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A switched dynamical system approach towards the economic dispatch of renewable hybrid power systems

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ABSTRACT

This paper considers an economic dispatch problem of renewable hybrid power systems. According to the analysis of the renewable hybrid power system dynamic behavior, the problem is modelled as an optimal control problem of switched dynamic systems. As is known to all, the frequent switching may cause that the engine wear is increased, and the service life is reduced. Then, some switching constraints are imposed to the switched dynamic system model. However, these switching constraints lead to a non-connected feasible region for the optimal control problem with unknown switching instants, integer variables, and continuous variables. Thus, it is difficult to solve such problem by using conventional optimization methods, such as sequential quadratic programming. To overcome this difficulty, by using the time-scaling transformation technology and introducing an auxiliary continuous vector derive a more tractable equivalent problem, in which the variable switching instants and the switching sequence are replaced with conventional continuous parameter variables. Then, based on an exact penalty function, an alternative computational method is developed for solving the problem. Finally, three numerical examples are solved by using the proposed algorithm. The numerical results show that although the optimal costs with switching constraints slightly higher than the optimal costs without switching constraints, the proposed algorithm can effectively avoid the additional switches. In addition, the numerical results also show that the switched dynamical system approach is low time-consuming and obtains a better cost function value than the existing approaches.

1. Introduction

A microgrid is a small-scale power grid composed of distributed generation, distributed storage, and loads. There is now growing interest in microgrids in many countries due to their relatively low environmental impact, ability to meet the diverse needs of end users for higher quality power supplies, the restructuring of the electric power industry, and restrictions on the extension of power transmission and distribution facilities [1]. In addition, with the development of economy and society, energy demand is increasing rapidly, the resources are decreasing, and the resources are the main energy source for human in the past decades. Thus, renewable energy sources and their forecasting have aroused more and more attention in the world, and it is becoming a huge potential new industry [2–4,43–46]. Renewable hybrid power systems are a particular class of microgrids which include conventional generators, renewable energy sources, and energy storage devices [5–8]. The renewable hybrid power systems are very important for remote areas, where electric power infrastructures are not available and fuel is very expensive [9]. To reduce fuel demand and control costs, the renewable energy sources can be used to replenish the energy coming from the generators. However, the contribution of the renewable sources to the total energy output varies considerably throughout the day. Thus, battery banks can be used to store the redundant energy produced from the generators and the renewable resources.

Economic, environmental, and technology incentives are changing the face of electricity generation and transmission. Centralized generating facilities are giving way to distributed generation because of the loss of traditional economies of scale. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a microgrid [1]. Optimal control of microgrids is an active field of research. The most

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common objective is to minimize operating cost. Published studies mainly differ in their solution techniques and scope of the modeled microgrid. Proposed solution techniques include mathematical programming [10,11], heuristics [12,13], and priority rules [14]. The microgrid concept originates from electrical sub-networks. In these networks, minimum cost control affects the operation of distributed power generators, electrical storages, and electric power requirements [15]. For more discussion, the reader can refer to the works [5–7,9,40,41] and the references therein. Recently, model predictive control (MPC) of microgrid systems has received considerable attention due to the following factors [47]: it is based on the future behavior of the system and predictions, which is attractive because of systems greatly dependent on demand and renewable energy generation forecasts; it provides a feedback mechanism, which makes the system more robust against uncertainty; and it can deal with microgrid system constraints, such as generator capacity and ramp rate constraints. An MPC-based dynamic voltage and var control is proposed for reactive power control, in order to avoid unstable voltage conditions in microgrids, especially during islanded mode operation with no support from the utility grid [48]. Some works can be found in the existing literatures that address MPC for optimal dispatch problem of microgrid systems. In [49], an MPC framework is applied to solve the dynamic economic dispatch problem, which aims at minimizing the generation cost over a particular time interval. Then, the goal is to decide the power dispatch in order to meet the demand at minimum cost subject to limits on power generation and ramp rates. Qi, Liu, Chen, and Christofides [50] develop a supervisory control system via MPC for a wind/solar energy generation system, which computes the power references for the wind and solar subsystems at each sampling time while minimizing a suitable cost function. The power references are sent to two local controllers, which drive the two subsystems to the requested power references. Qi, Liu, and Christofides [51] replace the centralized supervisory MPC controller with two distributed supervisory MPC controllers, each responsible for providing optimal reference trajectories to the local controller of the corresponding subsystem. The supervisory optimization problem solved is nonlinear and nonconvex, and several issues are not addressed, e.g., system startup or shut down. For more discussion, the reader can refer to the works [52–57] and the references therein.

A switched dynamic system consists of several modes and a proper switching law that orchestrates switching between these modes [16]. In the past two decades, as a particular class of hybrid systems, switched dynamic systems have received considerable attention due to their significance in theory and applications [17]. Many complex processes, such as biochemical systems, automotive systems, manufacturing processes, and renewable hybrid power systems, can be modeled following a switched dynamic system approach [18]. Switched dynamic system optimal control problems are one of the most challenging and important problems, because the optimal solutions including the switching sequence and the continuous control input have to be found such that the performance criterion is minimized subject to some control input and state constraints [19]. Recently, switched dynamic system optimal control problems have been attracting researchers from various fields of science and engineering due to their theoretical and practical significance [20], considering both theoretical and numerical results [21]. The available theoretical results usually extend the classical maximum principle or the dynamic programming method to switched dynamic systems [22]. The numerical algorithms make use of efficient nonlinear optimization techniques and high-speed computers to obtain efficient numerical solutions of the switched dynamic system optimal control problems [23]. Theoretical results of switched dynamic system optimal control problems is now well developed. However, for switched dynamic systems with nonlinear modes, analytical techniques are not sufficient to find an optimal control strategy. In addition, many dynamic control processes are subject to continuous-state equality or inequality constraints, such as machine scheduling [24] and aircraft trajectory planning [25]. Since one continuous-state equality or inequality constraint is equivalent to an infinite number of conventional constraints, it is difficult to solve this problem by using conventional optimization algorithms. For more discussions on various literature results, the reader may refer to the works [26–36] and the references therein.

This paper considers an economic dispatch problem of renewable hybrid power systems. In addition to the start-up costs, the dominant running costs of a renewable hybrid power system are associated with diesel generators and battery banks. The operating cost of a diesel generator depends on fuel consumption, maintenance costs, and loading. On the one hand, frequent starts of the diesel generator from cold and running the generator for long hours at a low load increase engine wear and reduce fuel efficiency. On the other hand, incomplete charging and prolonged operation of a battery bank at a low charge state are two of the major factors limiting the battery bank life span. Thus, an efficient generator operating schedule is required not only to ensure a continuous electricity supply at the load, but also to keep operating costs to a minimum. Since the structure of the switched system is simple and easy to analyze, the problem is modelled as optimal control problem of switched dynamic systems with switching constraints. Then, based on an exact penalty function, an alternative computational method is developed for solving this problem. Finally, three numerical examples are solved by using the proposed algorithm. The numerical results show that although the optimal costs with switching constraints slightly higher than the optimal costs without switching constraints, the proposed algorithm can effectively avoid the additional switches, which is undesirable in engineering practice since the mechanical wear of the diesel generator is significantly increased, and the service life of the diesel generator is significantly reduced. In addition, the numerical results also show that the switched dynamical system approach is low time-consuming and obtains a better cost function value than the approaches described in the Ref. [41] and the work [42]. Thus, the proposed approach is an effective alternative approach for the renewable hybrid power system optimal economic dispatch problems.

The rest of the paper is organized as follows. In Section 2, the economic dispatch problem of renewable hybrid power systems is modelled as an optimal control problem of switched dynamic systems. In Section 3, by using the time-scaling transformation technology and introducing an auxiliary continuous vector, the optimal economic dispatch problem of renewable hybrid power systems is written as an equivalent problem with conventional continuous parameter variables. Since the feasible region is not connected, it is hard to find an optimal solution of this problem by using conventional numerical optimization algorithms. Then, in Section 4, by using an exact penalty function, the problem is written as a sequence of unconstrained optimization problems. Each of these unconstrained optimization problems can be effectively solved by using any gradient-based optimization methods. The gradient formulae of the objective function and the proposed algorithm are presented in Section 5. In Section 6, three numerical experiments are solved by using the proposed algorithm.

2. Problem formulation

Renewable hybrid power systems are very important for remote areas, where electric power infrastructures are not available and fuel is very expensive [9]. To reduce fuel demand and controlling costs, the renewable energy sources can be used to replenish the energy generated by the generators. However, the contribution of the renewable sources to the total energy output varies considerably throughout the day. Thus, battery banks can be used to store the redundant energy produced from the generators and the renewable resources. This paper reconsiders the renewable hybrid power system discussed in [40,41], and the schematic diagram of the renewable hybrid power system is illustrated in Fig. 1.

As shown by Fig. 1, the renewable hybrid power system is composed of renewable energy sources, a battery bank for energy storage, a bi-