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EVALUATION OF ECONOMIC IMPACT OF RENEWABLE ENERGY RESOURCES with ESS IN MULTIPERIOD OPTIMAL OPERATION OF POWER SYSTEMS

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Abstract : This paper deals with solar generation with Energy Storage Systems (ESS) added to the thermal generation. It analyses the influence of solar with ESS on the existing grid. Power generation, voltages and cost solar with and without ESS are observed and compared with the original grid. Optimization software called General Algebraic Modelling System (GAMS) is used for simulation. The proposed approach has been tested on the standard IEEE RTS 24-bus test system for a time period of 24-hours with dynamic load.

I. INTRODUCTION

Every economy in world is stepping towards Renewable Energy Sources (RES) due to the rise in environmental awareness, carbon footprint and other factors. 71 percentage of electricity is being generated by thermal generators in Indian [1]. But thermal energy needs fossil fuels like Coal, oil, and natural gas which are non-renewable in nature and on combustion releases carbon dioxide which is harmful to nature and causes global warming [2]. India being a tropic country is also rich in solar, wind resources and hydro resources which are renewable in nature and has very less environmental side effects.

Solar PV system, is one of the best renewable sources, has advantages like scalability in power, small amount of maintenance, simple installation and modularization [3]. Low cost, low area requirements and simple installation allows it available to common man and. Even though it has significant installation cost it has around 20- 30 years of life time and almost zero or low running cost. Solar PV uses energy from sun light for exciting electrons from valence band to conduction band of semiconductor [4].

Since renewable energy sources are not continuous in nature solar is usually complemented by ESS, in order to keep power supply uninterrupted for critical loads [5]. The stability of the system is maintained by storing energy during off-peak hours and using it during peak load hours with reduced cost. Multiperiod AC optimal power flow (AC-OPF) problem is implemented for a dynamic load in 24 hours is solved using 4 different cases, Case1-thermal alone with 10 generators is implemented, Case-2 thermal with 2 Energy Storage Systems at bus 19 and 21, Case3-thermal with solar at bus 4 and Case-4 thermal with ESS at bus 19 and 21 and solar at bus 4. All the cases are solved using nlp (nonlinear programming) in GAMS software [6].

II. MODELLING ENERGY STORAGE SYSTEMS

ESS is added at bus 19 and bus 21 with capacities 200MW and 100MW respectively. State of charge of ESS is formulated in equation (1)

$$SOC_{i,t}9 = SOC_{i,t-1} + P_{i,t}^{c}\eta_c - \frac{P_{i,t}^{d}}{\eta_d} \quad (1)$$

In the above equation $SOC_{i,t}$ is State of Charge for ESS at i^{th} and time t, $SOC_{i,t}$ is State of Charge for ESS at i^{th} and an hour before time t. Charging efficiency is 95% and discharging efficiency is 90%.

ESS charging and discharging limits are formulated in equations (2) and (3)

$$P^{c}_{i,min} < P^{c}_{i,t} < P^{c}_{i,max} \quad (2)$$

$$P^{d}_{i,min} < P^{d}_{i,t} < P^{d}_{i,max} \quad (3)$$

In the equation (2) and equation (3) $P^{c}_{i,t}$ is real charging power of ESS connected to i^{th} bus at time t, $P^{d}_{i,t}$ real discharging power of ESS connected to i^{th} bus at time t.$P^{c}_{i,max}$ is the maximum capacity of ESS connected to i^{th} bus and $P^{c}_{i,min}$ is the minimum capacity of ESS connected to i^{th} bus. since we have 2 ESS at bus 19 and bus 21, at bus at 19 $P^{c}_{i,min}$ is 0MW and $P^{c}_{i,max}$ is 200MW and for ESS at bus 21 $P^{c}_{i,min}$ is 0MW and $P^{c}_{i,max}$ is 100MW.

Considering Dynamic pricing system, the charging and discharge price of ESS varies continuously the values of ESS charging and discharge price are taken for a case of minimizing grid investment [7]. Since charging is considered as load and discharge is considered as source for charging costumer needs to pay to the grid whereas for discharge grid pays to the ESS station.

From 1st hour to 14th hour load attains a minimum at 5th hour which is 1678MW and maximum at 18th hour which is 2850MW. From the given demand values demand less than 1800MW is taken as valley period, demand more than 2500MW is considered as peak load and remaining time is considered as flat load and charging and discharging costs are taken accordingly.

III. PROBLEM FORMULATION

Multi-Period Optimal AC Power Flow:

a) Power flow equations:

The active and reactive power flows in each branch connecting bus i to bus j in the AC network are specified as follows.

$$P_{ij,t}=\text{real}\ \{S_{ij,t}\} = \frac{V_{i,t}^2}{Z_{ij}}\cos\theta_{ij} - \frac{V_{i,t}V_{j,t}}{Z_{ij}}\cos(\delta_{i,t}-\delta_{j,t}+\theta_{ij}) \quad (4)$$

$$Q_{ij,t}=\text{img}\ \{S_{ij,t}\} = \frac{V_{i,t}^2}{Z_{ij}}\sin\theta_{ij} - \frac{V_{i,t}V_{j,t}}{Z_{ij}}\sin(\delta_{i,t}-\delta_{j,t}+\theta_{ij}) - \frac{bV_{i,t}^2}{2} \quad (5)$$

Here $S_{ij,t}$ is the apparent power from the bus i to bus j , $V_{i,t}V_{j,t}$ are voltages of ith and j^{th} bus in per units respectively. Z_{ij} is the impedance between i^{th} and j^{th} bus.

b) Objective function:

The objective function (OF) is fuel cost of thermal generation, the objective is to minimize the OF over the scheduled time horizon of 24hours:

$$OF = \sum_{i,t}^{i=24,t=24} b_g(P^{g}_{i,t}) \quad (6)$$

Here, b_g *is the* Fuel cost coefficient of active power at thermal generating unit and $P^{g}_{i,t}$ is real power generation at g^{th} thermal unit at bus i and time t

c) Power balance constraint

$$P^{g}_{i,t}+P^{s}_{i,t}-P^{l}_{i,t} - P^{c}_{i,t} + P^{d}_{i,t}=\sum P_{ij,t} \quad (7)$$

$$Q^{g}_{i,t}-Q^{l}_{i,t}=\sum Q_{ij,t} \quad (8)$$

Here, $P^{l}_{i,t}$ is the Active power demand on bus i at time t, $P^{s}_{i,t}$ is the Solar active power at bus i and time t, $P^{c}_{i,t}$ Real charging power of ESS at bus i and time t, $P^{d}_{i,t}$ Real discharging power of ESS at bus i and time t and $\sum P_{ij,t}$ is the real power loss at time t $Q^{g}_{i,t}$ is reactive power generation at g^{th} thermal unit at bus i and time t,$Q^{l}_{i,t}$ is reactive power demand on bus i at time t and $\sum Q_{ij,t}$ is the reactive power loss at time t.

d) Generator limit constraints

$$-S^{max}_{ij} < S_{ij,t} < S^{max}_{ij} \quad (9)$$

$$P^{g,min}_{i} < P^{g}_{i,t} < P^{g,max}_{i} \quad (10)$$

$$Q^{g,min}_{i} < Q^{g}_{i,t} < Q^{g,max}_{i} \quad (11)$$

Here, S^{max}_{ij} is the maximum apparent power flow from i^{th} and j^{th} bus. $P^{g,max}_{i}$ is the maximum real power generation of gth thermal unit at bus i. $P^{g,min}_{i}$ is the minimum real power generation of gth thermal

unit at bus i. $Q_i^{g,max}$ is the maximum reactive power generation of gth thermal unit at bus i. $Q_i^{g,min}$ is the minimum reactive power generation of gth thermal unit at bus i.

e) Ramp up and ramp down constraints:

$$P_{i,t}^{g} - P_{i,t-1}^{g} < RU_g \quad (12)$$

$$P_{i,t-1}^{g} - P_{i,t}^{g} < RD_g \quad (13)$$

For thermal generation ramp rate constraints for each unit, output is limited by ramp up or ramp down rate at each hour. In the above equations RU_g is the ramp up value of thermal generator g connected to i^{th} bus and RD_g ramp down value of thermal generator g connected to i^{th} bus.

f) Solar PV:

In GAMS software $P_{i,t}^{s}$ is considered as variable that needs to be computed depending on balance equation modelled in equation (14).

Power constraint of solar is modelled as follows:

$$P_i^{s,min} < P_{i,t}^{s} < P_i^{s,max} \quad (14)$$

$P_{i,t}^{s}$ in the above equation Solar real power connected to i^{th} bus at time t, $P_i^{s,max}$ is the maximum capacity of solar pv connected to i^{th} bus and $P_i^{s,min}$ is the minimum value of solar pv output power connected to i^{th} bus.

Sometimes, the actual wind and solar powers are less than predicted ones. In this case, there are curtailments. Curtailment equation of solar are formulated in equation (15):

$$P_{i,t}^{sc} = P_{i,t}^{max} - P_{i,t}^{s} \quad (15)$$

$$0 < P_{i,t}^{sc} < P_i^{s,max} \quad (16)$$

In the above equation $P_{i,t}^{sc}$ is the solar power curtailment and solar curtailment is always less then maximum capacity of solar.

IV. METHODOLOGY

Multiperiod AC-OPF problem is solved using nonlinear programming by NLP solver in GAMS. The effect of ESS and Solar integration has been studied on the operation of thermal units.

Steps involved in Multiperiod AC-OPF Process:

- Sets: Time in hours - $t \in \{1, 2, 3\ldots, 24\}$ and busses for a 24-bus system
  i ∈{1,2,3….,24} sets and generating busses are defined as sets.
- Tables: generator parameters for thermal, dynamic load with respect to time, line data of 24-bus system etc.
  are added using Tables keyword in GAMS
- Variables: unknown values like real and reactive power of thermal generator are declared as variables
- Scaler: fixed quantity like ESS capacity and efficiency of ESS are added in GAMS using scalar keyword.
- Equation: Equation for multi period AC-OPF relating the data elements with sets are added using equation keyword in GAMS.
- Model and solver: all equation relating to multiperiod AC-OPF are modelled as single problem using model
  keyword in GAMS. All the equations in AC-OPF are solved using solve and nlp (non-linear programming)
  keywords in GAMS.
- Output: output is extracted from GDX file in GAMS

IV. RESULTS AND DISCUSSION

The IEEE RTS 24-bus network is shown in Fig. 1, Information about 10 thermal generating units is given in Table 1 It is a transmission network with the voltage levels of 138 kV, 230 kV, and Sbase = 100 MVA. Two ESS are installed, each with a capacity of 200 MW and 100 MW are connected to buses 19 and 21, respectively, also after considering voltages at non generating buses bus with least stable voltage is connected with solar power plant with a capacity of 100 MW is connected to bus 4.

Table 1. parameters of thermal generating units

Generating BUS	P_g^{max} (MW)	P_g^{min} (MW)	b_g ($/MW)	Q_g^{max} (Mvar)	Q_g^{min} (Mvar)	RU (MW/h)	RD (MW/h)
1	152	30.4	13.32	60	-50	21	21
2	152	30.4	13.32	60	-50	21	21

7	300	75	20.7	180	0	43	43
13	591	207	20.93	240	0	31	31
15	215	66.30	21	110	-50	28	28
16	155	54.30	10.52	80	-50	31	31
18	400	100	5.47	200	-50	70	70
21	400	100	5.47	200	-50	70	70
22	300	60	0	96	-60	53	53
23	660	248.4	10.52	310	-125	49	49

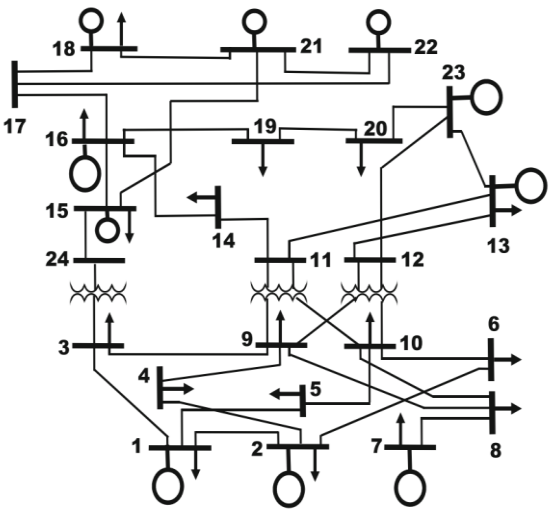

Fig. 1. IEEE RTS 24-bus system

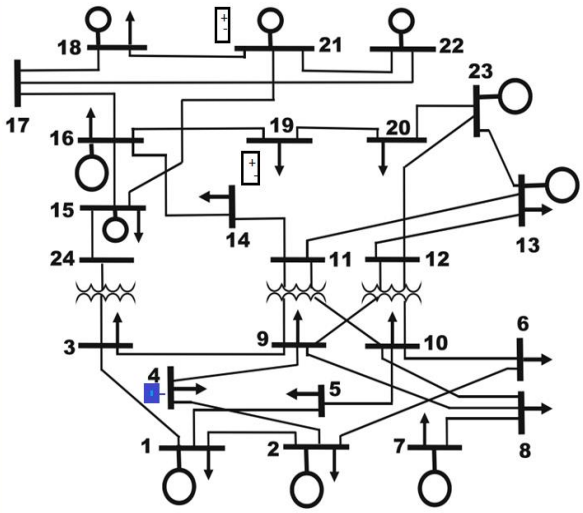

Fig. 2. Modified version of IEEE RTS 24-bus system

Results are obtained for Multiperiod AC- optimal power flow (AC-OPF) problem is implemented for a dynamic load in 24 hours is solved using 4 different cases, Case1-thermal alone with 10 generators is implemented, Case-2 thermal with 2 Energy Storage Systems at bus 19 and 21, Case3-thermal with solar at bus 4 and Case-4 thermal with ESS at bus 19 and 21 and solar at bus 4. All the cases are solved using nlp (nonlinear programming) in GAMS software. In Fig. 4 there is a deviation of generation to that of demand that is loss in the system, at 18th hour there is a peak demand so all generators are generating maximum at 18th hour.

Fig.6 shows graph of load with and without ESS, it is evident that peaks and valleys are reducing when we use ESS. Fig.7 shows charging and discharging values of ess1 and ess2 and both combined together, from load graph it is clear that there are 2 local minimum and ESS is charging at both valleys and discharging at both local minima thereby reducing peak loads and reduces thermal power generation at 18th hour.

From Fig. 10 shows solar power generation in normal day It is evident that solar is generating maximum Power at noon at 12. From FIg.9 shows total thermal Generation, solar generation and load in megawatts vs. time, from 9th hour to 16th hour it is clearly visible Adding solar reduces load on thermal generation. From Fig.12 it is clear that by using ESS load peaks and valleys are reducing and thereby reducing load at Generation side.

Fig.14 shows charging and discharging values of ess1 and ess2 and both combined together, from load graph it is clear that there are 2 local minimum and ESS is charging at both valleys and discharging at both local minima thereby reducing peak loads and reduces thermal power generation at 18th hour. Here, the charging and discharging is increased with solar. From FIg.13 shows total thermal Generation, solar generation and load with in megawatts vs. time, from 9th hour to 16th hour it is clearly visible Adding solar reduces load on thermal generation.

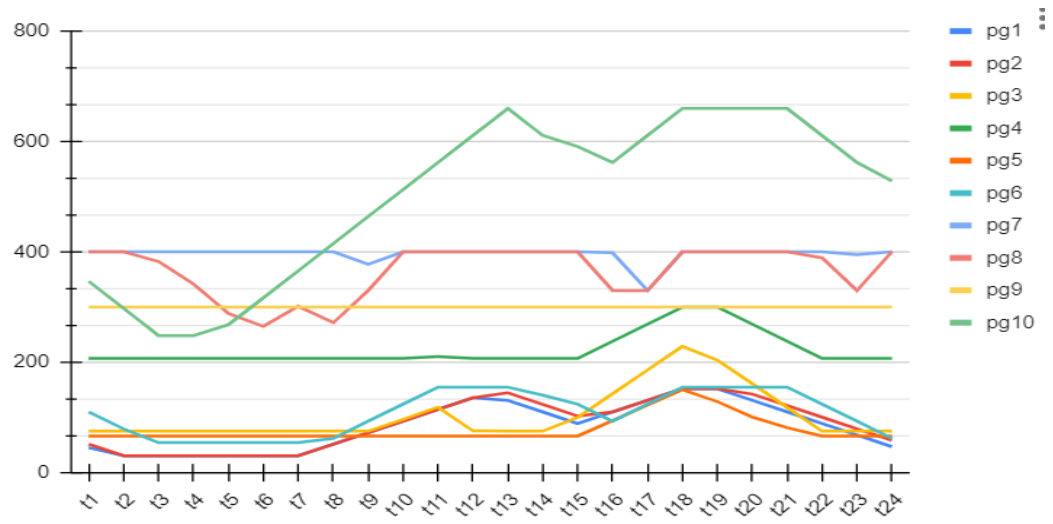

Fig. 3. Generation of individual thermal units without renewable and without ESS (case 1).

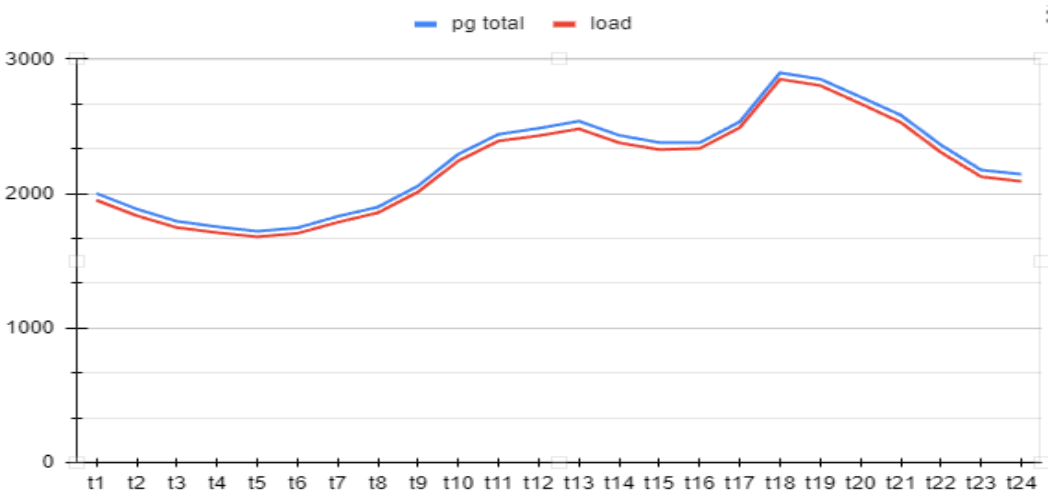

Fig. 4. Total thermal generation in megawatts and load in megawatts without renewable and without ESS (case 1).

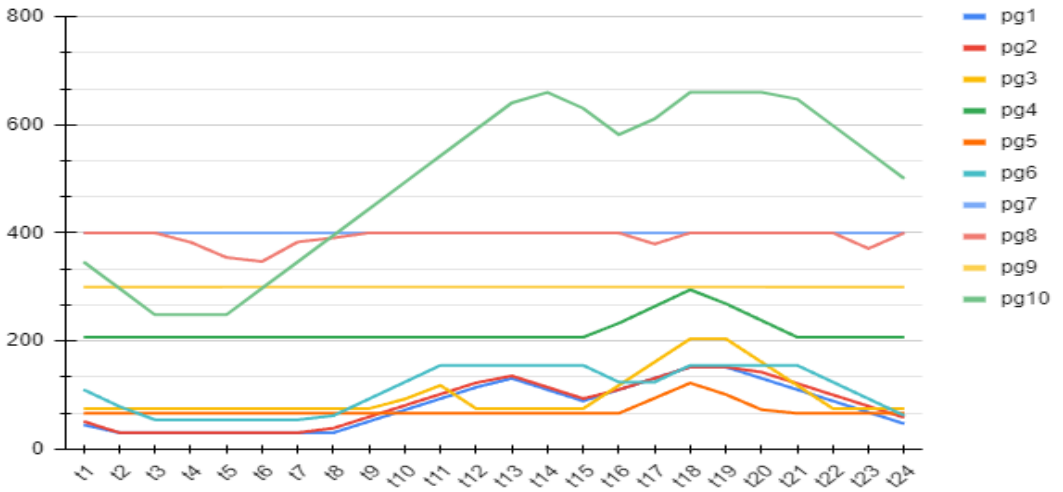

Fig. 5. Generation of individual thermal units with ESS (case 2)

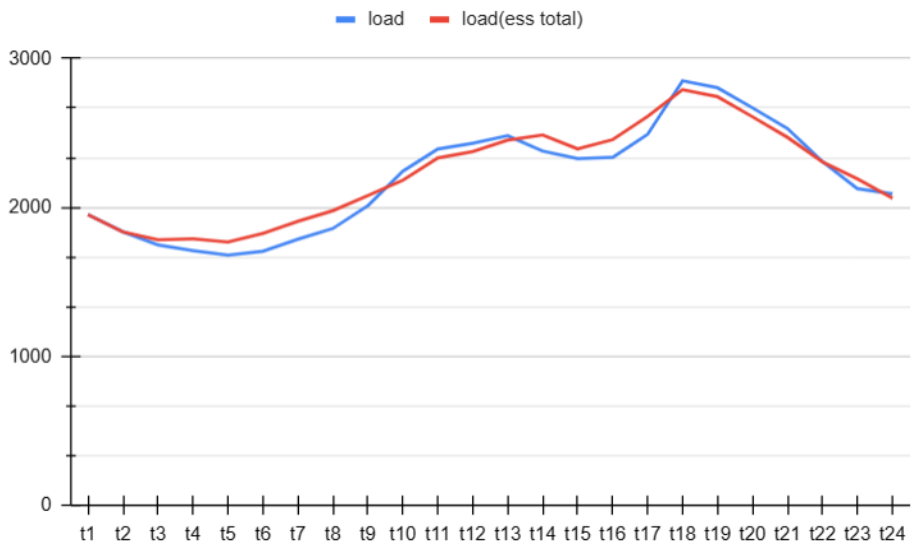

Fig. 6. Demand in megawatts with and without ESS (case 2)

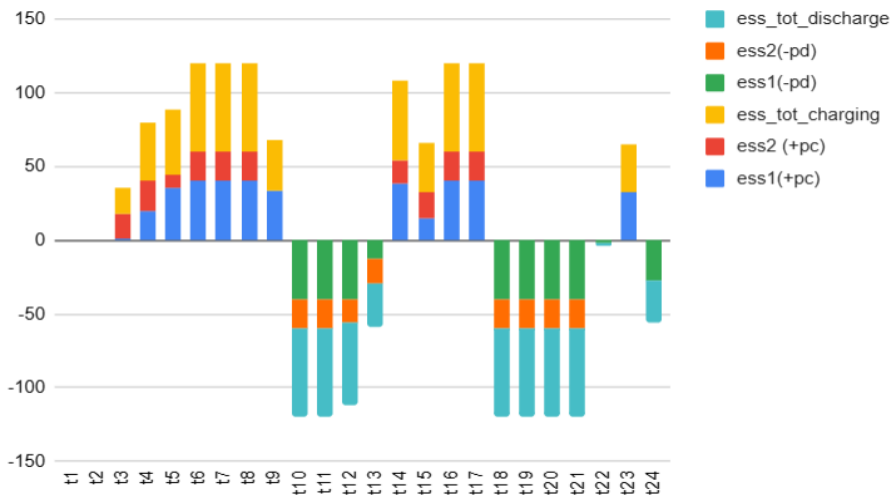

Fig. 7. ESS charging and discharge graph case (2).

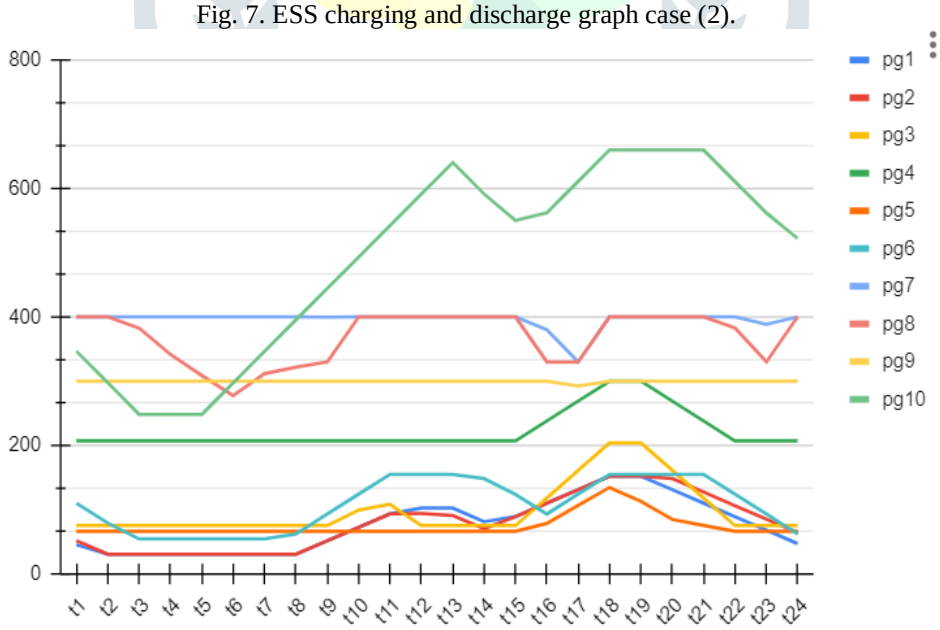

Fig. 8. Generation of thermal units with solar in Mega Watts (Case3).

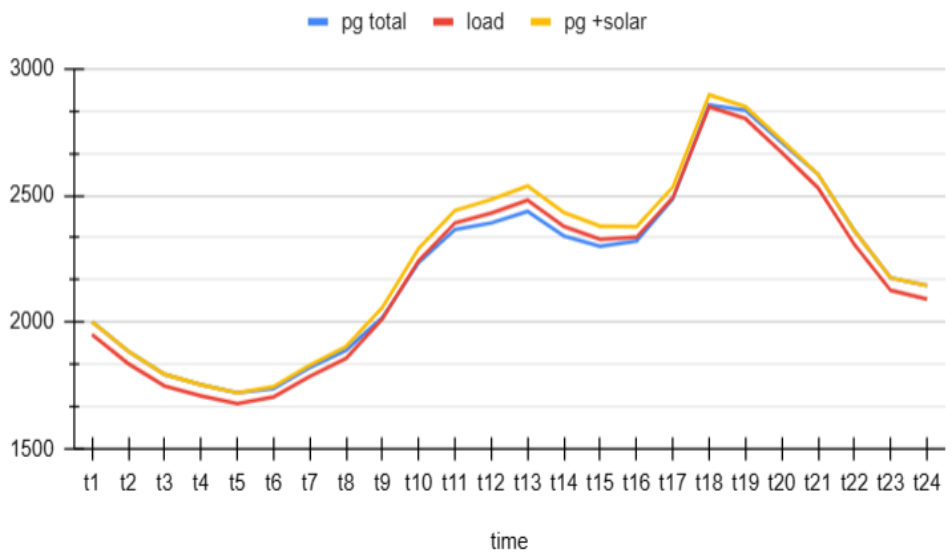

Fig. 9. Total thermal generation, solar generation and load in megawatts vs time (Case3)

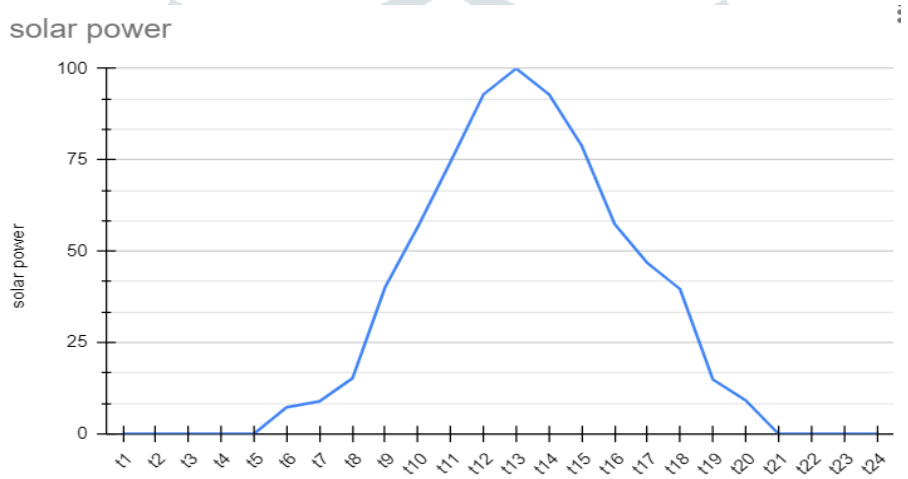

Fig.10 Solar power generation (Case3)

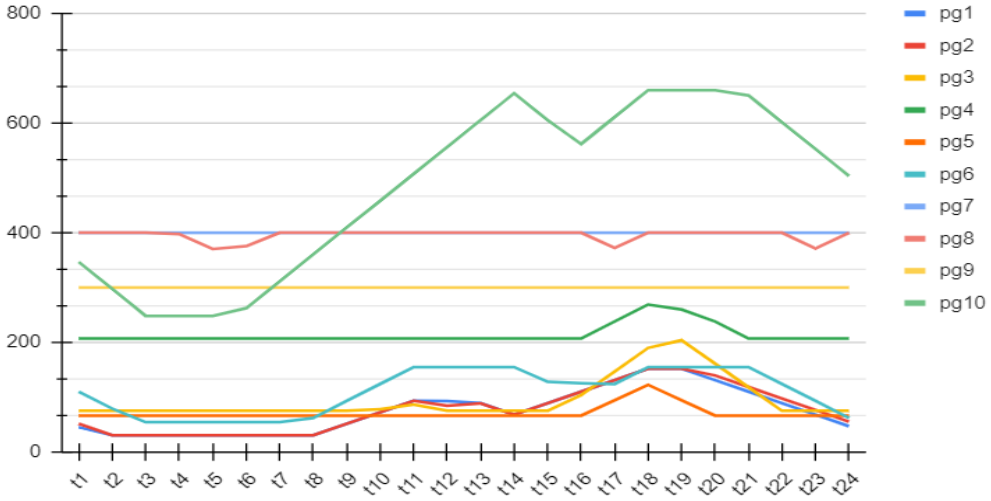

Fig.11. Generation of thermal units with solar and ESS (case4)

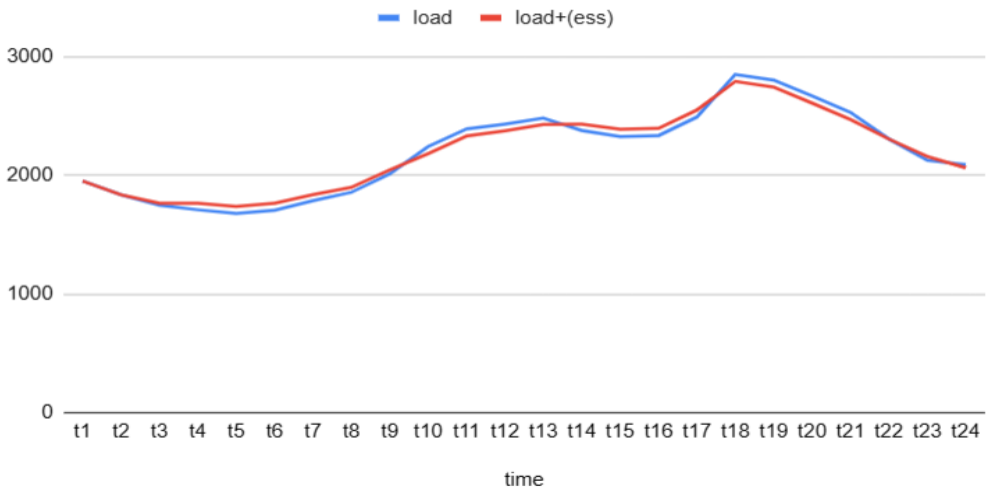

Fig.12. Load with and without ESS (case4)

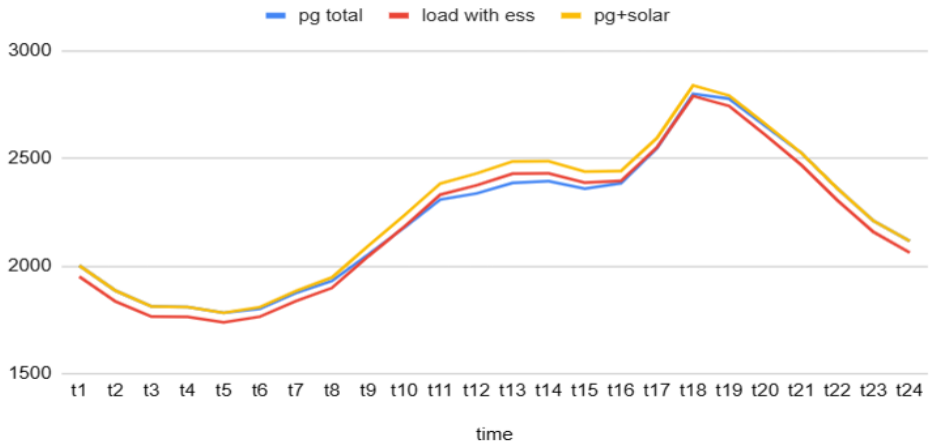

Fig.13. Thermal power, thermal with solar and load with time (case4)

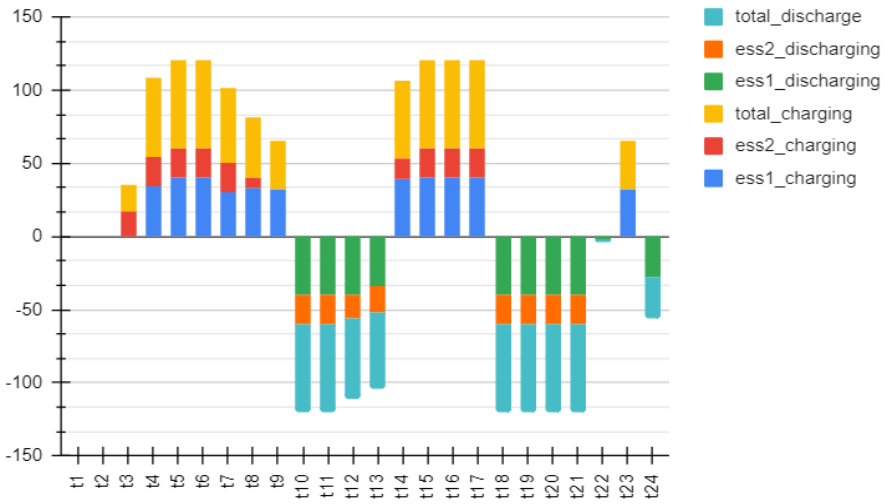

Fig. 14. ESS charging and discharging for thermal with solar and ESS (case4)

Table 2. charging and discharging cost of ESS

Parameters	Valley time	Flat time	peak time
Charging cost ($ per MWh)	42.1	97.4	395.3
Discharge cost ($ per MWh)	60.7	119.6	436.5

Table 3. cost estimation of thermal, solar and ESS ain all 4 cases

Parameters	Only thermal	Thermal with ESS	Thermal with Solar	Thermal with Solar and ESS
Thermal fuel cost ($)	5,11,187	5,04,199	4,99,380	492709
ESS charging cost ($)	0	2,19,541	0	2,29,899
ESS discharging cost ($)	0	2,07,272	0	2,17,051
Solar cost ($)	0	0	22356.8	22356.8
Solar curtailment ($)	0	0	0	0

V. CONCLUSION

From the results it is evident that, the integration of solar can reduce the generation cost, which makes the system more economical. Adding renewable sources helps in reducing fuel consumption. Adding ESS to system helps to store and use the active power generated from solar or other renewable sources. By adding ESS peak are lowered there by reducing burden to generating units. By adding solar and ESS to the grid helps in maintaining balance between generation and demand without interruption. GAMS helps solve multiperiod AC-OPF easily even for huge systems and GAMS can solve a wide variety of problems, and is capable of handling very large mathematical systems.

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