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Description	

A Linear Programming Model for Power Flow Control Problem Considering Controllable and Fluctuating Power Devices

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***Abstract*—The integration of renewable energy sources into grid, and ever growing power demand have increased the risks of stability and quality of power of the grid. The purpose of this paper is to present a new approach of formulating a power flow control problem using linear programming model which assigns power levels for controllable power devices and power flows between power sources and loads to accommodate power fluctuations caused by fluctuating power devices. In addition, different cost minimization criteria have been taken into consideration and their effects on power assignment has been investigated. Finally, Linear Programming Solver in MATLAB environment is used to find the solution of the proposed power flow control problem.**

***Index Terms*—Power flow control, Linear Programming (LP) method, power fluctuation, renewable power sources, LP solver**

I. Introduction

According to the 21st session of conference of the parties, global warming has been declared as a major global issue to be solved. The increasing concerns about global warming are forcing new emission reduction methods and policies targeting to reduce the gas emissions of the power sector. On the other hand, electricity demand has also increased due to growth in population, residential consumption, industrial and commercial development [1]. Consequently, power system operators need to increase their power generation and transmission capacities to meet increasing power demand. Renewable energy generation is an alternative to support the increase in power demand while reducing the gas emissions. However, the uncertain nature of renewable generation is a major barrier to use such power sources. The amount of renewable energy generated fluctuates depending on its intermittency and change of weather conditions. In this situation, sustainable and reliable power supply in real time becomes difficult especially when power supply and demand both change dynamically.

To manage power fluctuations efficiently, cooperation with controllable power devices seems to be the promising technology [2], [3], [4]. Information technology is now being used the power grids, where embedded smart power sensors, actuators, and controllers are responsible for continuous power measuring and control [5], [6]. Based on high controllability of these power devices, the amount and direction of power flow can be controlled accurately, which provide the technical grounds of our proposed *power flow control problem* [7].

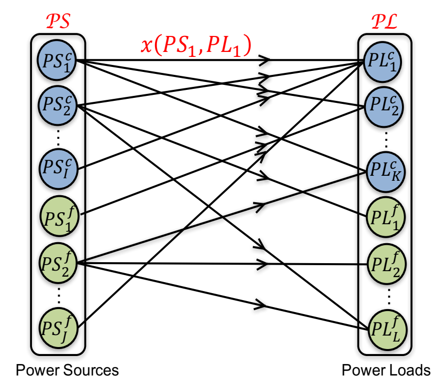

Fig. 1. System Model.

The goal of power flow control problem is to find power levels for controllable power devices and power flows between power sources and loads. Since fluctuating power sources and loads change power levels in each time instance, the power control mechanism is required for each time instance.

Hence, the purpose of this paper is to present a new approach of formulating a power flow control problem using linear programming model which assigns power levels to controllable power devices and power flows between power sources and loads to accommodate power fluctuations caused by fluctuating power devices. In addition, the total generation cost associated with controllable power sources while meeting the specified constraints have been taken into consideration and their effects on power assignment has been investigated. Finally, Linear Programming Solver in MATLAB environment is used to find the solution of the proposed power flow control problem.

This paper is organized as follows: Section II shows system overview with representation, and categorization of power devices and connections between power devices. Section III represents the problem formulation as a single objective linear programming model of our power flow control problem. Section IV shows simulation results to find the solution of the proposed problem. Finally, concluding remarks are given in Section V.

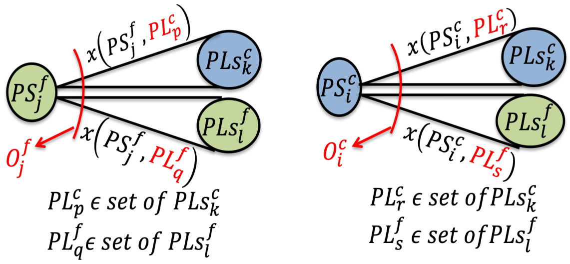

Fig. 2. Power Supply Limitation.

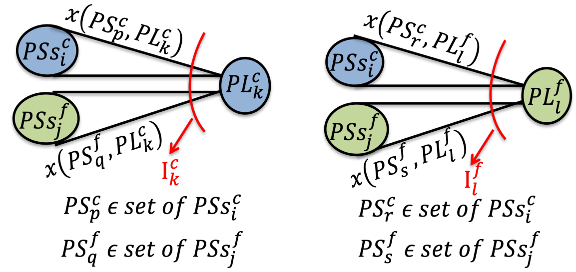

Fig. 3. Power Consumption Limitation.

II. System Overview

The proposed system model consists of distributed power sources, power loads, and connections between them. This section shows representation and categorization of power devices (i.e., power sources and loads) based on their characteristics and functionality. It also explains the power flow control problem for power sources and loads with both types.

A. Representation and Categorization of Power Devices

A power source, PS, can supply electric power to electric loads, e.g., photo-voltaic, wind turbine, utility grid, etc. A power load, PL, consumes electric power supplied by power sources. All power devices (i.e., sources and loads) are divided into two categories based on their types, characteristics, and functionality such as, *Controllable* PS^c/PL^c, and *Fluctuating* PS^f/PL^f. A controllable PS^c/PL^c can control its power (supply/consume) against power fluctuations whereas, fluctuating PS^f/PL^f cannot control its power. All power sources can be represented with unique identifiers as, $\mathcal{PS} = \{PS_1^c, PS_2^c, \cdots, PS_I^c, PS_1^f, PS_2^f, \cdots, PS_J^f\} = \{PS_1, PS_2, PS_3, \ldots, PS_{I+J}\}$, where I and J show the total numbers of controllable and fluctuating sources, respectively. Similarly, all power loads with both types can be indexed as, $\mathcal{PL} = \{PL_1^c, PL_2^c, \cdots, PL_K^c, PL_1^f, PL_2^f, \cdots, PL_L^f\} = \{PL_1, PL_2, PL_3, \ldots, PL_{K+L}\}$ where K and L show the total numbers of controllable and fluctuating power loads.

The actual power levels (i.e., generation and consumption) of sources and loads with both types can be represented as, ps_i^c, ps_j^f, $p\ell_k^c$ and $p\ell_\ell^f$, respectively.

A connection is a pair of a PS and a PL, (PS_m, PL_n). In order to represent connections between power sources and power loads, a bipartite graph is introduced as shown in Fig. 1. Each connection (PS_m, PL_n) is associated with some power level in Watt $x(PS_m, PL_n)$ to show the amount of power supplied from a power source PS_m to a power load PL_n via this connection, which is always non-negative real number. In figure, power devices are represented with different colors to distinguish the type of power devices i.e., controllable and fluctuating.

B. Power Flow Control Problem

The power supply/consumption of a fluctuating power source/load changes dynamically due to physical constraints and weather conditions. This shows that the power flows from/to fluctuating power devices are also changes. To accommodate power fluctuations, the power levels for controllable power devices and the amount of power on power flows are computed and assigned accordingly. The power flow control problem uses measured power levels of fluctuating power devices to control power levels for controllable power devices and power flows between power devices.

III. Problem Formulation

In this paper, the proposed power flow control problem has been formulated as a single objective linear programming model.

A. Objective Function

In this formulation, the power levels are assigned to controllable power sources and power flows between sources and loads to minimize cost as,

$$Min \quad \sum_{i=1}^{I} C_i \cdot ps_i^c(t) \tag{1}$$

where C_i is the power generation cost associated with controllable power sources. Here, ps_i^c is the power level for controllable power source which needs to be computed for each time instance.If the cost of a controllable power source is high, the cheapest power source would be selected for power assignment to supply power to power loads. The optimization problem is used to minimize the objective function in Eq. (1) subject to following constraints,

B. Power Supply Constraint

Each power device PS/PL has a minimum and maximum power generation/consumption limitation, which shows the range of operation and performance of that power device. One of the most obvious criteria is the generation capacity of a PS within minimum and maximum power limits. The minimum power generation limit, ps_i^{c-min}, and maximum power limit, ps_i^{c-max}, shows the capacity of a controllable source. That is, the controllable power source can supply power to connected power loads between its capacity range, which can be defined as,

$$ps_i^{c-min} \leq ps_i^c(t) \leq ps_i^{c-max} \tag{2}$$

The total power supply of a controllable power source must be equal to the sum of all power flows going out from this power source (see Fig. 2),

$$ps_i^c(t) = O_i^c = \sum x(PS_i^c, PL_r^c) + \sum x(PS_i^c, PL_s^f) \quad (3)$$

Similarly, ps_j^f shows power supply of jth fluctuating power source. The minimum and maximum power generation limits can be defined as, ps_j^{f-min}, and ps_j^{f-max}, respectively. According to the definition of fluctuating power device, the generated power of a fluctuating power source is based on the physical constraints and weather conditions. The generated capacity of a fluctuating power source can be written as,

$$ps_j^{f-min} \leq ps_j^f \leq ps_j^{f-max} \quad (4)$$

The total power supply can be written as,

$$ps_j^f = O_j^f = \sum x(PS_j^f, PL_p^c) + \sum x(PS_j^f, PL_q^f) \quad (5)$$

C. Power Consumption Constraint

All power loads are also bounded between minimum and maximum consumption limits. For example, maximum consumption limit shows strong operation mode and minimum power limit shows weak operation mode of a controllable power load. Since the power consumption can be controlled accurately based on the assigned power, the controllable power load can operate on any power level between minimum and maximum limits based on the available power supply. The consumption range can be defined as,

$$p\ell_k^{c-min} \leq p\ell_k^c(t) \leq p\ell_k^{c-max} \quad (6)$$

The total power consumption of a controllable power load must be equal to the sum of all incoming power flows (I_k^c) (see Fig. 3) as,

$$p\ell_k^c(t) = I_k^c = \sum x(PS_p^c, PL_k^c) + \sum x(PS_q^f, PL_k^c) \quad (7)$$

Similarly, the power consumption of fluctuating power load changes dynamically between minimum and maximum power consumption limits as,

$$p\ell_\ell^{f-min} \leq p\ell_\ell^f \leq p\ell_\ell^{f-max} \quad (8)$$

The total power consumption is,

$$p\ell_\ell^f = I_\ell^f = \sum x(PS_r^c, PL_\ell^f) + \sum x(PS_s^f, PL_\ell^f) \quad (9)$$

Note that, all minimum power levels of power sources and power loads with both types are non-negative real numbers.

IV. Simulation Results

The Linear Programming Solver in MATLAB environment is used to find the solution of the proposed power flow control problem. Here, we consider the system with four power sources and five power loads. Three of the power sources are selected as controllable (PS_1^c, PS_2^c, PS_3^c) and one is selected as fluctuating (PS_1^f). Similarly, three of the power loads are selected as controllable (PL_1^c, PL_2^c, PL_3^c) and other two power loads are selected as fluctuating (PL_1^f, PL_2^f). In

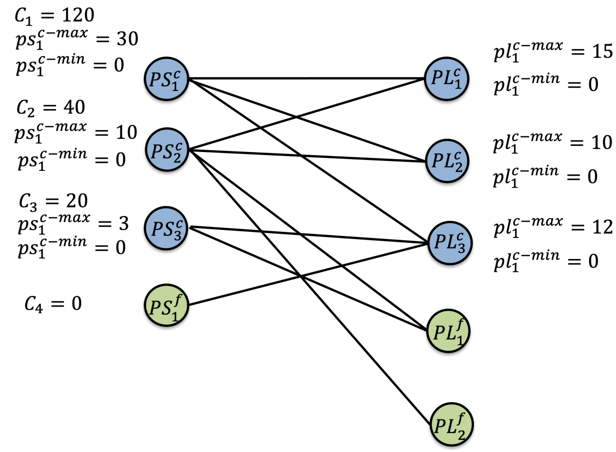

Fig. 4. Power devices and connection considered for simulation.

Fig. 4, the minimum and maximum power levels for each controllable power device (i.e., power source and load), and the power generation cost associated with each controllable power source are given. For example, the minimum power level $ps_1^{c-min} = 0$, maximum power level $ps_1^{c-max} = 30$ of PS_1^c and associated generations cost $C_1 = 120$ are given.

Since, the generation cost of each controllable power source can effect the power assignment from each power source to power load. Therefore, Figs. 5 and 6 show the power assignment to power sources and loads while considering the generation cost for controllable power sources. Note that, the minimum power consumption level for controllable power loads are considered as *zero* for this power assignment situation.

The simulation results show that the power supply from fluctuating power source (PS_1^f) is fully assigned to attached power loads because the power generation cost associated with this power source is $C4 = 0$. In order to satisfy power demand of fluctuating power loads (PL_1^f, PL_2^f) least cost power source i.e. PS_3^c is selected and power supply is assigned until the power generation reached to its maximum limit. Since the maximum power limit of this power source is not sufficient to satisfy connected power loads, the power supply from other power source is assigned based on the generation cost. The additional power supply is supplied from second least cost source i.e., PS_2^c.The most expensive power source PS_1^c is not assigned to supply power to power loads.

On the power load side (Fig. 6), the minimum power consumption limit for controllable power loads is assigned as *zero*, therefore, two controllable power loads did not consume any power. The power consumption of fluctuating power loads cannot be controlled. In order to satisfy power demand of fluctuating power devices, the power supply is assigned while minimizing generation cost and one controllable power load PL_3^c) absorb power fluctuation from fluctuating source.

The second simulation scenario shares the the same system as given in Fig. 4 except the minimum power levels for controllable power loads. In this simulation scenario, power

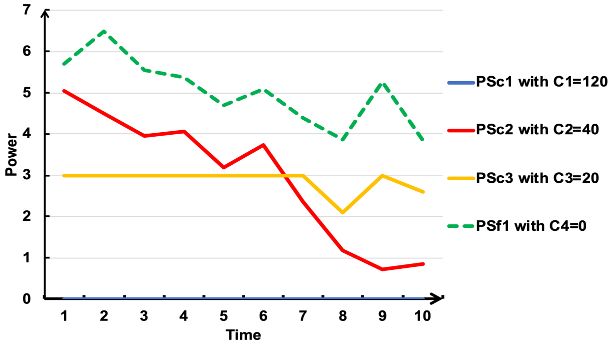

Fig. 5. Cost effective power assignment of power sources.

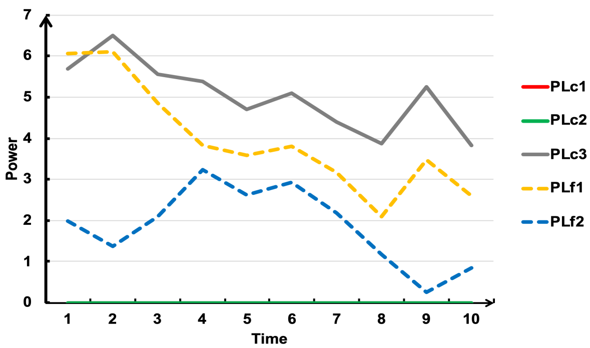

Fig. 6. Power assignment of power loads when minimum power requirement is zero.

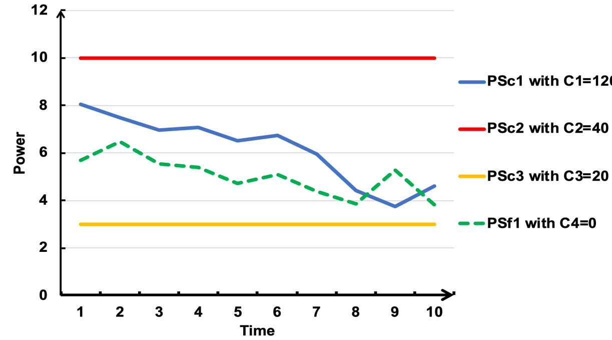

Fig. 7. Cost effective power assignment of power sources.

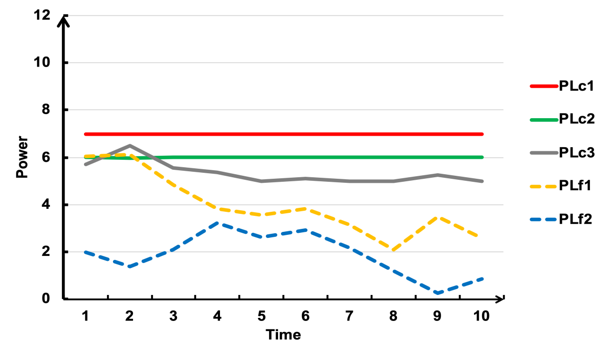

Fig. 8. Power assignment of power loads when minimum power requirement is not zero.

levels for controllable loads are considered as, ($PL_1^{c-min} = 7, PL_2^{c-min} = 6$, and $PL_3^{c-min} = 5$). The power assignment by power sources and power loads are shown in Figs. 7 and 8, respectively. Since the controllable power loads must need to satisfy their minimum power consumption limit, power sources are assigned to supply power to these power loads. Therefore, PS_1^c is also assigned to supply power because power supply from PS_2^c and PS_3^c reach to the maximum power generation limit.

V. Concluding Remarks

Energy saving and reduction in gas emissions jointly promoted the development of renewable energy sources, but the fluctuation of the output power together with dynamic power demand of power loads can affect the quality of power network due to their intermittent nature. From such point of view, a power flow control is introduced in each time instance which assigns power levels for controllable power devices and power flows between power sources and loads to accommodate power fluctuations caused by fluctuating power devices. The basic motivation of this paper is to present a new approach of formulating and implementing a power flow control problem using linear programming model. In addition, the power generation cost minimization criteria have been taken into consideration and their effects on power assignment has been discussed with simulation results. Hence, the Linear Programming Solver in MATLAB environment is used to show that every time the solution of power flow control problem can be found using Linear Programming.

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