OPTIMAL GENERATION DISPATCH MODEL FOR PROSUMER SMART GRIDS WITH PUMPED HYDRO STORAGE

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Abstract: A promising solution to smart grid stability and reliability issues resulting from the influx of renewable sources, like wind and solar, is the incorporation of pumped hydro storage (PHS). Hence, it is important to investigate the benefits of adding PHS to power grids. To this end, a model for the day-ahead economic generation dispatch of a smart grid with prosumers and pumped hydro storage is formulated. The model is tested using modified data for Ontario's power system. It is specified and solved with the Advanced Interactive Multidimensional Modelling System (AIMMS). An economic power output schedule for the gas-fired and PHS units in the grid is obtained. Also, the effect of the ramp rate of gas-fired units on grid operating cost is investigated; it is observed that the operating cost reduces with increase in ramp rate.

Key words: Economic dispatch, prosumer, pumped-hydro storage, smart grid.

Sets

t, T = Index and number of time slots

g, G = Index and number of gas units

n, N = Index and number of buildings

Parameters

Δt = Period of a time slot [hour]

E_{nuc}^{t} = Nuclear energy during t [MWh]

E_{hyd}^{t} = Hydro energy during t [MWh]

E_{win}^{t} = Wind energy during t [MWh]

E_{Sol}^{t} = Solar energy during t [MWh]

$E_{ren,n}^{t}$ = Renewable energy from building n during t [MWh]

$E_{load,n}^{t}$ = Energy supply to building n during t [MWh]

$E_{BGB,n}^{t}$ = Energy flow between grid and building n during t [MWh]

$P_{gas,g}^{min}$ = Minimum power output of gas unit g [MW]

$P_{gas,g}^{max}$ = Maximum power output of gas unit g [MW]

r = Ramping coefficient of gas unit

a_{gas}, b_{gas} & c_{gas} = Fuel cost parameters of gas unit g

$C_{gas,g}^{t}$ = Fuel cost of gas unit g [$]

f_{ming} & f_{maxg} = Minimum and maximum water discharge flow rate [hm^3/h]

f_{minp} & f_{maxp} = Minimum and maximum water pumping flow rate [hm^3/h]

V_{umin} & V_{umax} = Minimum and maximum reservoir content [hm^3]

E_{ming} & E_{maxg} = Minimum and maximum PHS generator output [MWh]

E_{minp} & E_{maxp} = Minimum and maximum energy supply to PHS pump [MWh]

Variables

$S_{gas,g}^{t}$ = On/Off status of gas unit g in t

S_{gen}^{t} = On/Off status of pumped hydro storage generator

S_{pump}^{t} = On/Off status of pumped hydro storage pump

$E_{gas,g}^{t}$ = Energy generated by gas unit g during t [MWh]

E_{gen}^{t} = Energy generated by pumped hydro storage generator [MWh]

E_{pump}^{t} = Energy consumed by pumped hydro storage pump [MWh]

$E_{BGB,n}^{t}$ = Energy transferred between grid and building n during t [MWh]

f_{gen}^{t} = Actual water discharge flow rate in t [hm^3/h]

f_{pump}^{t} = Actual water pumping flow rate in t [hm^3/h]

$P_{gas,g}^{t}$ = Power output of gas unit g in t [MW]

1. INTRODUCTION

Smart grids are equipped with sophisticated infrastructure, which enables them to accommodate renewable energy sources and prosumers. Prosumers are primarily users of electricity, but also have on-site renewable generation and so are able to feed electricity to the grid. They could be residential, commercial or industrial customers, with rooftop solar systems or wind turbines. The inherent intermittency of renewable power, particularly from solar and wind, combined with unpredictable power from prosumers makes accurate power forecasts nearly impossible to achieve in smart grids. This adversely affects power system planning. A way around this is to install more dispatchable generation units, which are able to compensate for renewable energy supply shortfalls. This is however an unattractive solution as most of these units emit noxious gases, thus making them harmful to the environment. The use of storage systems is another viable solution, and in terms of efficiency, the pumped hydro storage (PHS) is the preferred technology for storing large amounts of energy [1]. In [2], integration of pumped hydro storage with a standalone solar-powered grid is proposed to ensure grid reliability. Also, with the inclusion of PHS, better operational efficiencies can be obtained from thermal and nuclear plants [3]. A renewable energy assisted smart grid with nuclear and thermal plants and PHS is a practicable grid configuration. It is therefore important to investigate the economics of operation of such grid configurations. Of interest to system operators, is an appropriate model that can be used to obtain optimal day-ahead generation dispatch schedules. This model facilitates optimal operation of the grid.

A number of studies have been carried out on the economic operation of power systems with PHS. Optimal scheduling of PHS and wind power generation is investigated in [4]. In [5], a stochastic day-ahead generation model is proposed for a power system with PHS and wind power incorporated. A multi-objective model for optimal dispatch of a power system with thermal, hydro and wind power plants and PHS is considered in [6]. In [7], an optimal dispatch model is proposed for large-scale power systems with PHS and wind power. None of the above-mentioned studies consider prosumer generation.

The present study considers a power system made up of nuclear, hydro, gas, wind and solar plants and prosumer generation. An economic dispatch model is developed for scheduling power output of gas-fired and PHS units.

The rest of this paper is organized as follows: the diagrammatic model of the power system considered is presented in Section 2. Section 3 details the problem formulation. A description of the data used and simulation results are presented in Sections 4 and 5 respectively. The results are discussed in Section 6, and the paper concludes with Section 7.

2. SYSTEM MODEL

Figure 1 is a diagrammatic representation of the smart grid model considered in this study. It consists of nuclear, hydro, wind, solar and gas plants, PHS and prosumers. Permissible energy flow directions are shown in the figure. Grid energy management is performed centrally by a system operator. Excess energy from prosumers is sent to the grid and used either to serve other loads or to pump water to the upper reservoir of the PHS. Energy deficits can be supplied by the PHS generator.

3. PROBLEM FORMULATION

The objective function of the optimization model is taken to be the total cost of fuel expended by the gas units for the time horizon considered, as shown in (1). It is to be minimized.

$$Min \quad \sum_{t=1}^{T} \sum\nolimits_{g=1}^{G} (S_{gas,g}^{t} * C_{gas,g}^{t}) \qquad (1)$$

Where:

$$C_{gas,g}^{t} = a_g (P_{gas,g}^{t})^2 + b_g P_{gas,g}^{t} + c_{gas} \quad \text{(used in [8])} \quad (2)$$

Equation (3) ensures system energy balance in all the time slots.

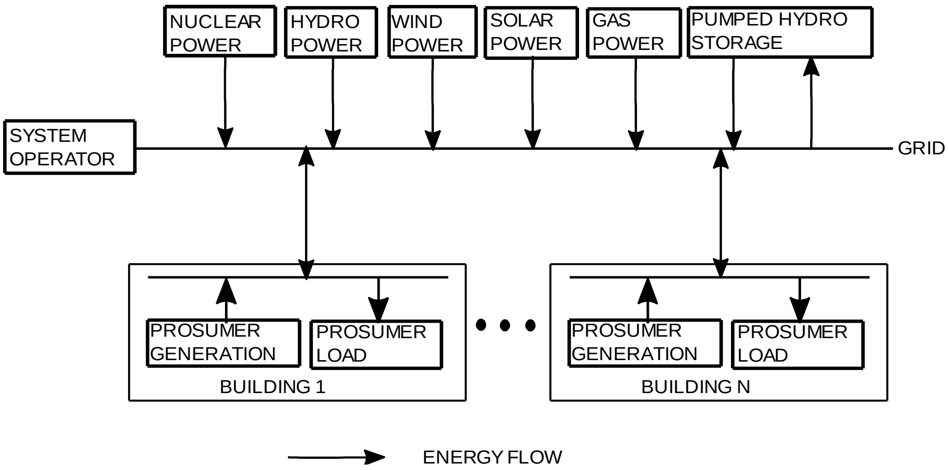

Figure 1: Illustrative prosumer smart grid model

$$E_{nuc}^{t} + E_{hyd}^{t} + E_{win}^{t} + E_{Sol}^{t} + \sum_{g=1}^{G}(S_{gas,g}^{t} * E_{gas,g}^{t}) + S_{gen}^{t} * E_{gen}^{t} - S_{pump}^{t} * E_{pump}^{t} + \sum_{n=1}^{N} E_{BGB,n}^{t} = 0 \quad \forall\ t \in [1,T] \tag{3}$$

For each building, equation (4) enforces building energy balance.

$$E_{ren,n}^{t} - E_{load,n}^{t} - E_{BGB,n}^{t} = 0 \ \forall\ n \in [1,N]\ \forall\ t \in [1,T] \tag{4}$$

Constraint (5) keeps the power output of all gas units within the permissible range [9] [10].

$$P_{gas,g}^{min} \le P_{gas,g}^{t} \le P_{gas,g}^{max} \forall\ g \in [1,G]\ \forall\ t \in [1,T] \tag{5}$$

Constraints (6) and (7) restrict upward and downward ramping of each gas unit [11].

$$P_{gas,g}^{t} - P_{gas,g}^{t-1} \le r * P_{gas,g}^{max}\ \forall\ g \in [1,G]\ \forall\ t \in (1,T] \tag{6}$$

$$P_{gas,g}^{t-1} - P_{gas,g}^{t} \le r * P_{gas,g}^{max}\ \forall\ g \in [1,G]\ \forall\ t \in (1,T] \tag{7}$$

Constraints (8) and (9) keep upward and downward flow rates within permissible limits

$$f_{ming} \le f_{gen}^{t} \le f_{maxg}\ \forall\ t \in [1,T] \tag{8}$$

$$f_{minp} \le f_{pump}^{t} \le f_{maxp}\ \forall\ t \in [1,T] \tag{9}$$

We assume the energy generated by the PHS generator increases linearly with downward flow rate of water, and head dependency is neglected [12].

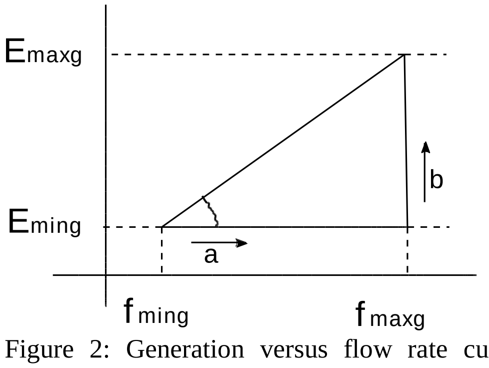

Figure 2: Generation versus flow rate curve of PHS generator (inspired in [12])

From Figure 2,

$$b = a * \tan\theta \tag{10}$$

When $a = f_{maxg} - f_{ming}$, $b = E_{maxg} - E_{ming}$

$$\tan\theta = \frac{E_{maxg} - E_{ming}}{f_{maxg} - f_{ming}} \tag{11}$$

When $a = f_{gen}^{t} - f_{ming}$, $b = E_{gen}^{t} - E_{ming}$

$$E_{gen}^{t} = E_{ming} + \left(f_{gen}^{t} - f_{ming}\right) * \tan\theta\ \forall\ t \in [1,T] \tag{12}$$

$$E_{gen}^{t} = E_{ming} + \left(f_{gen}^{t} - f_{ming}\right) * \left(\frac{E_{maxg} - E_{ming}}{f_{maxg} - f_{ming}}\right) \forall\ t \in [1,T] \tag{13}$$

Similarly, for the pump,

$$E_{pump}^{t} = E_{minp} + \left(f_{pump}^{t} - f_{minp}\right) * \left(\frac{E_{maxp} - E_{minp}}{f_{maxp} - f_{minp}}\right) \forall\ t \in [1,T] \tag{14}$$

Content dynamics of PHS upper reservoir is represented in (15) [12].

$$V_{u}^{t} = V_{u}^{t-1} + \Delta t * S_{pump}^{t} * f_{pump}^{t} - \Delta t * S_{gen}^{t} * f_{gen}^{t} \ \forall\ t \in [1,T] \tag{15}$$

Constraint (16) ensures that the content of the upper reservoir does not exceed its capacity

$$V_{umin} \le V_{u}^{t} \le V_{umax}\ \forall\ t \in [1,T] \tag{16}$$

The pump and turbine of a PHS unit cannot be operated simultaneously [13].

$$S_{pump}^{t} * S_{gen}^{t} = 0\ \forall\ t \in [1,T] \tag{17}$$

Table 1 Gas – fired unit parameters [16]

	$P_{gas,g}^{min}$(MW)	$P_{gas,g}^{max}$(KW)	$a_{gas}(\$/\mathrm{KW}^{2}h)$	$b_{gas}(\$/\mathrm{KWh})$	$c_{gas}(\$)$
Gas unit 1	20	80	0.10908	19.58	455.6
Gas unit 2	60	300	0.0007	23.9	471.6

Table 2 Modified Ontario grid data [14, 15]

Time slot	E_{nuc}^{t} (MWh)	E_{hyd}^{t} (MWh)	E_{win}^{t} (MWh)	E_{Sol}^{t} (MWh)	$E_{ren,5\%}^{t}$ (MWh)	$E_{load,5\%}^{t}$ (MWh)	$E_{load,95\%}^{t}$ (MWh)
1	10580	2497	726	0	223.4	708.5	13460.6
2	10598	2433	653	0	200.9	703.8	13372.2
3	10603	2380	722	0	222.2	707.9	13449.2
4	10610	2377	806	0	248.0	711.8	13524.2
5	10608	2499	720	0	221.5	710.6	13501.4
6	10596	2466	714	0	219.7	711.2	13511.9
7	10594	2673	1087	1	335.5	747.9	14209.2
8	10582	3062	1472	6	458.9	782.3	14862.8
9	10585	3206	2103	22	669.1	824.7	15668.4
10	10594	3374	2253	79	772.2	845.5	16064.5
11	10594	3508	2103	138	785.1	847.3	16097.8
12	10596	3233	2162	212	877.2	834.8	15860.3
13	10587	3048	2170	205	872.7	826.6	15704.5
14	10547	3084	2184	183	855.0	824.5	15665.5
15	10588	3055	2120	139	791.3	826.0	15694.0
16	10588	3199	2202	125	802.5	837.1	15904.0
17	10584	3202	2514	73	846.5	848.4	16119.6
18	10582	3307	2640	10	822.3	858.0	16301.1
19	10581	3582	2515	0	773.8	859.1	16322.9
20	10579	3435	2717	0	836.0	864.4	16423.6
21	10566	3159	2521	0	775.7	840.3	15964.8
22	10565	2789	2194	0	675.1	804.8	15291.2
23	10578	2512	1705	0	524.6	759.3	14426.7
24	10579	2436	1376	0	423.4	742.0	14097.1

Table 3 PHS generator and pump parameters

f_{ming} [hm^3/h]	f_{maxg} [hm^3/h]	f_{minp} [hm^3/h]	f_{maxp} [hm^3/h]	E_{ming} [MWh]	E_{maxg} [MWh]	E_{minp} [MWh]	E_{maxp} [MWh]	V_{umin} [hm^3]	V_{umax} [hm^3]
0.03	0.37	0.04	0.26	32.72	400	68.63	400	0	5

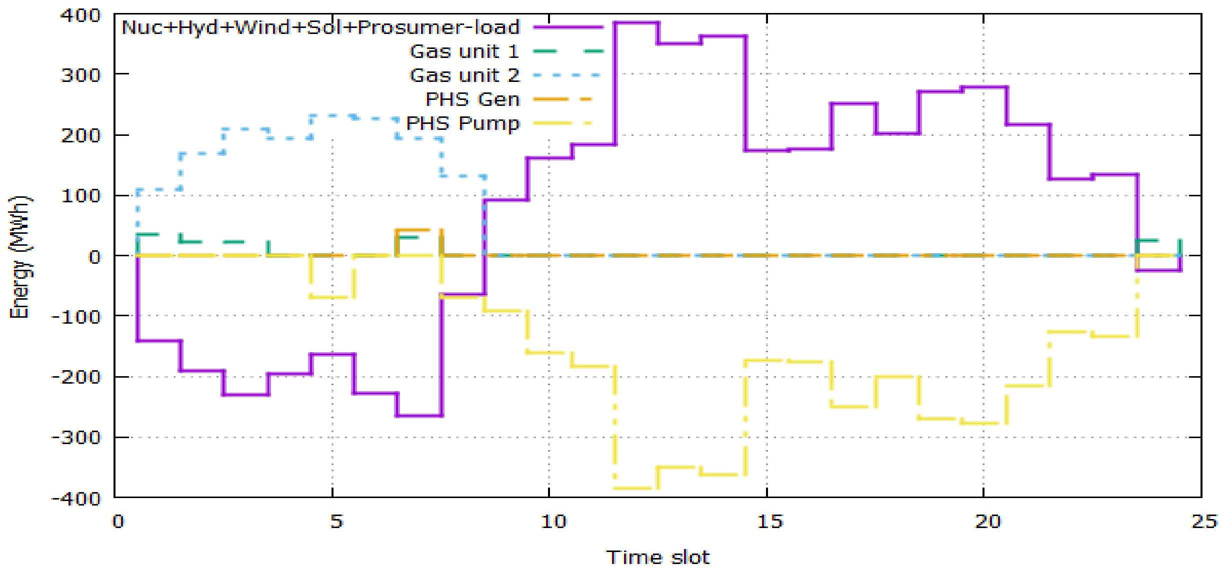

Figure 3: 24-hour horizon power schedule of gas and PHS units

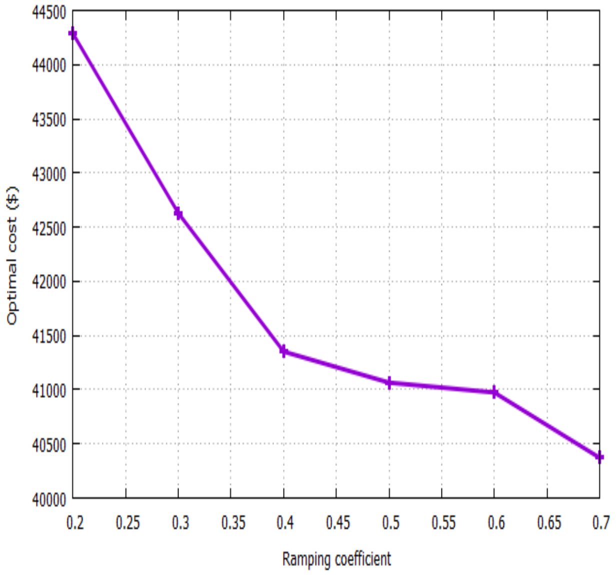

Figure 4: Grid operating cost versus ramp rate of gas units.

4. SIMULATION

Table 2 displays the data set for Ontario's grid on October 7, 2017 [14, 15], but the total market demand is divided into two sets: 5% and 95% of total demand (see 7th and 8th columns of Table 2). We assume that the customers that make up the 5% of demand (see 6th column of Table 2) are residential prosumers who have rooftop solar systems. The nuclear, hydro, wind, solar and onsite generation are assumed to be undispatchable, hence, we only dispatch the gas – fired and PHS units. The parameters for the gas units are shown in Table 1 [16]. PHS parameters are presented in Table 3. Advanced Interactive Multidimensional Modelling System (AIMMS) is employed to solve the model.

5. RESULTS

The economic power schedule for the gas – fired units and the PHS unit is presented in Figure 3. Figure 4 is a curve depicting the relationship between the ramp rates of gas-fired units and operating cost of the grid.

6. DISCUSSION OF RESULTS

In Figure 3, the energy deficit/surplus after total demand has been subtracted from aggregate supply from nuclear, hydro, wind and solar plants and prosumers is represented by the curve, " Nuc + Hyd + Wind + Sol + Prosumer – load". This energy deficit/surplus is expected to be supplied/absorbed by the gas – fired and PHS units. In the first eight (8) timeslots, it is observed that the energy deficit is supplied by the two gas – fired units and the PHS generator. Gas unit 2 is utilized more than Gas unit 1 because it has a lower operating cost. From timeslot 9 to 23, the energy surplus is absorbed by the PHS pump. The PHS unit is assumed to be a reversible pump/turbine configuration, hence its pump and generator cannot be in operation simultaneously. As a result, from timeslot 9 to 23, the PHS generator remains in its off state.

In Fig. 4, the operational cost of the grid, which is taken as the fuel cost of the gas - fired units in this study, reduces as the ramp rate of the gas units increases. The ramp rate of a unit is a measure of the extent to which the unit's power output can be changed (Upward or downward), from one time slot to an adjacent time slot. Its effect on the operating cost of the grid, as seen in Fig. 4, is due to the fact that at a higher ramp rate, more power can be obtained from the less expensive units thereby reducing the total operating cost. Gas – fired units with low operating costs and high ramp rates therefore offer economic benefits to system operators.

7. CONCLUSION

An economic generation dispatch model for a smart grid with prosumers and pumped hydro storage was developed. Economic power dispatch schedule for gas and PHS units was obtained. Due to their quick response, PHS systems are able to provide maintain system stability, by absorbing excess power in the grid and releasing power back to the grid when necessary. They are well suited for grids with high amounts of intermittent generation. The effect of ramp rate on operating cost of the grid is investigated. From results obtained, it can be concluded that gas units with low operating costs and high ramp rates are more economically beneficial.

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