Providing Ancillary Services with Photovoltaic Generation in Multi-Timescale Grid Operation

Preprint

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Providing Ancillary Services with Photovoltaic Generation in Multi-Timescale Grid Operation

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***Abstract*—With penetration levels of photovoltaic (PV) generation substaintially increasing, electric power systems need more flexible resources that can provide ancillary services to mitigate the variability and uncertainty of the PV. On one hand, the increase in PV generation necessitates more flexible resources; on the other hand, because of its low operation cost, PV generation has been replacing conventional generation, which is currenlty the main flexible resource. Consequently, there is a trend to require renewable generation, including PV, to provide flexible ancillary services. This paper proposes a multi-timescale grid operation model considering the various control strategies of PV providing different ancillary services. Numerical case studies demonstrate that with PV providing both regulation reserve and primary frequency reserve, the system operating costs and PV curtailment will be reduced significantly. Results show that not only the system reliability can be improved but also PV profitability with PV providing more ancillary services.**

***Index Terms*—PV generation, multi-timescale grid operation, ancillary services.**

I. NOMENCLATURE

A. *Indices*

b	Index for load buses from 1 to B
i	Index for generation units
t	Index for time interval
T	Time span for unit commitment problem
l	Index for transmission line constraints

B. *Constants*

SU_i	Startup cost of unit *i*
SD_i	Shutdown cost of unit *i*
R_i^U	Ramp-up limit for unit *i*
R_i^D	Ramp-down limit for unit *i*
R_i^{SU}	Ramp-up limit for unit *i* at the startup stage
R_i^{SD}	Ramp-down for unit *i* at the shutdown stage
$Limit_l$	Transmission limit for line *l*
$\overline{D_{b,t}}$	Forecasted power demand mean value
$\overline{P_{p,t}}$	Forecasted PV power (MPPT)
$G_{i,t}^{max}, G_{i,t}^{min}$	Maximum and minimum generation output
$T_{i,MinUp}$	Minimum uptime (MUT) for unit *i*
$T_{i,MinDn}$	Minimum downtime (MDT) for unit *i*
GSF_{l-i}	Generation shift factor from bus *i* to line *l*
LP	Load-shedding penalty price
RP/PFP	Regulation reserve and primary frequency reserve shortage penalty price
PFR_t^r	Primary frequency reserve requirement at time t
$Reg_{u,t}^r/Reg_{d,t}^r$	Regulation-up/-down reserve requirement at time t

C. *Variables*

$cp_{i,t}$	Production cost for unit *i* at time interval *t*
$G_{i,t}$	Generation output for unit *i* at time interval *t*
$\overline{G_{i,t}}$	Maximum available generation output for unit *i* at time interval *t*
$P_{p,t}$	PV power output for unit *p* at time *t*
$D_{b,t}$	Scheduled demand of bus *b* at time *t*
$\Delta D_{b,t}$	Load-shedding quantity of bus *b* at time *t*
ΔPFR_t	System PFR reserve capacity shortage
ΔD_t	System load-shedding at time interval *t*
$\Delta Reg_{u,t}/\Delta Reg_{d,t}$	System regulation ramp-up/-down shortage
$Reg_{u,i,t}/Reg_{d,i,t}$	Regulation-up/-down capacity provided by unit *i* at time interval *t*
$Reg_{u,p,t}/Reg_{d,p,t}$	Regulation-up/-down capacity provided by PV power plant *p* at time interval *t*
$PFR_{i,t}$	PFR capacity of unit *i*
$v_{i,t}$	Commitment status for unit *i*
$u_{i,t}$	Startup status for unit *i* of at time interval *t*
$w_{i,t}$	Startup status for unit *i* of at time interval *t*

II. INTRODUCTION

Because of the substantially increasing deployment of renewable generation, the portfolios of many electric power systems have significantly changed [1]–[4]. Renewable generation, especially photovoltaics (PV), necessitates more

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flexible resources to provide ancillary services to mitigate uncertainty and fluctuation in renewable power output [5]; however, because of the low operation cost of PV generation, conventional generation, the main source of grid flexibility, faces pressures of early retirement and decommissioning. Consequently, electric power systems need alternative resources to provide ancillary services to maintain reliability in systems with high PV penetration.

Regulation services are used to mitigate real-time power imbalances in system operation caused by forecasting errors and variations in load and renewable generation [6]. Primary frequency reserve is the capacity procured by the system operator to recover the system frequency after a potential contingency, such as an unforced generation outage [7]. These ancillary services are critical to maintaining system reliability, especially in systems with high PV penetration.

In [8], it was tested that PV has the capability to provide regulation services and its performance when following automatic generation control signals was better than that of conventional thermal units. Therefore, the benefits of PV providing ancillary services should be better modeled and understood to facilitate the flexibility of PV generation. In [9], the bidding strategy for PV considering both energy and ancillary services was proposed. In [10], the impact of wind power on primary frequency reserve (PFR) was investigated.

PV power, enabled by its inverter's fast response, has the capability to provide fast-responding ancillary services; however, the impact on multi-timescale system operation has not yet been studied, from day-ahead security-constrained unit commitment (SCUC) to real-time security-constrained economic dispatch (SCED). In this paper, we propose a multi-timescale system operation model from the day ahead to real time to comprehensively analyze the benefit of PV providing ancillary services.

The rest of this paper is organized as follows. Section III introduces ancillary service provision from PV generation. Section IV proposes the general SCUC model considering the ancillary service provision of PV. Section V performs the case studies in an 18-bus system to demonstrate the potential of PV power to provide regulation and PFR services. Section VI concludes the paper.

III. ILLUSTRATION OF PV PROVIDING ANCILLARY SERVICES

The PV ancillary service provision is illustrated in Fig. 1. PV can provide regulation-down capacity if its scheduled power output is greater than 0. Different from conventional generators, the regulation services from PV will not be restrained by the ramping capability because PV can reduce its power output very fast through the control of its inverters.

To provide regulation-up and PFR services, PV needs to withhold power capacity headroom from its maximum power output level. The detailed mathematic formulation for PV providing regulation-down/-up and PFR services will be introduced in the next section. The headroom will pose the opportunity cost for PV to provide regulation-up and PFR services because PV can sell this capacity to the energy market to earn more money. In a system with high PV penetration, however, the system curtails the PV power during the daytime PV peak period because of system constraints, such as ramping issues and the thermal units' minimum generation level limitations. PV curtailments have already happened in the California Independent System Operator system because of the ramping issue [11]. Under these circumstances, using curtailed PV capacity to provide regulation-up and PFR will be a viable option.

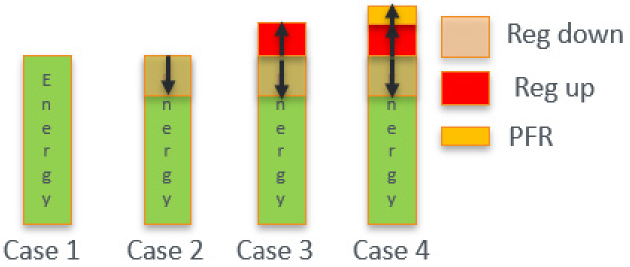

Fig. 1. Illustration of PV providing ancillary services

IV. UNIT COMMITMENT PROBLEM WITH FLEXIBLE RAMPING

This section presents the overall formulation of the SCUC problem including flexible ramping products.

A. *Objective Function*

The objective of the SCUC problem includes the operating cost of traditional units—represented by their generation costs and startup and shutdown costs—as well as the shortage penalties for the load, regulation, and PFR services, as follows:

$$\min \sum_{t\in T}\Big[\sum_{i\in g}\big(SU_i u_{i,t} + SD_i w_{i,t} + cp_{i,t}\big) + LP * \Delta D_t + PFP * \Delta PFR_t + RP * (\Delta Reg_{u,t} + \Delta Reg_{d,t})\Big] \tag{1}$$

$$cp_{i,t} = a_i v_{i,t} + b_i G_{i,t} + c_{i,t} G_{i,t}^2 \tag{2}$$

Note that the production cost, $cp_{i,t}$, of the traditional thermal unit shown in (2) can be approximated by a piecewise linear function from its quadratic production cost curve. In this model, we assume that the energy price of PV is 0. For ancillary services, the bidding prices are zero. The system co-optimizes the energy and ancillary services such that the opportunity cost of providing ancillary services will be respected.

B. *Constraints for the Single Unit*

The constraints for traditional thermal units are similar to those in [12] and are presented as follows for completeness. We also consider the start-up and shut-down trajectories of conventional generators in Eq. (7) and Eq. (8).

$$u_{i,t} + w_{i,t} \le 1 \tag{3}$$

$$v_{i,t} - v_{i,t-1} \le u_{i,t} - w_{i,t} \tag{4}$$

$$\sum_{\tau=t-T_{i,MinUp}+1}^{t} u_{i,t} \le v_{i,t} \tag{5}$$

$$\sum_{\tau=t-T_{i,MinDn}+1}^{t} w_{i,t} \le 1 - v_{i,t} \tag{6}$$

$$\overline{G_{i,t}} - G_{i,t-1} \le R_i^U v_{i,t-1} + R_i^{SU} u_{i,t} \tag{7}$$

$$G_{i,t-1} - G_{i,t} \le R_i^D v_{i,t} + R_i^{SD} w_{i,t} \tag{8}$$

$$\overline{G_{i,t}} \le G_{i,t}^{max} v_{i,t} \tag{9}$$

$$G_{i,t} + Reg_{u,i,t} \le \overline{G_{i,t+1}} \tag{10}$$

$$G_{i,t} + PFR_{i,t} \le \overline{G_{i,t+1}} \tag{11}$$

$$G_{i,t} - Reg_{d,i,t} \ge G_{i,t+1}^{min} v_{i,t+1} \tag{12}$$

$$G_{i,t} + Reg_{u,i,t} - G_{i,t-1} \le R_i^U \quad (13)$$
$$G_{i,t-1} - \left(G_{i,t} - Reg_{d,i,t}\right) \le R_i^D \quad (14)$$
$$v_{i,t}, u_{i,t}, w_{i,t} \in \{0,1\} \quad (15)$$

C. System Energy Balance, Reserve Constraints, Flexible Ramping, and Transmission Constraints

The system constraints include the energy balance constraint for every time interval, system regulation reserve, PFR, and transmission constraints, as follows:

$$\sum_{i\in g}\left(G_{i,t} + P_{p,t}\right) - \sum_{b\in B} D_{b,t} = 0 \quad (16)$$
$$D_{b,t} = \overline{D_{b,t}} - \Delta D_{b,t} \quad (17)$$
$$\Delta D_t = \sum_b \Delta D_{b,t} \quad (18)$$
$$\sum_{i\in g} PFR_{i,t} + \Delta PFR_t \ge PFR_t^r \quad (19)$$
$$\sum_{i\in g} Reg_{u,i,t} + \Delta Reg_{u,t} \ge Reg_{u,t}^r \quad (20)$$
$$\sum_{i\in g} Reg_{d,i,t} + \Delta Reg_{d,t} \ge Reg_{d,t}^r \quad (21)$$
$$-Limit_l \le \sum_{i\in Lg} GSF_{l-i}\left(G_{i,t} + P_{p,t}\right) - \sum_{b\in Lb} GSF_{l-b} D_{b,t} \le Limit_l \quad (22)$$

D. PV Power as Flexible Ramp Provider

If PV power participates in the market as an ancillary service provider, the following constraints should be added:

$$P_{p,t} + Reg_{u,p,t} \le \overline{P_{p,t}} \quad (23)$$
$$P_{p,t} + PFR_{p,t} \le \overline{P_{p,t}} \quad (24)$$
$$P_{p,t} - Reg_{d,p,t} \ge 0 \quad (25)$$

Note that only the day-ahead SCUC model is presented for the model conciseness. The real-time SCUC model is similar to the day-ahead SCUC model. The real-time SCED model is with the binary variables fixed as the values from the SCUC. The time resolution in the SCUC is 1 hour, and it is 5 minutes in the real-time SCED. The time span in the day-ahead SCUC is 24 hours, and it is 3 hours in the real-time SCUC. The time span in the real-time SCED is 2 hours, with 24 5-minutes intervals.

The regulation-down/-up requirements are assumed to be 3% of the system load. The PFR requirement is 4.75% of the system load. These numbers are chosen based on the system dynamic simulation to maintain reliability. A detailed model of how to decide the ancillary service requirements is outside the scope of this paper.

V. CASE STUDIES

This section tests the proposed model in an 18-bus system. The impact of PV providing regulation and PFR will be investigated and compared. The system cost and PV curtailment will be studied under different cases of PV ancillary service provision. All the simulations are performed in a Python-based scheduling tool on a personal laptop with Intel Core i5 as the central processing unit.

A. 18-Bus Test System

The test system has been modified from the 18-bus system depicted in Fig. 2. Detailed system data can be found in [13]. One 1,600-MW PV power plant is added to the system. Table I shows the generation parameters of each unit. The shutdown cost of the units is 0. The load-shedding penalty is \$100,000/MWh, and the regulation reserve and the PFR capacity shortage penalty is \$5,000/MW. The line limits are relaxed in the study to better analyze the impacts of PV ancillary services provision. Four cases are designed to study the impact of PV providing different ancillary services on the system. The system load and PV power curves are shown in Fig. 3. The peak PV power penetration is 50%.

Case 1: PV does not provide any ancillary services.
Case 2: PV provides only regulation-down service.
Case 3: PV provides both regulation-down/-up services.
Case 4: PV provides regulation-down/-up and PFR services.

TABLE I. GENERATION PARAMETERS

Unit	*C* (\$/MW)	Pmax (MW)	Ramp (MW/5 min)	MUT (h)	MDT (h)	SUcost (\$)
G1	18.144	600	5.500	8.25	24	3955
G2	19.79345	1200	5.5	8.25	24	4746
G3	1	600	16	0.25	0.25	0
G4	2	1200	16	0.25	0.25	0
PV	10	360	250	0	0	0

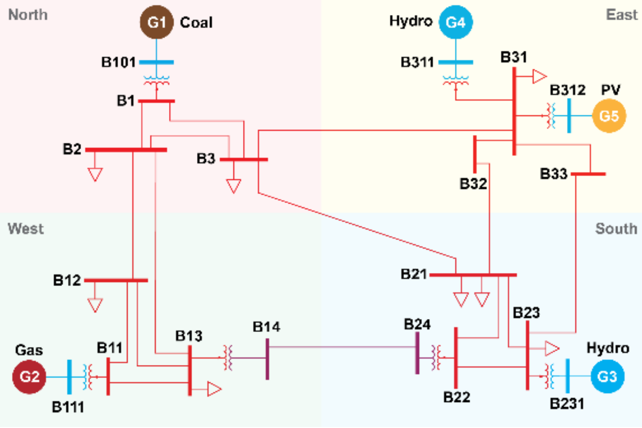

Fig. 2. 18-bus test system

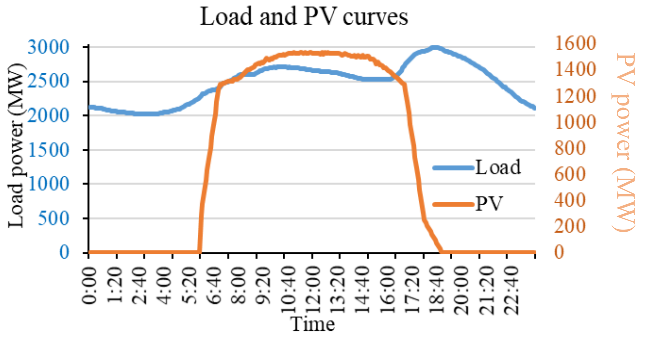

Fig. 3. System demand and PV power curves

B. Impact of PV Providing Regulation Reserve

This subsection compares the cases where PV provides only regulation-down services, Case 2, and both regulation-down/-up services, Case 3, to the case where PV does not provide any ancillary services, Case 1. The system generation dispatches in three cases are shown in Fig. 4, and the system generation costs are listed in Table 2. The red dashed line in Fig. 4 is the Case 1 PV peak output reference to show the PV energy difference in Case 2 and Case 3.

Fig. 4 shows that when PV provides regulation services, the scheduled PV energy increases. In Case 2, when PV provides regulation-down service, PV output during the daytime peak period can be increased. The reason is that regulation-down service from PV replaces the regulation-down services from the conventional generator G3. Therefore, the power output of G3 can be reduced to a lower level, as shown in Fig. 4, Case 2. In Case 3, when PV provides regulation-up service, the energy output during the PV daytime peak can be further increased, as shown in Fig. 4, Case 3. This is because the regulation-up service from PV can replace the regulation-up services from conventional generator G2. Consequently, G2 can be shut down during the PV peak period. In Case 1, because G2 needs to provide regulation-up service, it cannot be shut down.

TABLE 2. SYSTEM GENERATION COST IN THREE CASES

Case 1	Case 2	Case 3
$74,908.69	$70,025.02	$67,873.93

The energy price of PV is less than that of conventional generators. Therefore, if the system is not constrained by the flexibility conditions, such as the regulation requirements and ramping limits, the system will schedule as much PV as possible to minimize the total generation cost. When PV provides regulation-down and -up services, the limitations and constraints in the system flexibility can be relieved, and consequently PV output can be increased. Table 2 shows that the system generation costs reduce when PV provides regulation-down and -up services.

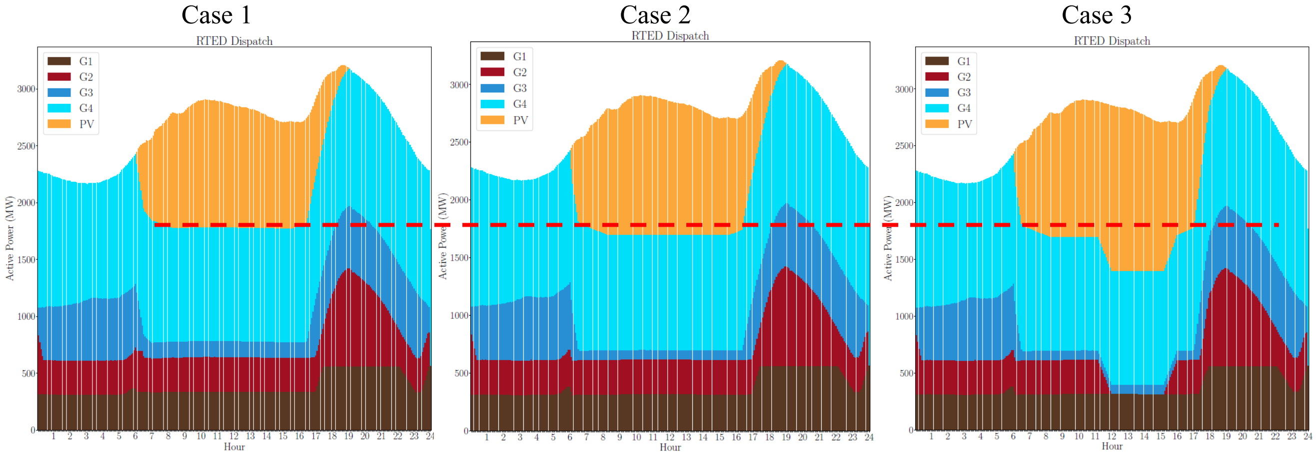

Fig. 4. Generation schedules in Case 1, Case 2 and Case 3

C. *Influence of PV Providing PFR*

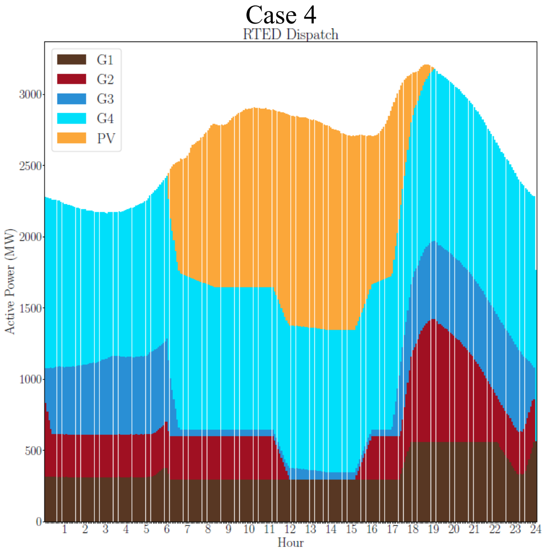

Fig. 5. Generation schedule in Case 4, PV providing regulation-down/-up and PFR services

This subsection analyzes Case 4 when PV provides PFR service. The generation schedule in Case 4 is depicted in Fig. 5. In Case 4, PV provides regulation-down/-up and PFR services. In the PFR formulation in Eq. (23) and Eq. (24), note that the regulation-up and PFR services are decoupled, which means that PV headroom can be used for both regulation-up and PFR services.

Fig. 5 shows that the PV output increases slightly compared to Case 3 after PV provides PFR. The system generation cost in Case 4 is $65,012.56, which is less than Case 3, as shown in Table 1. Therefore, when PV provides PFR service, the system cost and PV curtailment can be further reduced. Because the system in Case 1 has a large PV curtailment during the daytime PV peak period, this curtailed PV can be used for up-reserves, such as regulation-up and PFR, without additional opportunity cost. Therefore, the system generation cost can be reduced when PV provides up-reserves, such as regulation-up and PFR services.

D. *Analysis of PV Curtailment*

To better demonstrate the impact of PV ancillary service provision, this subsection analyzes the detailed PV schedules and curtailments in different cases. Fig. 6 demonstrates the PV power output in four cases. Fig. 7 shows the PV energy and ancillary service output in Case 4 when PV provides regulation-down/-up and PFR services. Table 3 lists the PV energy curtailment in four cases.

As shown in Fig. 6 and Table 3, when PV provides more ancillary services, its energy output can increase (its curtailment reduces), which means that PV can earn more money through selling more power to the system. In addition, the provision of ancillary services can help PV earn additional revenue from the ancillary service market. Note that the additional energy and ancillary service capacity are the curtailed PV capacity shown in Case 1. Therefore, using PV to provide ancillary services can improve not only the system reliability level but also PV profitability, especially under a system with high PV penetration.

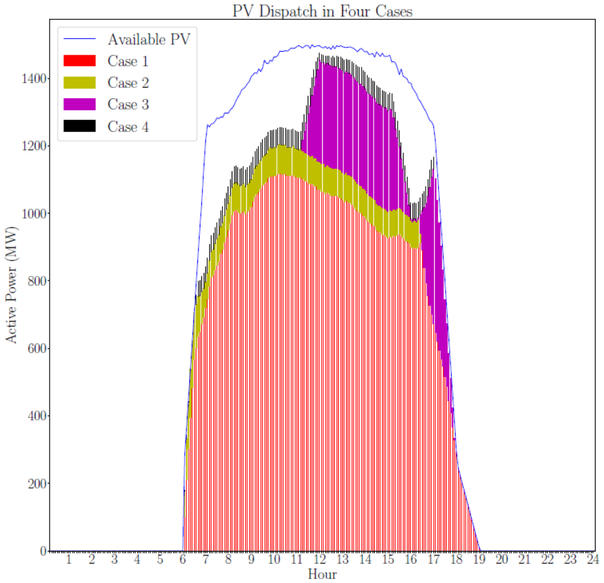

Fig. 6. PV scheduled power output in four cases

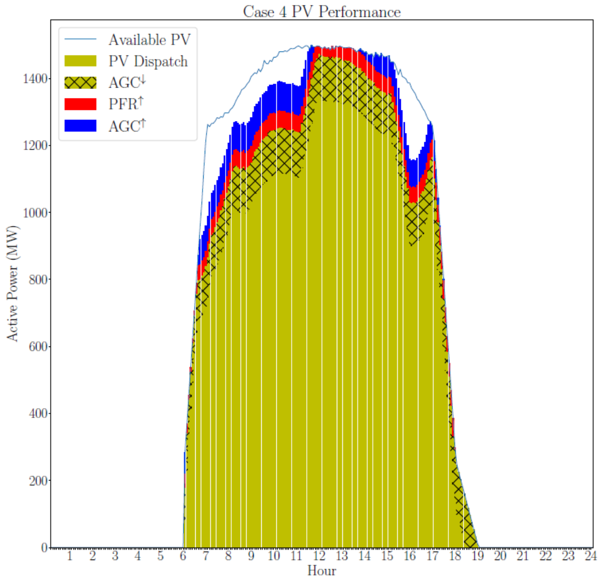

Fig. 7. PV power and ancillary service output in Case 4

TABLE 3. PV CURTAILMENTS IN FOUR CASES

	Case 1	**Case 2**	**Case 3**	**Case 4**
MWh	4,832.27	3,960.97	2,367.87	1,886.17

Fig. 7 demonstrates that the energy provision plus the ancillary service capacities can equal the maximum available PV output during the daytime PV peak period when PV is enabled to provide all ancillary services. This means that PV is fully used even under a high-penetration scenario (50% in this case).

VI. CONCLUSIONS

This paper analyzed the capability and benefit of PV generation to provide regulation and PFR services in system operation. The ancillary service requirement constraints, including regulation-down/-up and PFR, are modeled in the multi-timescale system operation. The simulation results demonstrate that PV power has significant potential to provide regulation-down/-up and PFR services. The system operating costs can be reduced greatly by using the ancillary services from PV. Treating the curtailed PV power as the up-reserve, including regulation-up and PFR services, can help the system to alleviate flexible resource limitations. More interesting, by enabling PV to provide ancillary services, the system can accommodate more PV energy, which will improve not only system reliability but also PV profitability in system operation. Future work will include the detailed revenue analysis of PV power participating in energy and ancillary service markets and the impact of the PV forecasting on ancillary service provision.

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