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A novel method of relieving congestion in hybrid deregulated market utilizing renewable energy sources

Joseph JESLIN DRUSILA NESAMALAR[*], **Paramasivam VENKATESH**,
Sathiasamuel CHARLES RAJA
Department of Electrical and Electronics Engineering, Faculty of Electrical Engineering, Thiagarajar College of Engineering, Affiliated to Anna University, Madurai, Tamil Nadu, India

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Abstract: This paper presents a congestion management technique in the deregulated power sector by optimally using renewable energy sources (RES). The proposed congestion management problem is formulated to minimize the generator rescheduling cost subjected to the real and reactive power balance, thermal line loading limit, and seasonal and day/night constraints of RES. Optimal selection of conventional and renewable participating generators has been identified by using real and reactive power generator sensitivities and the particle swarm optimization algorithm reduces the alteration of rescheduled values of generator power outputs from base case generation levels. The RES participation along with the seasonal and time variation is the pioneering topic in congestion management that has been studied in this work. The practical Indian Tamil Nadu 106-bus system has been analyzed to illustrate the proposed energy-saving technique. The results confirm the benefits of RES as the number of generators required for rescheduling as well as the rescheduling amount have been reduced predominantly when involving RES for rescheduling.

Key words: Renewable energy sources, seasonal variation, diurnal variation, congestion management, particle swarm optimization

1. Introduction

Deregulation of electrical utilities has opened up plentiful opportunities for generators and consumers to be involved in competition by power using transmission systems as a public resource in the deregulated environment. When trying to satisfy consumer needs for energy, at the same time, several system operating limits have to be observed, including thermal and stability limits [1]. Overloading of lines happens due to unexpected contingency or due to uncoordinated transactions. Therefore, congestion management is targeted at relieving congestion in transmission lines based on the willingness of generator rescheduling or load curtailment [2].

Electricity generated by fuel sources that regain their inexhaustible fuel in a short period of time is called renewable energy. It has considerable potential in reducing greenhouse gas emissions. Around the globe, a number of policies/incentives have been adopted to encourage more use of renewable sources to generate electricity. Research is being done to reduce the generation costs of renewable energy sources (RES) and by manufacturing efficient equipment to harness natural resources [3]. Extensive studies have already been done in the area of congestion management. Load curtailment was applied in [4] by introducing indices of the acceptance level by both load and supplier for congestion management. Congestion zones were identified to

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[*] Correspondence: jeslindrusila@gmail.com

reschedule the generators and loads based on transmission congestion distribution factors in [5]. Considering cost and sensitivity to line currents, generation rescheduling and load shedding were described in [6]. The impact of distributed resources on congestion management as developed by a fuzzy C-means clustering approach was discussed in [7]. Optimal rescheduling of generators based on particle swarm optimization was discussed in [8,9], but by taking the line flow limit as MW. A multiobjective particle swarm optimization for two confiicting objectives of alleviation of overload and minimization of cost of operation were optimized to provide Pareto optimal solutions in [10].

Renewable generating systems were configured optimally in residences using an optimization technique in [11]. Based on the statistics of geological data and potential of various renewable energy sources, peak load demand in India was managed in [12]. The effect on utilization of existing hydropower in a region where hydropower is already abundant was analyzed in [13]. Optimal involvement of renewable energy-based IPPs for industrial load management and off-grid hybrid electric systems was evaluated in [14,15].

However, limited studies have emphasized congestion management with RES. A generalized optimal model of congestion management for the deregulated power sector including RES was discussed in [16]. By combining the coordination among hydro and thermal generator companies, the cost of rescheduling both generators was formulated in [17]. However, even these models have not considered seasonal and timely variations. This topic gains more attention as higher penetration of renewable generation is expected in power systems.

This paper proposes a congestion management redispatch technique by considering the combined operation of renewable and conventional generating companies in a pool-based as well as bilateral energy market on a day-ahead and hourly basis. Furthermore, a new sensitivity factor is proposed to select generators to participate in congestion management. In addition, the effect of season and time is studied to achieve a worm's-eye view.

The remaining paper is subdivided as follows. Section 2 presents the RES dependency on season/time. Section 3 explains the renewable and nonrenewable combined congestion management problem formulation. Numerical results obtained after solving the proposed congestion management problem for the practical Indian Tamil Nadu (TN) 106-bus system are presented and discussed in Section 4, followed by concluding remarks in Section 5.

2. RES dependency on season/time

RES is subjected to seasonal variations of peak electricity production in winter or summer as well as diurnal and hourly changes. Electricity production by a solar plant has a seasonal variation with the peak in summer. It has a time variation on a diurnal basis from morning until night, peaking in the middle of the day [18]. The amounts of energy produced from wind turbines are higher in the day than the night and higher during the warm season than the cool season because of the change in wind speed [19]. The availability of raw material to operate biomass plants is quite large as it has less seasonal fluctuation, but there is no diurnal variation as the quantity is independent of time. As water is being stored in dams, small hydroplants are subjected to minimum deviations for seasonal variations and it has no effect for diurnal changes. In this paper, solar, wind, biomass, cogeneration, and small hydroplants have been considered.

2.1. Rescheduling active and reactive power of RES

Based on the sensitivity factor, a sensitive renewable generator can be chosen for rescheduling active power output to relieve congestion. There is variation in the maximum and minimum generation for wind and solar plants between day and night as they are highly dependent on diurnal changes. In particular, recent advances in RES makes even reactive power reschedule possible. Wind farms using induction generators normally consume reactive energy and they are usually fitted with reactive compensation systems. In this work, static compensation equipment is employed to meet the required reactive power support when rescheduling reactive power of wind and solar plants [20,21]. For the other renewable sources, reactive power rescheduling is done by generator voltage set point variation, thereby varying reactive power output [22].

3. Congestion management problem formulation involving RES

3.1. Proposed generator sensitivity (SP and SQ)

The real and reactive power flows in a transmission line connected between bus i and bus j are:

$$P_{ij} = -V_i^2 G_{ij} + V_i V_j G_{ij} cos\delta_{ij} + V_i V_j B_{ij} sin\delta_{ij}, \tag{1}$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i^2 B_i - V_i V_j G_{ij} sin\delta_{ij} + V_i V_j B_{ij} cos\delta_{ij}, \tag{2}$$

where P_{ij} and Q_{ij} are the real power and reactive power in line $i-j$, respectively; V_i and V_j are the voltage magnitude at bus i and bus j, respectively; δ_{ij} is the phase angle between buses i and j; and G_{ij}, B_{ij} are the conductance and susceptance of line $i-j$, respectively. From these basic equations, the apparent power can be written as:

$$\begin{array}{rcl} |S_{ij}| & = & (V_i^4(G_{ij}^2 + B_{ij}^2) + V_i^4 V_j^2 (G_{ij}^2 + B_{ij}^2) - 2V_i^3 V_j cos\delta_{ij}(G_{ij}^2 + B_{ij}^2) + 2V_i^4 B_{ij} B_i \\ & & +2V_i^3 V_j B_i (G_{ij} sin\delta_{ij} - B_{ij} cos\delta_{ij}) + V_i^4 B_i^2)^{1/2} \end{array}, \tag{3}$$

where S_{ij} is the apparent power in line $i-j$ and B_i is the susceptance at bus i.

In power system terminology, apparent power is denoted by S. Thus, the new sensitivity factor has been defined as SP and SQ.

SP for line k can be calculated by change in apparent power flow ΔS_k in a transmission line k with respect to the active power ΔP_g injection at a particular generator bus g and is written as:

$$SP_{k,g} = \frac{\Delta S_k}{\Delta P_g}. \tag{4}$$

Similarly, SQ can be calculated by change in apparent power flow ΔS_k in a transmission line k with respect to the reactive ΔQ_g injection at a particular generator bus g and is written as:

$$SQ_{k,g} = \frac{\Delta S_k}{\Delta Q_g}. \tag{5}$$

The change in apparent power flow incorporating SP and SQ can be written as:

$$\Delta S_k = (SP_{k,g} \times \Delta P_g) + (SQ_{k,g} \times \Delta Q_g). \tag{6}$$

Using Taylor series approximation and neglecting $P-V$ coupling and $Q-\theta$ coupling, Eqs. (**??**) and (**??**) can be written as:

$$SP_{k,g} = \frac{\partial S_k}{\partial \theta_i} . \frac{\partial \theta_i}{\partial P_g} + \frac{\partial S_k}{\partial \theta_j} . \frac{\partial \theta_j}{\partial P_g}, \tag{7}$$

$$SQ_{k,g} = \frac{\partial S_k}{\partial \left|V_i\right|}.\frac{\partial \left|V_i\right|}{\partial Q_g} + \frac{\partial S_k}{\partial \left|V_j\right|}.\frac{\partial \left|V_j\right|}{\partial Q_g}. \tag{8}$$

Differentiating Eq. (**??**) with respect to phasor angle and voltage, we get:

$$\frac{\partial S_{ij}}{\partial \theta i} = \left(\left|S_{ij}\right|^2\right)^{\frac{-1}{2}} \times \left[2V_i^3 V_j sin\delta_{ij}\left(G_{ij}^2 + B_{ij}^2\right) + V_i^3 V_j B_i \left(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}\right)\right], \tag{9}$$

$$\frac{\partial S_{ij}}{\partial \theta_j} = \left(\left|S_{ij}\right|^2\right)^{\frac{-1}{2}} \times \left[-2V_i^3 V_j sin\delta_{ij}\left(G_{ij}^2 + B_{ij}^2\right) - V_i^3 V_j B_i \left(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}\right)\right], \tag{10}$$

$$\frac{\partial S_{ij}}{\partial \left|V_i\right|} = \left(\left|S_{ij}\right|^2\right)^{\frac{-1}{2}} \times \left[\begin{array}{c} 2V_i^3\left(G_{ij}^2 + B_{ij}^2\right) + V_i V_j^2\left(G_{ij}^2 + B_{ij}^2\right) - 3V_i^2 V_j cos\delta_{ij}\left(G_{ij}^2 + B_{ij}^2\right) \\ +4V_i^3 B_i B_{ij} + 3V_i^2 V_j B_i G_{ij} sin\delta_{ij} - 3V_i^2 V_j B_i B_{ij} cos\delta_{ij} + 2V_i^3 B_i^2 \end{array}\right], \tag{11}$$

$$\frac{\partial S_{ij}}{\partial \left|V_j\right|} = \left(\left|S_{ij}\right|^2\right)^{\frac{-1}{2}} \times \left[V_i^2 V_j\left(G_{ij}^2 + B_{ij}^2\right) - V_i^3 cos\delta_{ij}\left[G_{ij}^2 + B_{ij}^2\right] + V_i^3 B_i\left(G_{ij}sin\delta_{ij} - B_{ij}cos\delta_{ij}\right)\right]. \tag{12}$$

The derivatives $\frac{\partial \theta_i}{\partial P_g}, \frac{\partial \theta_j}{\partial P_g}, \frac{\partial |V_i|}{\partial Q_g}, \frac{\partial |V_j|}{\partial Q_g}$ are obtained from the Jacobian matrix of the NewtonRaphson method and Eqs. (**??**) and (**??**) can be calculated.

3.2. Objective function and constraints

Appropriate variables are used to include the renewable generators in the objective function.

Minimization of congestion cost:

$$\sum_{p=1}^{ncg}\left(C_p \Delta P_g\right) + \sum_{p=1}^{nrg}\left(C_p \Delta P_g\right) + \sum_{q=1}^{nosw} C_q(\Delta Q_g)\Delta Q_g + \sum_{c=1}^{nsc} C_c(\Delta Q_c)\Delta Q_c, \tag{13}$$

where C_p is the incremental or decremental active power price bids submitted by generators, C_q and C_c are the cost of reactive power generation by generator and static compensation devices, ΔP_g is the active power adjustment of participating generators, ΔQ_g and ΔQ_c are the reactive power adjustment of generator and static compensation equipment, *ncg* and *nrg* are the number of participating conventional and renewable generators, *nosw* is the number of generators other than solar and wind generators, and *nsc* is the number of static compensation devices.

The objective function is subjected to:

$$P_{Gi} - P_{Di} - \left|V_i\right| \sum_{\substack{j = 1 \\ {}^{1}i}}^{nbus} \left\{\left(G_{ij}cos\delta_{ij} + B_{ij}sin\delta_{ij}\right)\left|V_j\right|\right\} = 0, \tag{14}$$

$$Q_{Gi} + Q_{ci} - Q_{Di} + \left|V_i\right|^2 B_{ii} - \left|V_i\right| \sum_{\substack{j = 1 \\ {}^{1}i}}^{nbus} \left\{\left(G_{ij}sin\delta_{ij} - B_{ij}cos\delta_{ij}\right)\left|V_j\right|\right\} = 0, \tag{15}$$

where P_{Gi} and P_{Di} are the active power generation and demand at bus i, Q_{Gi} and Q_{Di} are the reactive power generation and demand at bus i, and $nbus$ is the total number of buses.

$$(\, S_{ij} + \sum_{g=1}^{nfg,nrg} SP_{k,g} \times \Delta P_g + \sum_{n=1}^{nosw,nsc} SQ_{k,g} \times \Delta Q_g \,) \leq S_{ij}^{max}, ij \in N_l, \tag{16}$$

where S_{ij}^{max} is the thermal limit of transmission line $i-j$ and N_l is the congested line.

$$\Delta P_g^{min} \leq \Delta P_g \leq \Delta P_g^{max}, g = 1, 2, ..nosw \tag{17}$$

$$\Delta P_g^{min} \leq \Delta P_g \leq \Delta P_g^{max}, g = 1, 2..nswforday \tag{18}$$

$$\Delta P_g^{min} \leq \Delta P_g \leq \Delta P_g^{max}, g = 1, 2, ...nswfornight \tag{19}$$

$$\Delta Q_g^{min} \leq \Delta Q_g \leq \Delta Q_g^{max}, g = 1, 2, ..nosw \tag{20}$$

$$\Delta Q_c^{min} \leq \Delta Q_c \leq \Delta Q_c^{max}, c = 1, 2, ..nsc \tag{21}$$

$$\Delta V_g^{min} \leq \Delta V_g \leq \Delta V_g^{max}, g = 1, 2, ..ng \tag{22}$$

Here, Eq. (**??**) represents the active power generation of conventional and renewable generators whose capacity remains the same during day and night. It excludes solar and wind plants. Eqs. (**??**) and (**??**) represent active power generation of wind and solar plants whose generation varies during day and night. Eq. (**??**) represents the reactive power generation of generators, except solar and wind plants. Eq. (**??**) represents the reactive power generation of static compensation equipment at solar and wind plants. Eq. (**??**) represents the voltage magnitude of generator buses.

3.3. Reactive power rescheduled cost of generator and static compensation equipment

The associated cost $C_q(\Delta Q_g)$ of reactive power production ΔQ_g based on the opportunity theory [22] is given as:

$$C_q(\Delta Q_g) = \left\{ C_p(S_{max}) - C_p\left(\sqrt{S_{max}^2 - \Delta Q_g^2}\right) \right\} \times \rho, \tag{23}$$

where $C_p(\cdot)$ is the cost function for the active power production as in

$$C_p(P_g) = a_g P_g^2 + b_g P_g + c_g, \tag{24}$$

and ρ is the profit rate of active power generation, usually between 0.05 and 0.10.

$$S_{g-max} = \frac{P_{g-max}}{powerfactor} \tag{25}$$

In this study, the power factor is taken to be 0.8. The static compensation equipment installed can be switched capacitors, switched inductors, or static VAR compensators (SVC). For a static compensator with an initial cost of \$11,600.00/MVAR, lifetime of 30 years, and average use of 75% [22], the investment cost can be calculated as:

$$C_c(\Delta Q_c) = \frac{11,600}{30 \times 365 \times 24 \times 0.75} Q_c. \tag{26}$$

3.4. Congestion management using PSO with time-varying acceleration coefficient

The schooling patterns of birds and fish was observed and the technique particle swarm optimization (PSO) was brainstormed by Eberhart and Kennedy in 1995 [23]. In particular, the two primary operators, i.e. velocity and position, are updated at each generation. The movement of each particle is changed with respect to the previous best position and global best position. Then the new velocity value is used to calculate the next position of the particle among the random population. This process is then iterated until a minimum error is achieved or to a maximum number of iterations. The objective of using PSO with a time-varying acceleration coefficient [24] is to enhance the global search initially and to encourage the particles to converge toward the global optima at the search end. Clerc's constriction coefficient 'C' reduces the magnitude of a particle's oscillations and it concentrates on the local and neighborhood previous best points.

$$\begin{gathered} v_p^{iter+1} = C\{\omega \times v_p^{iter} + \left((c_{1f} - c_{1i})\,\frac{iter}{iter_{max}} + c_{1i}\right) \times rand_1 \times (pbest_p - x_p) + \\ \left((c_{2f} - c_{2i})\,\frac{iter}{iter_{max}} + c_{2i}\right) \times rand_2 \times (gbest_p - x_p)\} \end{gathered} \tag{27}$$

Here, $c_{1f}, c_{1i}, c_{2f}, c_{2i}$ are constants; $iter$ is the present iteration number; $iter_{max}$ is the maximum number of allowable iterations; C is Clerc's constriction factor; ω is the inertia weight factor; $pbest_p$ and $gbest_p$ are the local best and global best of the pth particle; and v_p^{iter} is the velocity at the present iteration number.

3.5. Algorithm

1. Run load flow analysis for the day-ahead schedule and get congested line details.
2. Get SP and SQ values and select necessary generators to participate in congestion management.
3. To apply PSO, generate a random population to get optimized active and reactive power output of generators. Minimize the objective function satisfying all constraints.
4. Find the global best values and end redispatch notice to conventional and renewable generators for day-ahead schedule.
5. Run hour-ahead schedule and if congestion occurs, repeat Step 2 to Step 4.

4. System description

The study area of Tamil Nadu lies within 8^{circ} 5′N to 13^{circ} 35′N and 76^{circ} 15′E to 80^{circ} 20′E in the southern end of India. The system comprises 41 generators, 162 transmission lines, and 94 loads. The bus and line data can be obtained from TNEB Statistics [25] at a glance. The single-line diagram is given in Figure 1 [26]. The season considered in this work is from May to September where, in Tamil Nadu, wind generation is peak, solar irradiation is also high, and biomass raw materials are satisfactory. First, the day-ahead schedule including pool and bilateral contracts will be analyzed by ISO. At that time, bilateral transaction at a particular hour causes congestion. Then generator rescheduling will be done to satisfy the objective function and constraints for the congested hour. Once the rescheduling notice has been sent to renewable and conventional generators, the day-ahead schedule will be dispatched as modified. Then, while running the hour-ahead schedule, the effects of line outage are studied and the corrective action is analyzed. The total cost savings and energy savings are discussed. The simulation of this algorithm is done using MATLAB 9.0 on a Pentium IV 2.4 GHz personal computer and the computation time is 12–14 s for all cases.

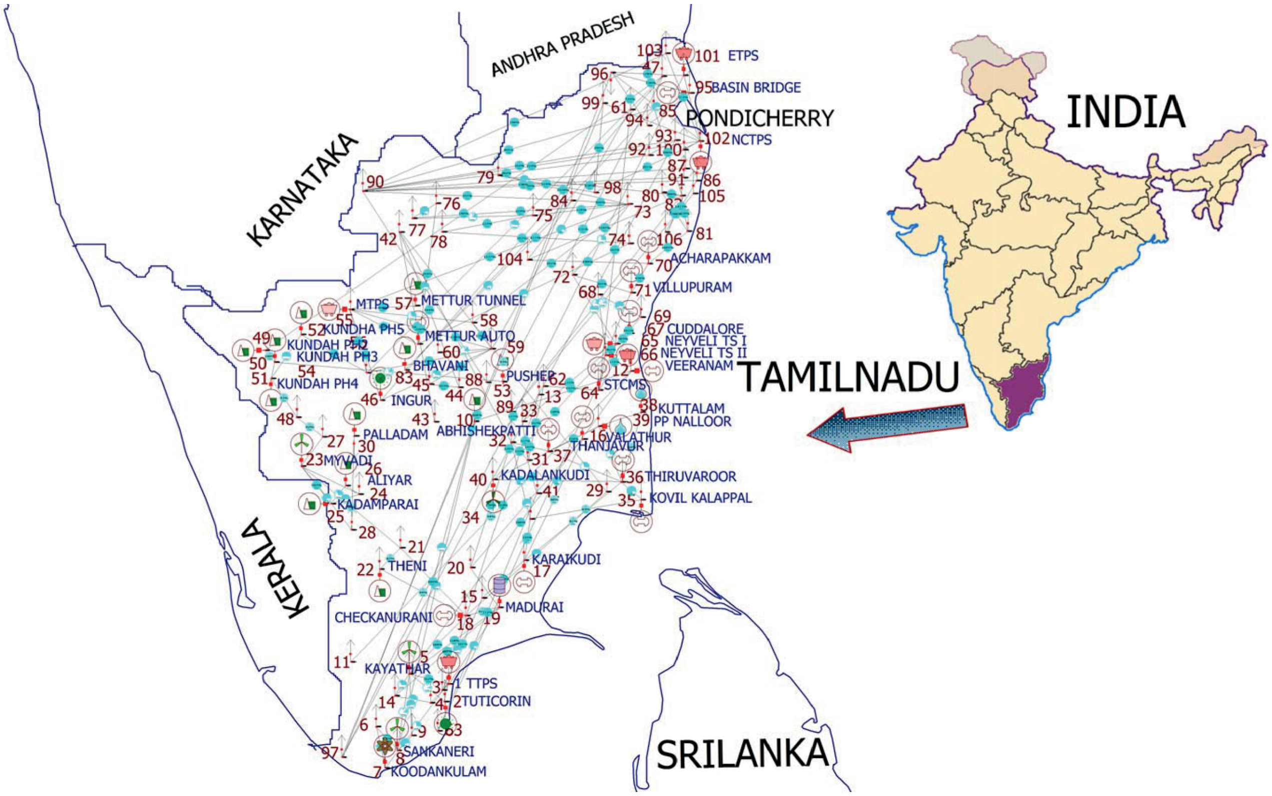

Figure 1. Single-line diagram of TN-106 Indian bus system.

4.1. Involvement of Tamil Nadu with RES

Tamil Nadu has already explored large hydroplants abundantly. In recent years, exponential growth has been seen in extracting energy from renewable sources. In the generation bus data, 2310 MW is from large hydroplants, 4.5 MW is from solar plants, 152 MW is from small hydroplants, 144 MW is from biomass plants, 90 MW is from cogeneration plants, and 290 MW is from a wind farm.

4.2. Day-ahead schedule

Congestion occurs while executing the day-ahead schedule due to the bilateral transaction of 50 MW from GENCO 25 to customer 28.

The congested line details are given in Table 1. The different cases considered for rescheduling are:

Table 1. Congested line detail of TN-106 bus system during day-ahead schedule.

Congested line	Active power flow (MW)	Reactive Power flow (MVAR)	Apparent power flow (MVA)	Line limit (MVA)
23-27	–153.36	52.21	162.1	140

Case 1: Conventional generators are considered for active power rescheduling.

Case 2: Conventional generators are considered for active and reactive power rescheduling.

Case 3: Conventional and renewable generators are considered for active power rescheduling.

Case 4: Conventional and renewable generators are considered for active and reactive power rescheduling.

The SP and SQ values for congested line 23-27 are shown in Figure 2. The SP values have been compared with those of [8], which are also given in Figure 2. It gives nearer values, but is more accurate as the sensitivity of apparent power with respect to the active power has been formulated. In [8], reactive power flow sensitivity is not considered. If the SP of the selected generator for a congested line is negative, then if generation is increased, power flow will be decreased in the congested line, and if generation is decreased, power flow will be increased in the congested line. At the same time, if SP is positive, then if generation is increased, power flow will be increased in the congested line, and if generation is decreased, power flow will be decreased in the congested line. To relieve congestion, power flow has to be decreased in the congested line. Thus, if SP is negative, the generation has to be increased, and if SP is positive, the generation has to be decreased. Applying this concept in choosing the generation population during optimization using PSO leads to quicker and optimized convergence.

Among the more positive and more negative SP and SQ values of conventional generators as shown in Figure 2, ten conventional generators have been selected for their active power rescheduling. Bus 1 is considered as slack. Rescheduled generation of Cases 1 and 2 is shown in Figure 3. From the concept behind SP values, for the generators whose SP is positive, the generation has been decreased, and for those whose SP is negative, the generation has been increased to relieve congestion. Without reactive power rescheduling of conventional generators, the congestion cost is \$2731.9. The congestion cost amounts to \$2124.8 for Case 2, which is 22% less than in Case 1. Thus, it is advantageous to reschedule reactive power also.

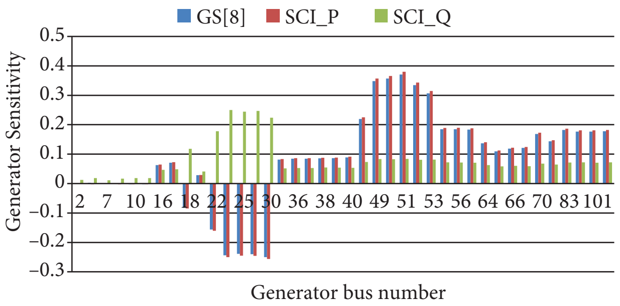

Figure 2. SP and SQ values of TN 106-bus system for congested line 23-27.

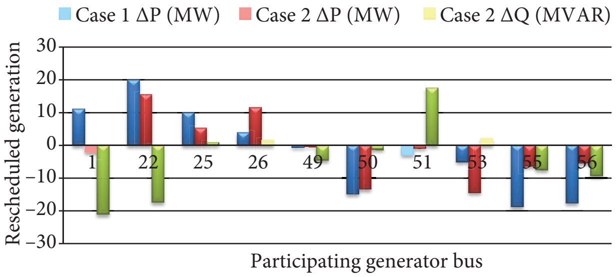

Figure 3. Rescheduling conventional generators (Case 1 and Case 2).

However, the involvement of renewable generators in congestion management has been superior. Figure 4 shows the rescheduled generation by considering both conventional and renewable generators in their active and reactive power rescheduling. For this congested line, among the renewable generators, bus numbers 23 (wind), 30 (small hydro), and 46 (cogeneration) are found to be sensitive. Rescheduling active power of conventional and renewable generators results in congestion cost of \$1936.8 and active power rescheduling of 76.54 MW. From Table 2, rescheduling conventional and renewable generators has resulted in a 33% decrease in congestion cost compared with rescheduling conventional generators as in Case 2. The active power rescheduling (Case 3) has been decreased by 37% as compared with Case 2. Thus, including both renewable and conventional generators for their real and reactive power rescheduling has been advantageous in terms of congestion cost as well as their rescheduling amount.

As seen in Figure 5, Case 4 has the lowest congestion cost of \$1822.1, which includes real and reactive power rescheduling of conventional and renewable generators. Renewable generators are mostly owned by private parties whose participation in terms of congestion management is not given much importance by the Tamil Nadu Generation and Distribution Company (TANGEDCO) as of now. Thus, if we also consider RES, it will reduce the congestion cost. Now ISO can select the rescheduling generation results obtained from Case 4 and send rescheduling notices to those rescheduling generators. Then, while running the hour-ahead schedule, the power flow goes fine for the particular hour. However, for another hour on that same day, outage of the line occurs. It will be noted while running the hour-ahead schedule.

Table 2. Total rescheduled generation and congestion cost for day-ahead schedule.

	Case 1	Case 2		Case 3	Case 4	
	ΔP (MW)	ΔP (MW)	ΔQ (MVAR)	ΔP (MW)	ΔP (MW)	ΔQ (MVAR)
Total rescheduling	95.59	71.39	83.51	76.54	60.03	199.11
Individual rescheduling cost ($)	2731.9	2067.7	57.11	1936.8	1651	171.14
Congestion cost ($)	2731.9	2124.8		1936.8	1822.14	

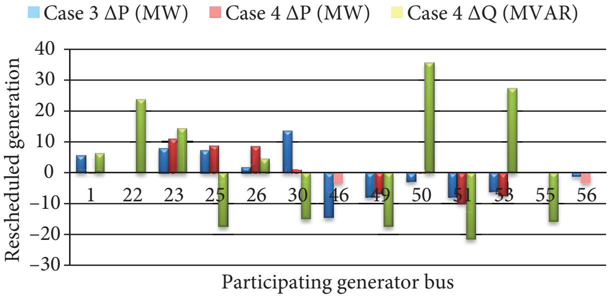

Figure 4. Rescheduling conventional generators and RES (Cases 3 and 4).

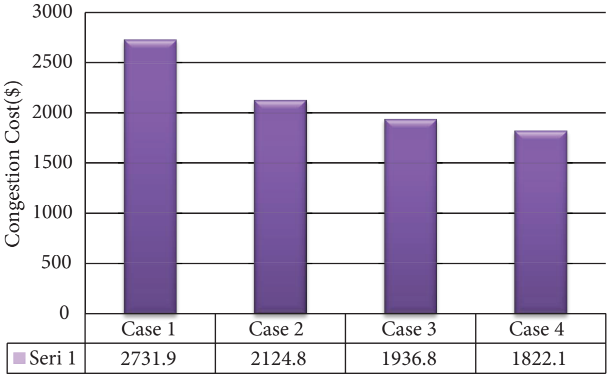

Figure 5. Congestion cost for day-ahead schedule.

4.3. Hour-ahead schedule

In this hour-ahead schedule, the following outage study has been considered.

Congestion occurs while executing the hour-ahead schedule due to outage of line 23-24 during the day time.

The power flow details of the congested line are given in Table 3. To relieve congestion, the same cases have been analyzed. The plot of SP and SQ for congested line 51-48 of the TN 106-bus system is depicted in Figure 6.

Table 3. Congested line detail of TN-106 bus system during hour-ahead schedule.

Congested line	Active power flow (MW)	Reactive power flow (MVAR)	Apparent power flow (MVA)	Line limit (MVA)	Line overload factor
51-48	332.34	22.69	333.11	300	1.11

Figure 7 shows the rescheduled generation of conventional generators for Cases 1 and 2. The total rescheduled generation is 153.83 MW for Case 1 and 145.2 MW for Case 2. Bus 1 is considered as slack. Figure

8 shows the rescheduled generation of conventional and renewable generators for Cases 3 and 4. Generator buses 23 (wind), 30 (small hydro), and 52 (small hydro) belong to renewable generators. Bus 23 has an increment of 15.89 MW, bus 30 has an increment of 9.34 MW, and bus 52 has a decrement of 9.19 MW.

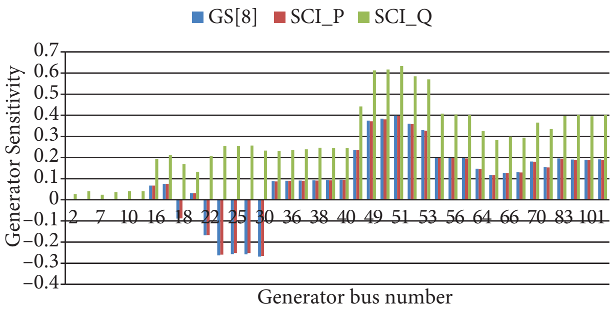

Figure 6. SP and SQ values of TN 106-bus system for congested line 51-48.

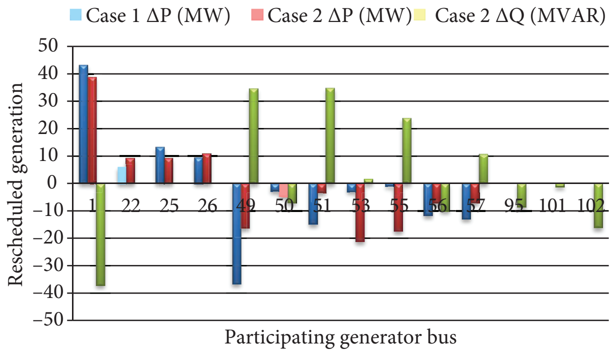

Figure 7. Rescheduling conventional generators (Case 1 and Case 2).

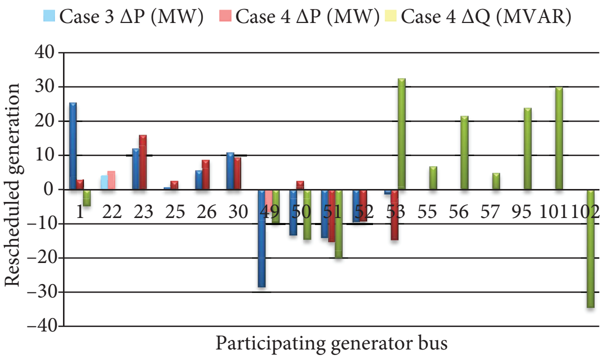

Figure 8. Rescheduling conventional generators and RES (Cases 3 and 4).

From Table 4, rescheduling both active and reactive power of conventional generators gives slightly lower cost than rescheduling only active power, but Case 4 has resulted in a 34.2% decrease in congestion cost compared with rescheduling conventional generators as in Case 2. The active power rescheduling has been decreased by 14% as compared with Case 2. Rescheduling active power of conventional and renewable generators results in congestion cost of $3480.8 and active power rescheduling of 124.50 MW.

Table 4. Total rescheduled generation and congestion cost for hour-ahead schedule.

	Case 1	Case 2		Case 3	Case 4	
Generator	ΔP (MW)	ΔP (MW)	ΔQ (MVAR)	ΔP (MW)	ΔP (MW)	ΔQ (MVAR)
Total rescheduling	154.82	145.20	185.78	124.50	92.660	202.56
Individual cost ($)	4270.2	4167.1	68.37	3480.8	2549.2	236.05
Congestion cost ($)	4270.2	4235.5		3480.8	2785.3	

Comparing all cases, as shown in Figure 9, rescheduling real and reactive power of conventional and renewable generators results in a decreased congestion cost of $2785.3. Even if we consider only active power rescheduling of conventional and renewable generators, it is still 15% less than the real and reactive rescheduling of conventional generators. Including both renewable and conventional generators for their real and reactive power rescheduling is advantageous in terms of congestion cost as well as their rescheduling amount.

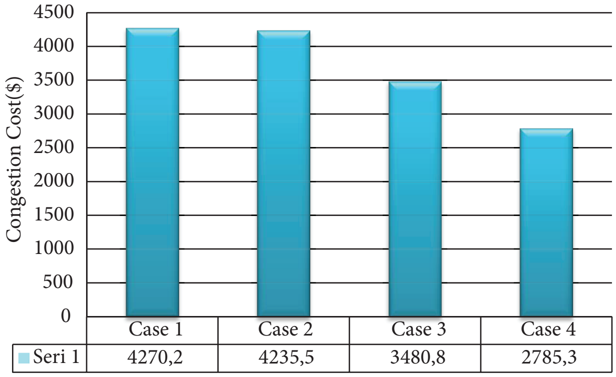

Figure 9. Congestion costs during hour-ahead schedule.

From [23], PSO with a time-varying acceleration coefficient technique is more efficient than standard-PSO and PSO with time-varying inertia weight. The convergence characteristic using PSO with a time-varying acceleration coefficient technique is shown in Figure 10. It has been compared with algorithms such as standard PSO and PSO with time-varying inertia weight. PSO with time-varying acceleration coefficient gives the lowest rescheduling cost because of the decrease in its cognitive component and rise in its social component, by changing the acceleration coefficients with time.

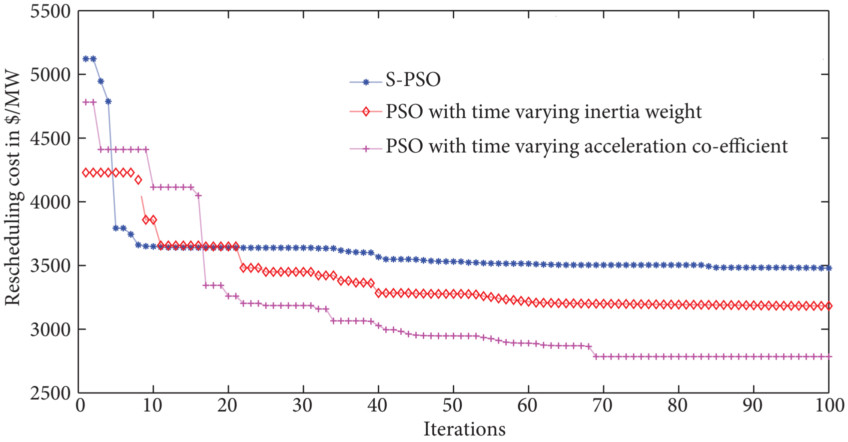

Figure 10. Convergence characteristics of Case 4 during hour-ahead schedule.

4.4. Effect of season

The effect of season in congestion management was studied when the small hydro potential and wind generation in Tamil Nadu is decreased from February to May. With the same bus data, comparing Case 4 for hour-ahead schedule and the new season, the congestion costs are increased. Bus 23 has been connected with a wind plant and buses 30 and 52 have been connected with a small hydro plant. The wind incremental power has been reduced from 15.88 MW to 3.11 MW, the small hydro plant at bus 30 has reduced active power from 9.34 MW to 4.87 MW, and the small hydro plant at bus 30 has increased decremental active power from 9.19 MW to 12.53 MW. The comparison of active power change between the old season and the new season is given in Figure 11. The congestion cost of the new season is $3123.7 and the total rescheduled active power is 105.43 MW.

4.5. Effect of diurnal variations

Day and night variations have a major impact on wind plants and solar plants. In our study, bus number 23 has been connected with a wind farm whose maximum generation is limited at night time, which abruptly yields a substantial reschedule decline from 15.89 MW to 8.56 MW at night time. The water available to run the small hydroplant is unwavering between day and night for a particular season. Therefore, its rescheduled changes are unarguable. There is no effect of diurnal difference with other RES as their raw material is independent of day and night. From Figure 12, the total rescheduled power of Case 4 during the hour-ahead schedule of day and night is 92.66 MW and 95.34 MW, respectively.

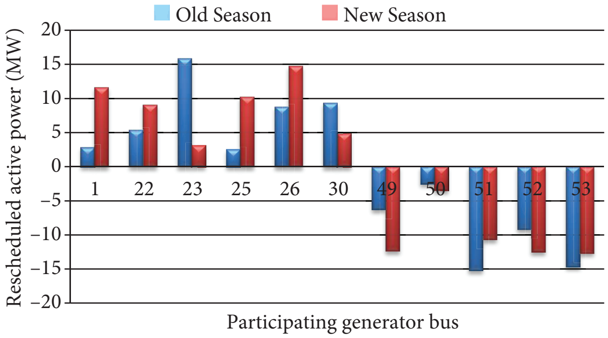

Figure 11. Effect of season in active power rescheduling.

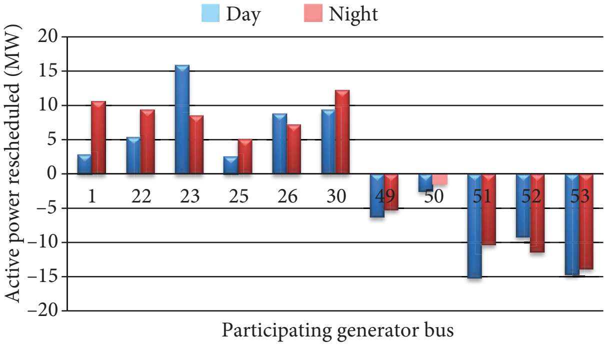

Figure 12. Effect of time in active power rescheduling.

4.6. Total congestion cost savings

For the particular day, when both types of congestion occur, the total congestion cost using real and reactive rescheduling of conventional and renewable generators is $4607.4 against $5417.6 of Case 3, $6360.3 of Case 2, and $7002.1 of Case 1. Using Case 4, there is a reduction of 34.19% in congestion cost; thus, involving RES saves rescheduling costs. Advances in the reactive power rescheduling of RES is the added advantage as we can include RES for reactive power rescheduling as well.

5. Conclusion

In this paper, the optimal involvement of renewable generators for congestion management has been studied considering seasonal and timely constraints of RES. The test results allow the following conclusions:

- The number of generators has been considerably reduced considering both active and reactive power rescheduling. Ten to fifteen generators are enough as compared to the total number of generators of 41.
- When involving RES, the rescheduling amount and congestion cost is decreased during congestion management.
- The rescheduling cost involving RES is higher at night than at day and when the season changes, the congestion cost changes. The rise or fall in congestion cost depends on whether RES are available plentifully or scarcely.

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