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Integrating hydro and wind resources for effective congestion management in a hybrid electricity market

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Abstract

Congestion management in deregulated electricity systems threatens system security and reliability. Integration of renewable energy sources, unpredictable wind power, load demand, and the requirement for quickly deployable reserves make congestion management more difficult. While deciding the dispatch of the generating units, many factors have to be considered for the economic, secure, and reliable operation of the power system. This study presents a congestion management strategy that has been developed specifically for hybrid power systems. Within a pool and bilateral power supply market structure, it introduces a generator rescheduling-based congestion management technique. Ensuring safe bilateral transactions between these companies is crucial. Renewable sources affect congestion management dynamics, according to the research. The optimization issue includes operational limitations for scenarios with and without renewable source units. Monte Carlo simulation (MCS) was used to sample hourly wind speed from the Weibull PDF wind model. GAMS CONOPT solver used the model. General Algebraic Modeling System (GAMS)-MATLAB interface imported the model into MATLAB to extract the response. The best combination of renewable sources is 2 hydro + 1 wind unit as savings of congestion cost are \$1403.6/h and \$1855.18/h in case 1 (3-line congestion) and case 2 (2-line congestion), respectively. Results were accomplished by updating the IEEE-24 bus reliability test system with hydro and wind generators.

Keywords: Wind turbine unit, Congestion management, IEEE-24 bus system, Inequality constraints, Distributed generation

Introduction

The importance of promoting renewable energy sources (RES) has increased significantly within the context of the more competitive environment that characterizes the market for energy. However, the increased integration of RES has the potential to cause frequent network congestion [1–3]. Congestion management is the process of coordinating transaction prioritization in order to efficiently avoid overloading a network. This is an essential component in addressing this difficulty. When it comes to the world of deregulated electricity systems, the function of congestion management appears as a keystone in the preservation of reliability and security. The power generation companies (GENCOs) and distribution companies (DISCOS) will submit bids to the independent system operator (ISO) in the context of a market for energy that is structured as a pool. The ISO will then make choices on the generation for the following day. After that, activities take place, which include generation and consumption, and they are all coordinated at a price that is agreed upon for the planned clearance [4–6]. Adjusting schedules for both producers and consumers is one of the strategic approaches that can be used to manage the congestion that transmission lines are experiencing.

This modification is essential, especially in a bilateral power market where the guarantee of transaction security in the midst of congestion management is crucial. This adaption is pivotal. The ISO, which orchestrates efforts to reduce congestion and supports flawless coordination, including dispatch, within the dynamic landscape of a hybrid market, plays a crucial role in this process. This function places the ISO at the center of the action and makes it an essential component [7–10]. However, it is of the utmost importance to acknowledge the fact that RES provides the best possible solution for satisfying the need for energy while preserving the integrity of the environment.

The production of electricity through hydro and wind power stands out as the option that is friendlier to the environment while also being more cost-effective. It is important to note that India's wind power production is constantly expanding, while hydro power generation ranks as the country's second-largest source of energy. Both hydro and wind power plants have minimal running costs and the ability to quickly become operational [11–14]. Because of their one-of-a-kind combination, they are well-suited to meet peak as well as emergency power needs. When considering a power system that incorporates hydro, wind, and thermal units, it is necessary to investigate the management of congestion. Unlike the scheduling of thermal units, which is determined entirely by the prices at which the market is clearing, the scheduling of hydro and wind units takes on the specific function of price suckers.

In [15], typical congestion management approaches emphasize optimization tools' importance. Evolution strategy and pool dispatch plan are discussed, along with current advances and methodologies in Germany, Europe, and the USA. Innovative methods can involve treating load and water input as random variables. The paper encourages power system engineers, students, professors, researchers, and utility engineers to explore congestion management and solve problems faster and smarter. A new zonal congestion management (CM) model using power tracing and power transfer distribution factors (PTDF) is presented in this research [9]. A congestion index (CI) creates an efficient congestion zone by assigning coefficients to network components. Optimization using unit rescheduling and load shedding eliminates congestion. It reduced line congestion on the IEEE 39-bus New England system, demonstrating real-time applications and scalability to different network sizes and situations.

This technique can be used for mid- and long-term research on renewable resource allocation, reactive power tracing, and flexible AC transmission (FACTS) modeling in zonal CM. Modified bat optimization and its derivatives are used to control congestion in [16]. Chaos-embedded Monarch butterfly optimization surpasses others on IEEE-30 and New England 39-bus systems, reducing overall rescheduling costs for effective line overload attenuation. Testing more sophisticated algorithms and studying load reduction and renewable energy integration are future goals. By intentionally increasing their income via bids, these units match energy prices to be as near as possible to the marginal price of the system [17]. It is thus of the highest significance to make headway towards the management of congestion within this varied energy environment [18–20].

In this article, congestion cost is minimized without (thermal units alone) and with renewable energy sources (hydro units, wind units, 1 hydro + 2 wind units, and 2 hydro + 1 wind units). Congestion management for bilateral and pool power markets uses mix-integer nonlinear programming. Rescheduling generators reduces congestion costs in congestion management. Producer-consumer transactions are secured using the GD matrix. Thermal and renewable generating units submit proposals to ISO. With and without renewable source unit operational limitations were applied to the optimization problem. Congestion management, in the context of deregulated electrical networks, is the range of measures used to reduce and effectively manage congestion caused by a mismatch between energy supply and demand along certain transmission lines. Congestion can result in inadequate utilization of the transmission network and inefficient market operations in deregulated systems, where various organizations produce and provide electricity.

In order to maintain a stable and cost-effective electricity arrangement, congestion management strategies include market-based operations, optimal power flow changes, and network reconfiguration are used. By reducing barriers while fostering efficient energy flow, it intends to optimize the utilization of existing transmission capacity, preserve grid stability, and support competitive and equitable electricity markets. In congestion management, wind and hydro units rely on wind and water levels. The Weibull PDF wind model and Monte Carlo simulation (MCS) technique have produced hourly wind speed samples. The optimization issue for congestion management models water discharge and scope. Based on line congestion sensitivity, case 1 (3-line congestion) and case 2 (2-line congestion) were investigated using a GAMS-MATLAB interface, mixed-integer nonlinear programming (MINLP) has solved congestion management. This unique technique was utilized in the IEEE-24 bus reliability test system, providing real results.

The strategy for managing congestion takes a comprehensive approach and utilizes Monte Carlo simulation for scenario analysis. After that, the optimization issues connected with congestion management are tackled by using the CONOPT solver that is included in the GAMS software. The GAMS-MATLAB interface improves both the flexibility and efficiency of the modeling process by providing for a smooth integration between the sophisticated modeling capabilities of GAMS and the extensive analysis tools that are available in MATLAB.

This allows for more overall flexibility and efficiency in the modeling process. This integrated technique offers a thorough investigation of a variety of situations, superior decision-making achieved by mathematical modeling, and effective execution of methods for congestion control in power systems.

Optimization model of secure bilateral transaction

The hybrid electricity market will smoothly merge a pool and bilateral or multilateral transactions. This architecture supports pool-based and bilateral agreements, improving transmission access in the hybrid market context. Power production and distribution are arranged via a centralized market (the pool) and direct agreements between buyers and sellers (the bilateral contracts) under a framework for managing congestion that is part of a market structure that includes both a pool and bilateral power supply contracts. The California market model illustrates this mixed configuration. The bilateral and pool models are used in many power market arrangements across the world [21–24]. Dispatching and scheduling vary among different models, affecting system stability, especially given transmission line limits and imbalances. In a bilateral market model, minimizing transaction variances improves system resilience. The objective function is subjected as follows:

$$\left\{ \sum_{k} \sum_{j} b_{kj} \left(GD_{kj} - GD_{kj}^{0} \right)^{2} \right\} \tag{1}$$

Equations (2) and (3) represent balances of real power (P_k) and reactive power (Q_k).

$$P_k = P_{gk} + P_{hk} + P_{wk} - P_{dk} = \sum_{j}^{N} V_k V_j Y_{kj} \cos\left(\delta_k - \delta_j - \theta_{kj}\right) \forall k = 1.2 \ldots\ldots\ldots\ldots\ldots N \tag{2}$$

$$Q_k = Q_{gk} + Q_{hk} + Q_{wk} - Q_{dk} = \sum_{j}^{N} V_k V_j Y_{kj} \sin\left(\delta_k - \delta_j - \theta_{kj}\right) \forall k = 1.2 \ldots\ldots\ldots\ldots\ldots N \tag{3}$$

Bilateral power generated by thermal generating units in MW (P_{gb}) and pool power generated by thermal generating units in MW (P_{gp}) produce the demand power (P_d), and generation power (P_g) balance equations using the bilateral transaction matrix GD for the hybrid market model are represented by Eqs. (4, 5, 6 and 7).

$$P_{db} = \sum_{k} GD_{kj} \tag{4}$$

$$P_{gb} = \sum_{j} GD_{kj} \tag{5}$$

$$P_g = P_{gb} + P_{gp} \tag{6}$$

$$P_d = P_{db} + P_{dp} \tag{7}$$

Power flow equations for bilateral power (P_{fb}) and pool power (P_{fbp}) are given in Eqs. (8) and (9), respectively.

$$P_{fb} = DF\left(P_{gb} - P_{db}\right) \tag{8}$$

$$P_{fbp} = DF\left(P_{gp} - P_{dp}\right) \tag{9}$$

The total amount of power (P_f) is being represented in Eq. (10).

$$P_f = P_{fb} + P_{fp} \tag{10}$$

Distribution factors (DF) can be obtained as discussed in [25]. Every generator generates power between its generation capacities. Equations (11, 12 and 13) are real power limits of thermal, hydro, and wind generators ($P_{gk}{}^{min}$), ($P_{hk}{}^{min}$), and ($P_{wk}{}^{min}$), and Eqs. (14, 15 and 16) are reactive power limits of thermal, hydro, and wind generators ($Q_{gk}{}^{min}$), ($Q_{hk}{}^{min}$), and ($Q_{wk}{}^{min}$), respectively.

$$P_{gk}^{\min} \leq P_{gk} \leq P_{gk}^{\max}; \forall k \varepsilon G \tag{11}$$

$$P_{hk}^{\min} \leq P_{hk} \leq P_{hk}^{\max}; \forall k \varepsilon H \tag{12}$$

$$P_{wk}^{\min} \leq P_{wk} \leq P_{wk}^{\max}; \forall k \varepsilon w \tag{13}$$

$$Q_{gk}^{\min} \leq Q_{gk} \leq Q_{gk}^{\max}; \forall k \varepsilon G \tag{14}$$

$$Q_{hk}^{\min} \leq Q_{hk} \leq Q_{hk}^{\max}; \forall k \varepsilon H \tag{15}$$

$$Q_{wk}^{\min} \leq Q_{wk} \leq Q_{wk}^{\max}; \forall k \varepsilon w \tag{16}$$

The lines angle ($\delta_{gk}{}^{min}$) and voltage restrictions ($V_{gk}{}^{min}$) are represented by Eqs. (17) and (18).

$$\delta_{gk}^{\min} \leq \delta_{gk} \leq \delta_{gk}^{\max} \tag{17}$$

$$V_{gk}^{\min} \leq V_{gk} \leq V_{gk}^{\max} \tag{18}$$

The maximum and minimum transaction restrictions ($GD_{kj}{}^{max}$) and ($GD_{kj}{}^{min}$) for the buyer and seller in (19) are represented by *bus-k* and *bus-j*, respectively.

$$GD_{kj}^{\min} \leq GD_{kj} \leq GD_{kj}^{\max} \leq \min\left(P_{gk}^{\max}, P_{dj}\right) \tag{19}$$

The maximum MVA ($MVA_{kj}{}^{max}$) limit for the lines in Eq. (20):

$$| MVA_{kj} | \leq MVA_{kj}^{\max} \tag{20}$$

Between 1.05 and 0.95p.u are allowed variations in line voltage. The secure bilateral transaction matrix has been obtained from the equation given above and used to reduce the congestion cost in the optimization problem.

Mathematical model for rescheduling of generators during congestion management

Congestion management strategies aim to reduce congestion costs in a wind and hydro system. This requires resolving operational equalities and inequities among these units and securing bilateral interactions. This framework includes up cost bid by thermal, hydro, and wind units in \$/MW h ($C_k^{up}\ \Delta C_{gk}^{up}$), ($C_k^{up}\ \Delta C_{hk}^{up}$), and ($C_k^{up}\ \Delta C_{wk}^{up}$). Similarly, down cost bid by thermal, hydro, and wind units in \$/MW h ($C_k^{down}\ \Delta C_{gk}^{down}$), ($C_k^{down}\ \Delta C_{hk}^{down}$), and ($C_k^{down}\ \Delta C_{wk}^{down}$) for all aimed towards congestion cost reduction [16, 26, 27]. The problem can represent mathematically below:

$$C_{\cos t} = \sum_{k\varepsilon g}\left(C_k^{up}\Delta C_{gk}^{up}\right)+\left(C_k^{down}\Delta C_{gk}^{down}\right)+\sum_{k\varepsilon h}(C_k^{up}\Delta P_{hk}^{up})+\left(C_k^{down}\Delta P_{hk}^{down}\right)+\sum_{k\varepsilon w}(C_k^{up}\Delta P_{wk}^{up})+\left(C_k^{down}\Delta P_{wk}^{down}\right) \tag{21}$$

The equality constraints

Equation (22) is injected with real power, and Eq. (23) is injected with reactive power at each bus.

$$P_k = \sum_{j}^{N} V_k V_j V_{kj} \cos\left(\delta_k - \delta_j - \theta_{kj}\right)\forall k = 1, 2, \ldots\ldots\ldots\ldots\ldots\ldots N \tag{22}$$

$$Q_k = \sum_{j}^{N} V_k V_j V_{kj} \sin\left(\delta_k - \delta_j - \theta_{kj}\right)\forall k = 1, 2, \ldots\ldots\ldots\ldots\ldots\ldots N \tag{23}$$

In order to effectively control congestion, the total increment of generation by thermal, hydro, and wind generation unit k in MW (ΔP_{gk}^{up}), (ΔP_{hk}^{up}), and (ΔP_{wk}^{up}). The total decrement of generation by thermal, hydro, and wind generation unit k in MW (ΔP_{gk}^{down}), (ΔP_{hk}^{down}), and (ΔP_{wk}^{down}) down generation of vehicles needs to Eq. (24).

$$\sum_{k}^{N}\left(\Delta P_{gk}^{up}\right) - \sum_{k}^{N}\left(\Delta P_{gk}^{down}\right) + \sum_{k}^{N}(\Delta P_{hk}^{up}) - \sum_{k}^{N}\left(\Delta P_{hk}^{down}\right) + \sum_{k}^{N}(\Delta P_{wk}^{up}) - \sum_{k}^{N}\left(\Delta P_{wk}^{down}\right) = 0; \forall k\varepsilon N \tag{24}$$

During congestion management, in N number of buses, the generator k's rescheduled generation is equivalent to the up and down in generation and the day-ahead schedule in Eq. (25).

$$P_{gnk} = P_k^0 + \Delta P_{gk}^{up} - \Delta P_{gk}^{down} + \Delta P_{hk}^{up} - \Delta P_{hk}^{down} + \Delta P_{wk}^{up} - \Delta P_{wk}^{down}; \forall k\varepsilon N \tag{25}$$

Both Eqs. (26) and (27) represent the real and reactive powers (P_k, Q_k) that are injected, respectively (Fig. 1).

$$P_k = P_{gnk} - P_{dk} \tag{26}$$

$$Q_k = Q_{gk} + Q_{hk} + Q_{wk} - Q_{di} \tag{27}$$

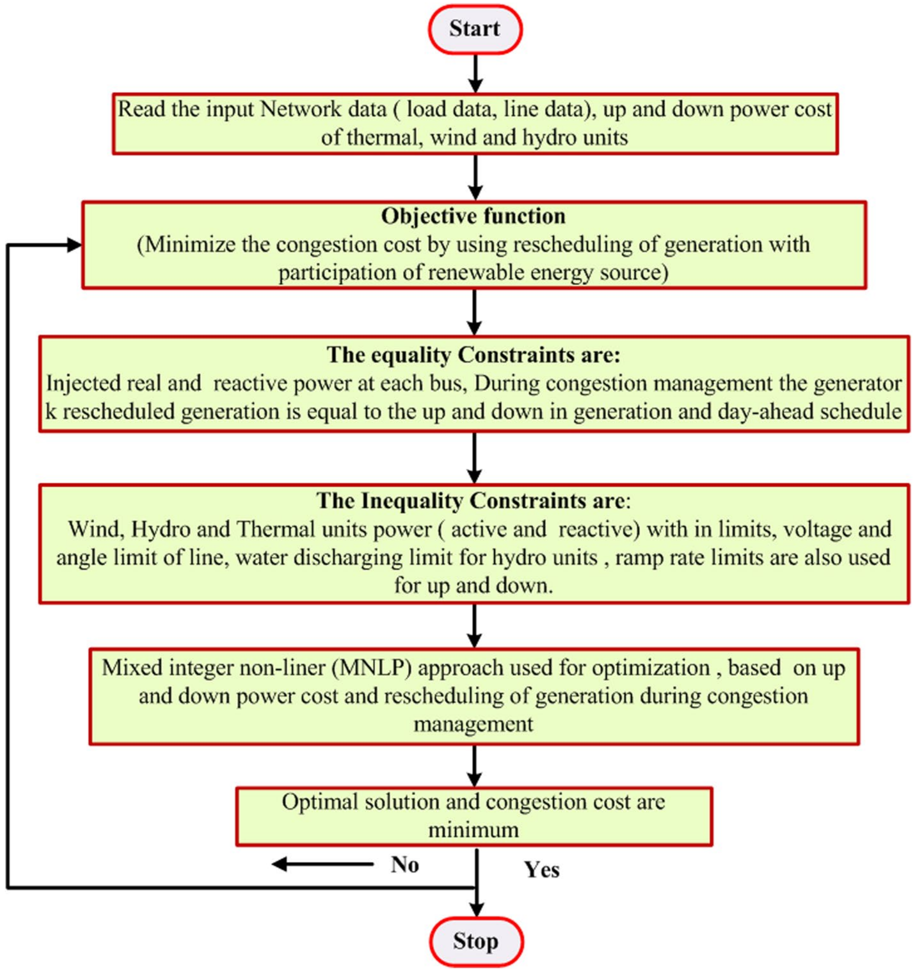

Fig. 1 Flow chart of the proposed methodology

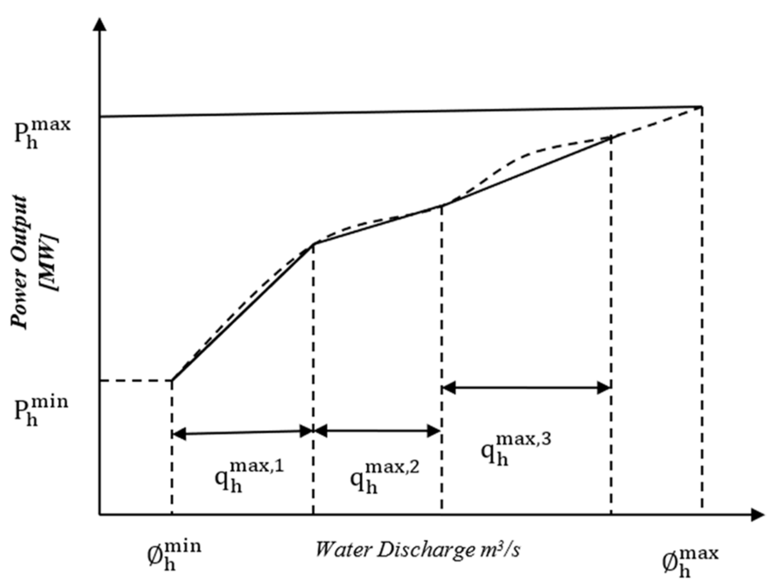

Fig. 2 Hydro units non-conclave piece-wise characteristics curves

The binary variables u_{hk} and ${V_{hk}}^I$ help to design the hydro unit performance modeled by using piecewise linear non-concave curves have been shown in Fig. 2 and explained in [28, 29]. The status of the hydro-generating unit is denoted by variable u_{hk} and during congestion management u_{hk} =1, then the unit is committed. When ${V_{hk}}^I$ is 1, the limit of lth block is exceeded due to the discharge of the water of the Kth unit. The hydro unit performance is neglected while a short-term congestion management solution is the head variations effect.

$$P_{hk}^{0} + \Delta P_{hk}^{up} - \Delta P_{hk}^{down} = P_{hk}^{\min} u_{hk} + \sum_{l=1}^{L} q_{hk}^{I} r_{hk}^{I}; \forall k \varepsilon H \tag{28}$$

$$\phi_{hk} = \phi_{hk}^{\min} + \sum_{l=1}^{L} q_{hk}^{I}; \forall k \varepsilon H \tag{29}$$

where ${r_{hk}}^I$ is the slope of the piecewise linear unit performance curve of the hydro-generator at the kth bus in block l MW/m^3/s. Hydro units ${\Delta P_{hk}}^{up}$ and ${\Delta P_{hk}}^{down}$ generation are dependent upon ${P_{hk}}^{min}$, and its generating power produced by ${q_{hk}}^I$ (water discharging for l period of the total block) is represented in Eq. (28). Equation (29) can be represented by all block of periods l on water discharge.

The inequality constraints

Generating units for thermal, hydro, and wind energy are all subject to a variety of inequality limitations. In Eq. (30), Eq. (31), and Eq. (32), the rescheduled minimum actual power produced by hydro, wind, and thermal units (${P_{gk}}^{min}$), (${P_{hk}}^{min}$), and (${P_{wk}}^{min}$), respectively. The rescheduled maximum actual power produced by hydro, wind, and thermal units (${P_{gk}}^{max}$), (${P_{hk}}^{max}$), and (${P_{wk}}^{max}$), respectively. These parameters need to stay within the allowed limits.

$$P_{gk}^{\min} \leq P_{gk}^{0} + \Delta P_{gk}^{up} - \Delta P_{gk}^{down} \leq \Delta P_{gk}^{\max}; \forall k \varepsilon G \tag{30}$$

$$P_{hk}^{\min} \leq P_{hk}^{0} + \Delta P_{hk}^{up} - \Delta P_{hk}^{down} \leq \Delta P_{hk}^{\max}; \forall k \varepsilon H \tag{31}$$

$$P_{wk}^{\min} \leq P_{wk}^{0} + \Delta P_{wk}^{up} - \Delta P_{wk}^{down} \leq \Delta P_{wk}^{\max}; \forall k \varepsilon W \tag{32}$$

Here, constants G, H, and W are sets of thermal, hydro, and wind generators. The minimum reactive power constraints of wind, hydro, and thermal units (${Q_{gk}}^{min}$), (${Q_{hk}}^{min}$), and (${Q_{wk}}^{min}$). The rescheduled maximum reactive power constraints of wind, hydro, and thermal units (${Q_{gk}}^{max}$), (${Q_{hk}}^{max}$), and (${Q_{wk}}^{max}$). These parameters need to be recognized and described in Eq. (33), Eq. (34), and Eq. (35), respectively.

$$Q_{gk}^{\min} \leq Q_{gk}^{0} \leq \Delta Q_{gk}^{\max}; \forall k \varepsilon G \tag{33}$$

$$Q_{gk}^{\min} \leq Q_{gk}^{0} \leq \Delta Q_{gk}^{\max}; \forall k \varepsilon H \tag{34}$$

$$Q_{wk}^{\min} \leq Q_{wk}^{0} \leq \Delta Q_{wk}^{\max}; \forall k \varepsilon w \tag{35}$$

The minimum voltage, angle restrictions ($V_k{}^{min}$), $\delta_k{}^{min}$ and maximum voltage, angle restrictions ($V_k{}^{max}$), $\delta_k{}^{max}$ on the lines are represented by Eq. (36) and Eq. (37), respectively.

$$V_k^{\min} \leq V_k \leq V_k^{\max} \tag{36}$$

$$\delta_k^{\min} \leq \delta_k \leq \delta_k^{\max} \tag{37}$$

The minimum and maximum amounts of water that can be discharged ($\phi_{\mathrm{hk}}{}^{\min}$, $\phi_{\mathrm{hk}}{}^{\max}$) by the hydro units are below their maximum amounts, as specified by Eqs. (38–42).

$$\phi_{hk}^{\min} u_{hk} \leq \phi_{hk} \leq \phi_{hk}^{\max} \tag{38}$$

$$q_{hk}^{l} \leq q_{hk}^{\max,l} u_{hk}; \forall l = 1, k \varepsilon H \tag{39}$$

$$q_{hk}^{l} \leq q_{hk}^{\max,l} v_{hk}^{l}; \forall l = 1, k \varepsilon H \tag{40}$$

$$q_{hk}^{l} \leq q_{hk}^{\max,l} v_{hk}^{l-1}; \forall l \neq 1, k \varepsilon H \tag{41}$$

$$q_{hk}^{l} \geq q_{hk}^{\max,l} v_{hk}^{l-1}; \forall l \neq 1, k \varepsilon H \tag{42}$$

The amount of water that is given to the power producers is the limiting element in the capacity of the hydro units while congestion management is being performed. However, in order to have a chance of creating energy, the water level for the projected power-generating units has to be accomplished at least 1 day in advance.

$$M \phi_{hk} \leq w_{hk}; \forall k \varepsilon H \tag{43}$$

In this instance, a conversion factor denoted by M is used so that m^3/s may be converted into H m^3/h. The W_{hk} value, which refers to the amount of water present, is taken from the kth bus and used by the hydro-generating business for rescheduling purposes in the management of congestion. In Eq. (44), the maximum MVA limit of crowded transmission lines has to be restricted all the way through the flow of electricity.

$$P_{kj}^2 + Q_{kj}^2 \leq \left(S_{kj}^{\max}\right)^2 \tag{44}$$

The strategy that was intended to be used in order to accomplish the goal (the reduction of the costs associated with congestion) is shown in Fig. 1. In addition to the top limitations, the ramp rate limits for each of the producing units are also employed for the up and down ramps ($\Delta P_{gk}{}^{up,ramp}$, $\Delta P_{hk}{}^{up,ramp}$, $\Delta P_{wk}{}^{up,ramp}$) and ($\Delta P_{gk}{}^{down,ramp}$, $\Delta P_{hk}{}^{down,ramp}$, $\Delta P_{wk}{}^{down,ramp}$). In accordance with Eqs. (45–50), ramp rates of wind, hydro, and thermal units were accordingly defined.

$$0 \leq \Delta P_{gk}^{up} \leq \Delta P_{gk}^{up,ramp}; \forall k \varepsilon G \tag{45}$$

$$0 \leq \Delta P_{gk}^{down} \leq \Delta P_{gk}^{down,ramp}; \forall k \varepsilon G \tag{46}$$

$$0 \leq \Delta P_{gk}^{up} \leq \Delta P_{gk}^{up,ramp}; \forall k \varepsilon G \tag{47}$$

$$0 \leq \Delta P_{hk}^{down} \leq \Delta P_{hk}^{down,ramp}; \forall k \varepsilon H \tag{48}$$

$$0 \leq \Delta P_{wk}^{up} \leq \Delta P_{wk}^{up,ramp}; \forall k \varepsilon w \tag{49}$$

$$0 \leq \Delta P_{wk}^{down} \leq \Delta P_{gk}^{down,ramp}; \forall k \varepsilon w \tag{50}$$

The generation and demand equations of power balance are represented by Eqs. (51) and (52) in the hybrid market model. These equations make use of the bilateral transaction GD matrix.

$$P_{db} = \sum_{k} GD_{kj} \tag{51}$$

$$P_{gb} = \sum_{j} GD_{kj} \tag{52}$$

$$P_g = P_{gb} + P_{gp} \tag{53}$$

$$P_d = P_{db} + P_{dp} \tag{54}$$

$$GD_{kj}^{\min} \leq GD_{kj} \leq GD_{kj}^{\max} \tag{55}$$

where P_g and P_{gp} represent the planned power for the day ahead and the rescheduled power after congestion management. Hydroelectric generators are essential to the generation of renewable energy because they generate clean, stable electricity from moving water. They are critical in the shift to a more sustainable energy system because of the positive effects they have on grid reliability, renewable energy diversification, and carbon emission reductions. Table 1 represents the IEEE-24 bus system hydro generator

Table 1 Hydro generator data for IEEE-24 bus system

P_h^{max} (MW)	P_h^{min} (MW)	Q_h^{max} (MVAR)	Q_h^{min} (MVAR)	w_f (Hm^3/h)	φ^{min} (m^3/s)	φ^{max} (m^3/s)
500	40	35	−5.0	1.4	10	100
590	81	54	−1.0	2.5	20	200
400	68	68	−50	1.5	10	120

data and includes vital information regarding hydroelectric generator performance and features.

As can be seen in Fig. 2, the piecewise linear non-concave curves that are used to illustrate the operational characteristics of hydroelectric units are used in this investigation. These curves provide a precise and segmental representation of the performance of the hydro units. Additionally, these units capture the nonlinear correlations between water flow and power production in a way that is more granular and realistic. A change in output or water flow causes a corresponding change in the cost per unit of power generated, as shown by these graphs. As a result of their complexity, non-concave features can provide difficulties in power system optimization and dispatch. In the context of power system management, the integration of renewable energy sources such as wind power, solar power, and hydropower brings a wide range of issues. These issues are caused by intermittency and variability, a mismatch between supply and demand, grid stability, reliability, congestion, transmission challenges, energy storage, flexibility, forecasting, predictive modeling, market design, and incentives.

Modeling of wind turbine generation pattern and cost function

The wind speed at the site is the most important factor in the generation of power by wind turbines and time-series model [30], data mining algorithm [31], and clustering approach [32]. Many other methods also model wind behavior. In this wind model, we used Weibull PDF for the variation of wind speed (v) and wind speed related to its characteristic function. The output of a wind turbine as follows:

$$PDF_w(v) = \left(\frac{i}{c}\right)\left(\frac{v}{c}\right)^{(i-1)} \exp\left[-\left(\frac{v}{c}\right)^{i}\right] \tag{56}$$

$$i = \left(\frac{\overline{\sigma}}{\mu}\right)^{-1.086} \tag{57}$$

$$c = \frac{\overline{\mu}}{\Gamma\left(\frac{1}{i}+1\right)} \tag{58}$$

where i is the shape and c is the scale factor of the Weibull PDF, $\overline{\sigma}$ is the means m/s, and $\overline{\mu}$ is the standard deviation m/s of weed speed, and hourly mean wind speed data for the month of May over the first 12 years (2015–2022) [33]. Monte Carlo simulation (MCS) is used for obtaining hourly samples of wind speed. The wind turbine-generated power is determined by its speed-power curve as follows:

$$P_k^w = \begin{cases} 0 & , if v \leq v_{in}^c or v \geq v_{out}^c \\ \frac{v-v_{in}^c}{v_{rated}^c - v_{in}^c} P_{k,r}^w & , if v_{in}^c \leq v \leq v_{rated}^c \\ P_{k,r}^w & , else \end{cases} \tag{59}$$

The $P_{k,r}^w$ is rated power, and P_k^w are generated power of wind turbine install in bus-k, and v_{out}^c is the cut-out speed, v_{in}^c is the cut-in speed, and v_{rated}^c is the rated speed of the wind turbine. Each wind turbine (turbine 1, turbine 2) has obtained the speed-power

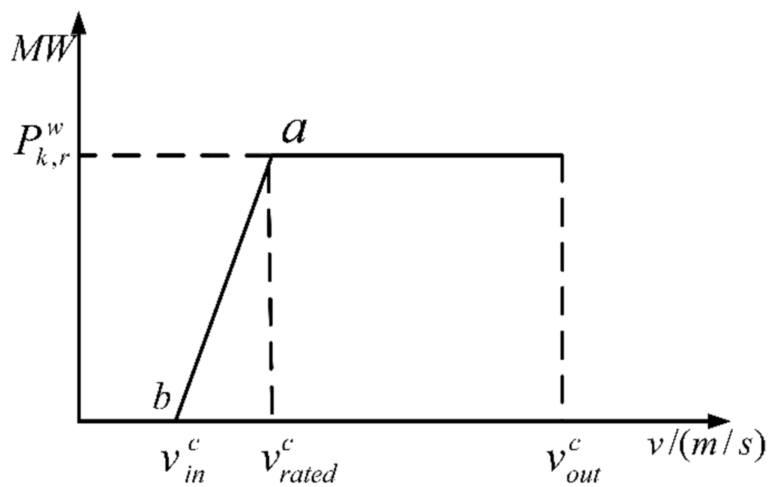

Fig. 3 Wind turbine characteristics

Table 2 Technical characteristics of wind turbine

Features	Turbine 1	Turbine 2
Rated power (MW) $P_{k,r}^{w}$	3	2
Cut-in speed (m/s) v_{in}^{c}	3	3
Rated speed (m/s) V_{rated}	15	15
Cut-out speed (m/s) V_{out}^{c}	25	25

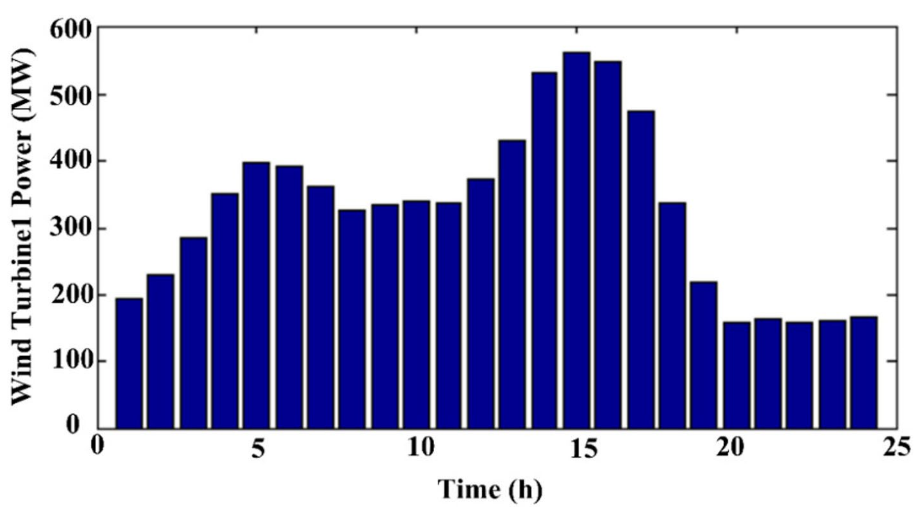

Fig. 4 Wind turbine 1 electricity generation pattern for 24 h

curve. The characteristics of the wind turbine can be drawn as depicted in Fig. 3. The technical characteristics of the wind turbine are observed in Table 2. In this, the average values of active power production for each wind turbine (turbine1 and turbine2)

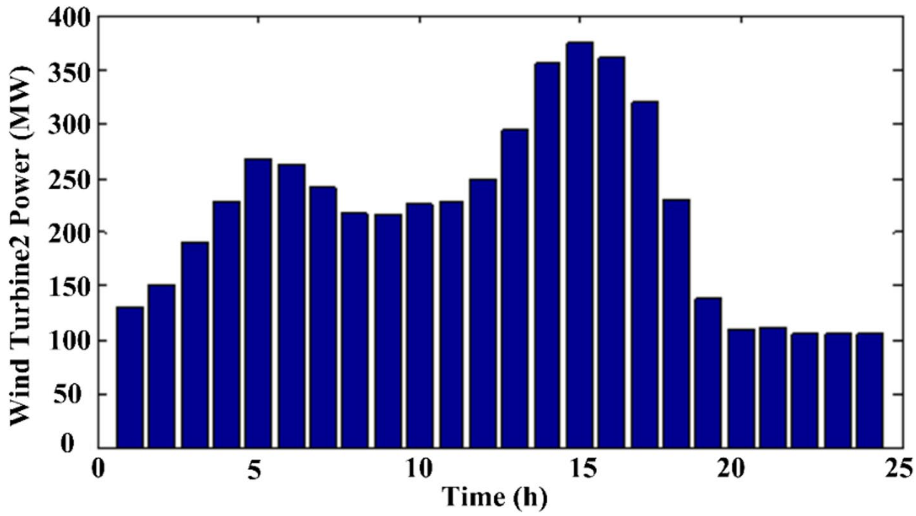

Fig. 5 Wind turbine 2 electricity generation pattern for 24 h

are assessed, as shown in Figs. 4 and 5, respectively. This can be seen in the diagrams. It is made up of a wind farm that generates the appropriate amount of electricity and has a total of one hundred wind turbines in each wind farm. Congestion management makes use of Monte Carlo analysis because of its versatility in simulating a wide variety of stochastic events. Weibull probability density function (PDF) wind models are used in this method to take into account the inherent variability and uncertainty of wind power output. This model accurately represents the distribution of possible wind speeds, allowing for their inclusion in Monte Carlo simulations. Together, these factors allow for a more accurate assessment of congestion situations, taking into account the inherent variability of renewable energy sources. Congestion management strategies in power networks, particularly in the presence of fluctuating renewable energy, may be made more realistic and successful by the use of Monte Carlo with a Weibull PDF wind model.

The average value of the power production is 325.5 MW, with wind plant 1 active power, and wind plant 2 active power each contributing 217.7 MW. The bid cost function of the wind turbine considered is:

$$P(C_{WT}) = a_{WT} + b_{WT}P_{WT} + c_{WT}P_{WT}^2 \tag{60}$$

where P (C_{WT}) is the cost function of WT-based DG and P_{WT} is the generated power in MW. The $a_{WT,}$ b_{WT}, c_{WT} is the cost coefficient of a wind turbine in \$, \$/MWh, and \$/MWh^2. For wind turbine 1, the cost function parameters are (a_{WT} = 4.46\$, b_{WT} =17.83 \$/MWh, c_{WT}= 0.0027 \$/MWh^2), and for wind turbine 2, the cost function parameters are (a_{WT} = 4.45\$, b_{WT} =17.54 \$/MWh, c_{WT}= 0.0028 \$/MWh^2). The data is available in [34].

Results and discussion

The issue of congestion management has been addressed thanks to the simulation studies that were carried out on the IEEE-24 bus system. The IEEE 24 bus test system has been adjusted to accommodate the changes made to the hydroelectric and wind power facilities. Rescheduling the operation of generators is one of the essential components of the congestion management method. In the event that congestion arises, the operating schedules of the generators are changed to ease transmission bottlenecks. This approach reduces the impact of system restrictions while optimizing the flow of electricity. To maximize output, MINLP is used to deliberately reschedule power plants. Sensitivity analysis can be used to identify crucial generators, allowing for more strategic bid placement. This dynamic approach ensures the electrical system is running at peak performance, cutting down on congestion, and increasing economic efficiency in the allocation of grid resources. The rescheduling of generation with and without renewable sources, taking into consideration various combinations of renewable sources, is described here with the purpose of minimizing the cost of congestion. The instances that have been considered include those with no renewable source (only existing thermal plants), with wind plants, with hydro plants, with two hydro plants and one wind plant, and with two wind plants and one hydro plant. In the IEEE-24 system, each of the eleven generators is linked to one of the buses (1, 2, 7–8, 13–18, 21–22, and 23). The buses numbered 8, 13, and 18 now have renewable source units attached, while buses numbered 1, 2, 7, 16, 21, 22, and 23 have thermal generating units. Two multi-line congestion cases have been considered:

(i) Case 1 (3-line congestion), with and without renewable sources.
(ii) Case 2 (2-line congestion), congestion with and without renewable sources.

Mixed-integer nonlinear programming (MINLP) emerges as a potent tool for congestion management in power systems when applied to 3-line and 2-line congestion situations using the GAMS-MATLAB interface. The combination of GAMS (general algebraic modeling system) with MATLAB allows for a streamlined and effective method of solution development. The MINLP framework provides a holistic description of

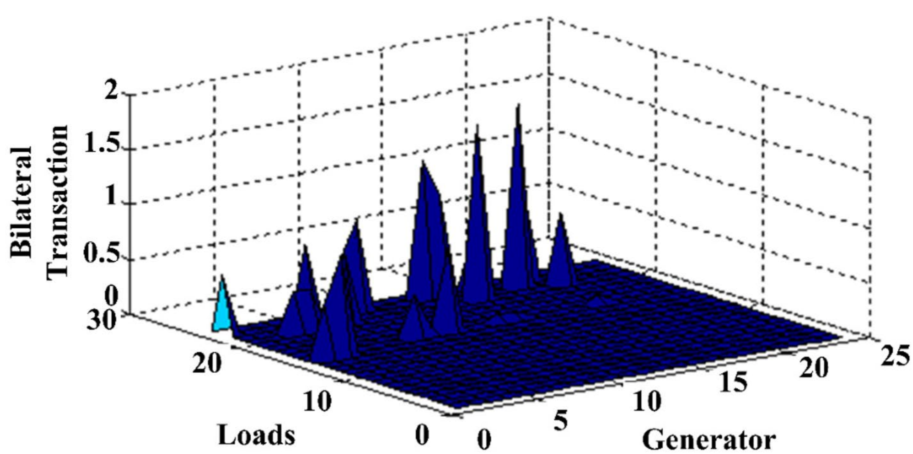

Fig. 6 During congestion management secure bilateral transaction pattern

power system dynamics by accommodating the simultaneous analysis of discrete choice variables (integers) and non-linear interactions. This modeling strategy accounts for the complexities of congestion management in situations with three or two congested transmission lines.

Congestion is reduced by developing and solving the minimal integrated network loss problem (MINLP), which involves rescheduling generating units and modifying power flows. Thus, a comprehensive and practical approach to congestion management is made possible by the GAMS-MATLAB interface in conjunction with MINLP, providing a flexible solution for a wide range of power system situations. It has been assumed that the congested lines have a line rating that is lower than the base case power flows. Along with thermal units, water and wind units have been taken into consideration in a modified version of the IEEE 24 bus test system. The resulting transaction matrix from the general ledger is shown in Fig. 6. The derived safe bilateral transaction matrix was put to use at a period when congestion management proved problematic. The unpredictable nature of renewable energy sources makes traffic control more difficult. Congestion is unexpected and may occur as a result of fluctuations in wind and solar power. In order to effectively manage congestion in the context of the ever-changing integration of renewable energy sources, this paper incorporates advanced forecasting, grid flexibility, and adaptive scheduling techniques.

Case 1: 3-line congestion

In this specific case, congestion management dynamics the three lines in question (14–16, 6–10, and 15–16) have been regarded as being lines that are experiencing congestion. The base power flow online (14–16) was 332.84 MVA, while the base power flow online (6–10) was 124.15 MVA, and the base power flow online (15–16) was 226.33 MVA. When taking into consideration these three lines, the line flow restrictions are dropped as follows: from 500 to 300 MVA, 175 to 100 MVA, and 500 to 150 MVA, respectively.

Table 3 presents the day-ahead projection (P_g) and the new generation schedule (P_{gn}), as well as the fluctuation in power (up and down) that occurs during congestion management, respectively, for situations with and without the presence of renewable sources. Figure 7 presents the updated generation schedule, which compares the case when renewable sources are used to the case where they are not. It is possible to see that the placement of a congested line is what determines the up-and-down generation change of generators. When there is congestion online (6–10), rescheduling by the units (2 and 7) is cost-effective. However, the line (6–10) was jammed up to the point where the units (2 and 7) did not engage in congestion management. Since the renewable source units will not be involved in congestion management, the cost of congestion management will be very high. The cost of congestion management without the renewable source unit is 5119.02 dollars per hour.

The cost of congestion management with a wind turbine unit, hydro unit, 1 hydro + 2 wind unit, and 2 hydro + 1 wind unit, respectively, is 4542.42 dollars per hour, 4252.89 dollars per hour, 4155.80 dollars per hour, and 3715.42 dollars per hour when renewable sources are included. Figure 8 shows the cost of the project. It has been shown that the use of renewable sources brings about a decrease in the costs associated with congestion

Table 3 Generation schedule with and without renewable energy source units participation per unit

Gen	3L congestion line (15–16), (14–16), and (6–10) without renewable resource				3L congestion line (15–16), (14–16) and (6–10) with wind units			3L congestion line (15–16), (14–16), and (6–10) with hydro units			3L congestion line (15–16), (14–16), and (6–10) with 1Hydro+2 wind units			3L congestion line (15–16), (14–16), and (6–10) with 2Hydro+1 wind units		
	P_g	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d
1	1.52	1.52	-	-	1.52	-	-	1.52	.2356		1.52			1.52		
2	1.52	1.90	0.38	-	1.52	0.2645	-	1.75			1.78	0.2626		1.77	0.253	
7	1.5	2.09	0.59	-	1.5	-	-	1.5			1.5			1.5		
8*	2.4	2.4	-	-	2.513	0.2394	-	2.4			2.37		0.0218	2.4		
13*	2.36	2.36	-		3.65	0.50	-	3.086	.7228		3.75	0.50		3.43	0.189	
15	4.5	3.7	-	0.80	3.7	-	0.80	3.70		.80	3.7		0.80	3.7		0.80
16	1.5	1.55	0.05	-	1.55	0.05	-	1.55	.05		1.55	0.05		1.55	0.05	
18*	3.5	3.5	-	-	2.85	-	0.50	3.5			2.75		0.50	2.7		0.80
21	3.0	2.2	-	0.80	2.74	-	0.2675	2.448		.552	2.73		0.26	2.8		0.19
22	3.1	2.86	-	0.23	3.0	-	0.10	2.753		.3468	3.0		0.10	3.0		0.10
23	3.5	4.3	0.80	-	3.85	0.1855	-	4.19	.6904		3.70	0.2092		3.99	0.4961	

*represents the number of Hydro units

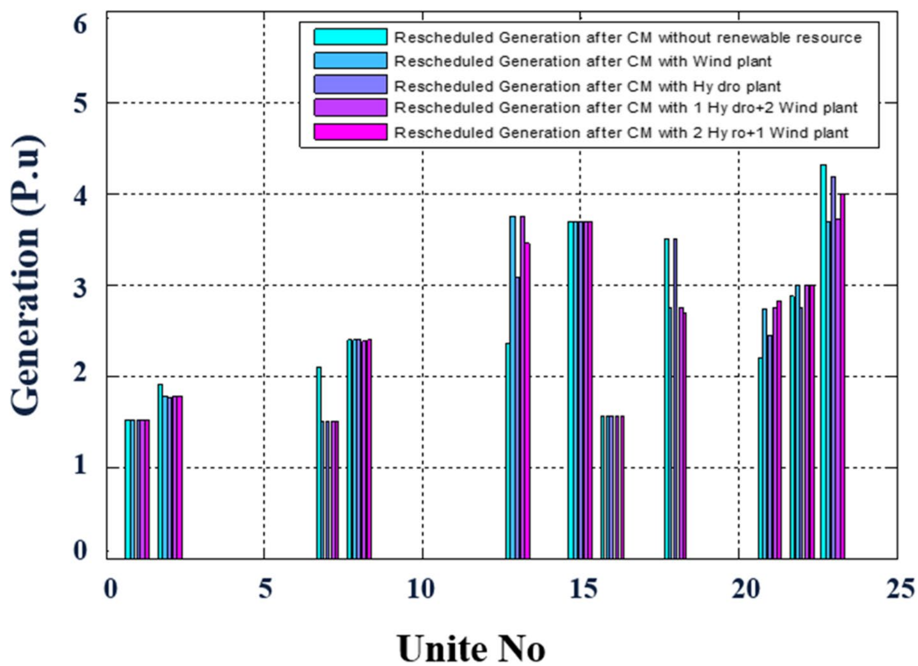

Fig. 7 Generators rescheduling for case 1 (3-line congestion) congestion management without and with a renewable source

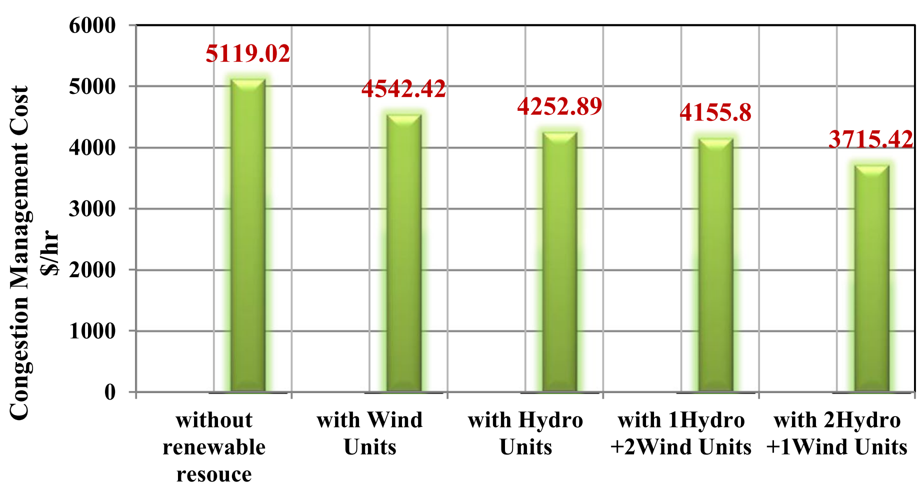

Fig. 8 Case 1 (3-line congestion) congestion management cost of with and without renewable resource

and the use of 2 hydro and 1 wind unit in the system results in the greatest reduction in these costs. Therefore, renewable source units do have an influence on the total cost and can be employed in an economically viable manner in the issue of congestion control.

Congestion management for case 1 (3-line congestion) is depicted in Figs. 9, 10, 11, 12, and 13, displaying the power demand and generation (pool and bilateral) as well as the up and down power by without and with renewable sources (with wind units, with hydro units, with 1 hydro + 2 wind units, and with 2 hydro + 1 wind units).

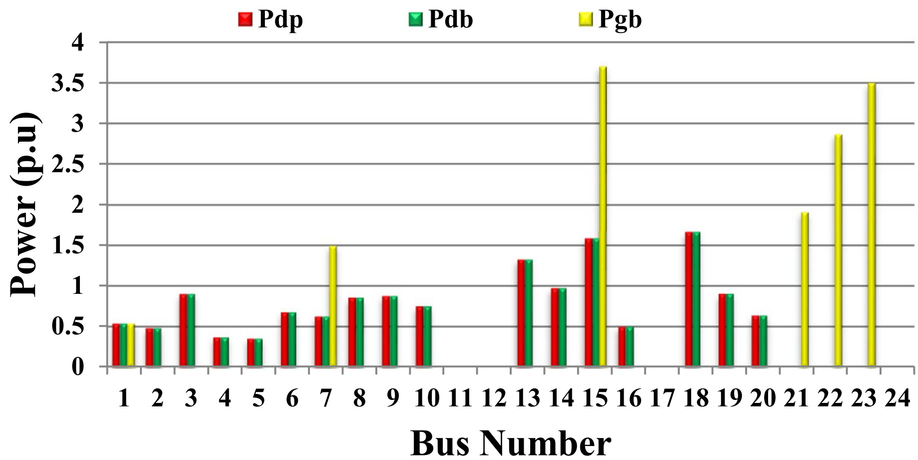

Fig. 9 Bilateral and pool power generation in case 1 (3-line congestion) without renewable source

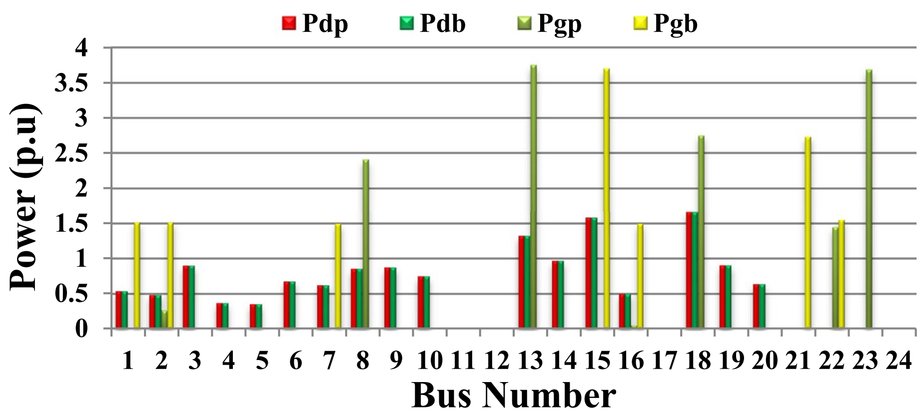

Fig. 10 Bilateral and pool power generation in case 1 (3-line congestion) with wind unit

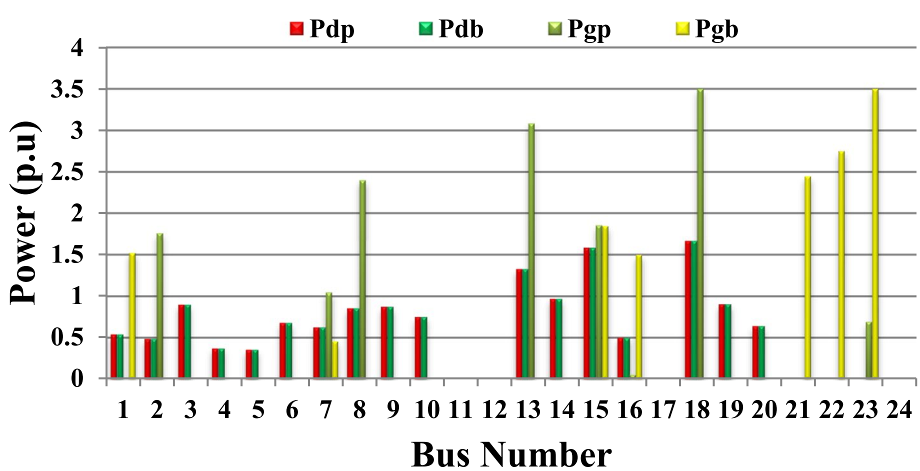

Fig. 11 Bilateral and pool power in case 1 (3-line congestion) with hydro units

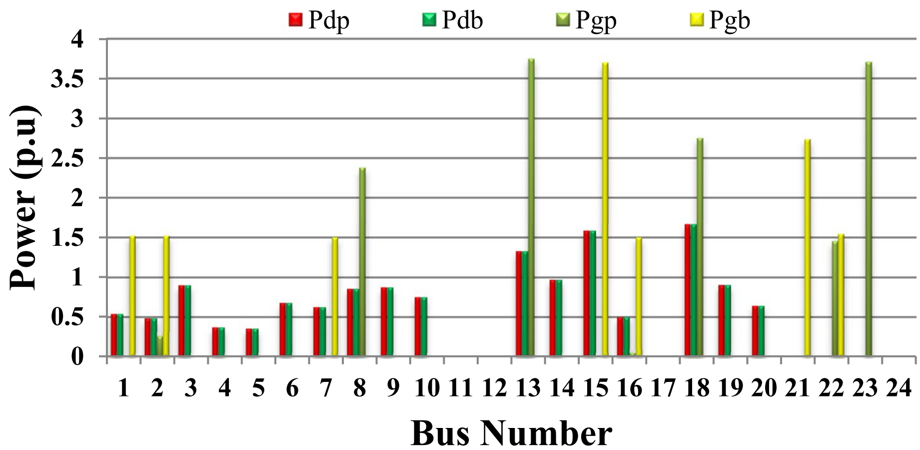

Fig. 12 Bilateral and pool power in case 1 (3-line congestion) congestion with 1 hydro + 2 wind units

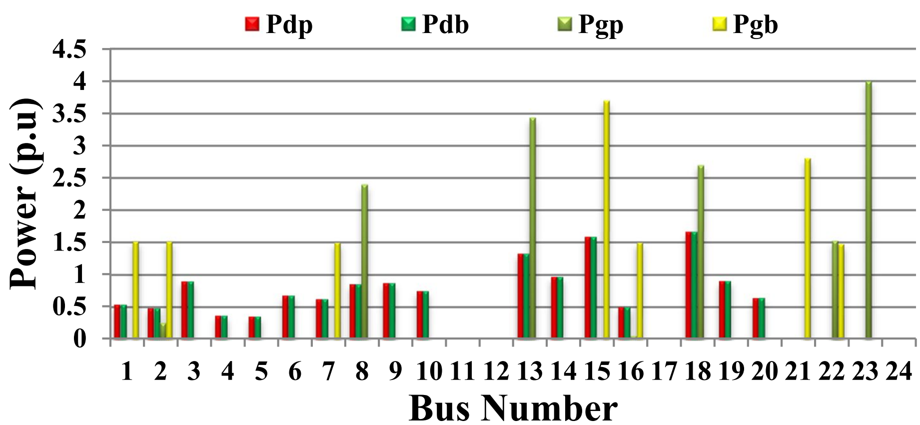

Fig. 13 Bilateral and pool power in case 1 (3-line congestion) with 2 hydro + 1 wind units

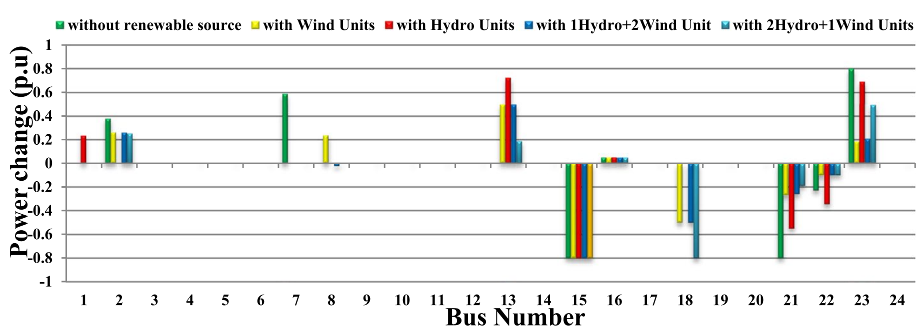

Fig. 14 Generation units up and down without and with renewable sources at case 1 (3-line congestion) of congestion management

In Fig. 14, we see the difference between the up and down generation with and without a renewable source during case 1 (3-line congestion) in congestion management. The congestion cost is reduced since renewable energy sources lower both the peak and the base loads.

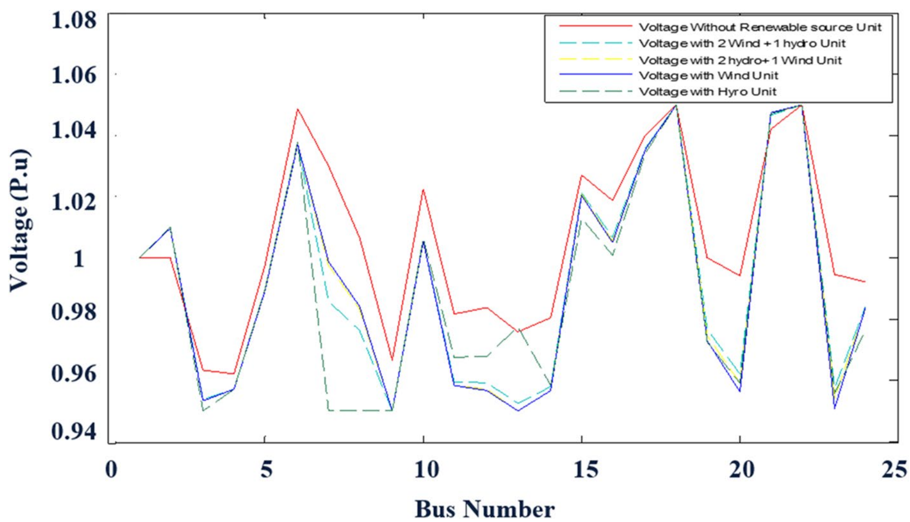

Fig. 15 Voltage profile with and without renewable source units in case 1 (3-line congestion) of congestion management

Table 4 Generation schedule with and without renewable energy source unit participation per unit

Gen	2L congestion line (15–16) and (14–16) without renewable resource				2L congestion line (15–16) and (14–16) with wind units			2L congestion line (15–16) and (14–16) with hydro units			2L congestion line (15–16) and (14–16) with 1 hydro + 2 wind units			2L congestion line (15–16) and (14–16) with 2 hydro + 1 wind units		
	P_g	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d	P_{gn}	ΔP_g^u	ΔP_g^d
1	1.52	1.52	-	-	1.52	-	-	1.52			1.52			1.52		
2	1.52	1.90	0.38	-	1.52		-	1.52			1.52			1.52		
7	1.5	2.09	0.59	-	1.5	-	-	1.5			1.5			1.5		
8*	2.4	2.4	-	-	2.513	0.343	-	2.47	.073		2.4			2.4		
13*	2.36	2.36	-		3.65	0.40	-	3.16	.80		3.75	0.50		3.34	0.099	
15	4.5	3.7	-	0.80	3.7	-	0.80	3.7		.80	3.7		0.80	3.7		0.80
16	1.5	1.55	0.05	-	1.55	0.05	-	1.55	.05		1.55	0.05		1.55	0.05	
18*	3.5	3.5	-	-	2.85	-	0.40	3.5			2.85		0.39	2.7		0.80
21	3.0	2.2	-	0.80	2.74	-	0.2595	2.75		.2415	2.75		0.24	2.91		0.085
22	3.1	2.86	-	0.23	3.0	-	0.10	2.41		.6824	3.0		0.10	3.0		0.10
23	3.5	4.3	0.80	-	3.85	0.35	-	4.3	.80		3.84	0.342		4.25	0.75	

*represents the number of Hydro units

The voltage profile at many buses was shown in Fig. 15 during case 1 congestion management with and without renewable source units. The voltage profile is measured to be within acceptable parameters during congestion control.

Case 2: two-line congestion management

In the case 2 analysis, the 15–16 and 14–16 lines are the ones that are judged to be crowded lines. The base power flows on line (15–16) were 226.33 MVA, while the base power flows on line (14–16) were 332.84 MVA. The maximum flow rates allowed on the lines have been reduced from 500 to 150 MVA and 300MVA, respectively. The

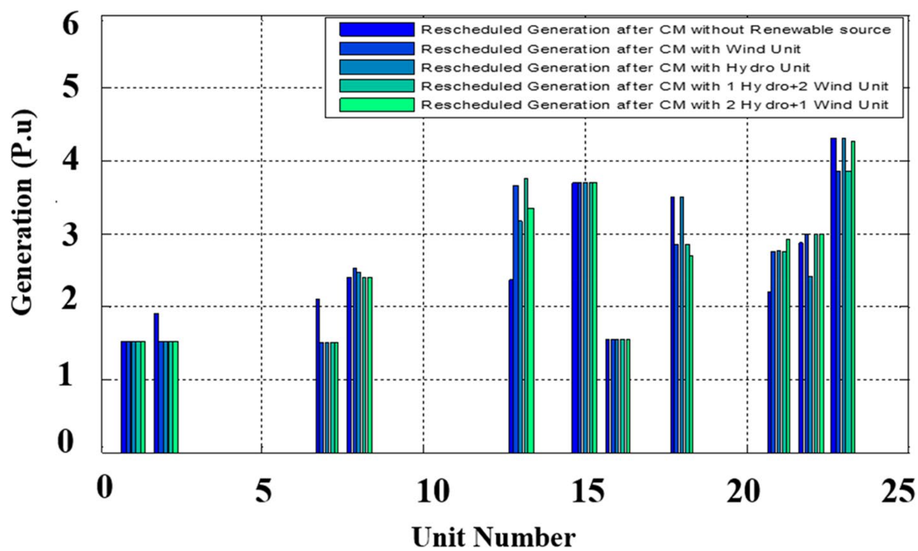

Fig. 16 Generators rescheduling for case 2 (2-line congestion) congestion management without and with renewable sources

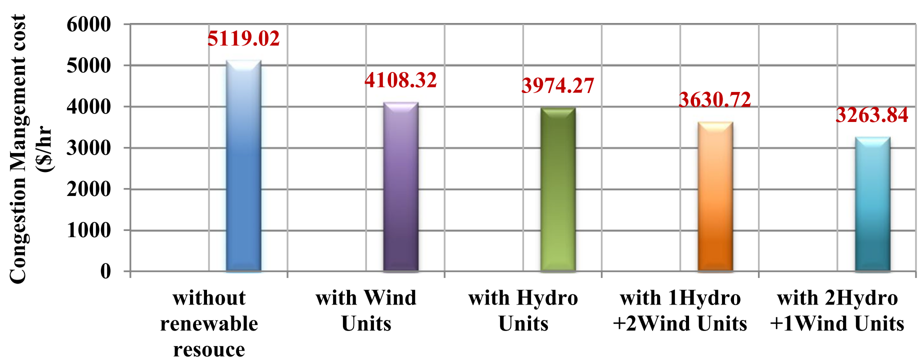

Fig. 17 Case 2 (2-line congestion) congestion management cost of with and without renewable resources

issue with congestion management has been resolved thanks to the implementation of based rescheduling. Both the day-head Pg and the new generation schedules Pgn may be derived both with and without the use of renewable sources. Different types of integrated and non-integrated renewable sources are used in wind units, hydro units, 1 hydro + 2 wind units, and 2 hydro +1 wind units, respectively, while working with renewable sources such as wind and hydro. Table 4 displays the up-down generation as well as the rescheduling of generators as a result of congestion management. It has come to our attention that (8, 13, 16, and 23) units are giving reduced bid prices and that their generation has been postponed up to their ramp limitations. The final bid pricing for the remaining generators is determined through adjustment.

The rescheduling of generation without renewable sources and with renewable sources (with wind units, with hydro units, with 1 hydro + 2 wind units and 2 hydro + 1 wind units) is depicted in Fig. 16 for the purpose of managing 2-line congestion and minimizing the cost of congestion. In case 2 (2-line congestion), it was observed that

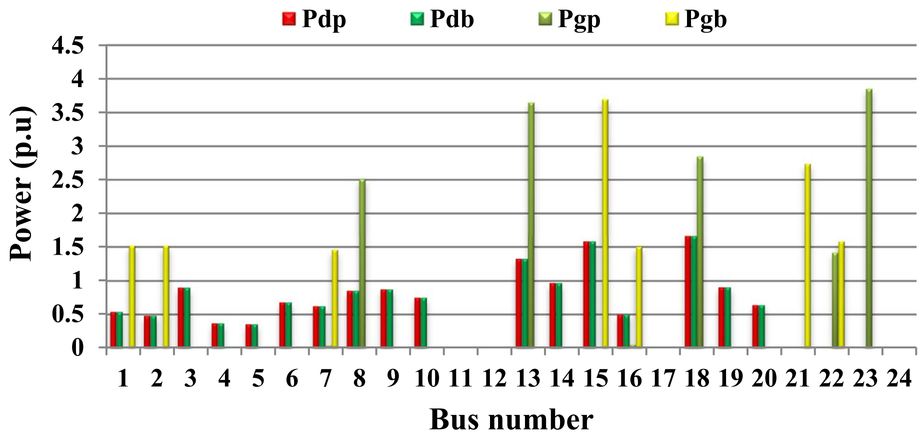

Fig. 18 Bilateral and pool power in case (2-line congestion) with wind unit

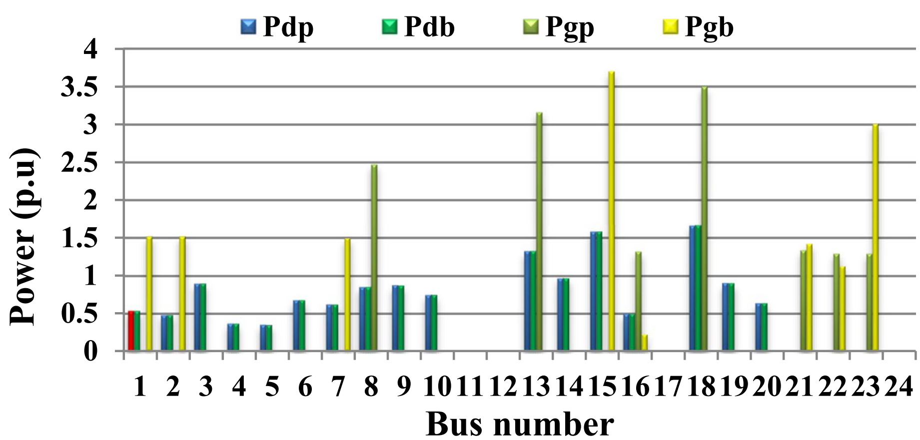

Fig. 19 Bilateral and pool power in case 2 (2-line congestion) with hydro unit

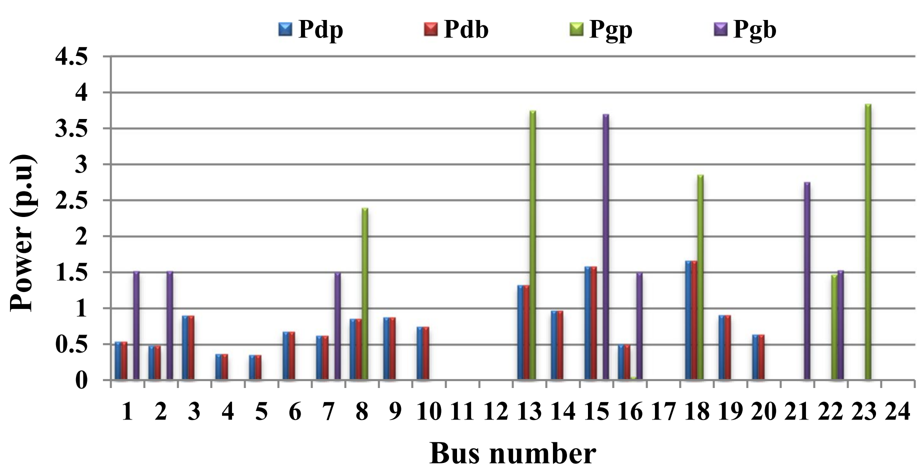

Fig. 20 Bilateral and pool power in case (2-line congestion) with 1 hydro + 2 wind units

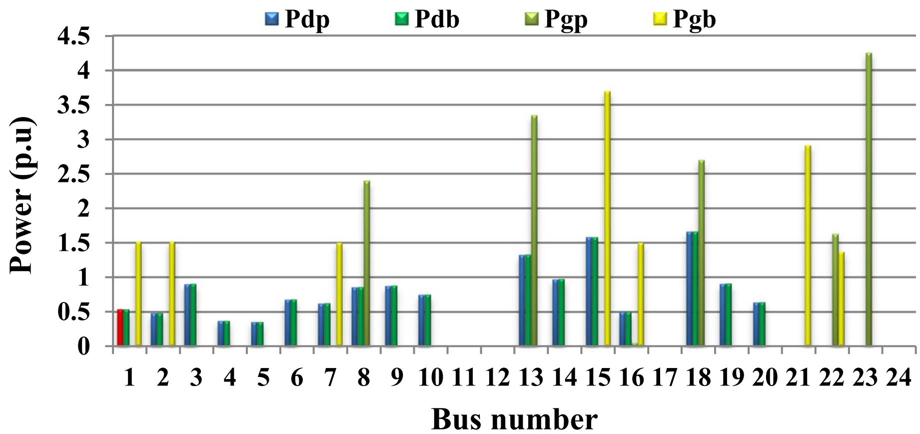

Fig. 21 Bilateral and pool power in case (2-line congestion) with 2 hydro + 1 wind units

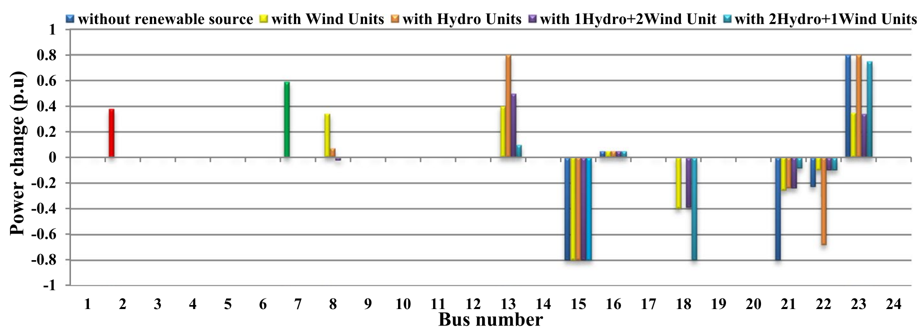

Fig. 22 Generation up and down without and with a renewable source at case 2 (2-line congestion) of congestion management

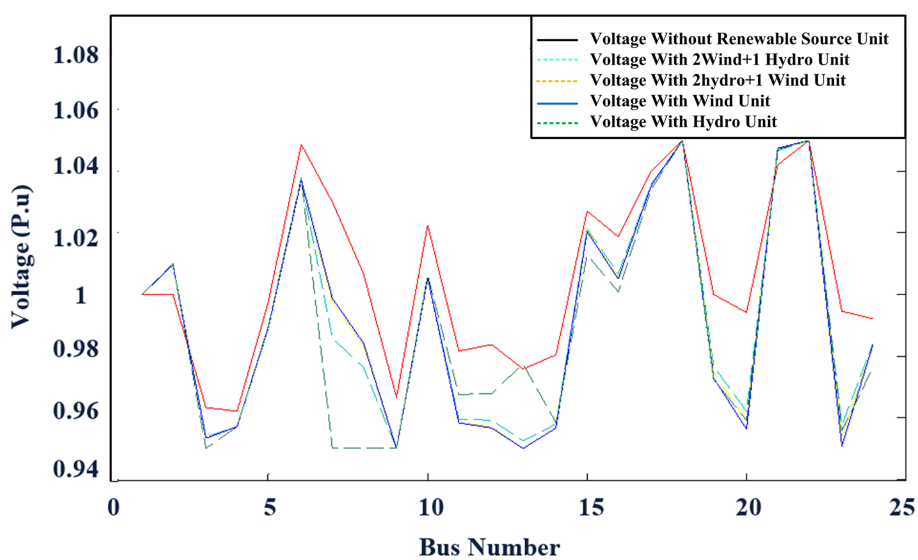

Fig. 23 Voltage profile with and without renewable source units in case 2 (2-line congestion) congestion management

the congestion management cost without and with renewable source is $5119.02/h without using a renewable source, $4108.32/r with wind units, $3974.27/h with hydro units, $3630.72/h with 1 hydro + 2 wind units, and $3263.84/h with 2 hydro + 1 wind units. These results can be seen in Fig. 17. It has been discovered that case 2 (2-line congestion) has a minimum congestion cost of 3263.84 dollars per hour while using 2 hydro and 1 wind unit. The comparison of the cost of managing congestion without renewable sources and with them reveals that we can save $1010.7 per hour with a wind unit, $1144.75 per hour with a hydro unit, $1488.3 per hour with one hydro unit and two wind units, and $1855.18 per hour with two hydro units and one hydro unit.

Figures 18, 19, 20, and 21 show the (pool and bilateral) power demand and generation along with up-down power by with renewable sources (with wind units, with hydro units, with 1 hydro + 2 wind units, and with 2 hydro + 1 wind units) units participating in congestion management for case 2 (2-line congestion). The generation up and down of case 2 (2-line congestion) in congestion management without and with renewable sources have been shown in Fig. 22. During congestion management without and with renewable source units in case 2 (2-line congestion), the voltage profile at various buses has been shown in Fig. 23. It is observed that the voltage profile is not improved but it is in under the limit.

Comparison of case 1 and case 2 without and with renewable source for congestion management

In Fig. 24, the cost comparison without and with renewable sources for case 1 (3-line congestion) and case 2 (2-line congestion) is shown. It is observed that in case 2 (2-line congestion), congestion cost is lower as compared to case 1 (3-line congestion) at with and without renewable sources. Without renewable sources, the congestion management cost is $5119.02/h in both case 1 (3-line congestion) and case 2 (2-line congestion). With renewable sources, the costs are $4542.42/h and $4108.32/h in case 1 (3-line congestion) and case 2 (2-line congestion) at with wind units, $4252.89/h and $3974.27/h in case 1 (3-line congestion) and case 2 (2-line congestion) at with hydro units, $4155.8/h

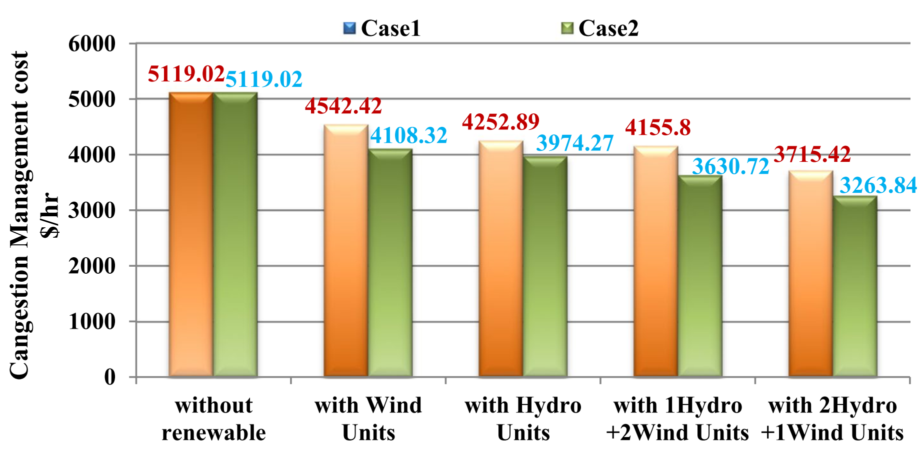

Fig. 24 Case 1 (3-line congestion) and case 2 (2-line congestion) congestion management cost of with and without renewable resources

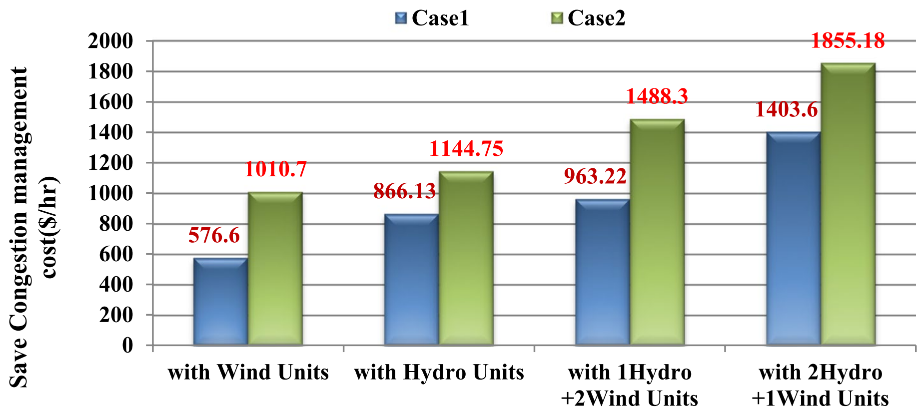

Fig. 25 Saving of congestion management cost with case 1 (3-line congestion) and case 2 (2-line congestion)

and \$3630.72/h in case 1 (3-line congestion) and case 2 (2-line congestion) at with 1 hydro + 2 wind units, and \$3715.42/h and \$3263.84/h in case 1 (3-line congestion) and case 2 (2-line congestion) at with 2 hydro + 1 wind units. With 2 hydro + 1 wind units for both cases (case 1 (3-line congestion) and case 2 (2-line congestion)), congestion costs are observed to lower.

The difference in cost between managing congestion without renewable sources and doing so with them is shown in Fig. 25. It is possible to draw the conclusion that in contrast to case 1 (which involves three lines of congestion) and case 2 (which involves two lines of congestion), the amount of money saved by using 2 hydro and 1 wind units is greater. When case 2 (2-line congestion) is contrasted with case 1 (3-line congestion), the total amount of money saved on congestion charges is larger in case 2 (2-line congestion) in all renewable combination units (with wind units, with hydro units, with 1 hydro + 2 wind units, and with 2 hydro + 1 wind units). This is the case regardless of whether the congestion is caused by wind, hydro, or a mix of the two. The use of wind units resulted in a cost savings of \$576.6 per hour for managing three-line congestion in case 1 and \$1010.7 per hour for managing two-line congestion in case 2. The term congestion cost savings refers to the reduction or avoidance of expenditures incurred due to grid congestion. These savings can be realized through the implementation of efficient congestion management solutions.

When using hydro units, the cost of congestion management may be reduced by \$866.13 per hour in case 1 (3-line congestion) and by \$1144.75 per hour in case 2 (2-line congestion). When 1 hydro and 2 wind units are used, the cost of congestion management may be reduced by \$963.22 per hour in case 1 (3-line congestion) and by \$1488.3 per hour in case 2 (2-line congestion). The most cost-effective combination of renewable energy sources is two hydro and one wind unit, which results in a savings of \$1403.6 per hour in case 1 with three lines of congestion and \$1855.18 per hour in case 2 with two lines of congestion. As a consequence of having major renewable energy sources, they have a considerable influence on the management of congestion. These sources are going to have a major proportion of the future energy markets, and they are going to play a crucial role in preventing congestion and helping the ISO/TSO manage the network more effectively.

Conclusions

This article discussed managing congestion using generator rescheduling and renewable energy sources. A piece-wise linear characteristics curve adds hydro unit performance. Renewable energy reduces congestion management costs. Combinations of hydro, wind, and conventional generating units yielded results. Two hydro + 1 wind units reduce congestion costs more in case 1 (3-line congestion) and case 2 (2-line congestion). Case 2 (2-line congestion) saved more congestion cost than case 1 (3-line congestion) for congestion management. In case 1 (3-line congestion) and case 2 (2-line congestion), integrating 2 hydro + 1 wind units minimizes transmission line congestion cost. Due to their cheap operating costs, hydro and wind units help reduce congestion costs. Hydro and wind units may significantly impact the future power market due to their cheap operating costs and fast start-up times. The ISO manages congestion with renewable sources incorporated into the system by judging their participation and making the power market economically more efficient during network congestion. This research will assist the ISO in deciding how to integrate hydro and wind units into thermal generation-dominated systems.

Abbreviations

GENCOs	Generation companies
DISCOs	Distribution companies
PTDF	Power transfer distribution factor
FACTs	Flexible AC transmission systems
CI	Congestion index
MCS	Monte Carlo simulation
RES	Renewable energy sources
ISO	Independent system operator
MINLP	Mixed integer nonlinear programming

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Authors' contributions
Ch. Lokeshwar Reddy was responsible for the preparation of the manuscript and its writing. K. Rayudu is the one responsible for collecting the crucial necessary data. The editing work on the manuscript has been finished by M. Sharanya. Regarding the congestion management system, Sridhar Patthi was responsible for organizing the manuscript sketch work as well as the data analysis. JVG Rama Rao has completed the edits as well as obtained the findings and saved them in MATLAB/Simulink. All authors have read and approved the manuscript.

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Declarations

Ethics approval and consent to participate
We declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. As the corresponding author, we confirm that the manuscript has been read and approved for submission by all the named authors.

Competing interests
The authors declare that they have no competing interests.

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