Interruptible Load Constrained Primary Frequency Response Scheduling with Photovoltaic Generation

Jyoti Sharma[1], Vivek Prakash[2], Rohit Bhakar[1]
[1]Centre for Energy & Environment
[2]Department of Electrical Engineering
Malaviya National Institute of Technology Jaipur, India

***Abstract*—Large penetration of intermittent photovoltaic generation (PV) would pose formidable challenges for utilities, to provide inertial and primary frequency response (PFR). PV generation would reduce the generation share of synchronous generators and hence reduce generator inertia & PFR. This necessitates an additional response from interruptible loads, to make frequency stable following contingency like generation outage. In this regard, this paper proposes a novel interruptible load (IL) constrained PFR scheduling framework with the objective of operation cost minimization. Case studies are carried out on IEEE RTS 24 bus and the performance of the proposed approach is analyzed in terms of PFR, IL and operation cost with variation in PV penetration. Results obtained shows that IL response supports the system frequency at conditions like low demand and minimum inertia following largest generation outage. Proposed model could be potentially enhanced to incorporate response from other load types and technologies like energy storage and electric vehicles.**

***Index Terms*- Unit commitment, interruptible load, PV generation; primary frequency response.**

NOMENCLATURE

Indices

i, NT	Generation unit index and set of generator units.
t, T	Time period index and set of time interval

Variables

$p_{i,t}$	Scheduled power of unit i during time period t (MW)
ΔP_{loss}	Power outage of unit i (MW)
IL	Interruptible load during time period t (MW)
PFR	Primary frequency response
PV_{power}	Power output of PV plant
$C_{i,t}$	Start up and shut down cost of generator i at time interval time t

Binary Variables

$y_{i,t}$	Generator up/down status(1 if unit i is on during time period t otherwise zero)
$y_{i,t}^{su}$	1 if unit i goes into start up at the time interval t otherwise zero
$y_{i,t}^{sd}$	1 if unit i goes into shut down at the time interval t otherwise zero

Parameters and constants

P_t^D	Total power demand during time period t (MW)
$C_{i,t}^{su}$	Startup cost of unit i during time period t ($)
$C_{i,t}^{sd}$	Shut down cost of unit i during time period t ($)
$C_{i,t}^{Run}$	Running cost of unit i during time period t ($)
$c_{i,t}^{f}$	fixed generation cost of unit i during time period t ($)
$e_{i,t}$	Cost coefficient of interruptible load
$b_{i,t}$	Linear generation cost of unit i during time ($)
$a_{i,t}$	Quadratic generation cost of unit i during time
R_i^{up}	Generator unit i ramp up limit(MW/h)
R_i^{dn}	Generator unit i ramp down limit(MW/h)
$Toff_i^{up}$	Generator unit i off time upper limit (h)
$Toff_i^{lo}$	Generator unit i off time lower limit (h)
TNT_i^{md}	Generator unit i, minimum down time at initial time period t
TNT_i^{mu}	Generator unit i, minimum up time at initial time period t
TR_i^{md}	Generator unit i, minimum down time at remaining time period t
TR_i^{mu}	Generator unit i, minimum up time at initial time period t
Apv_t	Availability of PV generation (MW)
H_{Load}^{eq}	Load inertia equivalent (sec)
H_{req}	Requirement of inertia(sec)
H_{sys}	System inertia(MWs)
LF_t	Forecasted load(MW)
$\overline{p_{i,t}}$	Maximum power limit of unit i during time t (MW)

978-1-5386-6159-8/18/$31.00©2018IEEE

$\underline{p_{i,t}}$	Minimum power output of unit i during time t (MW)
SI	System inertia (MW-sec)
$\overline{IL_t}$	Maximum limit of Interruptible load during time t (MW)
$\underline{IL_t}$	Minimum limit of Interruptible load during time t (MW)
t_d	Dead time of governor response (sec)
A	Area of PV panel (m^2)
$\eta^{Conversion}$	Conversion efficiency of solar panel
θ	Tilt angle of PV array (degree)
PF	Performance Factor
SR	Solar radiation (watt/$m^{2)}$

I. Introduction

Sub-sequential low carbon energy systems with a large share of wind & PV generation would play a vital role in socio-economic and environmental sustainability. These low carbon energy systems have potential to feed increasing energy demand. Larger integration of these resources into the grid will displace the conventional generation at a fast rate. Hence, this would pose operational challenge for the utilities such as system inertia reduction, weakening of system strength, increase in distributed generation and the prospect of advance technologies interface with the grid [1], [2].

During any contingent event like largest infeed loss or loss of large chunk of load, an automatic control action is taken by the system to retain system frequency at permissible limit. This automatic control action against frequency deviation is known as frequency response (FR) [3]. Conventionally, synchronous generators have the competency to grant inertia to trap the frequency deviations within initial few seconds and provide more time to generator governor for providing PFR. Penetration of large intermittent renewables to the power system reduces system inertia and PFR capability [4]. The imbalance between generation and demand is maintained either by increasing output from generators or shedding the load. Load shedding is an emergency control and could not be practiced in routine.

As the integration of renewable generation would increase at faster pace thus, PFR is expected to decline continuously, this necessitates an economical solution to improve system PFR adequacy. In this regard, this paper proposes a load response method, in which interruptible load (IL) resources are scheduled to automatically arrest frequency deviation following contingency like largest infeed loss and, thus, prevent emergency control like load shedding. IL is large commercial or industrial load which is able to switch off and shift their load whenever it is requested by utility with prior information. It is considered as secondary frequency response in the literature [5]–[7]. Earlier, load side controlling was considered as uncontrollable [8]-[10]. Nowadays, flourishing flexible load plays a vital role in providing PFR. These smart load shifts their load during the contingent event. Concept of Frequency Adaptive Power Energy Reschedule (FAPER) is reported [11]. These FAPER type controllers are designed for PFR. According to Pacific Northwest National Laboratory (PNNL) these grid friendly controller are set in to appliances and sense frequency deviation as result these equipment change their consumption over time until frequency do not stabilize. This load side response reduces the requirement of extra reserve cost. PNNL investigated the PFR capability of IL. It is inferred that IL is conceivable to deliver PFR. It is further observed that there are fewer chances with autonomous load response to degrade system reliability [12]. Hence, PFR adequacy is a timely research domain that requires in-depth investigation and the use of IL may play a significant role. IL, PFR contribution in scheduling problem with PV generation is given little attention in the literature and hence, requires wider investigation.

In this context main contribution of this paper could be summarized as follows:

(i) It proposes a novel IL constrained scheduling formulation concept that includes system's inertia & PFR constraints for assessment of systems' frequency response following largest generator outage.

(ii) It provides PFR schedules of committed generators and available IL response following a largest infeed loss.

(iii) It demonstrates the efficacy of the proposed model on IEEE 24 bus system for their PFR scheduling performance & cost performance with varying PV penetration.

Rest of the paper is as follows: In Section II, security limits for frequency stability is discussed along with PV power calculation. Section III describes problem formulation of the proposed scheduling model. Section IV discusses case studies and Section V draws conclusions.

II. Problem Description

A. System Frequency Security Limits

Detention of frequency deviation from its prescribed security limits, following contingencies is a primary concern for the interconnections. Security criteria that effect frequency response parameters like PFR capability, RoCoF (Rate of change of frequency), frequency deviation and steady state frequency.

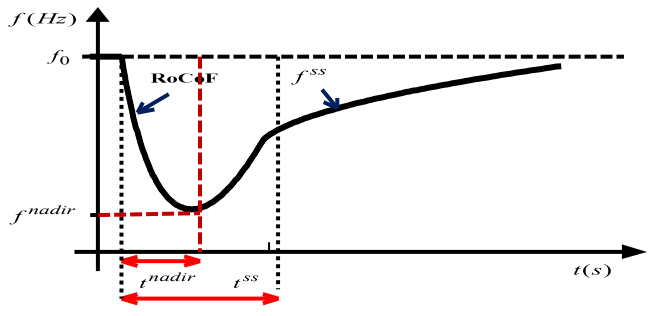

Fig.1. Frequency response characteristics following infeed loss [13]

RoCoF depends on the synchronized inertial response and the capacity of generation outage. The increasing RoCoF can violate generator protection settings and lead to detach of the demand. Therefore, PFR should inhibit frequency above frequency nadir and stabilize above steady state frequency. Full PFR is required to deliver between 10 s and 30 s [13]. This would depend on the droop constant setting, deadband, available headroom and load damping rate. Fig. 1 depicts frequency response characteristics following any contingency. It could be observed that frequency gets stabilized at intermediate level within 30 s.

As system inertia decreases, RoCoF increases and this in turn increases the PFR requirement. RoCoF and f^{nadir} are deciding factors for protection system to actuate. If frequency fails to be in range, under load frequency shedding acts as a protective measure for the system.

B. Solar Radiation to Power Conversion

PV variable generation is calculated using PV area, conversion efficiency of solar module, geographic location, tilt angle of PV array and performance factor. PV power varies according to atmospheric condition. In this model, PV power availability is considered for t8 to t17 hours. Power output is given by equation (1).

$$PV_{power} = A * \eta^{Conversion} * \theta * \mathrm{P}F * SR \tag{1}$$

III. Problem Formulation

The main objective of IL constrained generation scheduling is to minimize operation cost. It increases security of supply and provide PFR to the system. The objective function can be expressed as-

$$\min C = \begin{bmatrix} \sum_{t=1}^{T}\sum_{i=1}^{NT} \{ y_{i,t}^{su} C_{i,t}^{su} + y_{i,t}^{sd} C_{i,t}^{sd} + C_{i,t}^{Run}(y_{i,t}, p_{i,t}) \} \\ + \sum_{t=1}^{T}\sum_{i=1}^{NT} e_{i,t}(\mathrm{IL}_{i,t}) \end{bmatrix} \tag{2}$$

Where, C represents the total operating cost.

Objective function includes startup cost, shut down cost, running cost and IL cost. The running cost of unit i is given by Eqn. (3).

$$C_{i,t}^{Run}(y_{i,t}, p_{i,t}) = (c_{i,t}^{f} + b_{i,t} p_{i,t} + a_{i,t}(p_{i,t})^2) \times y_{i,t}, \quad \forall t \in T, i \in NT \tag{3}$$

Running cost function includes the fixed cost, linear generation cost and quadratic cost function. Objective function is subject to following generator and IL constraint.

A. Generator Start Up/Shut Down Constraints:

$$y_{i,t}^{up} - y_{i,t}^{dn} = y_{i,t} - y_{i,t-1} \qquad \forall t \in T, i \in NT \tag{4}$$

$$y_{i,t}^{up} + y_{i,t}^{dn} \le 1 \qquad \forall t \in T, i \in NT \tag{5}$$

Constraint (4) determines the generator startup or shutdown status at time interval t and $t-1$. Constraint (5) inhibit the generator to startup and shutdown within same time interval.

B. Minimum Up/Down Times:

$$y_{i,t} = y_{i,t_0}, \ \forall t \in \left[0, TNT_i^{mu} + TNT_i^{md}\right], i \in NT \tag{6}$$

$$\sum_{t-TR_i^{mu}+1} y_i^{up} \le y_{i,t}, \ \forall t \in \left[TNT_i^{mu}, T\right], i \in NT \tag{7}$$

$$\sum_{t-TR_i^{md}+1} y_i^{dn} \le 1 - y_{i,t}, \ \forall t \in \left[TNT_i^{md}, T\right], i \in NT \tag{8}$$

Constraint (6) gives the on/off status based on generator initial status. If first $T_i^{mu} + T_i^{md}$ hours is zero then $t_0 = 0$ Constraints (7) and (8) grant minimum up and down time for the rest time periods.

C. Generator Start-Up Cost:

$$C_{i,t} \le \sum_{Toff_i^{lo}}^{Toff_i^{up}} y_{i,t}^{dn}, \qquad \forall t \in T, i \in NT \tag{9}$$

$$\sum C_{i,t} = y_{up_{i,t}}, \qquad \forall t \in T, i \in NT \tag{10}$$

$$C_{i,t} = \sum C_{i,t}^{su} . C_{i,t}, \qquad \forall t \in T, i \in NT \tag{11}$$

Constraint (9) finds the correct point of generator start up curve at which generator has not been in service. Constraint (9) assures if $y_{i,t}^{up} = 1$ then $C_{i,t} = 1$. Constraint (11) determines the exact value of startup cost of generator.

D. Generator Constraints:

$$0 \le p_{i,t} \le y_{i,t} \overline{p_{i,t}} \quad \forall i \in NT, t \in T \tag{12}$$

$$-R_i^{dn} \le P_{i,t} - P_{i,t-1} \le R_i^{up} \tag{13}$$

Constraint (12) shows minimum and maximum limit of generation output. Ramp up and ramp down limit for each unit is determined by the constraint (13).

E. Operational Constraints with IL:

IL requirement for each hour is shown by the equation (14).

$$IL_t = P_t^D - \left(\sum_{t=1}^{T}\sum_{i=1}^{NT} y_{i,t} p_{i,t} + Apv_t \right) \quad \forall t \in T, i \in NT \tag{14}$$

Required IL capacity is calculated for each hour.

Subject to:

$$0 \le IL(t) \le \overline{IL} \tag{15}$$

$$IL_t \le \overline{IL_t} \tag{16}$$

Constraint (15) determine the minimum and maximum limit of interruptible load. Required interruptible load limit should always less than maximum limit of IL is shown by constraint (16).

F. Power Balance Constraint:

$$P_t^D = \sum_{t=1}^{T}\sum_{i=1}^{NT} y_{i,t} p_{i,t} + Apv_t \qquad \forall t \in T, i \in NT \tag{15}$$

Power balance equation consists the conventional thermal unit generation, availability of PV power generation. These all parameter should be balanced by the demand of total power in each hour. Net load calculation with PV penetration is given by Eqn. (16) as the difference between demand and availability of PV power for each hour.

$$Netload = P_t^D - Apv_t \tag{16}$$

Net load should be satisfied by the energy balance constraint.

$$\sum_{t=1}^{T}\sum_{i=1}^{NT} y_{i,t} * p_{i,t} = Netload \tag{17}$$

G. Frequency Response Constraints

Frequency response modelling is discussed in this section. Frequency behaviour after large imbalances, like large infeed loss, could be described using the motion equation of synchronously connected rotating mass, known as swing equation, and as shown in Eqn. (18).

$$2H_i \frac{df_i}{dt} = \frac{f_0^{\,2}}{Ap_{ni} f_i} \Delta P \tag{18}$$

Here, Ap_{ni} is the rated apparent power of generator i (VA), f_0 (Hz) is the nominal frequency, H_i (s) is the inertia constant of i and ΔP (MW) is the generation outage. Eqn. (19) could be expressed in terms of total system inertia and equivalent system frequency as:

$$RoCoF = \frac{df_{eq}}{dt} = f_0 \frac{\Delta P}{2H_{sys} Ap_{ni}} \tag{19}$$

From (19), it could be observed that as H_{sys} decreases, ROCOF would increase. That would lead to a higher frequency excursion and deeper f^{nadir} value at nadir time, t^{nadir} .

Governor response during inertial response time frame is negligible, as Δf is approximately zero. Hence, maximum value of ROCOF should satisfy minimum H_{sys} in case of maximum infeed loss, as mentioned in Eqn. (20).

$$H_{sys} = \frac{\sum_{i \in I} H_i * Ap_{ni} * y_{i,t} - \Delta P}{f_0} \geq \left| \frac{\Delta P}{2 * ROCOF_{\max}} \right| \tag{20}$$

Constraint (21) guarantees that sufficient inertial response is available, so that $ROCOF_{\max}$ does not cause instability.

$$\sum_{i \in I} \left\{ y_{i,t} * H_i * P_i^{\max} \right\} + H_{Load}^{eq} * LF_{t,} \geq H_{req} \quad \forall t \in T \tag{21}$$

After deployment of inertial response available with the system, governor PFR is deployed with maximum ramp rate. Eqn. (22) is formulated, such that available response is greater than the required response. Here, $Pf_{i,t}$ is the available PFR from generator i at time t , Pf_R^c is required PFR capacity, L^D is load damping rate and T^{de} is the PFR delivery time.

$$\sum_{i \in I} Pf_{i,t} \geq Pf_R^C - L^D * T^{de} * \frac{\Delta f^{\max}}{f_0}, \quad \forall t \in T \tag{22}$$

Eqn. (23) determines Δf^{nadir} , which depends on PFR delivered by generators and system inertia. Eqn. (24) determines the quasi-steady-state frequency value.

Frequency nadir is the lowest range of frequency during contingent event. Here Δf^{ss} is steady state frequency (Hz).

$$\Delta f^{nadir}(t) = -1 / H_{sys}(t) * ((\Delta p^2 / 2Pf_{i,t}) + \Delta p * T^{de}) \tag{23}$$

$$\Delta f^{ss} = \frac{\Delta P - Pf_{i,t}}{LD * LF_t} \leq \Delta f^{nadir} \tag{24}$$

IV. Case Study

IEEE RTS 24 bus system is used for this study [14]. The system consists of 24 buses and 12 generators. The total installed capacity of generators is 3375 MW and PV plant capacity is 300 MW with peak load demand 2650.5 MW. Generator characteristics, like heat rate, ramping rate, maximum and minimum capacity, minimum up and minimum down time and system dynamic parameters are considered. Fuel cost is obtained from [15]. The data is modified to include 300 MW generation from PV. Nominal frequency (f_0) of 50 Hz, governor droop of 5%, frequency dead band of 15 mHz and delivery time (T^{de}=10s) are chosen considering National Grid standards [16]. Maximum ROCOF of 1.176 Hz/s is considered for the studied test system, to avoid under frequency load shedding after largest infeed loss [17]. Two large nuclear plant with 400MW capacity is within the system and infeed loss of one of the unit is considered. Steady state frequency should be controlled before 49.5 Hz. System PFR capacity should limit $\Delta f^{\max}$ up to a minimum value of 49.2 Hz. Maximum PFR capacity requirements is assumed to be 30% of the total responsive capacity, while maximum allowed dead band for all governors should be greater than 100 mHz [18]. The penetration of PV plants is varied from 0% to 30%. Table I, shows IL parameters considered for this work.

TABLE I

IL PARAMETER

Offered IL Cost e_i (\$)	$\overline{IL}_t$ (MW)	$\underline{IL}$ (MW)	ΔP_{Loss} (MW)
0.2	100	0	400

Fig.2. shows the availability hours of PV power output in a profile of 24hrs.

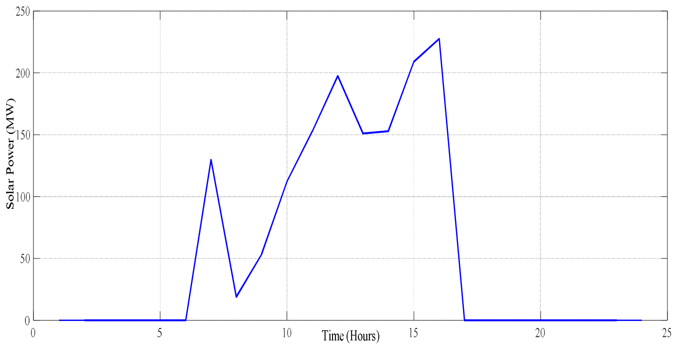

Fig.2. Generated PV power

A. IL Response with Increasing PV Penetration

This section provides IL response variation with incremental PV penetration as net load of the system is getting reduced as shown in Fig.3. There would be less system inertia available and in turn higher ROCOF as shown in Fig.4. This reduced inertia requires large PFR capacity. Fig. 4 depicts about variation in the net load with different PV penetration.

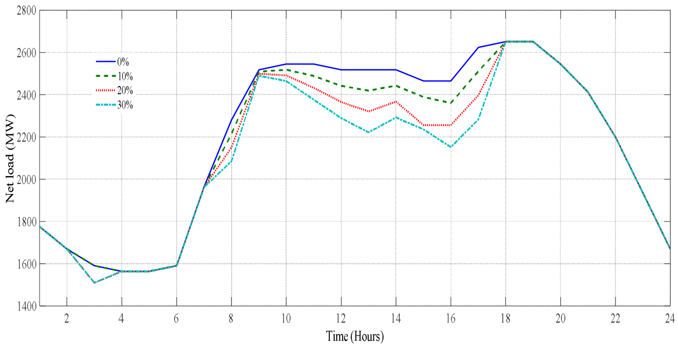

Fig.3. Net load variation with PV penetration.

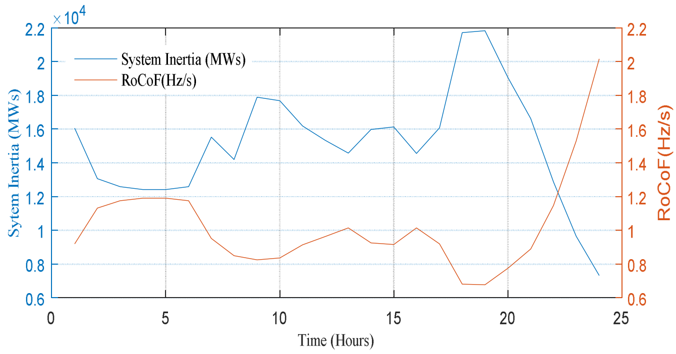

Fig.4. ROCOF variation in response to inertia variation for 24 Hrs.

TABLE II
FR PARAMETER VARIATION WITH PV PENETRATION

PVs (%)	RoCoF (Hz/s)	fdev (Hz)	PFR (MW)	IL (MW)
0%	0.544-0.871	-0.054- -0.105	116.49-146.16	0.009-55.8
10%	0.558-0.880	-0.058- -0.110	114.45-140.16	0.009-57.2
20%	0.676-0.174	-0.070- -0.124	100.75-282.67	0.008-53.3
30%	0.785-1.958	-0.075- -0.128	98.45-278.59	0.009-57.5

In table II, avialbale IL response along with FR parameter like ROCOF,frequency deviation and available generator PFR with PV penetration from 0% to 30% is presented. It could be observed that with increment in PV penetration there is high ROCOF along with increased frequency deviation. Fig.5. shows variation of IL with variation in net load. When PV penetration is higher, IL response is also high. This is because of increased PFR requirement. As these PVs are not able to provide inertial response and would require additional PFR capacity, to make system frequency stable.

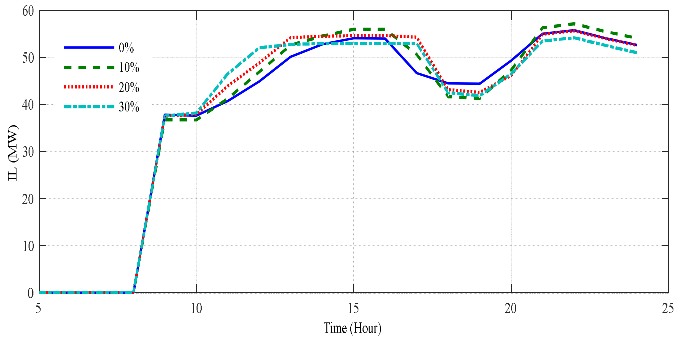

Fig.5. IL variation in each hour with increasing PV penetration

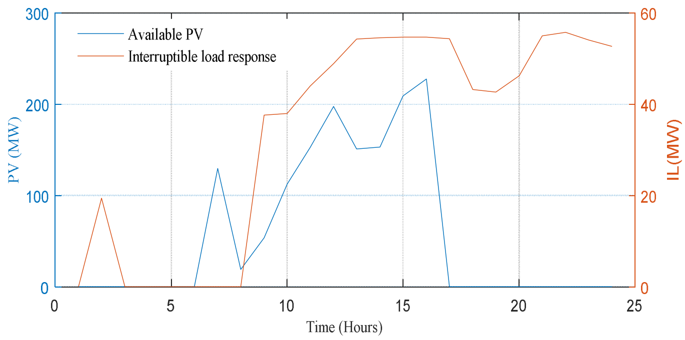

Fig.6. IL response with availaible PV power

Fig.6. shows IL response over the day with 20% PV power penetartion. It could be observe that when there is no PV or demand is reduced, IL is providing response requirement. When there is PV power available, there is reduced net load and increased PFR requirement. At these hours IL is providing the required response.

B. *Operation Cost Variation with Increasing PV Penetration*

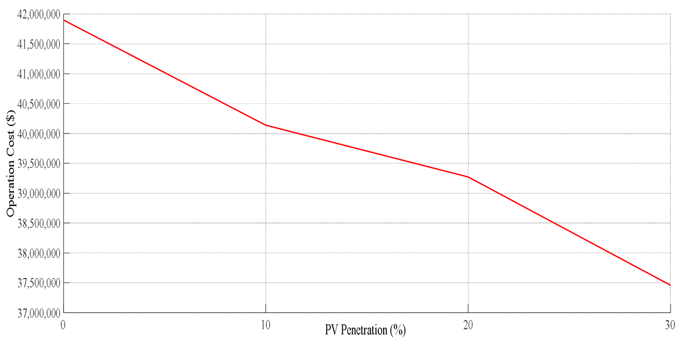

Fig.7. Operation Cost variation with increasing PV penetration

Fig.7. Shows the operation cost variation with increasing PV penetration. It could be observed when PV penetration is increased from 0% to 30%, operation cost reduces. Increasing PV penetration reduce the net load resulting in reduced number of synchronous generator committed per hour. IL offered cost is 0.1% of total operation cost which is not much higher. Hence, overall operation cost is reduced.

V. CONCLUSION

This paper proposes a novel IL constrained generation scheduling framework for PFR adequacy, to improve frequency control capability for low carbon generation systems. Net load is estimated in the presence of varying PV penetration for the proposed IL constrained UC model. System performance is being analyzed with respect to operating cost, system inertia, PFR from IL and frequency deviation. Numerical results show that with incorporation of IL, system's PFR capability is improved significantly. Further, it is observed that operation cost of the system reduces with increased penetration of PV, as these generation sources are having negligible operation cost. Proposed work could be potentially enhanced by considering PV power uncertainty along with formulation of IL contract in providing PFR.

VI. ACKNOWLEDEMENT

This work is supported by the DST grant for the UI-ASSIST project.

REFERENCES

[1] S. Sharma, S. Huang, and N. Sarma, "System inertial frequency response estimation and impact of renewable resources in ERCOT interconnection*," IEEE PES GM*, San Diego, July 2011.

[2] R. Doherty et al., "An assessment of the impact of wind generation on system frequency control," *IEEE Trans. Power Syst*., vol. 25, no. 1, pp. 452–60, Jan. 2010.

[3] North American Electric Reliability Corporation, "Frequency response initiative report—The reliability role of frequency response," NREC, Washington DC, USA, Tech. Rep., Oct. 2012.

[4] NERC, Frequency Response Initiative Report, North American Electric Reliability Council, Atlanta, GA, USA, Tech. Rep., Oct. 2012.

[5] B. Kirby, Spinning Reserve From Responsive Loads, Oak Ridge National Laboratory, Oak Ridge, TN, USA, Tech. Rep., Mar. 2003.

[6] O. Ma *et al.*, "Demand response for ancillary services," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1988–1995, 2013.

[7] L. Tuan and K. Bhattacharya, "Competitive framework for procurement of interruptible load services," *IEEE Trans. Power Syst.*, vol. 18, no. 2, pp. 889–897, May 2003.

[8] A. M. García, F. Bouffard and D. S. Kirschen,"Decentralized demand-side contribution to primary frequency control" *IEEE Trans. Power Systems*, vol. 26, no. 1, pp. 411-419, Feb. 2011

[9] J. Liu, W. Zhang, and Y. Liu "Primary frequency response from the controlling of LED lighting loads in commercial buildings" *IEEE Trans. Smart Grid*, vol. 8, no.6 ,pp. 2880-2889 , Nov. 2016.

[10] H. W. Qazi, D. Flynn and Z. H. Rather "Impact of electric vehicle load response variation on frequency stability" *PES ISGT Conf*., Europe, Feb. 2017.

[11] V. Trovato , S. H. Tindemans and G. Strbac, "Demand response contribution to effective inertia for system security in the GB 2020 gone green scenario" *PES ISGT Conf.,* Europe, Jan. 2014.

[12] M. Donnelly, S. Mattix, D. Trudnowski, and J. Dagle, Autonomous Demand Response for Primary Frequency Regulation, Pacific Northwest National Laboratory, Oak Ridge, TN, USA, Tech. Rep., Jan. 2003.

[13] V.Prakash,K.C.Sharma,R.Bhakar *et.al*, "Primary frequency response with stochastic scheduling under uncertain photovoltaic generation", *IEEE PES GM*, *Chicago*, 16-20 July 2017.

[14] Reliability Test System Task Force, "The IEEE reliability test system—1996," *IEEE Trans. Power Syst*., vol. 14, no. 3, pp. 1010–1020, Aug. 1999.

[15] "U.S. Energy Information Administration. 'Short-Term Energy Outlook," [Online].Available: http://www.eia.gov/forecasts/steo.

[16] "National Grid, Security and Quality of Supply Standards." [Online]. Available: http://www2.nationalgrid.com/UK/Industry-information/Electricity-codes/System-Security-and-Quality-of-Supply-Standards/.

[17] "International review of frequency control adaptation," Oct. 2016, [Online]. Available: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/FPSS-International-Review-of-Frequency-Control.pdf.

[18] V. Prakash, K. C. Sharma, R. Bhakar, H. P. Tiwari and F. Li, "Frequency response constrained modified Interval Scheduling Under Wind Uncertainty," *IEEE Trans. Sust. Energy*, vol. 9, no. 1, pp. 302-310, Jan. 2018.