Flexible Ramp Product Provision from Grid-Connected Energy Storage Systems

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***Abstract*— Renewable energy sources are becoming cost effective and are presented as cleaner source of electricity generation. Increasing penetration of such intermittent resources may pose significant challenges in power system operations due to their variability and uncertainty. Steeper net load ramps or unexpected variations in RE generation may leave controllable units with insufficient generation and/or ramping incapability and create load-generation imbalances in real-time. This necessitates flexibility requirements in power systems. Many system operators have introduced market-based flexibility products to address the ramp requirements in real-time operations. This paper aims to model such market based flexible ramp product (FRP) from pumped hydro energy storage (PHES). A MILP based 15-minute temporal day-ahead security constrained unit commitment and 5-minute re-dispatch with the co-optimization of energy, reserve and FRP are formulated for the studies. Further, benefits associated with utilizing PHES for flexibility provision are analysed. Effectiveness of proposed model is studied on IEEE RTS 24 bus test system using GAMS 24.2.3.**

Keywords- flexible ramp product; MILP; pumped hydro energy storage; renewable integration;

I. INTRODUCTION

Since the Paris agreement on climate change, the electricity sector landscape is rapidly changing to decarbonize the system. Emerging renewable energy technologies like solar and wind, are becoming cost effective and many nations are setting ambitious targets to increase the share of renewable energy sources (RES) in the generation mix. Large scale integration of such intermittent RES poses significant challenges in power system operations. Traditionally, thermal generators are utilized to counteract variability of load. But, in modern power systems, the available controllable generation is poised to meet any changes in net load (load minus renewable generation). Steeper net load ramps or unexpected variations in RE generation may leave controllable units with insufficient generation and/or ramping incapability. This necessitates flexibility requirement in power systems. Flexibility can be defined as the ability of system to vary energy production in a certain ramp rate to cope up with variations and uncertainties in net-load to maintain system reliability with minimum cost [1]. Systems with insufficient flexibility may experience frequent load & RE curtailments, area balance violations and extreme market price violations. The flexibility issue has drawn much interest in recent years [2]. Many ISOs like CAISO, MISO etc., are implementing market-based flexible ramp products (FRP) to address the ramp requirements in real-time dispatch. Unlike other ancillary services, FRP is the capacity deployed to meet ramp requirements of consecutive real-time dispatch intervals [3]. Many studies have identified demand response, energy storage systems, improved grid infrastructure & operations and fast start units as potential sources for improving flexibility in the system.

The line of research on flexibility focuses on assessing the flexibility requirements in the future operational time frames and analyzing the additional flexible reserve requirements to address uncertainty of RES in real-time [4 - 6]. Increasing reserve deployment would affect power system economics. In this context, FRPs are proving to be an efficient market product. Apart from deploying FRPs from conventional units, effectiveness of emerging technologies like demand response, energy storage and improved grid operations are studied [7, 8].

Driven by their benefits of quick start and ramping ability, energy storage systems (ESS) have become an increased interest [9]. Recent literature demonstrated the role of battery energy storage in flexibility provision and addressing load-generation imbalances [10, 11]. However, FRP provision from other emerging energy storage technologies has not been widely studied.

In this context, the paper aims to bridge the gap by analyzing the ability of pumped hydro energy storage (PHES) in FRP provision and its impact on system operations. A detailed modelling of PHES is incorporated in a scheduling problem with a 15-minute day-ahead security constrained unit commitment and 5-minute real-time re-dispatch. Effectiveness of the proposed model is analysed on IEEE RTS 24 bus test system. Various performance parameters like load and RE curtailment, operating cost and cycling of units is studied.

The reminder of the paper is organized as follows- Section II provides the mathematical formulation of the proposed model. Section III gives the methodology and case studies. Section IV concludes the work.

II. PROBLEM FORMULATION

This paper focuses on sequence of scheduling operations in power system - 15-minute temporal security constrained

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day-ahead scheduling in the co-optimization framework of energy, reserve and FRP and a real-time re-dispatch. Fig. 1 illustrates the step by step procedure followed in the proposed model.

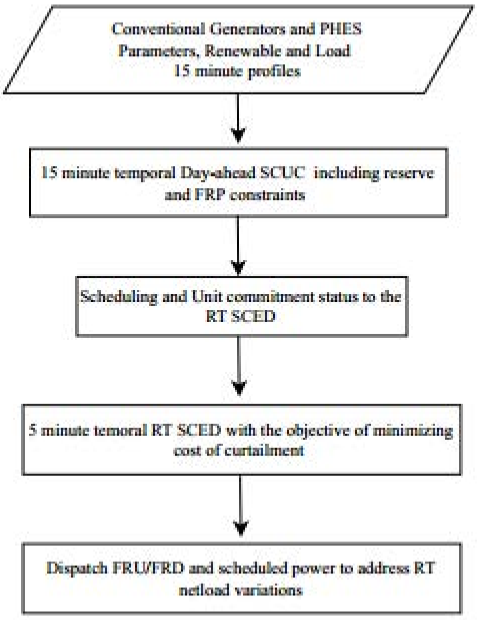

Figure 1: Simulation Methodology

A. Objective function

The objective function of the problem aims to minimize the total operating cost of energy, reserve, FRP and curtailments due to real-time load generation imbalances as given in (1)

$$Min\, C_{oper} = C^{D}_{ener} + C^{D}_{res} + C^{D}_{frp} + Lc^{RT} + Rc^{RT} \qquad (1)$$

Where $C^{D}_{(.)}$ represents operating cost of generating plants for energy (2) and costs incurred in the procurement of reserve (3) and FRP (4) in day ahead scheduling respectively.

$$C^{D}_{ener} = \sum_{i,t}\left\{C^{\min}_{i} u_{i,t} + \sum_{k} sl_{i,k} P^{k}_{i,k,t}\right\} + \sum_{i,t}\left\{C^{st}_{i} v_{i,t} + C^{sd}_{i} x_{i,t}\right\} + \sum_{ph,t}(C^{g\_stor}_{ph} P^{g\_stor}_{ph,t} + C^{m\_stor}_{ph} P^{m\_stor}_{ph,t}) \qquad (2)$$

$$C^{D}_{res} = \sum_{i,t} res^{gen}_{i,t} + \sum_{ph,t} res^{stor}_{ph,t} \qquad (3)$$

$$C^{D}_{frp} = \sum_{i,t}(C_{frp} RU^{gen}_{i,t} + C_{frp} RD^{gen}_{i,t}) + \sum_{ph,t}(C_{frp} RU^{stor}_{ph,t} + C_{frp} RD^{stor}_{ph,t}) \qquad (4)$$

The first term in (2) gives the generation cost of all scheduled generators. Piece-wise linearization is adopted to convert quadratic cost function to linear, as given in [11]. The second term represents the total start-up and shut-down cost of scheduled units. $v_{i,t}$ and $x_{i,t}$ are the binary variable indicating start up and shutdown status respectively.

B. Generator Constraints

The scheduled generating units' output power is constrained by maximum and minimum generation limit (5), ramp up and down (6)-(7). Relation between binary variables is given in (8).

$$\underline{P}_{i} u_{i,t} \le P_{i,t} \le \overline{P}_{i} u_{i,t} \qquad \forall i,t \qquad (5)$$

$$P_{i,t} - P_{i,t-1} + res^{gen}_{i,t} + RU^{gen}_{i,t} \le R^{t+}_{i} u_{i,t-1} + S^{+}_{i} v_{i,t} \quad \forall i,t \quad (6)$$

$$P_{i,t-1} - P_{i,t} - res^{gen}_{i,t} - RD^{gen}_{i,t} \le R^{t-}_{i} u_{i,t} + S^{-}_{i} x_{i,t} \quad \forall i,t \quad (7)$$

$$v_{i,t} - x_{i,t} = u_{i,t} - u_{i,t-1} \qquad \forall i,t \qquad (8)$$

R^{t+}_{i}, R^{t-}_{i} are the ramp up and down of unit i and S^{t+}_{i}, S^{t+}_{i} are its start-up and shutdown ramp capacity respectively.

C. Minimum UP and Down Constraints

The minimum up and down time are formulated as in [11] based on the initial status of unit operation at the time of optimization initialization u^{0}_{i}, from number of hours the unit is on U^{0}_{i} or off S^{0}_{i}.

D. Net-load and Renewable Energy Constraints

Equation (9) gives the value of net-load at every bus b

$$NL_{b,t} = L_{b,t} - \sum_{s \in S_b} P_{s,t} - \sum_{w \in W_b} P_{w,t} \quad \forall b,t \qquad (9)$$

S_b and W_b are the set of solar and wind farms connected to a bus b. Constraints (10) and (11) give solar and wind generation.

$$0 \le P_{s,t} \le P^{A}_{s,t} \qquad \forall s,t \qquad (10)$$

$$0 \le P_{w,t} \le P^{A}_{w,t} \qquad \forall w,t \qquad (11)$$

E. Pumped Hydro Energy Storage Modelling

Equations from (12) to (22) gives the mathematical modelling of PHES and constraints in its operation

$$P^{turb}_{ph,t} = (\eta_g \rho g H^{UR}).Q^{turb}_{ph,t} \qquad (12)$$

$$P^{pump}_{ph,t} = (\rho g H^{LR}).Q^{pump}_{ph,t} / \eta_m \qquad (13)$$

$$L^{UR}_{ph,t} = L^{UR}_{ph,t-1} + (Q^{pump}_{ph,t} - Q^{turb}_{ph,t})t \qquad (14)$$

$$L^{LR}_{ph,t} = L^{LR}_{ph,t-1} + (Q^{turb}_{ph,t} - Q^{pump}_{ph,t})t \qquad (15)$$

$$P^{g\_stor}_{ph,t} + RU^{stor}_{ph,t} \le P^{turb}_{ph,t} \qquad (16)$$

$$P^{m\_stor}_{ph,t} - RD^{stor}_{ph,t} \le P^{pump}_{ph,t} \qquad (17)$$

$$P^{g\_stor}_{ph,t} + res^{stor}_{ph,t} + RU^{stor}_{ph,t} \le P^{rated}_{ph,t} \qquad (18)$$

$$P^{m\_stor}_{ph,t} - res^{stor}_{ph,t} - RD^{stor}_{ph,t} \le P^{pump}_{ph,t} \qquad (19)$$

$$Q^{turb}_{ph,t}, Q^{pump}_{ph,t} \le Q^{\max}_{ph} \qquad (20)$$

$$L_{ph,t}^{LR\_\min} \le L_{ph,t}^{LR} \le L_{ph,t}^{LR\_\max} \qquad (21)$$

$$L_{ph,t}^{UR\_\min} \le L_{ph,t}^{UR} \le L_{ph,t}^{UR\_\max} \qquad (22)$$

Equations (12) and (13) gives the power generated and consumed during turbine and pump modes respectively. $Q_{ph,t}^{turb}, Q_{ph,t}^{pump}$ are discharge rates during turbine and pump modes, H^{UR} and H^{LR} are the heads of upper and lower reservoirs. (14) and (15) specifies the upper and lower reservoir water level at time t. Constraints (18) - (22) limits rated capacity, maximum discharge and water levels.

F. Ramp requirement Calculations

To handle uncertainty in real-time dispatch intervals, FRPs are procured from committed conventional units and other flexible resources.

$$RR_t^{up} = \sum_b RU_{i,t}^{gen} + \sum_b RU_{ph,t}^{stor} \qquad (23)$$

$$RR_t^{dn} = \sum_b RD_{i,t}^{gen} + \sum_b RD_{ph,t}^{stor} \qquad (24)$$

(23) and (24) gives the provision of flexible ramp up and down from the available and committed resources to meet ramp up requirement RR_t^{up} and ramp down requirements RR_t^{dn} respectively.

G. Power Flow Constraints

Power transferred between bus b and node n is given by (25) and constraint (26) limits the power flow between the upper and lower capacities of the line.

$$P_{b,n,t} = \gamma_{b,n}(\Phi_{b,t} - \Phi_{n,t}) \qquad \forall b,t \qquad (25)$$

$$-ll_{b,n} / S_{base} \le P_{b,n,t} \le ll_{b,n} / S_{base} \qquad \forall b,t \qquad (26)$$

H. Reserve Constraints

The committed units can contribute for reserve requirements of the system. Total spinning reserve requirement is considered to 50% of maximum capacity of the largest generator. (27) and (28) gives the reserve availability constraints for generators i and PHES ph . $u_{i,t}$ and $q_{ph,t}$ are binary variables which indicate commitment status of unit i and ph.

$$res_{i,t}^{gen} \le \overline{P}_i u_{i,t} - P_{i,t} \qquad \forall i,t \qquad (27)$$

$$res_{ph,t}^{stor} \le P_{ph,t}^{rated}\, q_{ph,t} - P_{ph,t}^{turb} \qquad \forall ph,t \qquad (28)$$

$$\sum_i res_{i,t}^{gen} + \sum_{ph} res_{ph,t}^{stor} = 0.5\max(\overline{P}_i\, u_{i,t}) \qquad (29)$$

I. Power Balance Equation

$$\sum_{i \in i_b} P_{i,t} + \sum_{ph \in ph_b} P_{ph,t}^{g\_stor} - \sum_{ph \in ph_b} P_{ph,t}^{m\_stor} - NL_{b,t} = P_{b,n,t} \qquad (30)$$

$$\begin{aligned} &\sum_{i \in i_b} P_{i,m}^{RT} + \sum_{ph \in ph_b} P_{ph,m}^{g\_stor\_RT} + \sum_{i \in i_b} FRU_{i,m}^{RT} \\ &- \sum_{ph \in ph_b} P_{ph,m}^{m\_stor\_RT} - \sum_{i \in i_b} FRD_{i,m}^{RT} - NL_{b,m}^{RT} = Pf_{b,n,m}^{RT} \end{aligned} \qquad (31)$$

Eq. (30) shows the power balance for day-ahead scheduling and (31) represents for real-time. Here t and m represents day-ahead 15-minute and real-time 5-minute scheduling blocks respectively.

$$NLR_m^{RT\_up} = \max(0, NL_m^{RT} - NL_{m-1}^{RT}) \qquad (32)$$

$$NLR_m^{RT\_dn} = \max(0, NL_{m-1}^{RT} - NL_m^{RT}) \qquad (33)$$

$$\sum_i RU_{i,m}^{RT\_gen} + \sum_{ph} RU_{i,m}^{RT\_stor} = NLR_m^{RT\_up} \qquad (34)$$

$$\sum_i RD_{i,m}^{RT\_gen} + \sum_{ph} RD_{i,m}^{RT\_stor} = NLR_m^{RT\_dn} \qquad (35)$$

Eq. (32) and (33) gives the ramp requirements in real time. (34) and (35) gives the dispatch of resources for ramp provision.

III. DATA AND CASE STUDY

The proposed model is implemented on IEEE RTS 24 bus test system with a peak load of 2650 MW and 3250MW of installed capacity. Solar and wind generation is assumed to be integrated at buses 3,5,20 and 23. Solar radiation and wind speed in the CAISO region for the month of July is taken from [12]. Load data for the considered location is normalized to the test system capacity. Fig. 2 shows the day-ahead renewable profile and system load at 30% RE integration. Cost of load and RE curtailments is assumed to be \$100/MWh. Opportunity cost for the reserve is taken as \$ \$3.34/MW and the cost of FRP procurement is considered to be 20% higher than the average market clearing price of energy.

Ramp requirement in day-ahead operation is assumed to be K σ_t where, σ_t is the standard deviation of net-load NL_t from the historical data and K is a constant. The constant K is based on the confidence interval. For the studies, ramp requirement is assumed to be $\pm 2.5\sigma_t$. A PHES of 200MW rated capacity with a discharge time of 08 hours and a reservoir (upper and lower) capacity of 1TMC is considered [13, 14].

The proposed mixed integer problem (MIP) is formulated using GAMS 24.2.3 and solved using CPLEX solver on 3.4 GHz, Intel i7 processor with 16 GB RAM.

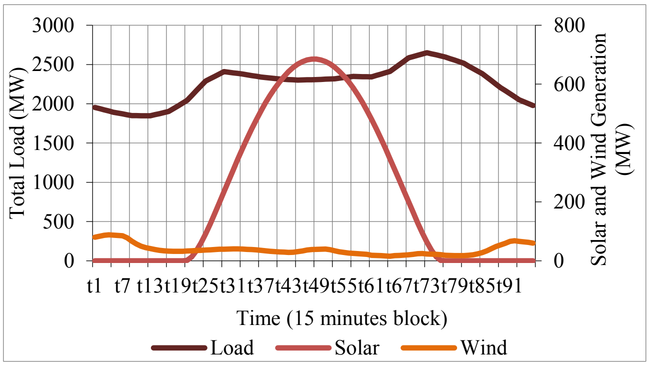

Figure 2. Day-ahead load and renewable profile at 30% RE integration

To study the effectiveness of FRP and participation of PHES in flexibility market, 2 case studies are considered at 30% and 40% renewable integration levels

1) Case-I: FRP provision from conventional units

A 15-minute temporal day-ahead security constrained scheduling with the co-optimization of energy, reserve and FRP is performed on the test system to meet the forecasted net-load. To meet reserve and FRP in day-ahead operations along with forecasted net-load variations, cycling of committed units increased and it resulted in higher operating costs. Figure 3 shows the participation of committed and available units in different markets of DA scheduling at 30% RE penetration.

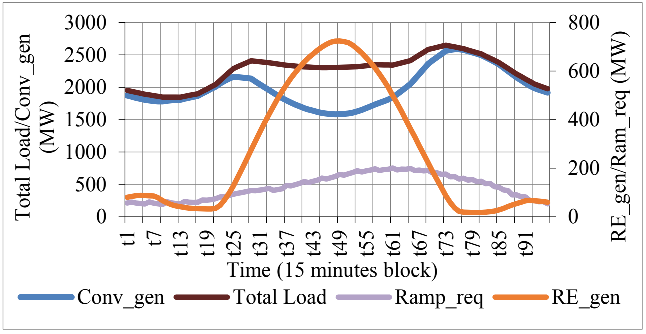

Figure 3. Day-ahead scheduling at 30% RE integration

To address the real time variability of load and renewable generation, 5-minute real time re-dispatch is carried out. The Commitment status and scheduling of committed units is taken as input for the re-dispatch. Changes in net-load from the day-ahead forecast is supplied by up and down FRPs. Figure 4 represents the power balance in the real-time. Ramping incapability of committed units between dispatch intervals resulted in huge load curtailment with a maximum of 285 MW at block m190. For the considered case, a continuous requirement for the flexible ramp up (FRU) is observed throughout the optimization time frame.

2) *Case-II: FRP provision from conventional units and PHES*

PHES is utilized for flexibility provision along with conventional units. Figure 5 shows the participation of committed and available units in different markets of DA scheduling at 30% RE integration. Compared with figure 3, day-ahead operation in case-I, power generation from conventional units is considerably decreased in case-2. Due to its lower operating cost and higher ramp rates, PHES has contributed more in reserve and FRP markets.

Real-time re-dispatch with coordinated operation of conventional units and energy storage resulted in reduction of operating cost and cycling of conventional units. Figure 6 represents the power balance in the real-time. With the provision of upward FRP from both conventional units and PHES, the maximum load curtailment in the case has decreased to 136 MW. However, deviation of PHES pumping in real time is observed compared to its day-ahead schedule.

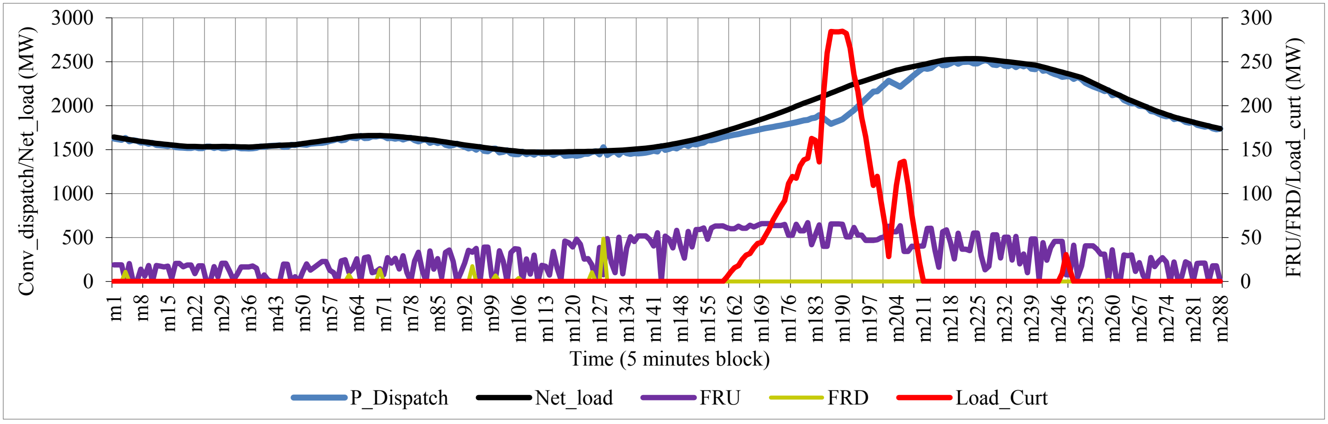

Figure 4. Real-Time Power balance at 30% RE integration

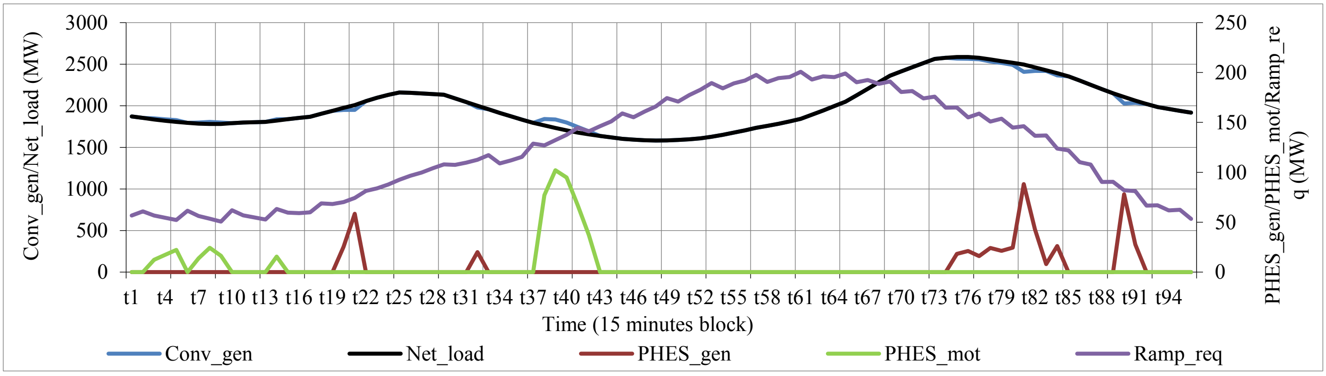

Figure 5. Day-ahead scheduling of conventional units and PHES at 30% RE integration

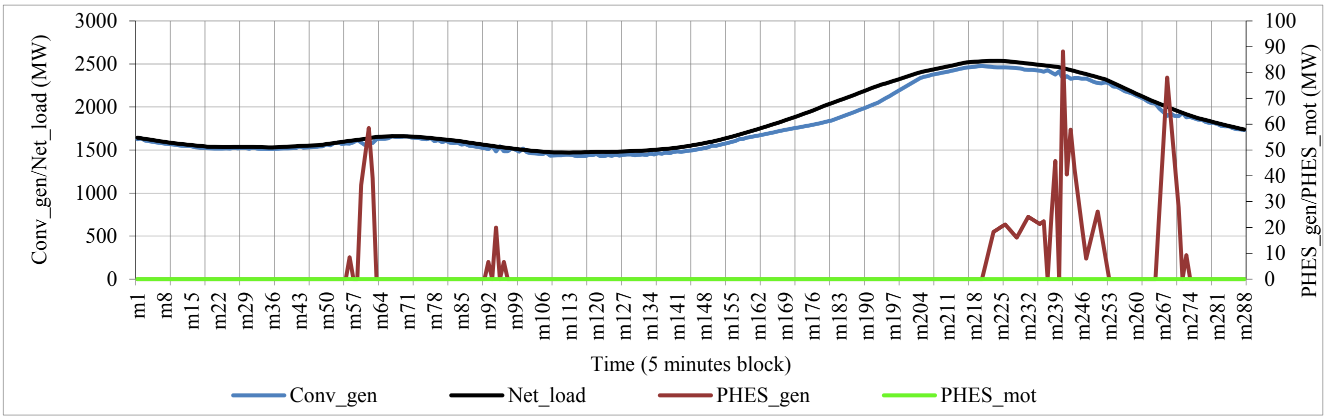

Figure 6. Real-time power balance with conventional units and PHES at 30% RE integration

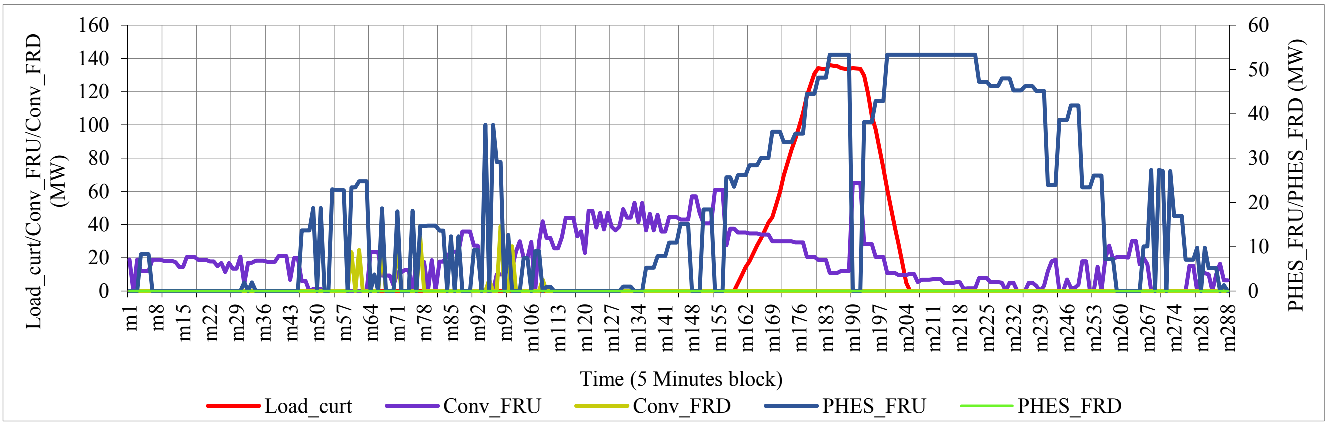

Figure 7. FRP provision from conventional units and PHES in real-time at 30% RE integration

Table 1 depicts the comparison of both the cases at different scenarios

Parameter	**30% RE Integration**	**40% RE Integration**
Case-I		
Operating Cost ($)	4596032	4165769
Computational Cost (Secs)	95	300
Load Curtailment (MWh)	515	358
FRU deployed (MW)	8595	8880
FRD deployed (MW)	123	270
Case-II		
Operating Cost ($)	4170586	3904470
Computational Cost (Secs)	104	360
Load Curtailment (MWh)	307	250
FRU deployed (MW)	9590	10332
FRD deployed (MW)	217	158

IV. CONCLUSION

Variability and uncertainty associated with renewable energy sources necessitates the need for flexible resources in the system. This paper proposed a market-based flexibility product from the coordinated operation of conventional generating units and pumped hydro energy storage (PHES). Detailed modelling of PHES is formulated and incorporated in deterministic 15- minute temporal day-ahead scheduling and a 5-minute dispatch problem to depict the system ramping capability in real-time operations. The following conclusions are drawn from the numerical analysis-

1) Although the results are case sensitive, Integration of fast start units like PHES resulted in reduction in cycling of conventional units.

2) Use of peaking units decreased and thus reduction in operating costs and load curtailment at different RE penetrations is observed.

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