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Optimal spatial and temporal demand side management in a power system comprising renewable energy sources

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ABSTRACT

The increase in installed capacity of renewable energy sources (RES) has a positive effect on the development of smart grids and demand side management (DSM). The reason for this is the intermittent nature of renewable energy, which is directly related to the problem of balancing the production and consumption of power within the power system. By using the DSM, the power consumption in the system comprising RES can be easier adjusted to the power production. The paper proposes an improved concept of DSM through the spatial and temporal DSM. The optimal spatial and temporal DSM aims at determining the power diagram of each individual load bus in order to achieve the optimal state in the whole system. The optimal state of the system can be quantified through the minimum daily energy losses or minimum daily operating costs. A mathematical definition of the optimal spatial and temporal DSM problem is presented as well as the algorithm for its solution. The proposed methodology has been tested by three test networks. The results confirm the overall system performance improvements that include: reduction of energy losses in the system, reduction of the operating costs and the increase of the voltage quality within the system.

1. Introduction

Environmental protection requirements and limited reserves of fossil fuels have led to the expansion of renewable energy sources (RES) [1,2]. However, the emergence of renewable energy in the power systems has led to new problems associated with power balancing between production and consumption [3]. The reason for this is the intermittent nature of RES. In order to successfully maintain power balance between production and consumption, any increase of the installed capacities of intermittent RES must be accompanied by the corresponding changes in management strategy of other power plants within power system, primarily conventional power plants [4].

Application of smart grids and demand side management (DSM) represent possible solution for a large-scale integration of RES [5]. With DSM included, the consumption ceases to be a passive element of the system, which opens up to the operator additional options for power system control. In this paper, an analysis of the possibilities offered by load shifting in the process of integration of renewable energy into a power system is carried out. Load shifting implies shifting of one part of the load from one hour to another within a specified time interval under condition that the total energy taken within that interval remains constant. Depending on whether a device can or cannot participate in the load shifting process, the devices can be load deferrable or load non-deferrable. The load non-deferrable type includes all devices whose control would interrupt the comfort of human living or jeopardize the work processes of industrial consumers. Therefore, the system operator does not have the freedom of controlling them directly. For households, these include lighting, televisions, computers, etc. The deferrable load is electric power demand that can be served at any time within certain time span. This includes devices whose power can be time shifted without significant disruption of the comfort of living, like washing machines, storage heaters, refrigerators, dishwashers, etc. The management of these devices is described in the literature [6–12].

DSM can be done directly or indirectly. In a direct DSM, distribution system operator directly controls operation of deferrable devices. In an indirect DSM, consumers are encouraged by tariff differences to consume more electricity during low load hours [13]. In this case, the categorization of devices to deferrable and non-deferrable is unnecessary because, due to the tariff

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policy, consumers can also change load diagrams of devices categorized non-deferrable. These include cookers, microwave ovens, etc. Besides households, industrial and commercial consumers are also very important as regards DSM. The possibility of DSM within these categories was analyzed in the literature [14–18].

Integration of RES through DSM is nowadays the subject of considerable research work. The basic idea is to shift load from the hours when production of renewable energy is low to the hours when this production is large. The analyses of DSM in microgrids and households comprising distributed RES were carried out in Refs. [19–21]. These analyses were aimed at reducing dependence of these systems upon external network. Although these analyses do not include operation of the entire system, they provide a good insight in how consumption may be balanced with production of intermittent RES by applying DSM. The effect of DSM on integration of Wind Power Plants (WPP) into power system was analyzed in Ref. [22]. Similar work was done in Ref. [23], where these analyses were done on examples from China, with the emphasis on heat consumers. The optimal dimensioning of various types of RES to be used, together with the systems for energy storage and DSM, for the purpose of reducing the usage of fossil fuel power plants in Ontario, Canada was analyzed in Ref. [24]. A similar analysis was performed in Ref. [25], however, the analyses are in this case performed on the example of a residential building. In Refs. [26,27] an overview of the existing methodologies for integration of renewable energy with the DSM is presented.

In the cited literature, the optimal DSM is used in order to maintain, at the system level, power balance between production and consumption in systems comprising intermittent energy sources. The temporal component of DSM has been considered only. RES, as predominantly distributed energy sources, are dispersed throughout the system. The available types of RES, in general, have different variations in time at different geographic locations, therefore, when operation of the system is being planned, in addition to the intermittent nature of RES, it is necessary to consider their dispersed locations and the corresponding spatial variation of production.

In this paper, the spatial component of DSM is introduced into the optimization problems of minimizing the energy losses in the system with integrated RES, optimal economic dispatching of the conventional power plants and the optimal voltage control in power network. When the optimal spatial and temporal DSM is applied, during a large-scale production of RES, the consumption should not be forced in all network buses, which is assumed by DSM involving only the temporal coordinate, but only in those buses that are electrically the nearest to the RES. In this way, the energy is produced and consumed locally, thereby reducing power flows in the system. This offers many benefits: reduction of power system losses, transmission capacity release, increases of system stability, low variation of voltage magnitudes, etc. However, since it is usually impossible to completely align production with consumption of RES at the local level, the spatial and temporal optimization of DSM needs to be treated at the level of the entire power system. The time interval for all analyzes is 24 h, but this interval may be varied.

The paper is organized as follows: the methodology of spatial and temporal DSM in a power system comprising RES is defined in Section 2. The defined optimization problem is solved by using Interior Point Method in Section 3. Proposed methodology and the algorithm has been tested by three test networks, including one distribution and one transmission. It is shown that the proposed methodology can have practical applicability in the day ahead operational planning of the system.

2. The optimization problem definition

In this Section, the optimization process aimed at determining the values of the control variables that will provide an optimal state of a power system is described. The optimal state is defined either through the minimum daily operating costs of power plants or minimum daily energy losses. In conventional power systems, system management is only possible in generation buses, which is done through the control of their active powers and voltages. With the advent of DSM and emergence of modern power electronic devices, primarily FACTS devices [28,29], load buses have also become an active part of the system management. The goal of optimization defined in this paper is to determine the optimal diagrams of production and consumption, as well as voltage diagrams, which indirectly includes the optimal control of reactive power.

Every optimization problem can be written in the following form:

$$\min f(x), \tag{2.1}$$

$$g(x) = 0, \tag{2.2}$$

$$h_l \le h(x) \le h_u. \tag{2.3}$$

Equation (2.1) defines the objective function, (2.2) equality constraints, (2.3) inequality constraints, and x is the vector of unknown variables.

In the optimization problem defined in this paper, vector x is defined by the set of equations (2.4)–(2.7):

$$x = [P \quad U \quad \Theta]^T, \tag{2.4}$$

$$P = [P_1 \quad P_2 \quad \dots \quad P_i \quad \dots \quad P_{n-1} \quad P_n]^T, \tag{2.5}$$

$$U = [U_1 \quad U_2 \quad \dots \quad U_i \quad \dots \quad U_{n-1} \quad U_n]^T, \tag{2.6}$$

$$\Theta = [\Theta_1 \quad \Theta_2 \quad \dots \quad \Theta_i \quad \dots \quad \Theta_{n-1} \quad \Theta_n]^T, \ \Theta_n = 0. \tag{2.7}$$

In equations (2.5)–(2.7), P_i defines the vector of unknown average hourly power injection into bus i, U_i and Θ_i are vectors of the voltage magnitudes and the voltage angles in bus i. The system has n buses and the voltage angles of the last bus are taken for the reference, therefore, $\Theta_n = 0$. In this paper, DSM is done for the time period of one day, with hourly resolution. Therefore, each vector has 24 elements which correspond to the average hourly values of the specified variables.

Vector of power injection in each bus i can be obtained by subtracting the vectors of power generation (P_i^G) and power consumption (P_i^L):

$$P = \left[P_1^G - P_1^L \ P_2^G - P_2^L \ \dots \ P_i^G - P_i^L \ \dots \ P_{n-1}^G - P_{n-1}^L \ P_n^G - P_n^L\right]^T. \tag{2.8}$$

In Equation (2.8), it is formally mathematically assumed that in each bus both production and consumption can exist. In the case that a power plant is connected to bus i or there is a distributed production from RES, power generation vector can be different from zero, otherwise its value is a zero vector.

The load diagram consists of two parts – deferrable and non-deferrable. Fig. 1 shows an example of the daily load diagram with its deferrable and non-deferrable part.

According to Fig. 1, load in bus i within an arbitrary hour t can be represented as the sum of its deferrable and non-deferrable parts: