Sequential Optimization of Energy and Reserve Market by Optimal Placement of Renewable Energy Sources Including Participation of Pumped Storage Plant

Ritu Jain[1] and Vasundhara Mahajan[1,*]

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A B S T R A C T

This paper presents the sequential optimization of both energy market (EM) and reserve market (RM) with renewable energy sources (RES). Since RES is intermittent in nature, probability distribution function (PDF) is utilized to model its uncertainty. The wind and solar based distributed generation (DG) are placed at the optimal location in order to minimize the total generation cost of energy in both EM and RM, including the generation cost of pumped storage plant (PSP). This work utilizes two approaches for optimally placing the DG. First technique focuses on higher Locational Marginal Price (LMP), second relies on higher consumer payment method. Economic parameters like DG profit, load payment and system generation cost are compared for both the approaches. The DG size is increased from 5% to 25% of peak load for optimal DG penetration. The DG placement with higher customer payment method reduces generation cost and load payment by 1.14 % and 0.54 % respectively. It is observed that participation of DGs and PSP minimize the system cost. The placement of PSP results in 0.66% and 0.44% reduction in load payment and generation cost, respectively. The IEEE 30 bus system is the used to perform this study.

1. INTRODUCTION

The traditional power industry is made up of a vertically integrated system that includes generation, transmission, and distribution. The price of energy is quite high due to the monopoly in the system, and the consumer has no option for service providers. However, the world has witnessed the deregulation of the electrical grid in recent decades. The primary goal of deregulation is to bring competition to the market and eliminate monopoly [1]. This controls the continuous rise of energy price and increases the social benefit. The competitive market comprised of privately and pool negotiated contracts. The social welfare is used to evaluate the performance of market. Social welfare is the term used to describe the gap between the consumer payment and the generation cost. Due to transmission open access (TOA) and the steady increase in energy demand, independent system operators (ISO) are finding it challenging to maintain system security and resilience [2]. TOA allows any market participant to use a third-party-controlled transmission network. As a result, the transmission lines get overloaded, causing problems in the system.

Studies on the transmission congestion and cost management have led to the establishment of bilateral and pool electricity market models. The congestion in lines can be reduced by the rescheduling of generators [3], load shedding, by use of FACTs devices [4-6] and incorporation of distributed generation (DG) [7-14]. DG is the small decentralized power plants placed closed to the load centers. Different authors have proposed different types of DGs in their research. According to Ref [15], there are four types of DG. Whereas, five types of renewable energy generators (REGs) are proposed in Ref [16]. The Type 1 REG injects only real power, the Type 2 injects only reactive power, the Type 3 injects both real and reactive power at varying power factors, and the Type 4 injects both real and reactive power in conjunction with the Types 1 and 2. In Type5, multi REGs provide real power. Based on size it is categorized into micro, small, medium and large DG. Due to industrialization there is continuous rise in energy demand. This demand has to be fulfilled in order to maintain the demand and supply balance. Earlier the power system is dependent on fossil fuel based conventional energy sources (CESs) for the supply of demand. Increased reliance on fossil fuels has a negative impact on the environment by causing green house gas (GHG) emissions that severely impact the climate [17].

Thus, Renewable Energy Source (RES) presents a possible alternative scenario for reducing GHG emissions. Accordingly, share of power generation through RES is rising and power generation through CESs like coal, oil, and gas is witnessing a decreasing tendency. Though, RES

[1]*Sardar Vallabhbhai National Institute of Technology, Surat-395007, Gujarat, India.*
**Corresponding author:* Vasundhara Mahajan; Email: vmahajan@eed.svnit.ac.in.

presents a more viable alternative, but it increases the load on power system operations, due to its variable and intermittent nature. Now that RES availability is unpredictable, ISO's duty of managing energy has become more challenging [18]. The system operator's biggest challenge now is to deal with uncertainties. Under the penetration of RES, it becomes crucial to make precise decisions for the secure operation of the electricity system.

In the power system, there are a number of uncertain parameters that should be considered before making any decisions. These include technical elements like line outages and generator outages, operational parameters like load demand and generating output, and economic parameters like governmental regulations, fuel prices, and economic growth. In order to optimize market benefits, it is crucial for RES based generation companies to forecast their production and make appropriate market bids. When generating firms make decisions, they must consider two important factors: RES variability and unpredictability. Because RES is intermittent and non-dispatchable, it should be equipped with energy storage devices to enhance its efficiency. Because DG is near to load, its adoption in deregulated electricity system helps to alleviate transmission line congestion. When DG is employed in the system it offers a number of advantages, including cost savings, less impact on the environment and technological benefits. Although its location and size must be appropriate, otherwise it could increase power loss and congestion, making the system unreliable [19-25].

To effectively meet the real demand and supply gap in energy market we need ancillary services (AS), which can reduce the pressure on electrical equipment and thereby reduce failure rates [26]. Ancillary Services are further divided into voltage control services (via reactive power support), frequency control services (such as load following, regulation and operating reserves), and emergency services (via black-start) and are recognized as the primary AS in almost all electricity markets [27]. Through spinning reserve, the grid can be synchronized and effectively deploy the idle capacity within ten minutes of receiving dispatch signals from the ISO. Market clearing process involves the determination of quantity to be traded at nodal price. For clearing the energy market (EM) and AS market, ISO employs a variety of techniques [28].

Merit order dispatch (MOD): In this the independent stacks of energy amount and offers are taken into account for the EM and AS market. After that, the bid blocks are organized in merit order. After then, the energy market is dispatched until the load and the demand are equal. For the AS market, the identical procedure is done. If EM and AS markets are coupled then this technique is straightforward and simple to comprehend. But if there is no coupling between the products, the results will be impractical. Coupling means that the total of energy and reserve dispatch should be within unit maximum limit.

Sequential dispatch optimization: The energy and AS markets have the same generation limit in this case. The energy and AS markets are dispatched sequentially and independently. The EM market gets cleared first, followed by the AS market. Because both markets are dispatched separately, thus determining the winner is simple.

Simultaneous optimization: The purpose of this method is to distribute a large number of indivisible products to bidders while minimizing the total cost for delivering energy and AS. It is challenging to justify the schedule and cost with this mechanism. This technique shows strong coupling between the products as compared to others.

Various researchers have worked on different methods of market clearing techniques with/without placement of DG but none of them have shown focused on the optimal location and size of DG [29-34]. In [35], the sequential optimization of energy and reserve market (RM) is done but the probabilistic approach for wind and solar modeling is not incorporated. In [36], simultaneous optimization of both EM and ASM is performed but the placement of RES is not optimal. For optimal placement of DG, higher LMP and higher customer payment method is discussed in Ref. [37].

In this study, two different methodologies for optimum DG placement is considered and comparative analysis between both the approaches is performed considering the economic parameters of the system. The first approach is based on higher LMP based method and second is based on higher customer payment method. The DG size is increased from 5% to 25% of peak load to find the optimum DG penetration. The impact of its size and placement methods on DG owner profit, generator cost and load payment are observed. Pumped Storage Plant (PSP) is employed to absorbs the surplus power of RES and participate in energy and reserve market. It also acts as standby reserve. The major contribution of this paper is highlighted below.

1. The sequential optimization of energy and reserve market is performed considering RES and PSP based energy storage.
2. The wind and solar power modeling are formulated with corresponding probability distribution function (PDF).
3. Two different methods are used for optimal placement of DG i.e. higher LMP based method and customer payment-based method.
4. The comparative analysis between both the placement method of DG is performed considering economic parameters.
5. The effect of DG size on DG owner profit, generation cost and load payment are also observed.
6. For effectively utilizing the non-dispatchable generating units like solar and wind plants, PSP is used as energy storage device.
7. The dispatch of all the generation is observed in both energy and reserve market.

2. UNCERTAINITY MODELING OF WIND SPEED AND SOLAR INSOLATION

2.1. Wind turbine generator modeling

Wind energy is the widely used non-conventional sources of energy. The power output of a wind turbine generator (WTG) is proportional to the wind speed, as given in Eq. 1 [38].

$$P_w = \frac{1}{2} \times \rho \times A \times v^3 \tag{1}$$

where, Pw is the power produced by WTG, A is the blade area in m^2, v is the wind speed in m/sec and ρ is the density of air in kg/m^3. The Eq. 2 defines the power produced by WTG.

$$P_{WT} = \begin{cases} 0; v < v_i, v > v_o \\ P_{rated} \times \dfrac{(v - v_i)}{v_r - v_i}; v_i < v < v_r \\ P_{rated}; v_r < v < v_o \end{cases} \tag{2}$$

where, P_{rated} denotes the rated power of WTG. v_i, v_r and v_o represents the cut-in, rated and cut-out wind speed in m/sec. Eq.3 states the Weibull PDF for wind speed [39]. Here, form factor is k and the scale factor is c. In Rayleigh PDF has a value of 2 for k. This PDF has high and low wind speed intervals.

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{\left\{-\left(\frac{v}{c}\right)^k\right\}} \tag{3}$$

2.2. Solar Power Uncertainty modeling

For solar uncertainty modeling beta pdf is used [40].

$$f_{pv}(ir) = \begin{cases} \left(\dfrac{\Gamma(\alpha_i + \beta_i)}{\Gamma(\alpha_i)\Gamma(\beta_i)} \times ir^{\alpha_i - 1} * (1 - ir)^{(\beta_i - 1)}, \;\; for \;\; 0 \le ir \le 1, \alpha_i \ge 0, \beta_i \ge 0\right. \\ 0, otherwise \end{cases} \tag{4}$$

Eq. 5 can be used to calculate alpha and beta; where μ and σ represents mean and standard deviation of solar insolation respectively.

$$\begin{aligned} \beta_i &= (1-\mu) \times \left(\frac{\mu \times (1+\mu)}{\sigma^2} - 1\right) \\ \alpha_i &= \frac{\mu \times \beta_i}{1-\mu} \end{aligned} \tag{5}$$

The power of PV module is calculated using Eq.6 to Eq.10.

$$P_{pv}(hr) = N \times FF \times V(hr) \times I(hr) \tag{6}$$

$$FF = \frac{V_{MPP} \times I_{MPP}}{V_{ocv} \times I_{scc}} \tag{7}$$

$$V(hr) = V_{ocv} - k_v \times T_{cl} \tag{8}$$

$$I(hr) = S_i \times [I_{scc} + k_i(T_{cl} - 25)] \tag{9}$$

$$T_{cl} = T_a + S_i \times \left(\frac{N_{OT} - 20}{0.8}\right) \tag{10}$$

where, P_{pv} is output power of PV plant. FF and hr is fill factor and time in hours respectively. The maximum power point's voltage and current, measured in volts and amperes, are known as V_{MPP} and I_{MPP}. The open circuit voltages and short circuit current are designated as V_{ocv} and I_{scc}. S_i is the solar irradiance and N_{OT} is the normal operating temperature. The ambient and cell temperatures of a PV cell are T_a and T_{cl} in ◦C.

3. PROPOSED METHODOLOGY AND OBJECTIVE FUNCTION

3.1. Locational Marginal Price (LMP)

The price of supplying additional MW at the specific node is referred as the LMP or nodal price. It helps market players to calculate the spot price of a specific bus. The LMP is comprised of three primary components; energy cost (LMP_n^{ref}), congestion cost (LMP_n^{cong}) and cost due to losses (LMP_n^{loss}) [1, 41].

$$LMP_n = LMP_n^{ref} + LMP_n^{cong} + LMP_n^{loss} \tag{11}$$

$$LMP_n^{ref} = \lambda \tag{12}$$

$$LMP_n^{loss} = (DF_n - 1) * LMP_n^{ref} \tag{13}$$

$$LMP_n^{cong} = \sum_{k \in K} GSF_{nk} * \beta_k \tag{14}$$

Here, LMP_n denotes the LMP at bus n. Here, the generating shift factor of bus n on line k is denoted by GSF_{nk} while the delivery factor is denoted by DF_n.

3.2. Proposed Methodology

In power market, the generation and distribution companies submit their bids/offers in day-ahead market. In this paper, only the generator bids for energy and price in both EM and RM is considered. Customers do not participate in bidding. The market model considered is based on sequential dispatch mechanism. The energy market is cleared first and then from the available capacity, the reserve is dispatched. The major factor influencing the widespread adoption of this approach is its simplicity and transparency. The approach is shown in Fig. 1.

The first step is to run OPF for the base case when only conventional generators (CGs) are present and there is no DG in the system. For this case, LMP and customer payment at every load bus is calculated. The details of both the methods is explained below [37].

Higher LMP method: The LMP is used as the key factor to manage and locate congestion. It is defined as the amount of supplying 1 MW of additional power to the particular bus [41, 42]. In this higher LMP method, load buses are positioned in decreasing order of their LMPs and the top buses are selected for DG placement.

$$LMP = [LMP_1, LMP_2 ....LMP_n] \tag{15}$$

$$DG_{SITE} = index(\max(LMP)) \tag{16}$$

Higher customer payment method: Customer payment is calculated by the multiplication of load in MW with the LMP at that specific bus.

$$Cpay_n = LMP_n * Load_n \tag{17}$$

$$DG_{SITE} = index(\max(Cpay)) \tag{18}$$

In order to incorporate DG in the system it is essential to identify its type, location and penetration. After identifying the optimal site for DG by above methods, it is necessary to find its size. For DG penetration, the size of DG is increased from 5% to 25% of peak load and its effect on DG owner profit and generation cost is analyzed for both the approaches. The type of DG incorporated in this work is based on renewable energy sources. Two DGs are placed one is based on wind turbine generator and the DG2 is based on solar PV. The uncertainty associated with RES is modeled through their probability distribution function. Rayleigh and beta pdf are used for wind and solar irradiance modeling respectively. In the vertically integrated systems, for reduction of the fuel cost and emission, hydro-thermal coordination is implemented. The system base load is provided by the hydropower plant and the peak load is provided by thermal, nuclear and PSP. In this study, the PSP plant is integrated with non-conventional energy sources to optimally utilize their capacity. When after EM clearance, excess of RES is available then this energy is pumped to the PSP plant for storage, so it can be used in the next interval in the EM and RM markets. Fig. 2 depicts a flowchart that explains the methodology.

If $P_{iCG,RC_{avl}}(h)$, $P_{iWP,RC_{avl}}(h)$ and $P_{iPV,RC_{avl}}(h)$ is the remaining capacity (RC) by conventional generators, wind plant (WP) and solar plant respectively after energy market clearance.

$$P_{iCG,RC_{avl}}(h) = P_{iCG,\max}(h) - P_{iCG,E_{sch}}(h) \tag{19}$$

$$P_{iWP,RC_{avl}}(h) = P_{iWP,\max}(h) - P_{iWP,E_{sch}}(h) \tag{20}$$

$$P_{iPV,RC_{avl}}(h) = P_{iPV,\max}(h) - P_{iPV,E_{sch}}(h) \tag{21}$$

After the clearing of energy market at each hour, reserve energy available with conventional generator is the minimum of ramp rate and the remaining capacity. Here RR is the 10 mins ramp rate for CGs and $P_{iCG,R_{avl}}(h)$ is the reserve available by CGs to participate in reserve market.

$$P_{iCG,R_{avl}}(h) = \min(P_{iCG,RC_{avl}}(h), RR) \tag{22}$$

The residual (or surplus) RES is dumped if energy storage is not connected to it. If PSP is connected to RES then it will store the surplus energy and deliver the stored power in next interval. The surplus capacity from Wind plants and PV plant at hour h is stored in PSP so that it can participate in EM at h+1 hour. This is shown in equation below. Here, $P_{iPSP1,avl}$ and $P_{iPSP2,avl}$ are the available stored energy in PSP1 and PSP2 at h^{th} hour respectively. $P_{iPSP1,sch}$ and $P_{iPSP2,sch}$ are the energy dispatched in PSP1 and PSP2 respectively. Where η is the efficiency of PSP.

$$P_{iPSP1,avl}(h+1) = \eta \times P_{iWP,RC_{avl}}(h) + (P_{iPSP1,avl}(h) - P_{iPSP1,sch}(h)) \tag{23}$$

$$P_{iPSP2}(h+1) = \eta \times P_{iPV,RC_{avl}}(h) + (P_{iPSP2,avl}(h) - P_{iPSP2,sch}(h)) \tag{24}$$

Assumptions: The following assumptions has been made while performing this study:

1. The load bus chosen for DG placement should not have any CGs.
2. Auction is single sided.
3. The fixed cost coefficient in cost function is taken as zero for simplification.
4. The load is fixed not dispatchable.
5. The bidding price by generators are high in RM.

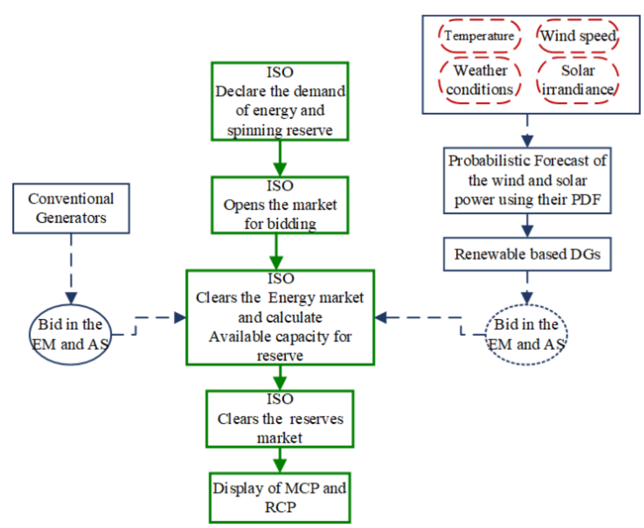

Fig. 1. Sequential EM and RM clearing mechanism in Power market.

3.3. Objective Function

The objective function is to minimize the generation cost in EM and RM. The conventional generator bid cost is considered as quadratic in nature whereas the DG bid is linear in nature during EM whereas during the RM market the bid from both conventional and renewable generator is linear. The market clearance process is implemented in following steps:

Step 1: Minimizing the generation cost in EM.

$$\min C^E = \sum_{h=1}^{24} \left\{ \begin{array}{l} \left(\sum_{i=1}^{N_G} CE_{i,h}(P^E_{iCG,h}) \right) + \left(\sum_{j=1}^{N_{DG}} CE_{j,h}(P^E_{jDG,h}) \right) \\ + \left(\sum_{j=1}^{N_{PSP}} CE_{j,h}(P^E_{jPSP,h}) \right) \end{array} \right\} \quad (25)$$

such that;

$$P_i^E = P^E_{i,CG} + P^E_{i,DG} + P^E_{i,PSP} - P^E_{i,D} \quad (26)$$

$$Q_i^E = Q^E_{i,CG} + Q^E_{i,DG} + Q^E_{i,PSP} - Q^E_{i,D}; \quad (27)$$

$$Q_{iCG,\min} \le Q^E_{iCG} \le Q_{iCG,\max} \quad (28)$$

$$P_{iCG,\min} \le P^E_{iCG} \le P_{iCG,\max} \quad (29)$$

$$P_{jDG,\min} \le P^E_{jDG} \le P_{jDG,\max} \quad (30)$$

$$Q_{jDG,\min} \le Q^E_{jDG} \le Q_{jDG,\max} \quad (31)$$

$$V_{i,\min} \le V_i \le V_{i.\max} \quad (32)$$

$$P^E_{jPSP,h=0} = 0 \quad (33)$$

Step 2: Minimizing the generation cost in RM.

$$\min C^R = \sum_{h=1}^{24} \left\{ \begin{array}{l} \left(\sum_{i=1}^{N_G} CR_{i,h}(P^R_{iCG,h}) \right) + \left(\sum_{j=1}^{N_{DG}} CR_{j,h}(P^R_{jDG,h}) \right) \\ + \left(\sum_{j=1}^{N_{PSP}} CR_{j,h}(P^R_{jPSP,h}) \right) \end{array} \right\} \quad (34)$$

such that;

$$P^E_{iCG,h} + P^R_{iCG,h} \le P_{iCG,\max} \quad (35)$$

The objective function is subjected to equality and inequality constraints. Inequality constraints may or may not be binding, whereas equality constraints are binding. Here P_i^E and Q_i^E is the real and reactive power injected at i^{th} bus in EM. P_{iCG}^E and P_{jDG}^E, Q_{iCG}^E and Q_{jDG}^E are the active and reactive power dispatched by CG and DG in EM. The initial energy stored in PSP is zero stated in Eq. 33.

4. 4. RESULTS AND DISCUSSION

In this work, the study is performed on IEEE 30 bus system. The system data is taken from Ref [43] and modified for simplification of analysis. There are 6 CGs placed at bus 1, 2, 5, 8, 11 and 13. The generator data and its cost coefficient and ramp rate (RR) are shown in Table 1. The demand data for energy and reserve market is given in Fig. 3. The reserve requirement in this work is specified as 10% of the demand in EM. The standard deviation and mean wind speed are taken into account for wind modeling and for solar power, temperature, fill factor and the solar irradiance are used. The values for mean solar irradiation and wind speed are taken from Ref [44]. The Fig. 4 depicts the predicted wind speed and solar irradiation for 24 hours. Two strategies are applied to predict the location of DGs. The first method is based on higher LMP method (Case1) and second method is based on customer payment method (Case2). The research is divided into four cases.

Case 1: Market clearance by optimal DG placement and sizing using higher LMP method.

Case 2: Market clearance by optimal DG placement and sizing using higher customer payment method.

Case 3: Placement of PSP based energy storage in Case1.

Case 4: Placement of PSP based energy storage in Case2.

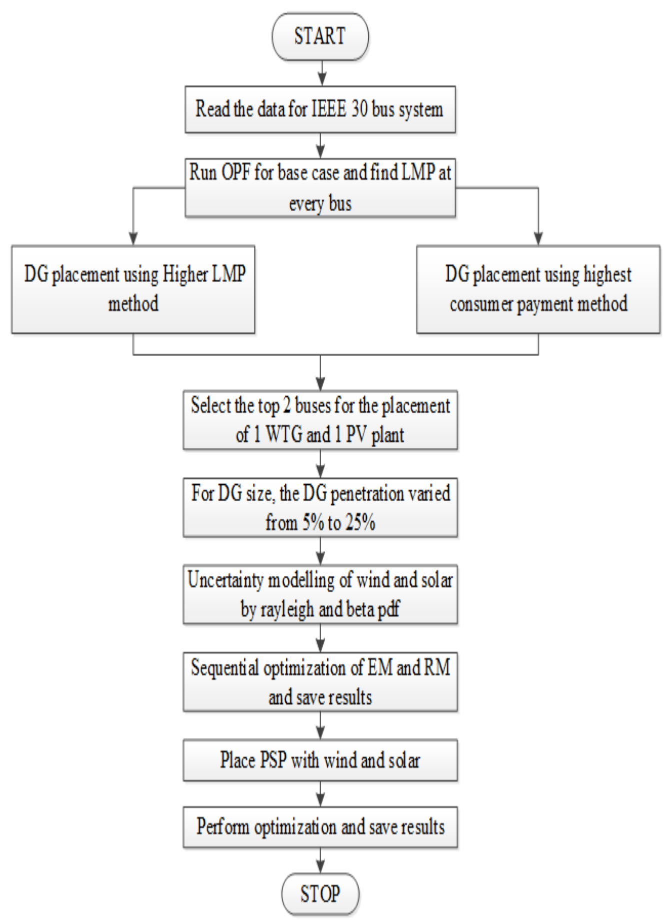

Fig. 2 : Proposed Methodology.

Case 1: In case 1, after running OPF for base case during peak load (only CG in the system), all the load buses are ranked in decreasing order of their LMP. The top two buses are chosen for placement of WTG and PV plants. The Table 2 presents the ranking of various load buses using these methods. From the Table 2, it can be observed that for case1, the optimal location for DG placement is bus 30 (for WTG) and bus 26 (for PV). After identifying the prime location for DGs, the next step is to find the optimal penetration for it. The size of each DG is taken as same. This is done by considering the ratio of the LMP method. For example, if the total DG penetration is 5% of peak load i.e. 18MW then each WTG and PV have 9 MW penetration. This is considered because in case1, the ratio of LMP at bus 30 and bus 26 is almost equal to 1. This is valid for this case study but for different test system the ratio of LMP will differ and size of wind and solar penetration will be taken as per the LMP ratio calculated. Now for calculating the total RES penetration (wind+solar) in the system, the penetration level is varied from 5% to 25% of the peak load and its impact on the system parameter are like DG owner profit, generation cost and load payment is calculated.

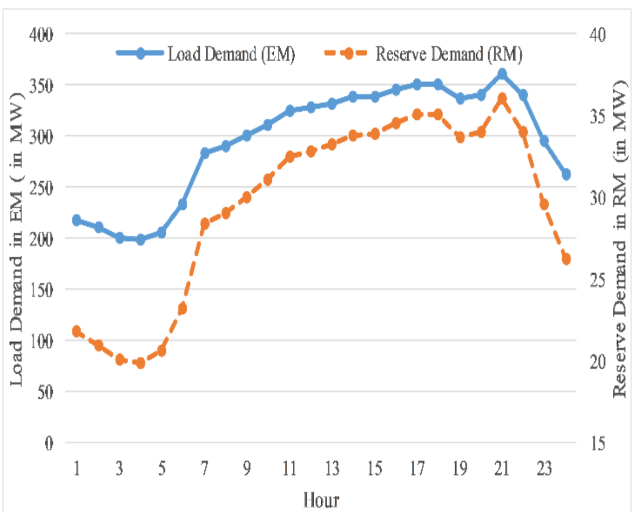

Fig. 3: Load demand and Spinning reserve demand.

Table 1. Generator data for IEEE bus system

No.	Pmax (MW)	Energy Price			Reserve price($/MW)	RR
		α ($/MW²h)	β ($/MWh)	γ ($/h)		
G1	200	0.00375	2	0	2.25	20
G2	80	0.0175	1.75	0	2	12
G3	35	0.0625	1	0	1.5	8
G4	50	0.00834	3.25	0	3.5	6
G5	30	0.025	3	0	3.25	5
G6	40	0.025	3	0	3.35	8
WTG	45	0	1.75	0	1.75	-
PV	45	0	2	0	2	-

The Table 3 shows the generator cost and load payment in both energy and reserve market in case1. The Fig. 5 shows the DG owner profit using both the approaches.

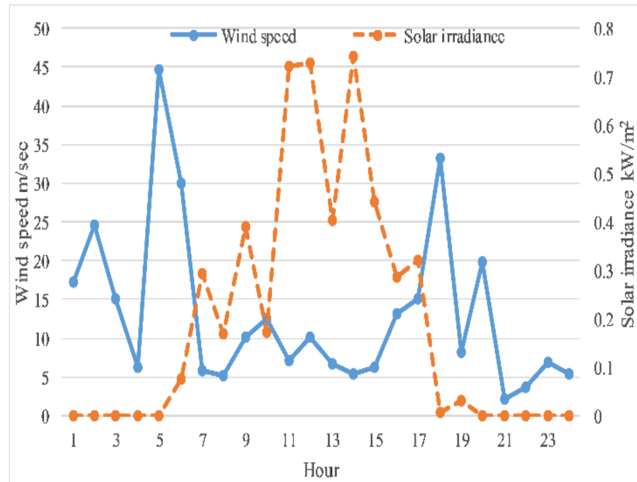

Fig. 4: Expected solar irradiance and wind speed.

From Fig. 5, it can be analyzed that after clearing both EM and RM using case1, DG owner profit is highest (689.29 $/day) when total DG size is equal to 15% of peak load i.e. 54MW. After increasing the DG size beyond 54 MW will further reduce its profit as well as the generation cost. Thus, for optimal size of DG the trade-off between DG owner profit and generation cost is done. Since the goal of this research is minimizing the generation cost, therefore 25% of peak load is taken as the total DG penetration is selected i.e. 90 MW. After energy market clearance, the reserve capacity available with CGs are utilized in the RM but the surplus energy of RES is not utilized due to absence of energy storage device. Fig. 6 shows the available wind and solar power. Fig. 7 and Fig. 8 shows the dispatched power by CGs and RES based DG in EM. In 1st hour, the power scheduled by G1 is 127.69 MW but its maximum capacity is 200 MW. Thus,72 MW is available as the remaining capacity of G1 after clearing of EM. Now since the 10 mins ramp rate (RR) of G1 is 20 MW thus only 20 MW is available with G1 as the spinning reserve in reserve market. Out of 20 MW only, 1.86 MW is dispatched in RM because cheaper generators have sufficient capacity to supply the load demand.

From Fig. 8, it is analyzed that RES is not fully utilized in EM and its surplus energy is wasted (not utilized in RM) because there is no energy storage device in the system. The surplus energy of WTG and PV after EM clearance is shown in Fig. 9. The surplus wind power is available during hour 1,2,3,10,16,17 and 20. Whereas, the surplus solar power is available during 9,10,11,12,14, 16 and 17. The scheduled dispatch by generators in RM is shown in Fig. 10. Only CG will participate in RM. The available reserve capacity by RES is zero due to absence of energy storage. The total generation cost and load payment after clearing both the market are 20837.48 \$/day and 27746.58 \$/day.

Table 2. Ranking of buses with Case 1 and Case 2

Rank	Case 1		Case 2	
	Bus	LMP	Bus	Customer Payment
1	30	4.5686	5	530.95
2	26	4.4533	8	161.50
3	29	4.4528	7	126.11
4	5	4.4372	2	113.74
5	24	4.3639	21	95.22
6	7	4.3547	12	59.02
7	19	4.3537	30	61.54
8	25	4.3452	19	52.55
9	18	4.3404	17	48.54
10	23	4.3346	24	48.22

Table 3. Generation cost and load payment after market clearance by varying the DG sizes in Case1

DG Size (%) of peak load	Energy Market		Reserve Market	
	Generation Cost(\$/day)	Load Payment (\$/day)	Generation Cost (\$/day)	Load Payment (\$/day)
5%	20213.30	26827.02	1476.54	2037.30
10%	19945.46	26494.07	1459.36	1969.52
15%	19701.66	26228.91	1449.58	1959.00
20%	19505.44	26003.67	1429.86	1848.87
25%	19414.16	25932.13	1423.32	1814.45

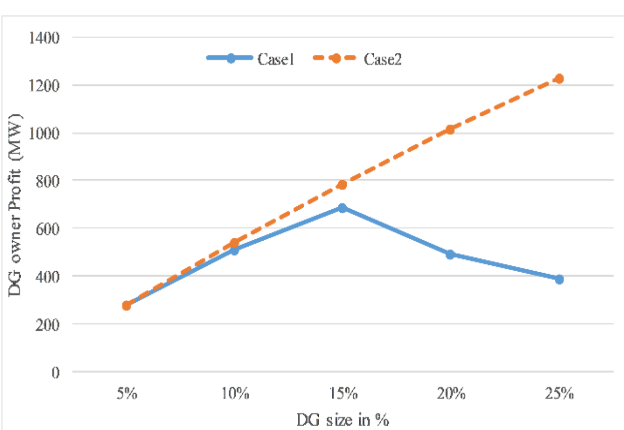

Fig. 5 : DG owner profit vs DG size.

Case 2: In case 2, the customer payment at each bus is arranged in decreasing order and the optimal location for DG is identified as shown in Table 2. The customer payment is highest on bus5 but it is a generator bus with a load and CG. However, the assumption in this work is that the bus which is prime location of DG placement should not have a CG. For similar reasons bus 8 and bus 2 are not considered as optimal site for placement. Therefore, bus 7 (for WTG) and bus 21 (for PV) is chosen as the prime location in case2. Similar to case1, in case2 also the ratio of LMP at bus 7 and bus 21 is almost 1. Table 4 shows the generator cost and load payment in both energy and reserve market by varying DG size in case2. From Figure 5, it is analyzed that after market clearance, the DG profit is rising sharply from 5% DG (18 MW) size to 25% DG size (90 MW). The

Table **3** and Table 4 shows that in both the cases (case1 and case2), the generator cost and load payment decrease by the increase in the DG penetration size. But since the DG owner profit is decreasing with increase in DG size in case1 whereas profit increases in case2. Thus, optimal DG size is taken as 25% in order to show the comparative analysis in both the cases. The energy supplied by CGs in EM and RM is shown in Fig. 11 and Fig. 12.

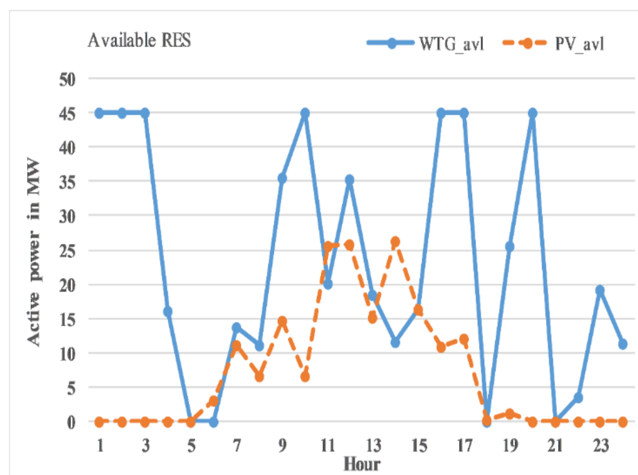

Fig. 6. Available RES.

Table 4. Generation cost and load payment after market clearance by varying the DG sizes in Case2

DG Size (%) of peak load	Energy Market		Reserve Market	
	Generation Cost(\$/day)	Load Payment (\$/day)	Generation Cost (\$/day)	Load Payment (\$/day)
5%	20226.66	26855.61	1478.87	2037.40
10%	19950.23	26523.09	1463.56	1969.67
15%	19684.44	26262.62	1451.72	1959.09
20%	19427.06	26035.23	1430.47	1848.85
25%	19177.21	25815.96	1422.48	1781.42

From the figures, it is concluded that during hour1, the maximum capacity of G1 is 200 MW among which 121.47 MW is dispatched in EM. The remaining capacity (RC) is 78.53 MW and the ramp rate (RR) of G1 is 20 MW. Thus, minimum among the RC and RR is available as reserve in RM. The spinning reserve of 20 MW is available by G1 and from this only 1.87 MW is dispatched in RM because cheaper generators are sufficient to supply the load demand. Similarly, the spinning reserve from other generators is calculated. In this case the RESs are fully utilized in the Energy Market thus no surplus energy as reserve is available by them. The total generation cost and load payment after both the market clearing process is 20599.68 $/day and 27597.37 $/day.

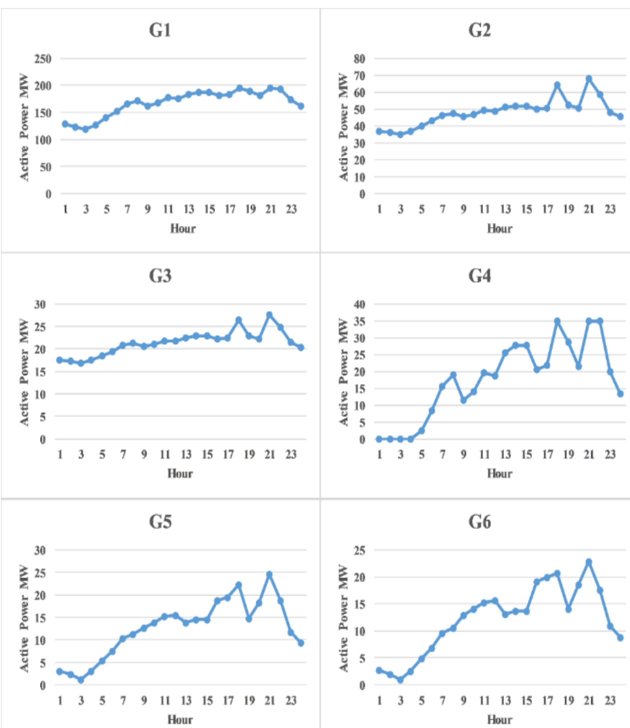

Fig. 7. CGs dispatched in EM in Case 1.

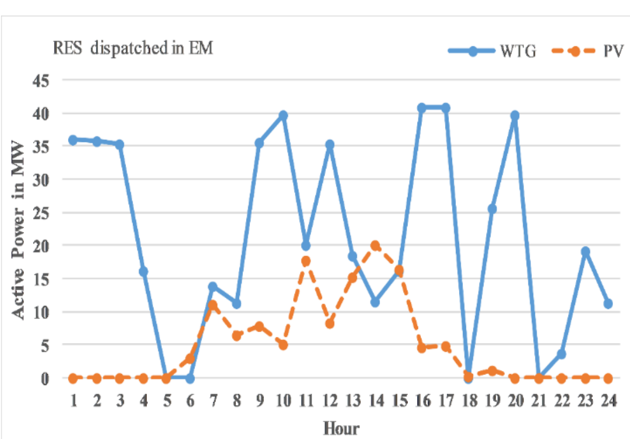

Fig. 8. RES dispatched in EM in Case 1.

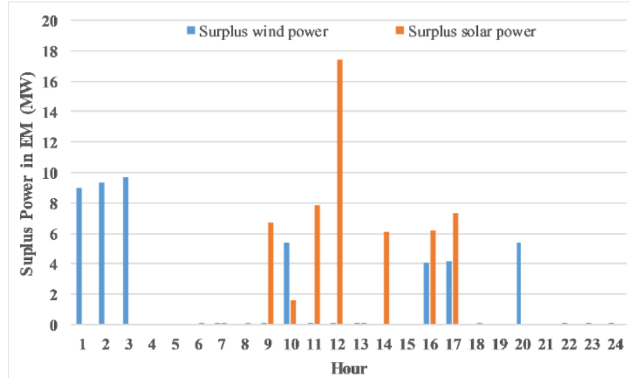

Fig. 9. Surplus RES in energy market in Case 1.

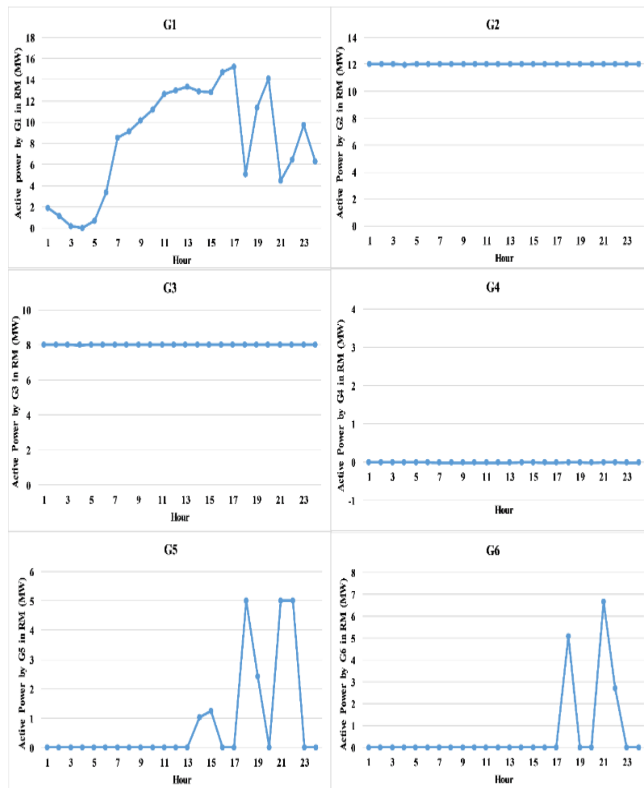

Fig. 10. CG dispatched in RM in Case 1.

Case 3: In case3, two PSP are placed in conjunction with WTG (PSP1) and PV plant (PSP2) to utilized the surplus power in energy and reserve market available in case1. The excessive renewable energy is stored by PSP and delivered in next intervals. Now PSP can also participate in the EM and RM. First the stored energy is utilized in EM. If after EM clearance there is available stored energy in PSP then this energy is utilized in RM. The store energy by PSP at *hour=1* is taken as zero. The stored energy at h^{th} hour (shown in Eq.19 and 20) is equal to the sum of η (efficiency of PSP) times the surplus RES at *(h-1)* hour and available storage after dispatch of PSP in *(h-1)*. The energy dispatched by CGs, RES and PSP in EM is shown in Fig. 13, Fig. 14 and Fig. 15 respectively. The power dispatched by CGs is reduced during few hours due to participation of PSP in EM. The energy cost associated with PSP is less than few CGs thus it will be given priority in market. In this case the surplus RES which is wasted in case1 is effectively utilized which further reduce the load payment and generation cost. The load payment and total generation cost for this case is 27560.72 $/day and 20746.56 $/day respectively.

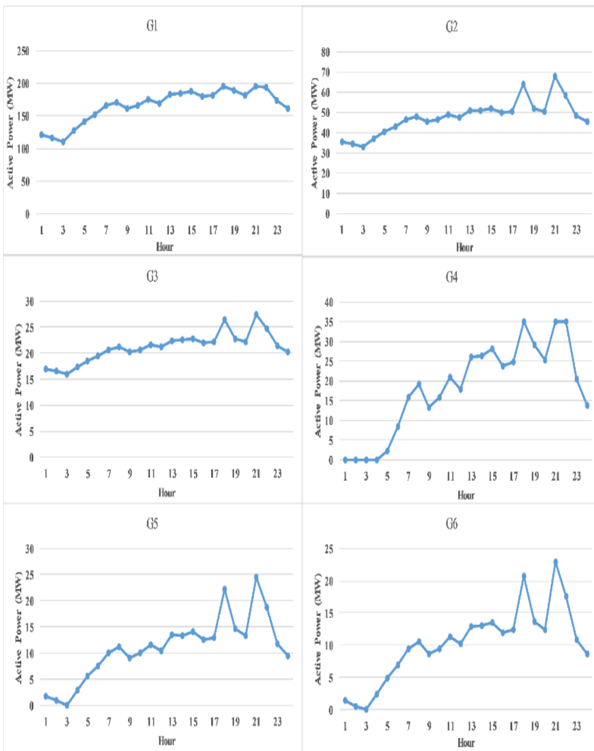

Fig. 11. Scheduled CGs in EM in Case2

Case 4: In this case, DG is optimally placed using higher customer payment method and PSP is placed with WTG and PV to effectively utilize the surplus power in EM and RM. Since from case2, it is clear that all the RES is utilized during EM thus no storage is needed. Thus, this case replicates the case2. The generation cost and load payment will be same as in case2. But if the RES availability is high then the surplus power can be stored in PSP and utilized in the hours of scarcity.

The comparison between case2 and case3 with respect to case1 in shown in Table 5. From Table 5, it can be concluded that the percentage reduction in load payment and generation cost in case2 is 0.54% and 1.14% due to location of DG. Thus, customer payment method proves its supremacy over higher LMP method for this case study. In case3, due to placement of PSP plant the generation cost and load payment is reduced to 0.44% and 0.66% respectively compared to case1.

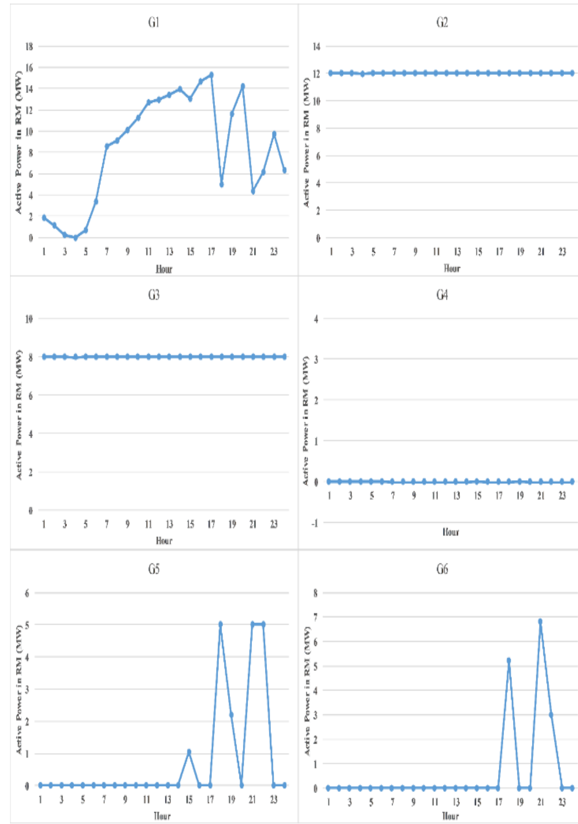

Fig. 12. Scheduled CGs in RM in Case2

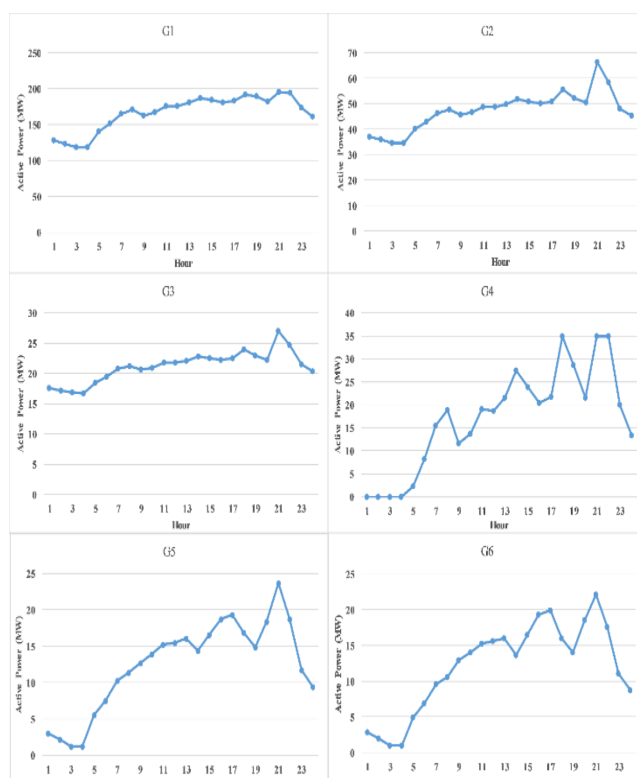

Fig. 13. Scheduled CGs in EM in Case 3.

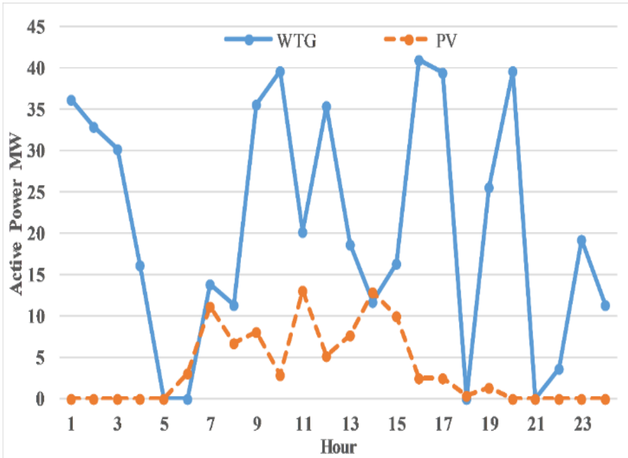

Fig. 14. Scheduled RES in EM in Case 3.

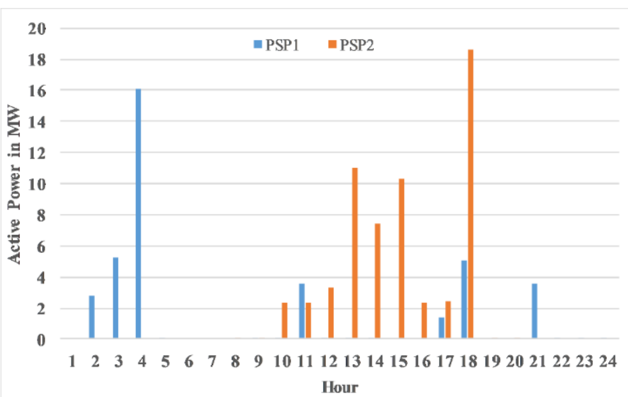

Fig. 15. Scheduled PSP in EM in Case 3.

Table 5. Comparison between Case1, Case2 and Case3

Case	Generation cost ($/day)	Load payment ($/day)	% reduction in Gen cost	% reduction in load payment
Case1	20837.48	27746.58	-	-
Case2	20599.68	27597.37	1.14	0.54
Case3	20746.56	27560.72	0.44	0.66

5. 5. CONCLUSION

This study emphasizes the significance of a market-based strategy for the integration of RES based generators and storage scheme for the procurement of energy and spinning reserve in a deregulated power system. It is shown that by using PSP, the surplus capacity of DGs is effectively utilized in market scenarios. For the placement of DGs, higher LMP method and higher customer payment method is used. The comparative analysis of both the methods is performed. The customer payment method shows it supremacy over higher LMP method for this case study. The reduction in generation cost and load payment is observed as 1.14% and 0.54 % by placement of DG using higher customer payment method.

The proposed study shows the participation of conventional and renewable based distributed generators in the EM and RM. The optimal power flow aids in the formulation of an optimization problem that may efficiently meet real supply and demand requirements (solving physical constraints such as generating limits and ramping restrictions), thereby assisting conventional and RES generators to meet demand. It is observed that by participation of DGs and PSP in the market the total cost gets reduced. By placement of PSP, the decrement in load payment and generation cost is observed as 0.66% and 0.44% respectively.

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