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J. Electrical Systems 16-2 (2020): 257-275

Regular paper

Hourly Congestion Management by Adopting Distributed Energy Storage System using Hybrid Optimization

Journal of Electrical Systems

In this paper, the optimal location and sizing of DESS are proposed for transmission congestion management. Transmission Congestion Cost (TCC) is used to find the optimal location of DESS, whereas hybrid optimization based on Flower Pollination Algorithm (FPA) and Differential Evolution (DE) is proposed for optimal sizing of DESS. The methodology considering Solar PV and Energy Storage System (ESS) as sources of energy is being used. 24 hours real temperature and solar irradiance data of Delhi are taken to mathematically model the generation from Solar PV to manage congestion throughout the 24 hours. ESS is used to store surplus energy. The proposed approach is tested on IEEE-30 and IEEE-57 bus systems, and 24 hours demand is assumed to follow the hourly load shape (summer season) of the IEEE reliability test system. The performance of the proposed approach is validated by comparing the results obtained through hybrid (FPA-DE) optimization with the results obtained through DE optimization. It is observed from the experiment that both the optimization techniques (DE, Hybrid) performed well in managing congestion. However, DE has a higher consumption of resources that lead to shortage of resources at the end of the day; hence fails to manage congestion the next day, when solar irradiance is not available. In contrast, hybrid optimization provides very encouraging results, and at the end of the day saves approx. 39% of ESS, thus can participate in congestion management for the next day in the absence of solar irradiance.

Keywords: Energy storage system; transmission congestion cost; locational marginal price; flower pollination algorithm; differential evolution; hybrid optimization

Article history: Received 6September 2019, Accepted 15 May 2020

1. Introduction

The electric network must operate within security limits, such as stability limits, voltage limits, and thermal limits to ensure the security and reliability of the network. Congestion in the power system is defined as the overloading of one or more transmission lines and/or transformers. In the deregulated electricity market, congestion occurs if transmission lines fail to accommodate all transactions due to violation of line limits. Electrical utilities operate transmission lines close to stability limits to maximize profits from different transactions that leads to violation of limits. Since it is very difficult to alleviate congestion with the random variation in power transactions [1], therefore, many algorithms for congestion management have been suggested to date. These are based on generation rescheduling [1-4], reactive power management [5-6], transmission line switching [7], Flexible AC Transmission Systems (FACTS) device placement [8-12], Distributed Generation (DG) placement [13-15], and load curtailment [3,16]. Generation re-scheduling is usually the first approach taken by the system operator to manage congestion, while the load curtailment is the last option available with them. The congestion management

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strategies are generally a two-step process that is optimal selection/location and optimal rescheduling/sizing. In the past, this two step process has successfully been implemented for generator rescheduling [1-4] and FACTS placement [8-12] for transmission congestion management. In the present scenario, this two step process is also adopted for DG [13-15]. The advantage of DG is that, it can supply power in a particular direction, at a particular time when the load exceeds the transmission capacity. Penetration of DG has many technical merits like system reliability, loss reduction, congestion management, and voltage profile improvement. The benefit of DG is more predominant in the highly congested area [17]. Unlike traditional large central power plant, DG is a small scale power station which is used to satisfy local load [15]. There are many sources of DG like photovoltaic, fuel cells, wind, biomass, geothermal, and gas turbine. Since the majority of network assets were constructed in the last century, network congestion in the world has significantly increased. It is due to aging of the pre-planned and limited capacity of existing networks. Also, the network is becoming highly constrained with the regular penetration of renewable sources (DG) and has an increasing trend [18]. The generation from these sources depends completely on the availability of solar irradiance for solar PV, wind speed for wind power, and so on. Therefore to handle the uncertainty, Energy Storage System (ESS) as an emerging technology manages the penetration during On-Peak and Off-Peak time. ESS is now widely being used in the deregulated environment. In the UK alone, usage of ESS is forecasted to reach 1.6GW by 2020 [19]. Many authors [20,21] show the benefit of ESS, such as improvement in operating capabilities of the network, minimizing operating cost, and reduction in network investments. Different ESS strategies have been proposed by the authors in [22], but the complex characteristic metrics and lack of pricing method makes it difficult to promote ESS. Absence of appropriate pricing and lack of clarity regarding ESS operation are among the many factors that affect the penetration of ESS as examined by the governing and research authorities in the UK [23,24,25], EU & US [26,27]. To solve the challenging issues regarding ESS, authors in [18] suggested a novel Locational Marginal Price (LMP) based pricing mechanism for ESS that manages to handle congestion by controlling the charging/discharging strategy of ESS using Binary Search Method (BSM), which response to system congestion cost over time. They found that the LMP-based pricing strategy efficiently captures the signal of congestion in the network. LMP has several advantages over other pricing strategies, that's why it is widely adopted in competitive electricity markets like NYISO and CAISO and still an active research area. LMP is the by-product of security-constrained Optimal Power Flow (OPF). In a deregulated environment, LMP is the pricing mechanism and also a signal for the degree of congestion in the network. The price reflects in LMP comprise of price due to energy, congestion, and losses in the network. LMP reaches a higher value in congested areas than non-congested areas [28]. The objective of the system operator in the deregulated environment is to minimize the LMP difference in the network. In the past, many authors [14, 28-29] have successfully applied LMP based approach for congestion management by optimally placing DG in the network. Authors in [28] considered the maximum LMP node as a candidate node for DG placement, and they have reformulated the OPF by considering the DG cost function to find the optimal size. The results show that they reduced the LMP to some extent. Later authors in [14] suggested that the highest LMP approach may cause congestion in other lines and they proposed transmission congestion cost (TCC) or congestion rent based approach for optimal DG placement. The authors calculated the optimal size of DG by evaluating all possible sizes and select the one that maximizes the social benefit. The placement carried out with location and size should be optimal to maximize social welfare and minimize congestion in the network. Improper placement may result in the collapse of the entire network that may lead to huge economic and social losses. TCC based approach is also proposed by authors [29] for optimal placement of DG and able to reduce LMP difference up to a large extent. Therefore TCC based approach is proved to be a better way for optimal placement of DG. System operators (SO) regularly perform the optimal power flow (OPF) to manage congestion by maintaining security constraints (transmission and operational constraints). The OPF problem is commonly non-linear, non-convex, and non-differential optimization problem that never guarantees an optimal solution because of many local optima in power systems [30]. Consequently, conventional optimization problems are prone to the local optimal solution, and some of the conventional approaches require good characteristics of function such as continuity, and differentiability. Moreover, the penetration of DG makes the OPF problem even more complex, which may not be effectively solved using a single optimization technique [11]. Even with the successful optimization of single-objective, a population-based optimization technique minimizing only one objective function which is not sufficient in the power system. Usually, the congestion management problem in the power system needs many objectives to be optimized, such as fuel cost, optimal location, and cost for placement, optimal sizing and many more. With the presence of many objective functions, the number of incompatible optimal solutions become infinite, and the compromised solutions are called Pareto optimal solutions [31]. The best way to solve this problem is by converting multi-objective OPF (MO-OPF) problems into single objective OPF (SO-OPF). SO-OPF problem can be formulated by associating weights to the different objective functions. In the past, many well-proposed multi-objective evolutionary algorithms (MOEAs) have been successfully applied in different fields of science and engineering. Some of the hybrid optimization techniques [11,32,33] have also been proposed to solve MO-OPF problems, considering optimal placement and sizing of FACTS and DG. However, optimizing the OPF problems is still an active research area and needs to put more efforts to develop an improved hybrid optimization algorithm. As the concept of hybrid optimization combines the idea of exploration and exploitation, therefore the improvement in search strategy is required that improves the quality solution of MO-OPF. In this paper, the exploration of FPA and the exploitation of DE are combined to develop a hybrid(FPA-DE) optimization technique for hourly congestion management problems.

The main contributions of this paper are:

(i). Hourly congestion management is proposed for 24 hours
(ii). Solar PV as a source of DG is considered
(iii). Real solar irradiance and temperature data of Delhi are taken to mathematically model the generation of Solar PV
(iv). Energy Storage System (ESS) is also integrated to store remaining energy to be used for congestion management.
(v). DESS (DG + ESS) is optimally placed using TCC based approach which significantly reduces the search space

(vi) Hybrid (FPA – DE) optimization is used for optimal sizing of DESS
(vii). Provision to ensure the congestion management for morning hours of the next day when solar is not participating

2. Notations

The notations used throughout the paper are stated below.

Indexes:

x,y	bus x and bus y

Constants:

t	time
N	generator number
$\mathrm{Solar}_{\mathrm{Generation}}^{t}$	generation from Solar plant at time t
$\mathrm{Solar}_{\mathrm{Rated}}$	rated capacity of Solar plant
$\mathrm{T}_{\mathrm{ref}}$	reference temperature
$\mathrm{T}_{\mathrm{amb}}$	ambient temperature
$\propto$	temperature coefficients
$\mathrm{Irradiance}^{t}$	solar irradiance at time t
TCC_{xy}	transmission congestion Cost between bus x and bus y
$\lvert\Delta\mathrm{LMP}_{xy}\rvert$	absolute difference of LMPs between bus x and bus y
LMP_{x}	bus x locational marginal price
LMP_{y}	bus y locational marginal price
FL_{xy}	flow of power between bus x and bus y
$\mathrm{f}_{\mathrm{N}}\left(\mathrm{P}_{\mathrm{Generation}}^{\mathrm{N}}\right)$	cost of active power generation at a given dispatch point for generator N
$\mathrm{P}_{\mathrm{Generation}}^{\mathrm{N}}$	total active power generation by generator N
$\mathrm{Q}_{\mathrm{Generation}}^{\mathrm{N}}$	total reactive power generation by generator N
$\mathrm{P}_{\mathrm{GenerationN}}^{\min}$	minimum active power generation by generator N
$\mathrm{P}_{\mathrm{GenerationN}}^{\max}$	maximum active power generation by generator N
$\mathrm{Q}_{\mathrm{GenerationN}}^{\min}$	minimum reactive power generation by generator N
$\mathrm{Q}_{\mathrm{GenerationN}}^{\max}$	maximum reactive power generation by generator N
$\mathrm{FL}_{xy}^{\max}$	maximum power flow between bus x and bus y
FL_{xy}	power flow between bus x and bus y
$\mathrm{V}_{\mathrm{B}}^{\min}$	minimum voltage limit at bus B
$\mathrm{V}_{\mathrm{B}}^{\max}$	maximum voltage limit at bus B
G_{xy}	transfer conductance between bus x and y
B_{xy}	transfer susceptance between bus x and y
δ_{x}	voltage phase angles at bus x
δ_{y}	voltage phase angles at busy
M	total number of generators
NB	total number of buses
a_{N}, b_{N}, and c_{N}	generator bids of generator N
$\mathrm{P}_{\mathrm{Generation}}^{\mathrm{B}}$	active power available at bus B
$\mathrm{P}_{\mathrm{Demand}}^{\mathrm{B}}$	active power demand at bus B
$\mathrm{Q}_{\mathrm{Generation}}^{\mathrm{B}}$	reactive power available at bus B

Q^{B}_{Demand}	reactive power demand at bus B
λ and μ	Lagrangian multiplier vectors
TCC_k	transmission Congestion Cost of kth line
P_{Lk}	power loss in the kth line
w1	TCC Weight factor (0.7)
w2	power loss Weight Factor (0.15)
w3	DESS Cost Weight Factor (0.15)
NL	number of lines in the network
$Cost_{DESS}$	solar tariff (0.22 $/KWh)

3. Distributed Energy Storage System

The term DG is used to represent the sources, often renewable sources that produce electricity near the point of use instead of centralized sources of generation like power plants. It is commonly known as Distributed Energy Resources (DER). In recent times DG or DER systems are more flexible technologies that are modular, close to loads, and decentralized. In combination with some Energy Storage Systems (ESSs), the DER is often called as Distributed Energy Storage System (DESS). In this paper, the congestion management problem is handled by integrating DESS with the network. The solar power plant as an energy source that can averagely produce approximately. 10 MW of energy in 24 hours duration with ESSs is considered as a DESS. ESSs are used when solar generation is either not sufficient to manage congestion or solar irradiance becomes zero. The power generated by solar plant can be represented as [34]:

$$Solar^{t}_{Generation} = Solar_{Rated}\left\{1 + \left(T_{ref} - T_{amb}\right) \times \propto\right\} \times \frac{Irradiance^{t}}{1000} \qquad (1)$$

Since loads are unpredictable and location of power injection from DESS can't be transferred with the increment or decrement in loads. Also, generation from solar is dependent on solar irradiance condition which is also unpredictable. Therefore, optimal locations, as well as optimal sizing of DESS, are important to use this technology to manage congestion in the network for a longer duration.

4. Problem Formulation

The objectives of the proposed work presented in this paper are:

- Optimal Location of DESS and
- Optimal sizing of DESS

4.1. Optimal Location of DESS Placement

The TCC of a line is the degree of connectedness, which increases as congestion increases in the network. In a network, TCC of each line is first obtained, and the line having maximum TCC value is the most congested. The node having a higher LMP of the most congested line is the optimal location for DESS placement. TCC of a line can be calculated using the formula:

$$TCC_{xy} = |\Delta LMP_{xy}| \times FL_{xy} = |LMP_x - LMP_y| \times FL_{xy} \qquad (2)$$

Generally, a non-linear optimization problem is an optimization problem of the form

$$\begin{aligned} & minimize\ f(x) \\ & subject\ to\ g_i(x) \leq 0\ \forall\ i \in \{1,2,\dots,N\} \\ & \qquad\qquad h_i(x) = 0\ \forall\ i \in \{1,2,\dots,M\} \\ & x \in X \end{aligned}$$

The OPF model for secure and economical dispatch of power, minimizing fuel cost can be formulated as:

$$\text{Minimize } \sum_{N=1}^{M} f_N(P_{Generation}^{N}) \qquad (3)$$

Subject to:

1. Equality or power balance constraints at bus B

$$\boldsymbol{P_B = f_P(V,\delta) = 0} \quad \text{or}$$

$$\boldsymbol{P_{Generation}^{B} - P_{Demand}^{B} - V_x \sum_{y=1}^{NB} V_y \left[G_{xy} \cos(\delta_x - \delta_y) + B_{xy} \sin(\delta_x - \delta_y)\right] = 0} \qquad (4)$$

$$\boldsymbol{Q_N = f_Q(V,\delta) = 0} \quad \text{or}$$

$$\boldsymbol{Q_{Generation}^{B} - Q_{Demand}^{B} - V_x \sum_{y=1}^{NB} V_y \left[G_{xy} \sin(\delta_x - \delta_y) - B_{xy} \cos(\delta_x - \delta_y)\right] = 0} \qquad (5)$$

2. Inequality constraints:

(i). Power transfer capability constraints

$$\boldsymbol{FL_{xy}^{min} \leq f_{FL}(V,\delta) \leq FL_{xy}^{max}} \qquad (6)$$

(ii). Power generation limits for N^th^ Generator

$$\boldsymbol{P_{GenerationN}^{min} \leq P_{Generation}^{N} \leq P_{GenerationN}^{max}} \qquad (7)$$

$$\boldsymbol{Q_{GenerationN}^{min} \leq Q_{Generation}^{N} \leq Q_{GenerationN}^{max}} \qquad (8)$$

(iii). Bus voltage limits

$$\boldsymbol{V_B^{min} \leq V_B \leq V_B^{max}} \qquad (9)$$

where,

$$\mathrm{f_N}(\mathrm{P_{Generation}^{N}}) = \mathrm{a_N} + \mathrm{b_N} \times \mathrm{P_{Generation}^{N}} + \mathrm{c_N} \times (\mathrm{P_{Generation}^{N}})^2$$

The optimization of the objective function formulated in OPF incorporating all operating constraints is done using Lagrangian Method. The multipliers used in formulating the Lagrangian function is called dual prices or shadow prices.

$$\begin{aligned} L(P_{Generation}^{B}, P_{Demand}^{B}, \lambda_B, \mu_B) = {} & \sum_{N=1}^{M} f_N(P_{Generation}^{N}) + \lambda_{P_B}\Big(P_{Generation}^{B} - P_{Demand}^{B} - \\ & V_x \sum_{y=1}^{NB} V_y \left[G_{xy} \cos(\delta_x - \delta_y) + B_{xy} \sin(\delta_x - \delta_y)\right]\Big) + \lambda_{Q_B}\Big(Q_{Generation}^{B} - Q_{Demand}^{B} - \\ & V_x \sum_{y=1}^{NB} V_y \left[G_{xy} \sin(\delta_x - \delta_y) - B_{xy} \cos(\delta_x - \delta_y)\right]\Big) + \mu_{min,flow}(FL_{xy}^{min} - FL_{xy}) + \\ & \mu_{max,flow}(FL_{xy} - FL_{xy}^{max}) + \mu_{min,V}(V_B^{min} - V_B) + \mu_{max,V}(V_B - V_B^{max}) + \\ & \mu_{min,P}(P_{GenerationN}^{min} - P_{Generation}^{N}) + \mu_{max,P}(P_{Generation}^{N} - P_{GenerationN}^{max}) + \\ & \mu_{min,Q}(Q_{GenerationN}^{min} - Q_{Generation}^{N}) + \mu_{max,Q}(Q_{Generation}^{N} - Q_{GenerationN}^{max}) \end{aligned} \qquad (10)$$

Where λ and μ are Lagrangian multipliers vectors associated with equality and inequality constraints. LMP through Lagrangian multiplier can be represented as [35]:

$$\text{LMP} = \lambda$$

MATPOWER 6.0 [36] with Interior Point Solver is used to perform OPF and calculated LMPs at each bus.

4.2. Optimal sizing of DESS using hybrid optimization

The optimal operating DESS value can be obtained by minimizing multi-objective fitness function given in equation (11) using hybrid optimization. Multi-objective fitness function includes three components- Transmission Congestion Cost (TCC), real power losses in the network, and generation cost for hourly congestion management.

$$Objective = w1 * \sum_{k=1}^{NL} TCC_k + w2 * \sum_{k=1}^{NL} P_{Lk} + w3 * Cost_{DESS} \quad (11)$$

Where, $\mathrm{w1} + \mathrm{w2} + \mathrm{w3} = 1$ (12)

5. Hybrid optimization

Evolutionary algorithms are very popular, effective, and easily applicable in solving single/multi-objective optimization problems while meeting all operational constraints. The solution quality of these algorithms is normally good with moderate size optimization problems having low complexity [37]. But a hybrid approach is required as complexity or problem size increases. In this paper, hybrid approach is suggested for the congestion management problem. Since FPA has great exploration and DE has exploitation capability therefore first FPA searches for the quality solution and then the solution obtained by FPA passes to DE for further searching and exploitation.FPA is a recent meta-heuristic optimization technique in which flower constancy can be used to increment using similarity and difference of two flowers, the steps for Flower Pollination Algorithm are taken as discussed [38]. DE a vector population based stochastic optimization problem introduced by Ken Price and Rainer Storn [39] for solving optimization problems usually characterized by nonlinear functions. DE is used when classical methods either fail to find the exact solution or these methods tend to be too slow. Due to its easy implementation, it has developed rapidly and is being used to solve many real life optimization problems. The DE algorithm contains the constituents like Population Initialization, Base vector perturbation, Diversity enhancement, Selection of best vector and steps are repeated until the stopping condition is satisfied or it reaches maximum iteration limit [40].

5.1 Algorithm for hybrid optimization

fitness	fitness function given in eqn. (11)
iteration	maximum number of iteration
$p \in [0,1]$	switching Probability
gbest	global best solution in FPA
dim	dimension of search space
rand	uniformly distributed random numbers between (0,1)
P	population size of both FPA and DE
F	control Variable
Size	optimal size
CR	cross over Probability
best	best solution in DE
TCC	transmission congestion cost (TCC)

PL	Power Losses
X	Array of DESS size for population P

```
1. Input network, load and bid data
2. Input optimization parameters (FPA and DE)
3. $X = [x_1, x_2, x_3, \ldots.., x_P]$
// Flower pollination population initialization
4. Find the best solution in X (gbest)
5. for iter = 1 to iteration
    fori = 1 to P
        Run OPF and calculate TCC and  PL in each line
        $\mathrm{obj} = \mathrm{fitness}(x_i^{iter})$
        ifobj is better than fitness(gbest)
            $\mathrm{gbest} = x_i^{iter}$
        endif
ifrand ≤ p
            $x_i^{iter+1} = x_i^{iter} + L(\lambda) * (x_i^{iter} - \mathrm{gbest})$
//global pollination
        else
            $x_i^{iter+1} = x_i^{iter} + \mathrm{rand} * (x_i^{iter} - \mathrm{gbest})$
// location pollination
        endif
    endfor
endfor
6. $X^{DE} = X$
// Initialize initial population of DE with the final solution of  FPA
7.  best = gbest
8. for iter = 1 to iteration
    forj = 1 to P
        Run OPF and calculate TCC and PL in each line
        Choose two random numbers r1, r2
       where1 ≤ r1, r2 ≤ P and r1 ≠ r2 ≠ j
        $y = \mathrm{best} + F(x_{r1} - x_{r2})$
        $u = \begin{cases} y & \text{if rand} \leq CR \\ x_j & \text{otherwise} \end{cases}$

        if fitness(u) better than fitness($x_j$) then
            $x_j = u$
        endif
        iffitness(u) better than fitness(best) then
            best = u
        endif
    endfor
endfor
9. Set Size = best
10. Exit
```

Hybrid optimization is used to find the optimal size of DESS by minimizing the multi-objective fitness function given in equation (11). The optimal sizing using hybrid optimization is discussed in detail in section 4.2 and the complete workflow is presented in the flowchart (Fig 1).

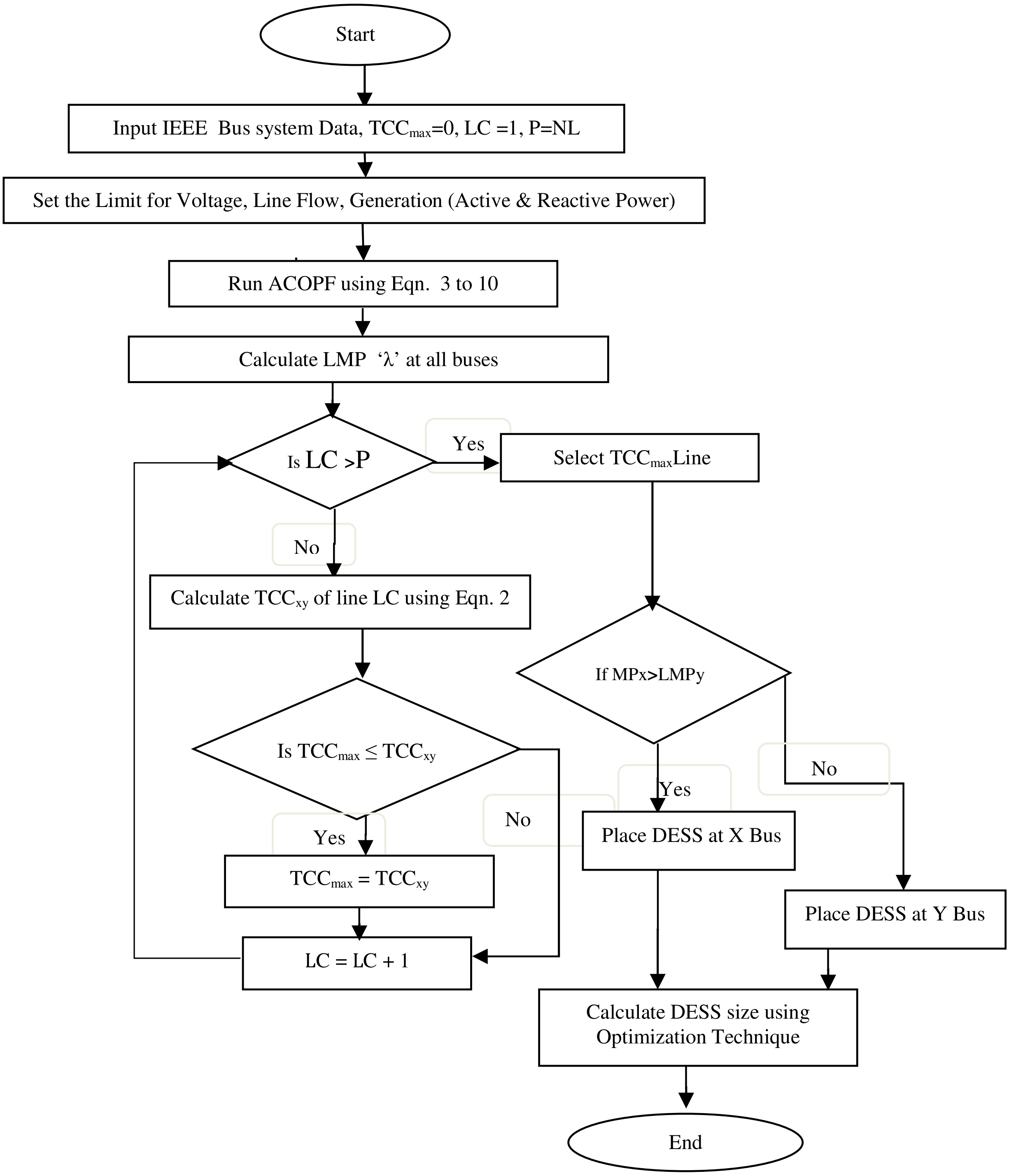

Fig. 1. Flow Chart for optimal location of DESS Placement.

6. Results and discussion

The approach proposed in this paper is tested on the IEEE-30 [36, 41] and the IEEE-57 [36] bus system. An hourly congestion management approach is used with DESS, where the size of the DESS is calculated every hour according to the demand. 24 hours of demand data is generated as per the hourly load shape (summer season) of the IEEE Reliability Test System (RTS) [42]. The demand at each bus increases/decreases uniformly according to the load curve. The maximum size of DESS is the sum of power generated from the PV source and the available ESS. Hourly solar irradiance and temperature data of Delhi as shown in Table I, is used to generate solar power [43]. The rated capacity of PV (PV_{Rated}) is 40 MW that can produce maximum of 15 MW when the solar irradiance is maximum on 05th June 2018 as shown in Fig 2, temperature coefficient ($\propto$) is considered as -0.0025. The peak load of the IEEE-30 and IEEE-57 bus systems are 189.2 MW and 1250.80 MW respectively.

The variability and uncertainty of renewable generation like PV undermine the reliability of the power system, requiring additional reserve capacities [45, 46].To handle the uncertainty, the Energy Storage System (ESS) is integrated with the PV system. Since solar is non-active for approx. 10 hours as shown in Fig. 2, therefore in such conditions, ESS is used to manage congestion. ESS becomes active when PV is not active, or PV alone fails to provide the required power needed to manage the congestion. The Size of ESS is taken as 25 MW and initially, it is considered fully charged. The charging rate of ESS is 1/5th of ESS capacity when the cells are between 10% and 85% of the state of charge (SOC), 1/10th in between 85% and 95% and 1/15th beyond 95 % [44].

Table 1: Solar radiation, temperature and power demand on 05thof June 2018

Time	Temperature (^{0} C)	Global Solar Radiation (w/m^2)	Power Generation from Solar Power Plant using Eq^n 1 (MW)	Power Demand (MW)	% demand of peak
00-01	33	0.00	0.00	121.09	64
01-02	33	0.00	0.00	113.52	60
02-03	32	0.00	0.00	109.74	58
03-04	32	0.00	0.00	105.95	56
04-05	32	0.00	0.00	105.95	56
05-06	32	7.13	0.28	109.74	58
06-07	32	63.50	2.49	121.09	64
07-08	33	129.07	5.06	143.79	76
08-09	34	219.08	8.59	164.60	87
09-10	35	257.82	10.11	179.74	95
10-11	36	295.25	11.57	187.31	99
11-12	37	335.13	13.14	189.20	100
12-13	38	365.36	14.32	187.31	99
13-14	39	372.62	14.61	189.20	100
14-15	40	384.61	15.08	189.20	100
15-16	40	354.96	13.91	183.52	97
16-17	40	231.94	9.09	181.63	96

17-18	39	154.63	6.06	181.63	96
18-19	37	49.75	1.95	175.96	93
19-20	36	1.26	0.05	174.06	92
20-21	35	0.00	0.00	174.06	92
21-22	34	0.00	0.00	175.96	93
22-23	34	0.00	0.00	164.60	87
23-00	34	0.00	0.00	136.22	72

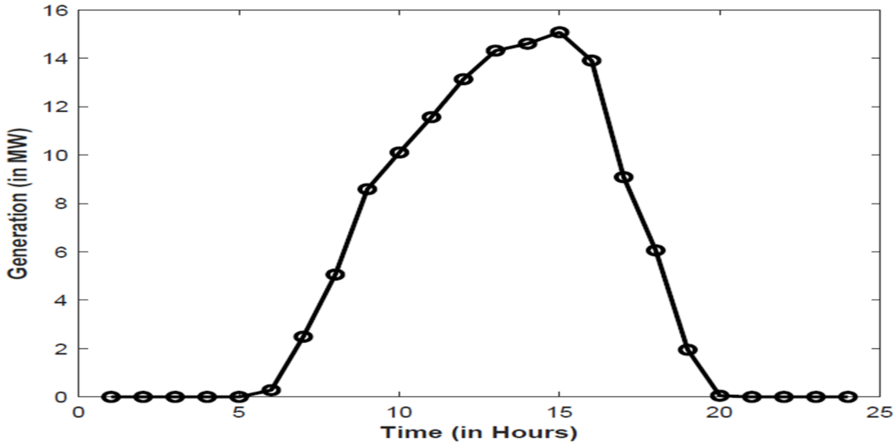

Fig.2. Hourly solar generation pattern

6.1. Optimal location and sizing of DESS

Initially, the network at the original load is considered as congestion-free, therefore the congestion is created by fixing the line limit connecting bus 6 and bus 8 to 30 MW for IEEE-30 bus system and the bus 7 and bus 29 to 62 MW for IEEE-57 bus system. The congestion management problem for optimal location and sizing of DESS is first solved without placing DESS and then after placing DESS. LMPs at each node and total congestion cost (TCC) before and after DESS placement for 24 hours demand are compared to check the effectiveness of the proposed approach. MATPOWER software [36] is used to run the AC-OPF model and obtained results are used to find the TCC in each line, which helps in finding the optimal location for DESS placement.

Since we are considering AC-OPF to calculate LMP at each bus, therefore LMP difference can never be zero even in congestion-free network. The optimal location of DESS is calculated using TCC, whereas hybrid and DE optimization techniques are used to find the optimal sizing of DESS. The goal of both DE and hybrid optimization is to minimize the multi-objective function given in equation (11). The LMPs that are calculating hourly can be quite volatile. As a rule, any congestion in the network causes price depression in the region where generators are concentrated and elevation in areas where load predominates [47]. The difference in pricing becomes higher as congestion increases in the network and vice versa. Therefore, the goal of optimal locating and sizing of DESS is to control the power flow of the network to avoid congestion, which results in the least LMPs difference. Optimal location and sizing of DESS are performed hourly for a particular load. Since the demand at each bus is varying uniformly, therefore TCC returns a single optimal location in each hour. The optimal location is bus 8 for the IEEE-30 bus system, whereas bus 31 for the IEEE-57 bus system. The optimal location remains the same throughout 24 hours duration even though the loads are different.

Results in terms of minimum and maximum LMP, TCC, and PV and ESS contributions before and after DESS placement are reported using both the optimization techniques completely shown in tables II (IEEE-30 bus system) and III (IEEE-57 bus system). Both the optimization techniques work well in minimizing the LMP difference, which results in minimum congestion cost however the major difference between these optimizations can be observed in sharing patterns from solar and ESS. The reason for this difference is the presence of multiple optima in the network and DE converge at local optima.

Table II: Comparison of minimum and maximum LMP, Total Congestion Cost, Optimal Generation of DESS before and after DESS placement by using Hybrid & DE for IEEE-30 bus system

Time	Optimization Technique	LMP ($/MWh)				Total Congestion Cost ($/h)		DESS	Optimal Generation from DESS		ESS Available (in MW)
		Before		After		Before	After		Solar Contribution (MW)	ESS Contribution (MW)	
		Min	Max	Min	Max						
00-01	Hybrid DE	37.98	41.06	37.98	41.06	200.48	200.48	No	0.00 0.00	0.00 0.00	25.00 25.00
01-02	Hybrid DE	37.56	40.50	37.56	40.50	199.97	199.97	No	0.00 0.00	0.00 0.00	25.00 25.00
02-03	Hybrid DE	35.63	38.35	35.63	38.35	180.05	180.05	No	0.00 0.00	0.00 0.00	25.00 25.00
03-04	Hybrid DE	33.70	36.20	33.70	36.20	161.53	161.53	No	0.00 0.00	0.00 0.00	25.00 25.00
04-05	Hybrid DE	33.70	36.20	33.70	36.20	161.53	161.53	No	0.00 0.00	0.00 0.00	25.00 25.00
05-06	Hybrid DE	35.63	38.35	35.63	38.35	180.05	180.05	No	0.00 0.00	0.00 0.00	25.00 25.00
06-07	Hybrid DE	37.98	41.06	37.98	41.06	200.48	200.48	No	0.00 0.00	0.00 0.00	25.00 25.00
07-08	Hybrid DE	38.32	41.42	38.32	41.42	204.66	204.66	No	0.00 0.00	0.00 0.00	25.00 25.00
08-09	Hybrid DE	38.15	47.74	38.48	41.70	410.10	217.65	Yes	2.31 4.70	0.00 0.00	25.00 25.00
09-10	Hybrid DE	37.94	53.37	38.60	41.90	617.94	221.52	Yes	4.39 9.19	0.00 0.00	25.00 25.00
10-11	Hybrid DE	37.24	68.27	38.67	42.00	1240.94	223.71	Yes	5.45 11.43	0.00 0.00	25.00 25.00
11-12	Hybrid DE	36.50	87.00	38.68	42.03	2045.46	223.36	Yes	5.70 12.96	0.00 0.00	25.00 25.00
12-13	Hybrid DE	37.24	68.27	38.67	42.00	1240.94	223.71	Yes	5.43 11.42	0.00 0.00	25.00 25.00
13-14	Hybrid DE	36.50	87.00	38.68	42.03	2045.46	223.36	Yes	5.75 13.25	0.00 0.00	25.00 25.00

14-15	Hybrid DE	36.50	87.00	38.68	42.03	2045.46	223.36	Yes	5.73 12.75	0.00 0.00	25.00 25.00
15-16	Hybrid DE	37.68	58.64	38.63	41.95	833.97	222.81	Yes	4.91 10.95	0.00 0.00	25.00 25.00
16-17	Hybrid DE	37.82	55.74	38.62	41.93	714.25	222.09	Yes	4.65 9.09	0.00 1.75	25.00 23.25
17-18	Hybrid DE	37.82	55.74	38.62	41.93	714.25	222.09	Yes	4.71 6.06	0.00 5.17	25.00 18.08
18-19	Hybrid DE	37.99	51.91	38.57	41.85	557.52	220.68	Yes	1.95 1.95	1.92 2.29	23.08 15.79
19-20	Hybrid DE	38.02	51.21	38.56	41.83	529.57	220.35	Yes	0.05 0.05	3.55 7.90	19.53 7.89
20-21	Hybrid DE	38.02	51.21	38.56	41.83	529.57	220.35	Yes	0.00 0.00	3.65 7.89	15.88 0.00
21-22	Hybrid DE	37.99 37.99	51.91 51.91	38.57 37.99	41.85 51.91	557.52 557.52	220.68 557.52	Yes	0.00 0.00	3.90 0.00	11.98 0.00
22-23	Hybrid DE	38.15 38.15	47.74 47.74	38.48 38.15	41.70 47.74	410.10 410.10	218.68 410.10	Yes	0.00 0.00	2.30 0.00	9.68 0.00
23-00	Hybrid DE	38.24	41.31	38.24	41.31	202.59	202.59	No	0.00 0.00	0.00 0.00	9.68 0.00

Table III: Comparison of minimum and maximum LMP, Total Congestion Cost, Optimal Generation of DESS before and after DESS placement by using Hybrid & DE for IEEE-57 bus system

Time	Optimization Technique	LMP ($/MWh)				Total Congestion Cost ($/h)		DESS	Optimal Generation from DESS		ESS Available (in MW)
		Before		After		Before	After		Solar Contribution (MW)	ESS Contribution (MW)	
		Min	Max	Min	Max						
00-01	Hybrid DE	36.65	41.25	36.65	41.25	573.33	573.33	No	0.00 0.00	0.00 0.00	25.00 25.00
01-02	Hybrid DE	35.62	39.78	35.62	39.78	490.84	490.84	No	0.00 0.00	0.00 0.00	25.00 25.00
02-03	Hybrid DE	35.10	39.07	35.10	39.07	452.55	452.55	No	0.00 0.00	0.00 0.00	25.00 25.00
03-04	Hybrid DE	34.58	38.35	34.58	38.35	416.18	416.18	No	0.00 0.00	0.00 0.00	25.00 25.00
04-05	Hybrid DE	34.58	38.35	34.58	38.35	416.18	416.18	No	0.00 0.00	0.00 0.00	25.00 25.00
05-06	Hybrid DE	35.10	39.07	35.10	39.07	452.55	452.55	No	0.00 0.00	0.00 0.00	25.00 25.00
06-07	Hybrid DE	36.65	41.25	36.65	41.25	573.33	573.33	No	0.00 0.00	0.00 0.00	25.00 25.00
07-08	Hybrid DE	38.89	44.68	38.89	44.68	811.22	811.22	No	0.00 0.00	0.00 0.00	25.00 25.00
08-09	Hybrid DE	39.60	46.34	39.60	46.34	1007.65	1007.65	No	0.00 0.00	0.00 0.00	25.00 25.00
09-10	Hybrid	38.81	58.33	40.06	47.54	2908.41	1197.64	Yes	6.22	0.00	25.00

	DE								10.11	3.67	21.33
10-11	Hybrid	36.17	105.13	40.29	48.18	7388.40	1306.72	Yes	9.61	0.00	25.00
	DE								11.57	3.63	17.70
11-12	Hybrid	35.10	133.89	40.35	48.33	9395.92	1332.17	Yes	10.50	0.00	25.00
	DE								13.14	4.43	13.27
12-13	Hybrid	36.17	105.13	40.29	48.19	7388.40	1305.94	Yes	9.63	0.00	25.00
	DE								14.11	0.00	13.27
13-14	Hybrid	35.10	133.89	40.38	48.36	9395.92	1332.93	Yes	10.51	0.00	25.00
	DE								14.61	3.02	10.25
14-15	Hybrid	35.10	133.89	40.38	48.36	9395.92	1335.01	Yes	10.53	0.00	25.00
	DE								15.08	2.52	7.73
15-16	Hybrid	38.13	66.63	40.17	47.88	3952.13	1249.80	Yes	7.88	0.00	25.00
	DE								13.91	1.32	6.41
16-17	Hybrid	38.50	62.01	40.12	47.71	3374.14	1220.21	Yes	7.04	0.00	25.00
	DE								9.09	4.88	1.53
17-18	Hybrid	38.50	62.01	40.12	47.70	3374.14	1222.20	Yes	6.05	0.99	25.00
	DE								6.06	1.53	0.00
18-19	Hybrid	39.31	53.15	39.95	47.24	2234.99	1145.95	Yes	1.95	2.53	24.01
	DE			39.73	49.76	2234.99	1670.12		1.95	0.00	0.00
19-20	Hybrid	39.55	50.82	39.89	47.08	1931.70	1122.26	Yes	0.05	3.58	21.48
	DE			39.56	50.70	1931.70	1916.31		0.05	0.00	0.00
20-21	Hybrid	39.55	50.82	39.89	47.12	1931.70	1118.65	Yes	0.00	3.63	17.90
	DE								0.00	0.00	0.00
21-22	Hybrid	39.31	53.15	39.95	47.26	2234.99	1143.54	Yes	0.00	4.46	14.27
	DE								0.00	0.00	0.00
22-23	Hybrid	39.60	46.34	39.60	46.32	1007.65	1007.65	No	0.00	0.00	9.81
	DE								0.00	0.00	0.00
23-00	Hybrid	38.61	44.06	38.61	44.06	754.47	754.47	No	0.00	0.00	9.81
	DE								0.00	0.00	0.00

The Sharing patterns of solar and ESS using hybrid optimization for the IEEE-30 and IEEE-57 bus systems are shown in Fig. 3 and Fig. 4 respectively. While the sharing patterns using DE optimization are shown in Fig. 5 and Fig. 6 for the IEEE-30 and IEEE-57 bus systems.

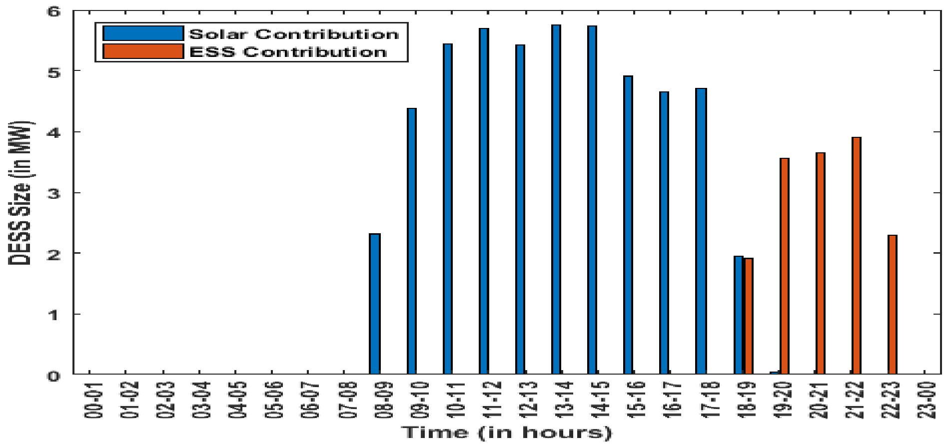

Fig. 3. Sharing patterns of solar and ESS using Hybrid for IEEE-30 bus system

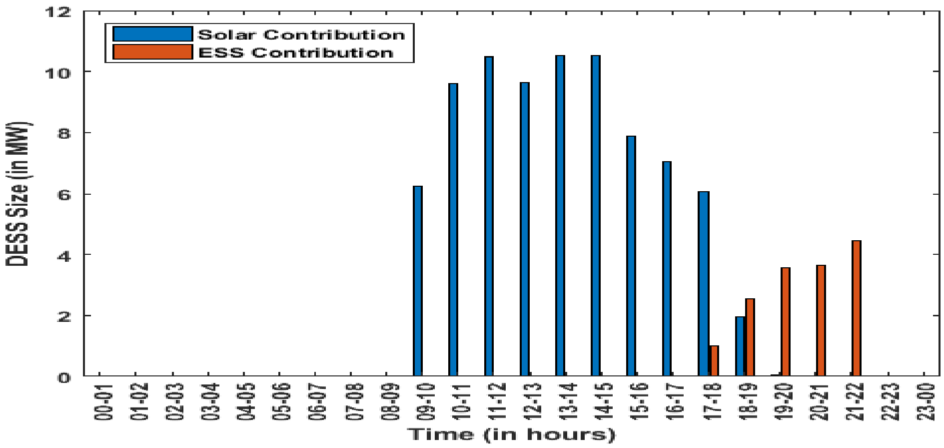

Fig. 4. Sharing patterns of solar and ESS using Hybrid for IEEE-57 bus system

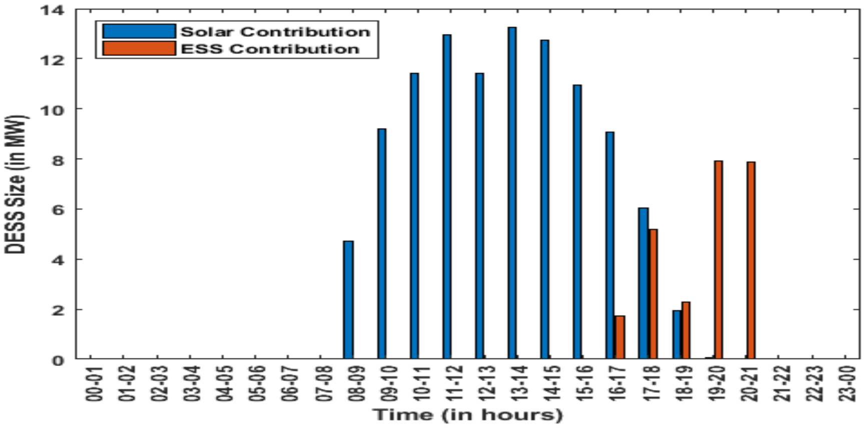

Fig.5. Sharing patterns of solar and ESS using DE for IEEE-30 bus system

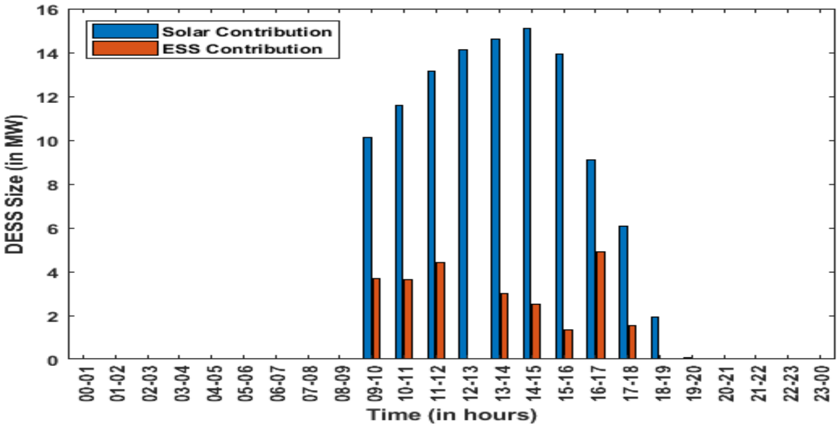

Fig. 6. Sharing patterns of solar and ESS using DE for IEEE-57 bus system

The total contribution from PV and ESS for the IEEE-30 and IEEE-57 bus systems are presented in Table IV and Table V.

Total contribution of DESS, using hybrid optimization for the IEEE-30 and IEEE-57 bus system is 66.35 MW and 95.16 MW. While it is 128.80 MW and 134.68 MW using DE optimization, which is 94.12% and 41.53% more than the hybrid optimization. Moreover, the participation of ESS using DE starts hours before than hybrid optimization and ends hours before the end of the day. This shows more power from DESS is needed to manage congestion in the large networks than the small networks.

Since the cost of usage of DESS is 0.22 $/KWh, therefore the total cost of consuming 128.80 MW and 134.68 MW of DESS using DE for the IEEE-30 and IEEE-57 bus systems are $28336.0 and $29629. While the total cost of consuming 65.35 MW and 95.16 MW of DESS using hybrid optimization for the IEEE-30 and IEEE-57 bus systems are $14597.0 and $20935.2 respectively. So there is a large saving in terms of cost of DESS using hybrid optimization, and it saves 94.12% and 41.53% cost on DESS. The savings on the large systems are less as compared to the small systems.

As can be seen from Table II and Table III that DE contributes more power from DESS to manage the same level of congestion compared to hybrid optimization, this leads to the shortage of ESS before the end of the day.

Table IV &Table V : Contribution from DESS and their usage cost for IEEE- 30 Bus System and IEEE- 57 Bus System, respectively.

Contribution IEEE- 30 Bus	DE	Hybrid
Solar (MW)	103.80	51.03
ESS (MW)	25.00	15.32
Total (MW)	128.80	66.35
Total Cost (in $)	28336.0	14597.0

Contribution IEEE- 57 Bus	DE	Hybrid
Solar (MW)	109.68	79.97
ESS (MW)	25.00	15.19
Total (MW)	134.68	95.16
Total Cost (in $)	29629.60	23078.00

Since solar is not available for many hours in the morning and the evening; therefore, in this duration, we can totally rely on ESS to manage any unpredicted congestion in the network. Also, ESS should be saved to manage congestion the next day because solar becomes active after 6 hours in the morning. During morning hours, sufficient ESS should be available to manage the congestion in the network. And, this could be achieved using hybrid optimization, because total ESS available at the end of the day for the IEEE-30 bus and IEEE-57 bus system is 9.68 MW and 9.81 MW respectively, that can be used next day to manage congestion. Therefore, it can be concluded that the hybrid optimization efficiently manages the DESS due to its optimal or near-optimal converging nature. And, the proposed approach saves approx. 39% of ESS at the end of the day, for both small and large systems that are very helpful in managing congestion the next day in the absence of solar.

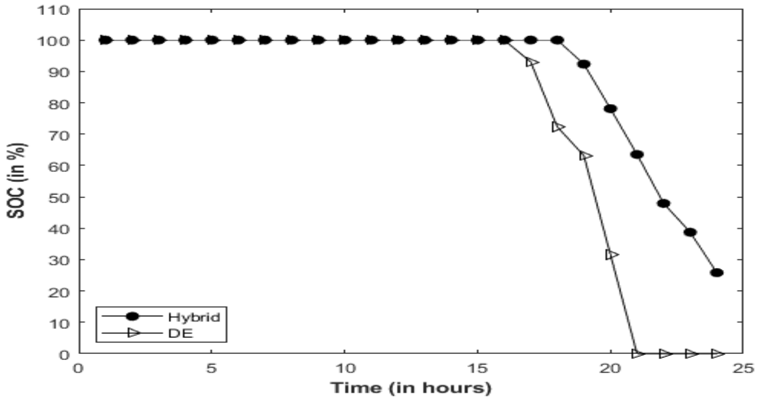

Fig.7. ESS State Of Charge (SOC) vs Time for IEEE-30 Bus System

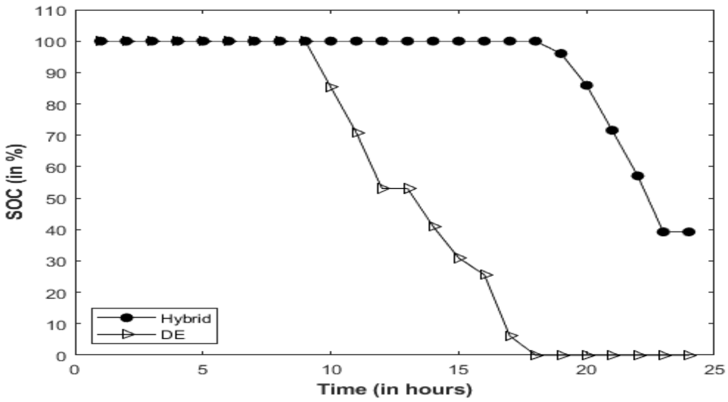

Fig 8. ESS State Of Charge (SOC) vs Time for IEEE-57 Bus System

7. Conclusion

In this paper, an Hybrid and TCC based algorithm are suggested for sizing and optimal location of DESS, minimizing multi-objective fitness function which comprises 1. Generation Cost 2. Transmission Congestion Cost (TCC) and 3. Real Power Loss in the network, for hourly congestion management in the IEEE-30 and IEEE-57 bus systems. The contribution of this paper can be concluded as:

1. Hourly congestion management is proposed with the help of solar and ESS.
2. 40 MW solar power plant is considered which can produce a maximum of 15 MW when the solar irradiance is maximum on 05th June 2018
3. Real 24 hours solar irradiance data of Delhi are taken to generate energy from solar power plants and 25 MW ESS is taken to store surplus energy.
4. TCC is used to find the optimal location for DESS placement while hybrid optimization technique is used for optimal sizing of DESS.
5. DESS participates for congestion management, and during participation, the priority is given to the solar and then ESS.
6. Obtained results are compared with the DE based optimization technique.

Both the optimization techniques (DE, hybrid) perform well in managing congestion while DE has a higher consumption of resources to manage congestion which leads to a shortage of resources at the end of the day. Thus may lead to huge social and economic losses if any unpredicted congestion occurs on the network the same day or next day when solar is not available. In contrast, hybrid optimization gives very encouraging results and at the end of the day, it saves approx. 39% of ESS, thus can participate in congestion management the next day when solar irradiance is not available.

Therefore, this experiment shows that a single optimization technique like DE as well as a hybrid optimization technique can well handle congestion in the availability of resources. But hybrid optimization technique performs far better in managing the available resources due to optimal or near-optimal nature of convergence.

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