Those Pareto optimal solutions are found for three different cycle efficiencies of the p–s unit. The obtained savings in terms of sum of total fuel and emission costs, solution times, generation values and some hydraulic quantities of the p–s unit are presented for each Pareto optimal solution.

In the proposed solution algorithm, dispatch problem of each subinterval is solved via the F-MSG method while the net water usage of the p–s unit is adjusted by controlling the pseudo water price. In the F-MSG method, the bus voltage magnitudes and phase angles, the off nominal tap settings of the off nominal turns ratio transformers and the susceptances of the svar systems are taken as independent variables. Since all the constraints can be written in terms of those independent variables, security constraints such as transmission line capacity constraints and bus voltage magnitude constraints are handled together in the same model easily. The load flow equations are imported into the model as equality constraints; therefore, *the actual system loss* is inserted into the solution process automatically. In the F-MSG algorithm, the upper bound for the cost function value is specified in advance, and the algorithm tries to find a solution where the cost function is less than or equal to the upper bound while all the constraints are satisfied (feasible solution). If the algorithm finds a feasible solution, the upper bound is *decreased* by a certain amount; otherwise the upper bound is *increased* by a certain amount. The amount of decrease or increase on the upper bound for the next iteration depends on if any feasible or infeasible solution was obtained in the previous iterations. This process continues until absolute value of the change in the upper bound is less than a predefined tolerance value. Note that a specific initial increase/decrease amount for the cost function is selected at the beginning of the algorithm. *The way of search and the formation of the sharp augmented LaGrange function, which are employed in the F-MSG algorithm, make finding of the absolute minimum cost possible once the cost function is non-convex*. To find the initial bus voltage magnitude and phase angles, a load flow calculation is performed with the selected initial unit generations *at the beginning of the algorithm only*. No more load flow calculation is performed in the subsequent stages of the proposed solution process. Since the F-MSG algorithm works with only the equality constraints, we convert inequality constraints into equality constraints by using a method which does *not* add any extra independent variable into the optimization model and reduces the solution time because of it.

As a summary, the dispatch problem of each subinterval is solved via the F-MSG method. After that, the net water usage by the p–s unit is calculated. If absolute value of the net water usage is less than a predetermined tolerance value, the solution procedure is terminated and the solution is retained. If it is not, a new pseudo water price value is calculated via the bisection method, and a new iteration is started. Each Pareto-optimal solution of the dispatch problem is calculated in this manner.

This paper is organized as follows. List of symbols that are used in the paper is given just after Introduction section. Detailed optimization model of the dispatch problem is presented in section of Problem formulation. In order to write the cost function of the optimization model in terms of the independent (decision) variables, the necessary line flow equations and determination of unit generations via the line flows are given in the section just after Problem formulation. Conversion of the inequality constraints into the corresponding equality constraints via the method, which does not add any extra independent variable into the optimization model, is explained in Converting inequality constraints into equality constraints. General explanation of the F-MSG algorithm is presented in The modified subgradient algorithm based on feasible values. Application of F-MSG algorithm into the j^{th} subinterval of the considered dispatch problem is given in the next section. In The proposed solution technique for the dispatch problem section, the proposed solution method, where the F-MSG and pseudo water price are used, is given as pseudo-code form. Data related with the test power system is presented in Numerical example section. The results related with the Pareto optimal solution of the test power system without the p–s unit are given in Pareto optimal solutions of the dispatch problem of the example power system without the p–s unit section. The application of the proposed dispatch technique into the dispatch problems of the test power system, where the p–s unit with three different cycle efficiencies is included, are discussed in the next section. The results obtained from the direct application of the F-MSG method to the dispatch problem of the test system, where the p–s unit with 75% cycle efficiency is