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RESEARCH ARTICLE

Transmission Congestion Management Using Generator Sensitivity Factors for Active and Reactive Power Rescheduling Using Particle Swarm Optimization Algorithm

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ABSTRACT Independent System Operators have difficulty in fulfilling all contractual power transactions in a competitive energy market due to transmission network congestion. As a result, applications of generator rescheduling become one of the antidotes in alleviating this difficulty in the consequence of ever-increasing numerous power transactions. The goal of this research is to lower the cost of active and reactive power of the generators by reducing the deviation of rescheduled active and reactive power from scheduled values. The inclusion of reactive power rescheduling and voltage stability in this paper is innovative, as compare to other existing methodologies solely examine active power rescheduling. This paper made the following contributions: formulated a multi-objective function for congestion control in an electric transmission network. Furthermore, formulated the generator sensitivity factors to identify overloaded lines and which generators will be involved in congestion management. Developed a particle swarm optimization (PSO) algorithm to solve the multi-objective function of the transmission congestion management system. In addition, the developed PSO method for CM approach was validated on three IEEE standard test system networks (14, 30, and 118). The simulation results prove that reduces active and reactive power, lowering the cost of generator rescheduling, and demonstrating the usefulness of developed PSO method for transmission network congestion. Furthermore, voltage stability and voltage profile improvements demonstrate the performance effectiveness of the PSO algorithm used in this work.

INDEX TERMS Congestion management, generator rescheduling, particle swarm optimization, sensitivity factors, voltage stability.

NOMENCLATURE

C_{Pg}	Cost of rescheduling active power by the partaking generator in congestion management
C_{Qg}	Cost of rescheduling reactive power by the partaking generator in congestion management
ΔP_g	Generator's active power adjustments
ΔQ_g	Generator's reactive power adjustments
L_{max}	Maximum voltage stability indicator
PF	Penalty factor
S_{Gmax}	Generator's maximum nominal apparent power
C_g^P	Cost of generating reactive power by the generator
φ	Profit rate of reactive power generation
NB	Number of buses
P_{Gi}	Active power produced at bus i
Q_{Gi}	Reactive power produced at bus i
P_{Di}	Active power demand at bus i

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Q_{Di}	Reactive power demand at bus i
$\lvert V_i\rvert < \delta_i$	Bus i complex voltage
$\lvert V_j\rvert < \delta_j$	Bus j complex voltage
$\lvert Y_{ij}\rvert < \delta_{ij}$	Bus i and j mutual admittance
θ_{ij}	Bus i and j impedance angle
P_g^{min}	Minimum active power generation
P_g^{max}	Maximum active power generation
Q_g^{min}	Minimum reactive power generation
Q_g^{max}	Maximum reactive power generation
ΔP_g^{min}	Change in minimum active power generation
ΔP_g^{max}	Change in maximum active power generation
ΔQ_g^{min}	Change in minimum reactive power generation
ΔQ_g^{max}	Change in maximum reactive power generation
V_i^{min}	Bus i minimum voltage
V_i^{max}	Bus i maximum voltage
ΔV_i^{min}	Change in minimum voltage at bus i
ΔV_i^{max}	Change in maximum voltage at bus i
S_k	Transmission line k power flow
S_k^{max}	Maximum power flow on transmission line k
P_{ij}	Active power flow at bus i and j
Q_{ij}	Reactive power flow at bus i and j
N_g	Overall number of generator buses
N_d	Overall number of load buses
N_l	Overall number of transmission lines
N_b	Overall number of buses
x^{min}	Minimum variable limit
x^{max}	Minimum variable limit
k_n	Penalty function constant (i.e n $= 1, 2, \ldots$n)
PG_{gn}	Generator's active power
QG_{gn}	Generator's reactive power
V_i	Voltage at bus i
θ_i	Phase angle at bus i
G_{ij}	Line k conductance
B_{ij}	Line k susceptance
$V[]$	Particles velocity
ω	Inertia weight
N_p	Overall particles number in the swarm
n	Overall, members number in one particle
$V_{g,i}$	Initial velocity of the particles
$P_{g,i}$	Initial position of all members of the particles
$V_{g,i}^{min}$	Previously calculated minimum velocity
$V_{g,i}^{max}$	Previously calculated maximum velocity
$V_{g,i}^{new^l}$	New or updated velocity
$P_{g,i}^{new^l}$	New or updated position
$Iter$	Total number of iterations
$P^{best}[]$	Personal best solution at every iteration
$G^{best}[]$	Global best solution of all solutions
$Iter^{max}$	Overall number of iterations
$P_{present}[]$	Position of the current particle
$c1andc2$	Are acceleration coefficients
a_n, b_n, c_n	Are generators predetermining cost coefficients
h_1, h_2, h_3, h_4	Are normalization vectors

ABBREVIATION

GENCOs	Generations
TRANCOs	Transmissions
DISCOs	Distributions
PSO	Particle swarm optimization
CM	Congestion management
GR	Generator rescheduling
DG	Distributed generation
DR	Demand response
FACTS	Flexible alternating current transmission systems
ATC	Available transfer capability
TCSC	Thyristor control series capacitor
PI	Performance index
GA	Genetic algorithm
POD	Power oscillator damper
SSSC	Static series-shut capacitor
UPFC	Unified power flow compensator
SPEA	Strength pareto evolutionary algorithm
SA	Simulated annealing
OPF	Optimal power flow
N-R	Newton Raphson
PV	Generator or voltage control bus
PQ	Load bus
SOC	Second order cone
ESSs	Energy storage systems
GAMS	Generalized Algebraic Modelling System
SCUC	Security-constraint unit commitment
SCOPF	Security-constraint optimal power flow
ACCT	Available congestion clearing time
TCR	Transmission congestion rent
RHCM	Real-time hierarchical congestion management
NSGAII	Non-dominated sorting Genetic Algorithm
RTS	Reliability test system

I. INTRODUCTION

The electrical power structure has traditionally been divided into three parts: generation (GENCOs), transmission (TRANCOs), and distribution (DISCOs) [1]. Initially, all three divisions of the power system were monitored and controlled by a single authority known as a vertically integrated utility. However, with rapid population growth, rapid industrialization, and technological advancement, there is a tremendous and exponential demand for more clean and reliable energy at the consumer end. As a result, the global electric power industries are experiencing restructuring and deregulation in several countries [2].

The reforming and deregulating of the electric power industry have ensued in various consumers' high open-access penetration of the network. Each customer competes to access a very affordable and consistent supply from the cheapest available generator, regardless of distance. Aside from the primary goal of restructuring the electric power system to meet the high demand for electricity supply, some other disadvantages contribute significantly to the system's unhealthy state, such as ancillary service, inefficient market, congestion, and market power. Congestion is the most serious of the disadvantages associated with the deregulation of the electric power industry, and more attention is being paid to it.

Congestion occurs when a transmission line's thermal, voltage, and stability limits are violated or exceeded due to overloading. Other unexpected scenarios that contributed to the electric transmission network congestion included a sudden power outage, equipment failure, and an unexpected increase/decrease in demand. Congestion management (CM) techniques are used to mitigate these scenarios. However, any traces of congestion must be dealt with immediately to maintain a good and well-functioning system and avoid total system collapse, which can lead to total blackout. Therefore, a proper congestion management strategy must also be implemented.

Congestion management is critical for system balancing, system security, and reliability, as well as providing solutions to any financial problems caused by congestion. Therefore, several CM methods have been discussed in the literature, and a significant amount of research efforts have been devoted to identifying the appropriate congestion management techniques that can alleviate congestion in transmission networks while causing no or little disruption in consumer demand for electricity. According to the literature, popular CM techniques include Generators Rescheduling (GR), Flexible Alternating Current Transmission System (FACTS) devices, Optimization techniques, Re-dispatch, and CM-based Available Transfer Capability (ATC) [3], [4], [5]. Fig. 1 depict various types of congestion management methods.

Ref [6] presented a technique for verifying the best position and size of FACTS devices (TCSC) with GA for CM. The method was successfully validated by examining the effects of TCSC on the IEEE 30-bus network, and it was confirmed that the compensated network with TCSC reduced congestion. It was also determined that the device was adequate for long-term congestion control. [7] investigated active power Performance Index (PI)-based optimum allocation of FACTS devices to address CM technical issues in power system deregulation. The approach was validated using MATLAB Simulink on an IEEE 14 bus system.

Ref [8] presented a cost-free approach to optimal global allotment of FACTS devices using GA to mitigate overloading in a liberalized power system network. The objective function in congestion management was solved with GA because it was nonlinear. This strategy's applicability to a real-world practical system was demonstrated using the IEEE 30-bus system network. In [9], a novel approach to alleviating power system congestion was validated by combining a Power Oscillation Damper (POD) with FACTS devices (SSSC and UPFC). The proposed solution decongests the congested lines while also increasing the capability power of the lines. Ref [10] applied phase shift transformer method to relieve congestion on congested lines. The method was validated on a modified IEEE 24-bus test system network. [11] proposed a thyristor-controlled phase shifting transformer technique using GAMS solver to alleviate congestion. The viability of the technique was examined on the IEEE 24-bus network.

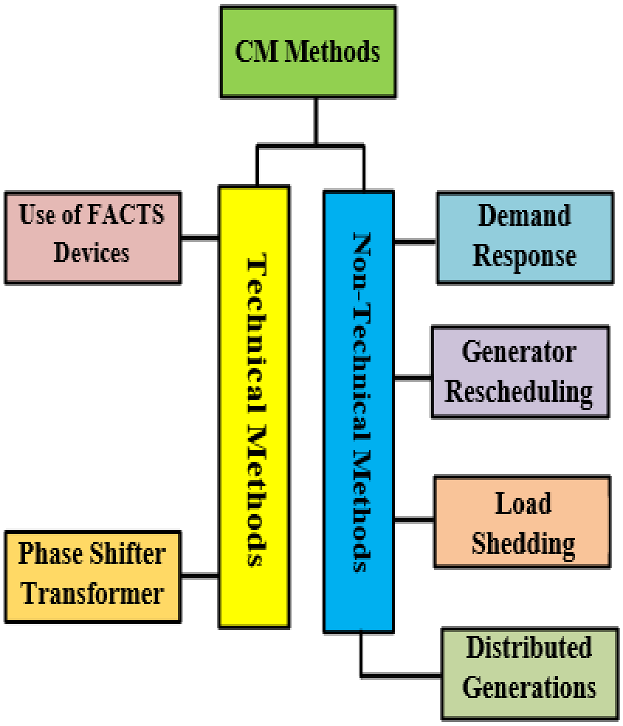


FIGURE 1. Types of congestion management methods.

Authors in Ref [12] developed a cost-free approach to CM by investigating TCSC potentials. The FACTS results, as mentioned earlier, were compared and validated using the IEEE 14-bus system network and MATLAB software. [13] proposed a congestion management solution based on simulated annealing (SA) algorithm-based optimal placement of UPFC. The purported method was utilized to unravel the multi-objective function problem of UPFC placement. MATLAB software was employed to validate the proposed method. Ref [14] presented a unique technique for optimum allocation of FACTS controllers-based GA and the Strength Pareto Evolutionary Algorithm (SPEA). Both approaches were used concurrently for single-objective and three-objective optimization on power systems. The method was validated using MATLAB software on an IEEE 30 bus test setup. Ref [15] created a modified UPFC control circuit to alleviate congestion. A sensitivity-based technique was used to pinpoint the UPFC's location. In PSCAD/EMTDC, a 5-buses, 7-line transmission network was utilized to simulate the model. Authors in [16] describe numerous index techniques for optimal FACTS device placement. An IEEE 30-bus test system network was utilized to validate the method.

Ref [2] proposed a survey on methodologies and approaches to reducing congestion on power transmission lines and reviewed several major CM strategies used by researchers. In [17], the author makes use of a novel demand response programs to alleviate congestion. The optimal time of execution of DRPs using wind power and the proposed model was validated on IEEE 39-bus system network. Ref [18] suggested a generator rescheduling method to avoid congestion. The authors make use of firefly optimization algorithm to reschedule the output power of the participating generator to the congested lines. The model's capability was tested on the IEEE 39-bus system network. Authors [19] created a novel method for CM in transmission networks by creating a control algorithm that manages active power flow in the network and validating it on an IEEE 5-bus test system network. Ref [20] proposed a probability occurrence method for CM, which analyzed the most critical lines and validated the technique's performance using the IEEE 14-bus system network. Many of these techniques/methods relieve transmission network congestion by rescheduling only active output power of participating generators to congested lines.

A method of optimal placement of energy storage systems (ESSs) for the mitigation of congestion in electric power transmission network was proposed in [21]. The authors solved these multi-objective function by utilizing generalized algebraic modelling system (GAMS) based security constraint unit commitment (SCUC) and MATLAB. The effectiveness of this method was validated on the IEEE 24-bus RTS. The system operational cost was reported to be minimized in GAMS by SCUC, while the investment and storage costs are minimized in MATLAB by the NSGA-II algorithm which gives a set of Pareto optimal solutions. Authors in [22] proposed a novel real-time hierarchical congestion management (RHCM) method. The proposed method mitigate congestion by reschedules generators in two stages based on Available Congestion Clearing Time (ACCT) of the transmission lines in presence of renewable energy sources (solar and wind). The proposed two-stage RHCM method provides feasible solution to ISO to mitigate congestion in terms of minimum cost of relieving congestion.

Ref [23] proposed a potential probabilistic method based on wind power outputs to manage the congestion problems of power grids caused by variability of the loads. For the implementation and validation of the proposed approach, the author's utilized the historical data from the wind farms located on Jeju Island in South Korea to fit the Weibull distribution and implement Monte Carlo simulations. Authors in [24] proposed an hourly method of congestion management in deregulated power market. The authors utilized transmission congestion rent (TCR) to determined optimal location of the placement of DGs (solar PV and energy storage system) whereas optimal size of the DGs were determined by a hybrid deferential evolution and particle swarm optimization technique. The proposed method was carried out on IEEE 30-bu test system.

In [25], the authors proposed a novel transmission switching based cost-effective technique to alleviate congestion (overloading). The model was design to provides minimum voltage security index while easing transmission lines congestion. The proposed model was implemented on a 6-bus IEEE test system and 93-bus real test network (Transmission network of Fars province in Iran) to show the validity and authenticity of the work. Ref [26], developed a new congestion management model based on power system partitioning technique. The proposed model used congestion index to identify the congested lines and congestion management was performed by the identification of the candidate zones, in order to alleviate congestion on the critical lines. The model was implemented on IEEE 39-bus test system. Ref [27], proposed a probabilistic security-constrained optimal power flow (SCOPF) model for congestion management which was based on the non-linear ac formulation. For proper controlling power system devices, the proposed method used a second-order cone (soc) relaxation. The method was validated on modified IEEE-118 bus test system, and the results of the soc and the traditional ac power flow were compared. The state-of-the-art of the literature review for transmission congestion management systems based on technical and non-technical methods using the state-of-the-art devices and novel algorithm to relive the transmission congestion proposed by authors from the literature is summarized in Table 1 below.

Therefore, this paper presents an optimal power flow (OPF) analysis-based PSO algorithm method to identify participating generators to congestion and optimally reschedule their output (active and reactive power) while managing congestion at the lowest possible rescheduling cost. Furthermore, because the conventional method of OPF is premised on the exploration path, which is obtained from the function derivative, the output of the participating generators was optimally rescheduled to mitigate congestion using the PSO algorithm. The following are the study's contributions: i) Formulated multi-objective function mathematical model for congestion control in an electric transmission network. ii) Formulated the Generator Sensitivity Factor (GSF) for both active and reactive power in order to detect the congested lines. iii) Developed particle swarm optimization (PSO) algorithm for the multi-objective function to solve the transmission congestion management system. iv) The developed PSO method for CM approach was validated on three IEEE standard test system networks (14, 30, and 118) and its simulation results are presented.

TABLE 1. **State-of-the-art review on transmission congestion management techniques.**

References	Transmission congestion management method used	Device used to relieve transmission congestion		Algorithm Used	Sample system used to validate the algorithm
[6]	Technical Methods	FACT Devices		Genetic algorithm	IEEE 30-bus network
[7]		FACT Devices		Active power performance Index (PI)	IEEE 14-bus network
[8]		FACT Devices		Cost free approach-based GA	IEEE 30-bus network
[10]		Phase shift transformer		Generalized algebraic modelling system (GAMS) optimization	IEEE 24-bus network
[11]		Phase shift transformer		Generalized algebraic modelling system (GAMS) solver	Modified IEEE 24-bus network
[18]	Non-Technical Methods using DGs	Generator rescheduling		Firefly optimization algorithm	IEEE 39-bus network
[17]		Demand response		Demand response programs (DRPs)	IEEE 39-bus network
[22]		Renewable Energy resources (Solar and Wind)		Real-time hierarchical congestion management (RHCM)	IEEE 39-bus network
[24]		Distributed generation (Solar PV and Energy storage system)		Hybrid differential Evolution	IEEE 30-bus network
[25]		Transmission switching		Transmission switching based cost-effective	IEEE 6-bus and 93-bus Irania networks
[26]		System generators and loads		Power system partitioning technique	IEEE 39-bus network
[27]		Renewable Energy resources		Probabilistic security-constraint optimal power flow (SCOPF)	IEEE 118-bus network

II. PROBLEM FORMULATION FOR CONGESTION MANAGEMENT

A. OBJECTIVE FUNCTION

This work aimed at alleviating the electric transmission network congestion by reducing the rescheduling cost of the output power of the generators involved in congestion. The PSO algorithm is employed to unravel this nonlinear OPF problem. The sum of the overall amount of rescheduling needed by the designated generator can be written as (1) [28]:

$$Minimize \sum\nolimits_g^{N_g} C_{Pg}\left(\Delta P_g\right)\Delta P_g + \sum\nolimits_g^{N_g} C_{Qg}\left(\Delta Q_g\right)\Delta Q_g + k_1 L_{max} + k_2 \sum\nolimits_{i=1}^{N_d} |1 - V_i| + PF \tag{1}$$

$$C_{Qg}\left(\Delta Q_g\right) = \left\{C_g^P\left(S_{Gmax}\right) - C_g^P\left(\sqrt{S_{Gmax}^2 - \Delta Q_g^2}\right)\right\}\varphi \tag{2}$$

$$C_g^P\left(\Delta PG_{gn}\right) = a_n\left(\Delta PG_{gn}^2\right) + b_n\left(\Delta PG_{gn}\right) + c_n \tag{3}$$

Normalization for multi-objective functions can be made by utilizing weighting strategy (weighted fitness function) to convert both economic and technical parameters into a single objective function [29]. Any multi-objective function solutions without weighting strategy have a higher tendency to divert towards conflicting solutions. In this proposed work, the authors make use of normalized weights to form final fitness function for (1) to be optimized. The weighted multi-objective fitness function is expressed as:

$$Minimize\ J = \sum\nolimits_g^{N_g} h_1 * C_{Pg}\left(\Delta P_g\right)\Delta P_g + \sum\nolimits_g^{N_g} h_2 * C_{Qg}\left(\Delta Q_g\right)\Delta Q_g + h_3 L_{max} + h_4 * \sum\nolimits_{i=1}^{N_d} |1 - V_i| + PF$$

1) EQUALITY CONSTRAINTS

These are system power balance constraints, and they can be written as (4) and (5):

$$P_{Gi} - P_{Di} = \sum\nolimits_{n=1}^{NB} |V_i|\left|V_j\right|\left|Y_{ij}\right| cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{4}$$

$$Q_{Gi} - Q_{Di} = \sum\nolimits_{n=1}^{NB} |V_i|\left|V_j\right|\left|Y_{ij}\right| sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{5}$$

2) INEQUALITY CONSTRAINTS

These are constraints for control variables, and they can be written as (6) to (10):

$$P_g - P_g^{min} = \Delta P_g^{min} \le \Delta P_g \le \Delta P_g^{max} = P_g^{max} - P_g,\ g\forall N_g \tag{6}$$

$$Q_g - Q_g^{min} = \Delta Q_g^{min} \le \Delta Q_g \le \Delta Q_g^{max} = Q_g^{max} - Q_g,\ g\forall N_g \tag{7}$$

$$|S_k| \le S_k^{max},\ k\forall N_i \tag{8}$$

$$V_i - V_i^{min} = \Delta V_i^{min} \le \Delta V_i \le \Delta V_i^{max} = V_i^{max} - V_i,\ i\forall N_b \tag{9}$$

$$\left(\sum\nolimits_g^{N_g}\left(GS_{Pgn}^k \times \Delta P_g\right) + P_{ij}\right)^2 + \left(\sum\nolimits_g^{N_g}\left(GS_{Qgn}^k \times \Delta Q_g\right) + Q_{ij}\right)^2 \le \left(S_{ij}^{max}\right)^2, \quad ij \in N_l \tag{10}$$

The penalty function PF is expressed in (11) and (12) to control the limits of all the inequality constraint variables.

$$PF = k_3 \times f(P_i) + k_4 \times \sum_{i=1}^{N_g} f(Q_{gi}) + k_5 \times \sum_{i=1}^{N_b} f(V_i) + k_6 \times \sum_{i=1}^{N_l} f(S_k) \quad (11)$$

$$\mathrm{f}(\mathrm{x}) = \left\{ \begin{array}{cc} 0 & \text{if } \mathrm{x}^{\min} \le \mathrm{x} \le \mathrm{x}^{\max} \\ (\mathrm{x}-\mathrm{x}^{\mathrm{maax}})^2 & \text{if } \mathrm{x} > \mathrm{x}^{\max} \\ (\mathrm{x}^{\max}-\mathrm{x})^2 & \text{if } \mathrm{x} < \mathrm{x}^{\min} \end{array} \right\} \quad (12)$$

B. FORMATION OF THE GENERATOR SENSITIVITY FACTORS

With different sensitivity of generators to power flow on the overloaded lines, a change in power flow on transmission line k joining buses i and j subjected to unit variation in active and reactive power injection by generator-g at bus-n can be term as the generator sensitivity to the congested line (GSF).

1) GENERATOR SENSITIVITY FACTORS FOR ACTIVE POWER

Mathematically, GSF for active power at line k can be stated as (13) [28], [30]:

$$\mathrm{GSF}_{\mathrm{Pgn}}^{\mathrm{k}} = \frac{(\Delta P_{\mathrm{ij}})}{(\Delta \mathrm{PG}_{\mathrm{gn}})} \quad (13)$$

By disregarding the P-V coupling, (13) can be further uttered as (14):

$$\mathrm{GSF}_{\mathrm{Pg}}^{\mathrm{k}} = \frac{\partial \mathrm{P}_{\mathrm{ij}}}{\partial \theta_{\mathrm{i}}} \cdot \frac{\partial \theta_{\mathrm{i}}}{\partial \mathrm{PG}_{\mathrm{gn}}} + \frac{\partial \mathrm{P}_{\mathrm{ij}}}{\partial \theta_{\mathrm{j}}} \cdot \frac{\partial \theta_{\mathrm{j}}}{\partial \mathrm{PG}_{\mathrm{gn}}} \quad (14)$$

The congested line power flow equation can be stated as (15):

$$\mathrm{P}_{\mathrm{ij}} = -\mathrm{V}_{\mathrm{i}}^2 \mathrm{B}_{\mathrm{ij}} + \mathrm{V}_{\mathrm{i}} \mathrm{V}_{\mathrm{j}} \mathrm{G}_{\mathrm{ij}} \cos(\theta_{\mathrm{i}} - \theta_{\mathrm{j}}) + \ldots \mathrm{V}_{\mathrm{i}} \mathrm{V}_{\mathrm{j}} \mathrm{B}_{\mathrm{ij}} \sin(\theta_{\mathrm{i}} - \theta_{\mathrm{j}}) \quad (15)$$

Differentiating (15) gives the first and the third term of (14) and can be written as (16) and (17).

$$\frac{\partial P_{ij}}{\partial \theta_i} = -V_i V_j G_{ij} sin(\theta_i - \theta_j) + V_i V_j B_{ij} cos(\theta_i - \theta_j) \quad (16)$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = +V_i V_j G_{ij} sin(\theta_i - \theta_j) - V_i V_j B_{ij} cos(\theta_i - \theta_j) \quad (17)$$

The injected real power at bus i can be stated as (18):

$$P_i = P_{Gi} - P_{Di} \quad (18)$$

P_i can be conveyed as (19):

$$P_i = |V_i|^2 B_{ii} + |V_s| \sum_{\substack{j=1 \\ j \ne i}}^{n} \left\{ \left(G_{ij} cos(\theta_i - \theta_j) + B_{ij} sin(\theta_i - \theta_j) \right) |V_j| \right\} \quad (19)$$

Differentiating equation (19) w.r.t θ_i *and* θ_j gives (20) and (21), and disregarding the P-V coupling, the expression that governs the dependency of the incremental variation in active power at the system buses on the phase angles of voltages is given in matrix form as (22) to (24):

$$\frac{\partial P_i}{\partial \theta_j} = |V_s| |V_j| \left\{ \left(G_{ij} sin(\theta_i - \theta_j) - B_{ij} cos(\theta_i - \theta_j) \right) \right\} \quad (20)$$

$$\frac{\partial P_i}{\partial \theta_i} = |V_s| \sum_{\substack{j=1 \\ j \ne i}}^{n} \left\{ \left(-G_{ij} sin(\theta_i - \theta_j) + B_{ij} cos(\theta_i - \theta_j) \right) |V_j| \right\} \quad (21)$$

$$[\Delta P] = [H][\Delta \theta] \quad (22)$$

$$[\Delta \theta] = [H]^{-1}[\Delta P] \quad (23)$$

$$[M] = [H]^{-1} \quad (24)$$

2) REACTIVE POWER GENERATOR SENSITIVITY FACTORS

Mathematically, GSF for reactive power at line k can be conveyed as (25) [22]:

$$\mathrm{GSF}_{\mathrm{Qgn}}^{\mathrm{k}} = \frac{(\Delta Q_{\mathrm{ij}})}{(\Delta \mathrm{QG}_{\mathrm{gn}})} \quad (25)$$

By neglecting the $Q - \delta$ coupling, (25) can be further expressed as (26):

$$\mathrm{GSF}_{\mathrm{Qg}}^{\mathrm{k}} = \frac{\partial \mathrm{Q}_{\mathrm{ij}}}{\partial V_{\mathrm{i}}} \cdot \frac{\partial \theta_{\mathrm{i}}}{\partial \mathrm{QG}_{\mathrm{gn}}} + \frac{\partial \mathrm{Q}_{\mathrm{ij}}}{\partial V_{\mathrm{j}}} \cdot \frac{\partial V_{\mathrm{j}}}{\partial \mathrm{QG}_{\mathrm{gn}}} \quad (26)$$

The congested line reactive power flow equation can be penned as (27):

$$\mathrm{Q}_{\mathrm{ij}} = -\mathrm{V}_{\mathrm{i}}^2 \mathrm{B}_{\mathrm{ij}} + \mathrm{V}_{\mathrm{i}} \mathrm{V}_{\mathrm{j}} \mathrm{G}_{\mathrm{ij}} \sin(\theta_{\mathrm{i}} - \theta_{\mathrm{j}}) + \ldots \mathrm{V}_{\mathrm{i}} \mathrm{V}_{\mathrm{j}} \mathrm{B}_{\mathrm{ij}} \cos(\theta_{\mathrm{i}} - \theta_{\mathrm{j}}) \quad (27)$$

By differentiating (27), gives first and the third term of (26) and can be given as (28) and (29).

$$\frac{\partial Q_{ij}}{\partial V_i} = -2V_i B_{ij} + V_j G_{ij} sin(\theta_i - \theta_j) - V_j B_{ij} cos(\theta_i - \theta_j) \quad (28)$$

$$\frac{\partial Q_{ij}}{\partial V_j} = V_i G_{ij} sin(\theta_i - \theta_j) - V_i B_{ij} cos(\theta_i - \theta_j) \quad (29)$$

Therefore, injected reactive power at bus i can be written as (30):

$$Q_i = Q_{Gi} - Q_{Di} \quad (30)$$

Q_i can be expressed as (31):

$$Q_i = -|V_i|^2 B_{ii} + |V_i| \sum_{\substack{j=1 \\ j \ne i}}^{n} \left\{ \left(G_{ij} sin(\theta_i - \theta_j) + B_{ij} cos(\theta_i - \theta_j) \right) |V_j| \right\} \quad (31)$$

Differentiating equation (31) w.r.t θ_i *and* θ_j gives (32) and (33). The matrices of the partial derivatives for (32) and (33) w.r.t magnitude voltages at buses i and j can be stated as (34) and (35), respectively.

$$\frac{\partial Q_i}{\partial V_i} = -2B_{ii} V_i + \sum_{\substack{j=1 \\ j \ne i}}^{n} \left\{ \left(G_{ij} sin(\theta_i - \theta_j) + B_{ij} cos(\theta_i - \theta_j) \right) |V_j| \right\} \quad (32)$$

$$\frac{\partial Q_i}{\partial V_j} = |V_i| \sum_{\substack{j=1 \\ j \ne i}}^{n} \left\{ \left(G_{ij} sin(\theta_i - \theta_j) - B_{ij} cos(\theta_i - \theta_j) \right) \right\} \quad (33)$$

$$\frac{\delta V_{\mathrm{i}}}{\delta \mathrm{QG}_{\mathrm{g}}} = \left[\frac{\delta \mathrm{Q}_{\mathrm{i}}}{\delta V_{\mathrm{i}}} \right]^{-1} \quad (34)$$

$$\frac{\delta V_{\mathrm{j}}}{\delta \mathrm{QG}_{\mathrm{g}}} = \left[\frac{\delta \mathrm{Q}_{\mathrm{i}}}{\delta V_{\mathrm{j}}} \right]^{-1} \quad (35)$$

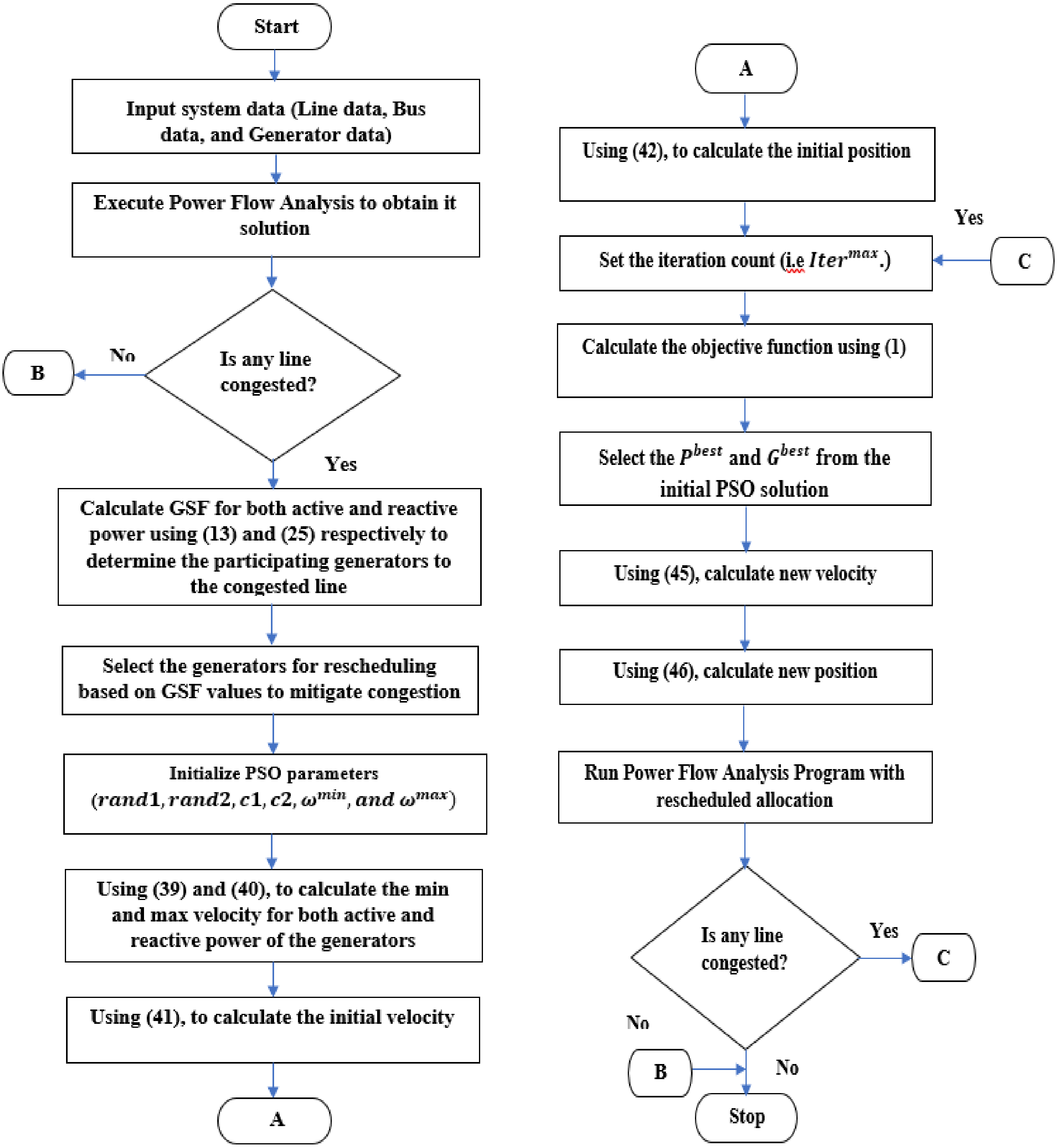


FIGURE 2. The proposed flowchart for the congestion management-based PSO.

III. OVERVIEW OF PSO AND ITS CONGESTION MANAGEMENT SOLUTION

Eberhart and Kennedy proposed PSO as a high-speed, uncomplicated, and effective population-based optimization technique [31], [32]. It was stirred by organism actions such as fish schooling. A 'SWARM' in PSO is a collection of particles representing various solutions. Each particle's coordinates are linked to two vectors: position and velocity vectors. Each position and velocity possess equal capacity with the capacity of the problem space. Swarm particles all

TABLE 2. IEEE 14-bus congested line details.

	Congested line	Power Flow (MW)	Line Limit (MW)
Pre-CM	6 (2-5)	55.618	50
Post-CM	6 (2-5)	48.3635	50

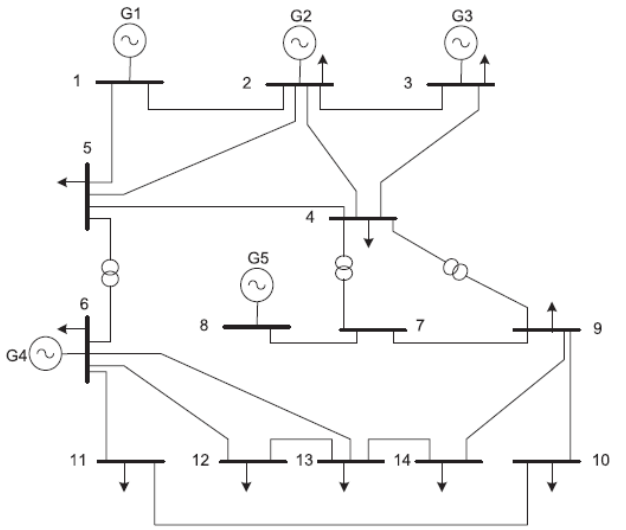
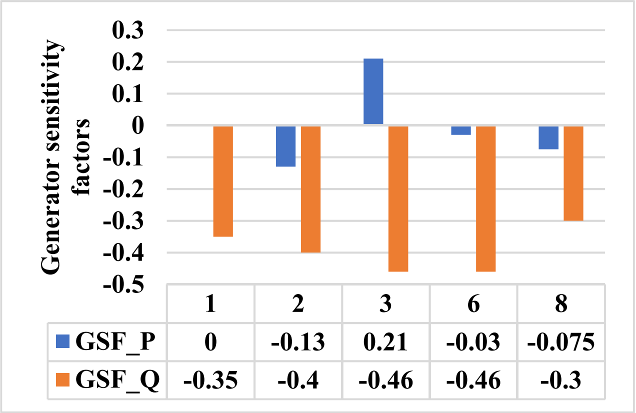


FIGURE 3. IEEE 14-bus one-line diagram.

fly through the search space in search of optimal solutions by updating the generation. The two best values update each particle in every iteration. The first value is called the personal best P^{best} solution of the particle at each iteration, and the second value is called the global best G^{best} solution of all the best particle solutions. For each particle, the velocity and positions are updated using (36) and (37), respectively [33]:

$$V[] = \omega V[] + c1rand1() * (P^{best}[] - P_{present}[]) + c2rand2() * (G^{best}[] - P_{present}[]) \quad (36)$$

$$P_{present}[] = P_{present}[] + V[] \quad (37)$$



	1	2	3	6	8
■ GSF_P	0	-0.13	0.21	-0.03	-0.075
■ GSF_Q	-0.35	-0.4	-0.46	-0.46	-0.3

FIGURE 4. IEEE 14-bus system generator's sensitivity factors of the congested lines.

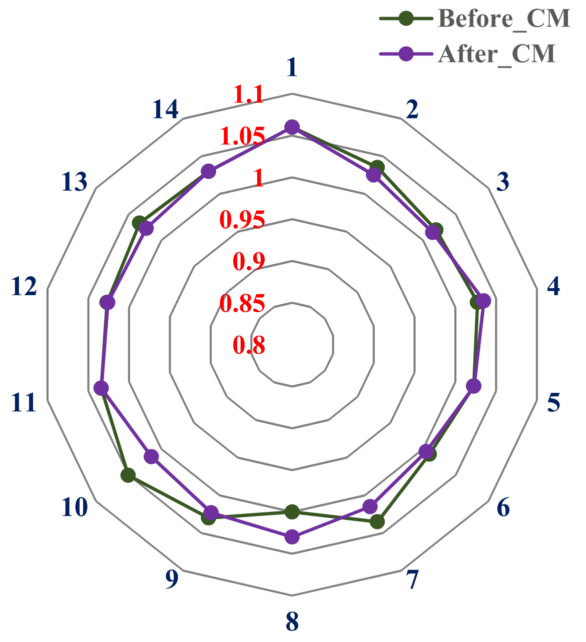


FIGURE 5. IEEE 14-bus voltage profile improvement before and after CM.

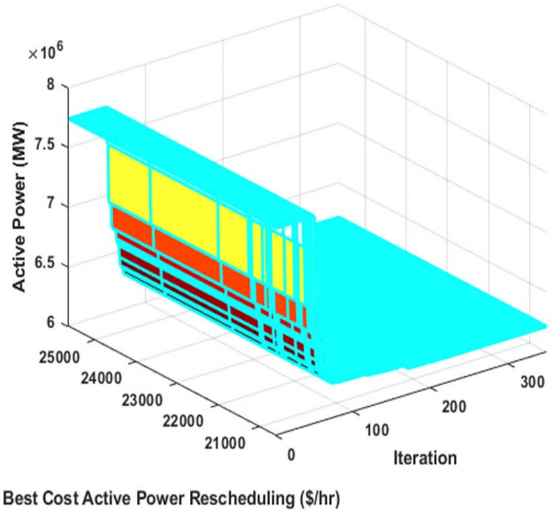


FIGURE 6. PSO-based active power convergence characteristic for IEEE 14-bus system.

The inertia weight can be expressed as (38):

$$\omega = \omega^{max} - \left(\frac{\omega^{max} - \omega^{min}}{Iter^{max}}\right) Iter \quad (38)$$

Without a limit enacted on the particles' maximum velocity (V_{max}), the particles may break away from the search space. Therefore, each particle velocity is coordinated between ($-V_{max}$) to (V_{max}). Also, a correct range of inertia weight in (38) gives good stability between global and local explorations.

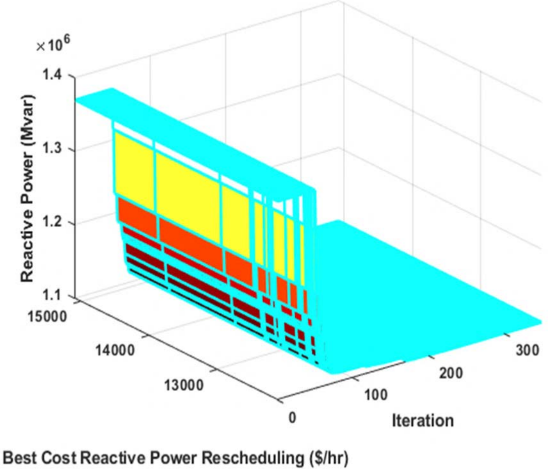


FIGURE 7. PSO-based reactive power convergence characteristic for IEEE 14-bus system.

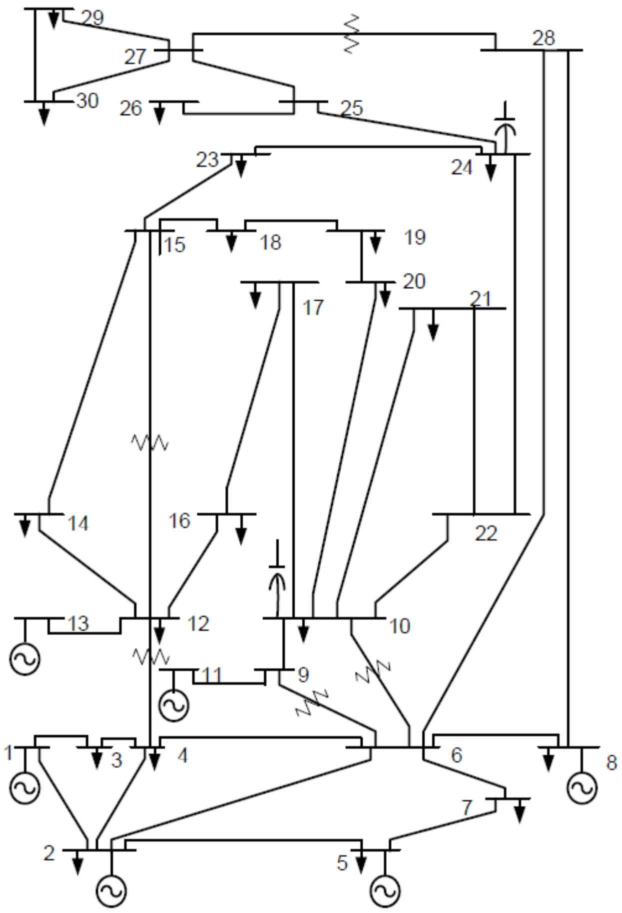
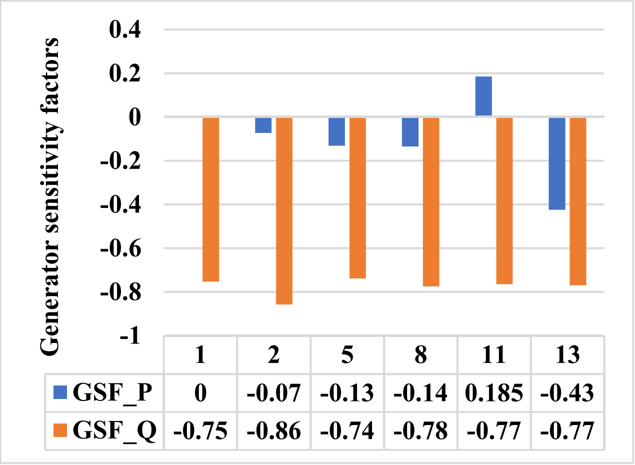


FIGURE 8. IEEE 30-bus single line diagram.

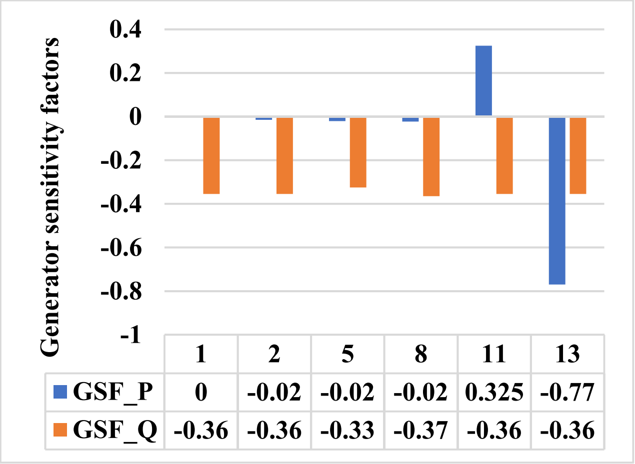
A. PSO ALGORITHM IMPLEMENTATION FOR CONGESTION MANAGEMENT

CM problem in the electric power transmission network is formulated mathematically in section II of this work.



	1	2	5	8	11	13
■ GSF_P	0	-0.07	-0.13	-0.14	0.185	-0.43
■ GSF_Q	-0.75	-0.86	-0.74	-0.78	-0.77	-0.77

FIGURE 9. IEEE 30-bus system generator's sensitivity factors of the congested lines 1.



	1	2	5	8	11	13
■ GSF_P	0	-0.02	-0.02	-0.02	0.325	-0.77
■ GSF_Q	-0.36	-0.36	-0.33	-0.37	-0.36	-0.36

FIGURE 10. IEEE 30-bus system generator's sensitivity factors of the congested lines 5.

The GSF for active and reactive power rescheduling is stated in (13) and (25), respectively. Inequality and equality constraints are given in sub-sections 1 and 2 of section II(A), and the penalty function (11) and (12) are utilized to formulate the objective function (1) for the congestion management problem. By incorporating the specific CM problem, the problem mentioned above is mitigated using the PSO algorithm. To map the CM problem to suit the PSO formation of velocity and position in (36) and (37). The following assumption was made:

1. Member's numbers in different particles in the swarm were assumed to equal the number of the generators.
2. The active and reactive power was made to represent the velocities variables utilized to explore the constraint's domain.
3. Finally, the particle number in the swarm was denoted by N_p.

Step 1: Input systems data for all the three IEEE networks (14, 30, and 118) considered.

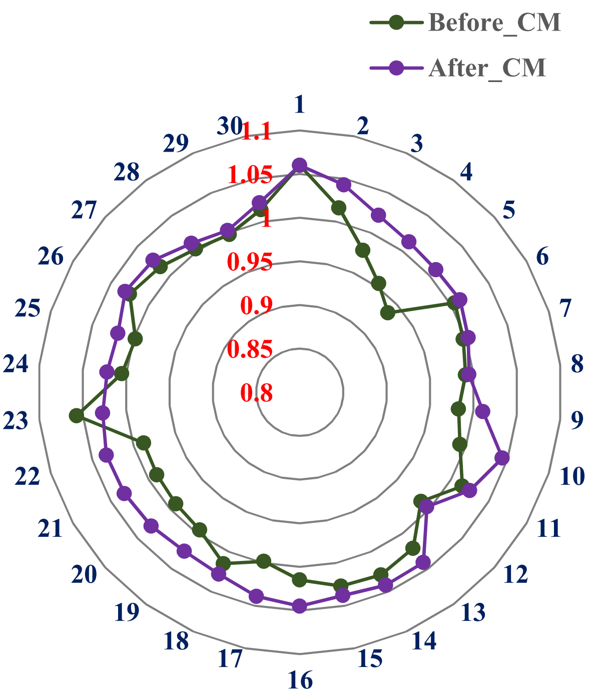


FIGURE 11. IEEE 30-bus voltage profile improvement before and after CM.

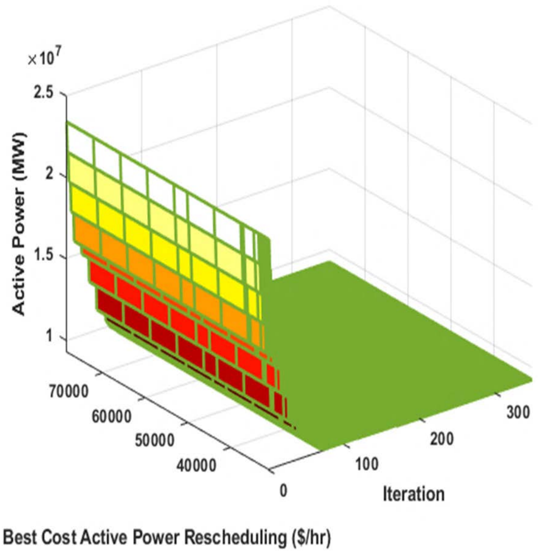


FIGURE 12. PSO-based active power convergence characteristic for IEEE 30-bus system.

Step 2: Run the Power Flow Analysis method by Newton-Raphson to determine the congested lines.

Step 3: Calculate Generator Sensitivities Factors (GSF) for all generators to the overloaded line using (13) and (25), respectively. This is done by checking out for both active and reactive power GSF of all generators matching the overloaded lines.

Step 4: Initialize PSO parameters; acceleration coefficients c1 and c2, inertia weight ω^{min} and ω^{max}, random values $rand1$ and $rand2$, and iterations limit $Iter^{max}$.

Step 5: Based on active and reactive power limits constraints, minimum and maximum initial velocities values were computed using (6) and (7) and are further expressed as follows:

$$-0.45P_{g,i}^{min} \leq V_g \leq +0.45P_{g,i}^{max}, \quad g = \overline{1, N_p}, \quad i = \overline{1, n-1} \tag{39}$$

$$-0.45Q_{g,i}^{min} \leq V_g \leq +0.45Q_{g,i}^{max}, \quad g = \overline{1, N_p}, \quad i = \overline{1, n-1} \tag{40}$$

The particle's velocity and position are calculated using (n-1) generators because one of the generators is selected as the slack generator.

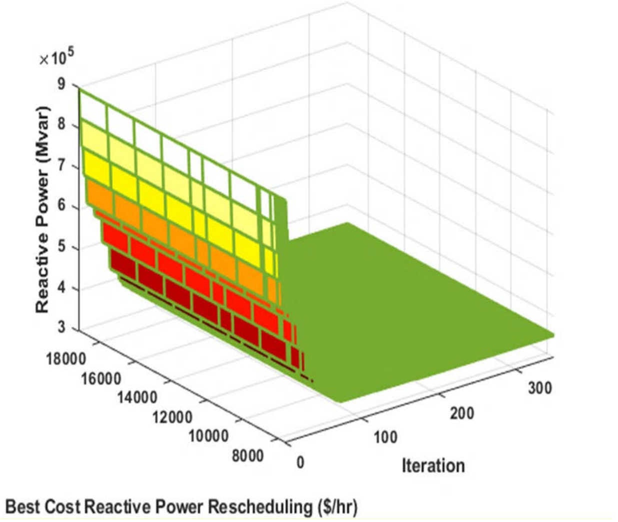


FIGURE 13. PSO-based reactive power convergence characteristic for IEEE 30-bus system.

Step 6: Except slack bus generator, the initial particle velocity is calculated using (41).

$$V_{g,i} = V_{g,i}^{min} + rand()\left(V_{g,i}^{max} - V_{g,i}^{min}\right), \quad g = \overline{1, N_p}, \quad i = \overline{1, n-1} \tag{41}$$

Step 7: Compute particle member's initial position using (42).

$$P_{g,i} = P_{g,i}^{min} + rand()\left(P_{g,i}^{max} - P_{g,i}^{min}\right), \quad g = \overline{1, N_p}, \quad i = \overline{1, n-1} \tag{42}$$

Traditionally, the electric power system buses are categorized into three, which are slack bus, voltage control (PV) bus, and load (PQ) bus. In addition, the nearer bus to the generator with higher generating capacity is called the slack bus. The function of a slack bus in implementing the Particle Swarm

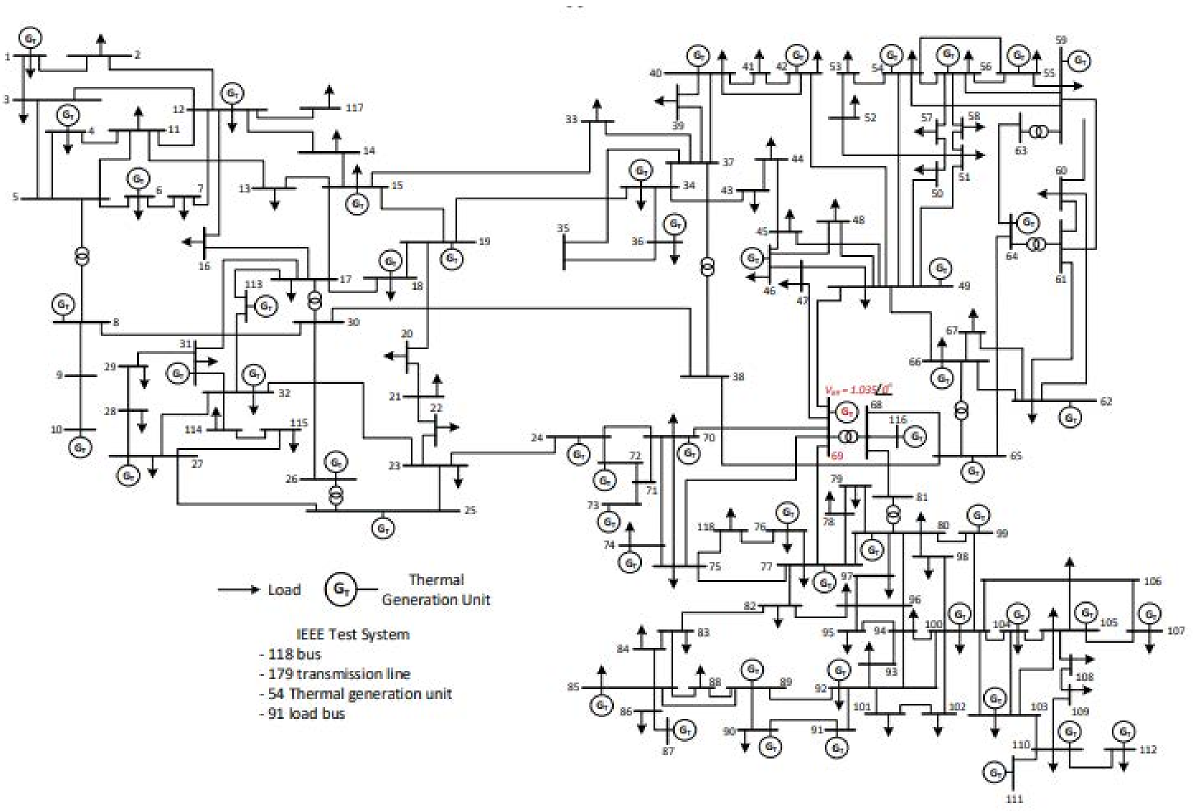


FIGURE 14. IEEE 118-bus system one-line diagram.

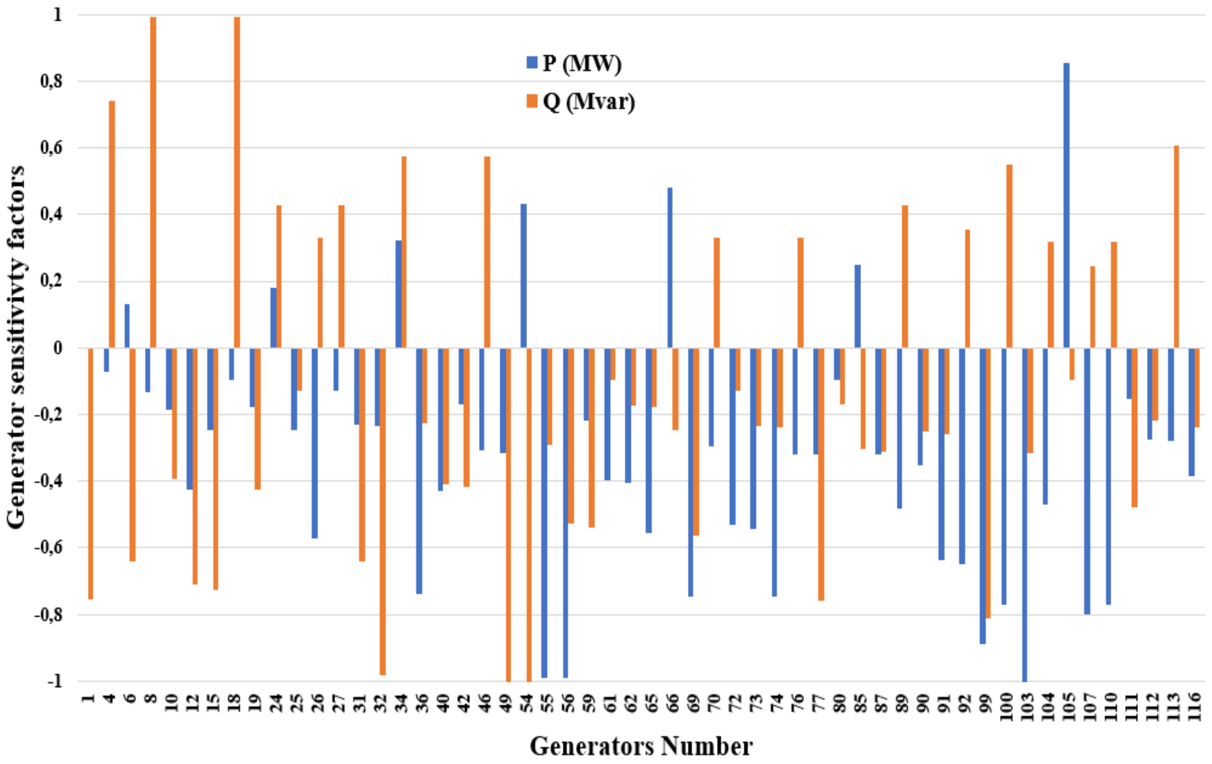


FIGURE 15. IEEE 118-bus generator's sensitivity factors for the congested line 9.

Optimization algorithm is to comply with the power balance constraint stated in (4) and (5).

Step 8: Compute the objective function for the initial positions using (1).

TABLE 3. Detail of optimally obtained PSO results of the ieee 14-bus system.

		Developed Method	Method Reported in [35]
Active power rescheduling cost ($/day)		2.06E+04	Not reported
Reactive power rescheduling cost ($/day)		1.21E+04	Not reported
Active power rescheduling (MW)	ΔP_1	140	157.7
	ΔP_2	50	77.8
	ΔP_3	0	49.274
	ΔP_6	20	14.274
	ΔP_8	60	23.394
Amount of active power rescheduling (MW)		270	322.442
Amount of active power demand (MW)		259	Not reported
Reactive power rescheduling (MVar)	ΔQ_1	24.928	Not reported
	ΔQ_2	24.5344	
	ΔQ_3	0	
	ΔQ_6	15.5268	
	ΔQ_8	1.1483	
Amount of reactive power rescheduling (MVar)		78.3475	
Amount of reactive power demand (MVar)		77.4	Not reported

TABLE 4. IEEE 30-bus congested line details.

Congested line	Power Flow (MW)		Line Limit (MW)
	Pre-CM	Post-CM	
1 (1 – 2)	179.152	125.293	130
5 (2 – 5)	83..008	59.173	65

Step 9: Compute the personal best and the global best as follows:

i) The personal best of the particles is computed using (43)

$$P_g^{best} = minP_{g,i}^{best}, \quad i = \overline{1, n}; \; g = \overline{1, N_g} \tag{43}$$

ii) The global best is calculated using (44)

$$G^{best} = minP_g^{best}, \quad g = \overline{1, N_g} \tag{44}$$

Step 10: New velocity is computed using (45):

$$V_{g,i}^{new^l} = \omega.V_{g,i}^{l-1} + c1.rand1\left(P_g^{best^{l-1}} - P_{g,i}^{l-1}\right) + c2.rand2\left(G^{best^{l-1}} - P_{g,i}^{l-1}\right), \quad g = \overline{1, N_p}, \quad i = \overline{1, n-1} \tag{45}$$

Step 11: New position in the particles is computed using (46):

$$P_{g,i}^{new^l} = P_{g,i}^{l-1} + P_{g,i}^{new^l}, \quad g = \overline{1, N_p}, \; i = \overline{1, n} \tag{46}$$

TABLE 5. Detail of optimally obtained PSO results of the ieee 30-bus system.

		Proposed method	Method reported in [37]	Method reported in [38]
Active power rescheduling cost ($/day)		3.10E+04	799.56	1196.35
Reactive power rescheduling cost ($/day)		7.58E+03	Not reported	Not reported
Active power rescheduling (MW)	ΔP_1	157.772	177.285	174.46
	ΔP_2	55.58	48.93	76.37
	ΔP_5	18.563	21.29	42.08
	ΔP_8	17.744	20.49	32.72
	ΔP_{11}	0	11.93	28.79
	ΔP_{13}	41.219	12.23	31.77
Total active power rescheduling (MW)		290.878	292.155	386.19
Total active power demand (MW)		283.4	Not reported	Not reported
Reactive power rescheduling (MVar)	ΔQ_1	28.498	Not reported	Not reported
	ΔQ_2	76.275		
	ΔQ_5	24.692		
	ΔQ_8	0.965		
	ΔQ_{11}	0		
	ΔQ_{13}	9.879		
Total reactive power rescheduling (MVar)		139.344		
Total reactive power demand (MVar)		126.2	Not reported	Not reported

TABLE 6. Ieee 118-bus congested line details.

Congested line	Power Flow (MW)		Line Limit (MW)
	Pre-CM	Post-CM	
9 (4 – 11)	86.543	73.935	80
112 (37 – 40)	73.41	42.183	55
148 (49 -50)	84.65	35.557	67
205 (64 – 65)	250.466	197.583	228
264 (80 – 98)	54.094	24.487	36
331 (100 – 106)	97.245	73.245	75

Step 12: Repeat step 2 to compute new line flows, new rescheduling active and reactive power, line losses, and new voltage magnitude in all buses.

Step 13: Compute penalty function for each particle using (11). This is done by finding constraint violations.

Step 14: Compute fitness function for each particle using (1)

Step 15: Find out the "global best" (G^{best}) particle and "personal best" (P^{best}) of all particles.

Step 16: Engender new population using (36) and (37).

Step 17: Repeat steps 3, 10 to 18 until the convergence criterion is met.

Step 18: Stop simulation.

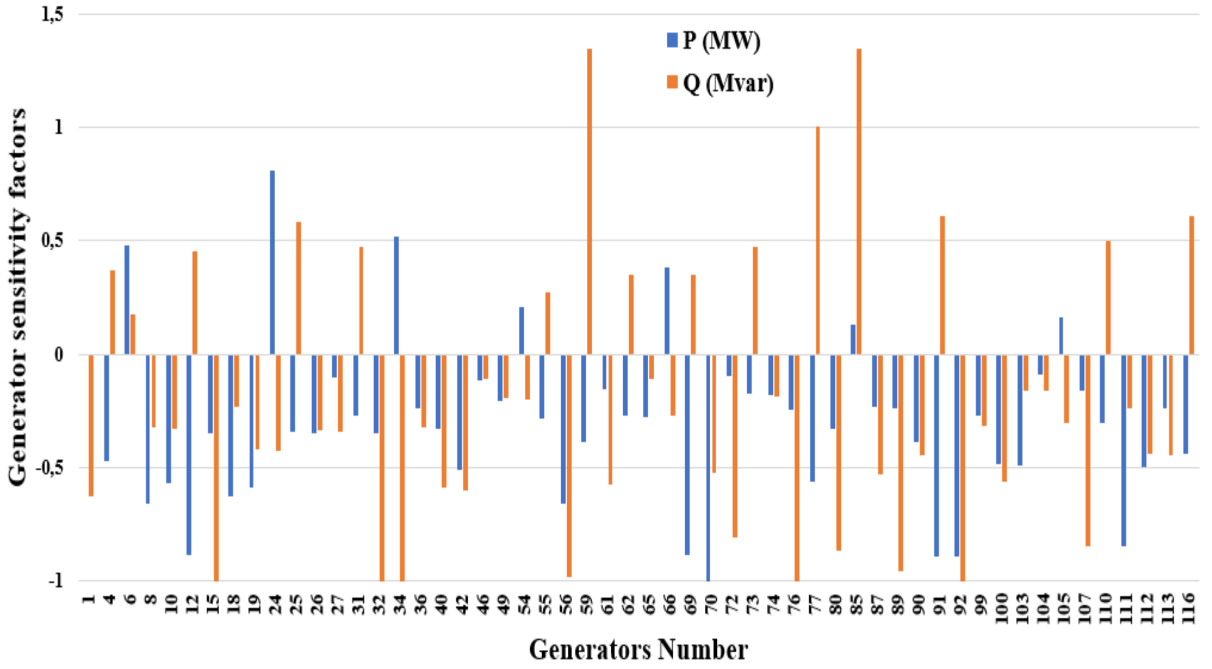


FIGURE 16. IEEE 118-bus generator's sensitivity factors for the congested line 112.

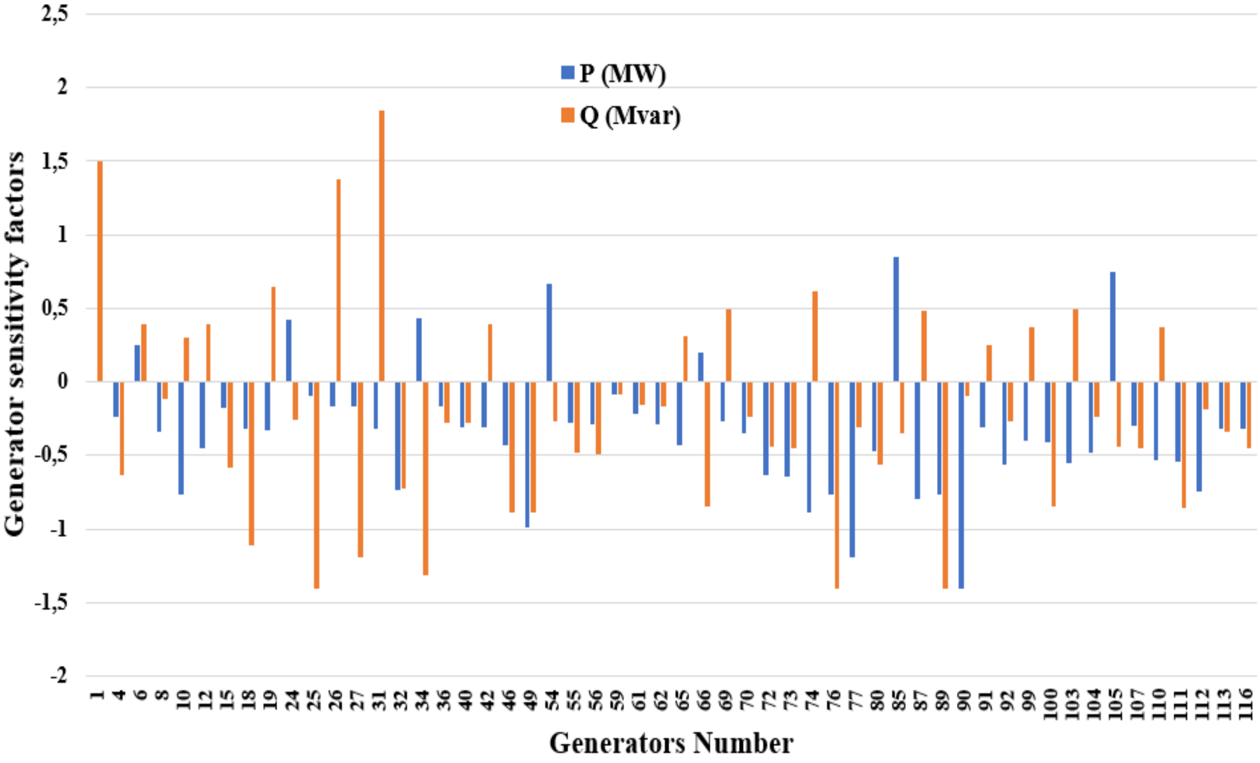


FIGURE 17. IEEE 118-bus generator's sensitivity factors for the congested line 148.

IV. SIMULATION RESULTS AND DISCUSSION

This section gives detailed, comprehensive findings based on the effectiveness of the proposed technique for managing transmission congestion. Three case studies of IEEE 14, 30, and 118 bus transmission networks, were considered in this work. Voltage profile improvement, optimal

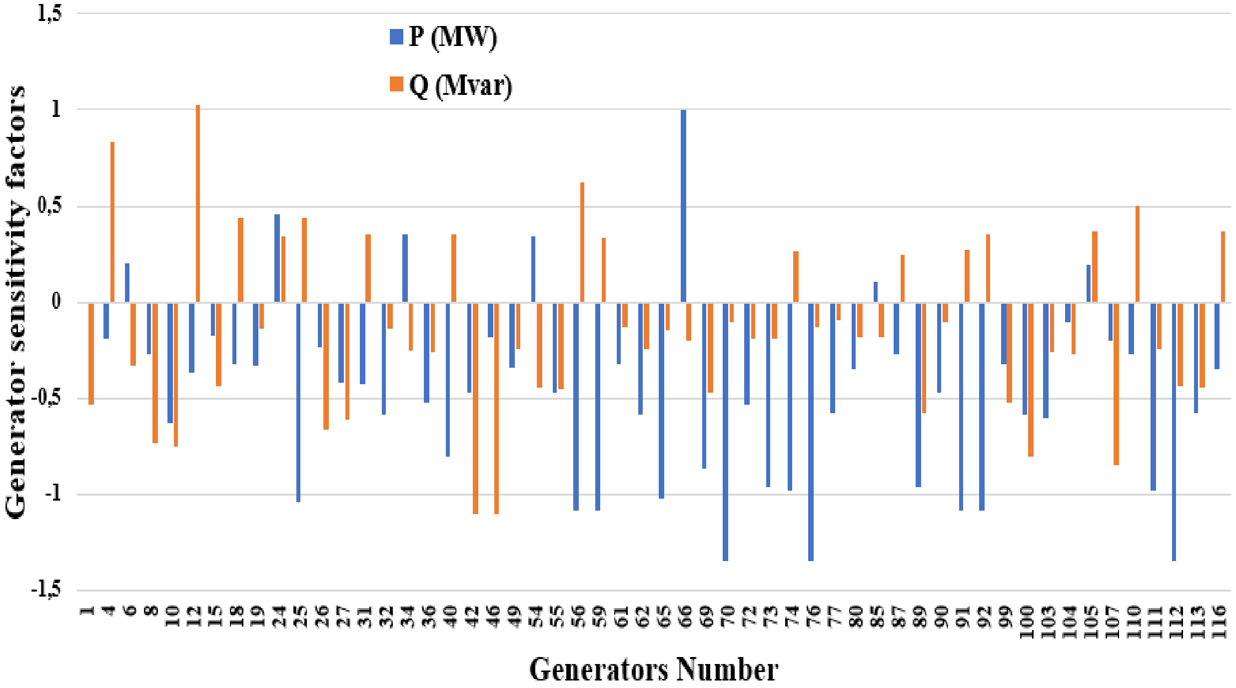


FIGURE 18. IEEE 118-bus generator's sensitivity factors for the congested line 205.

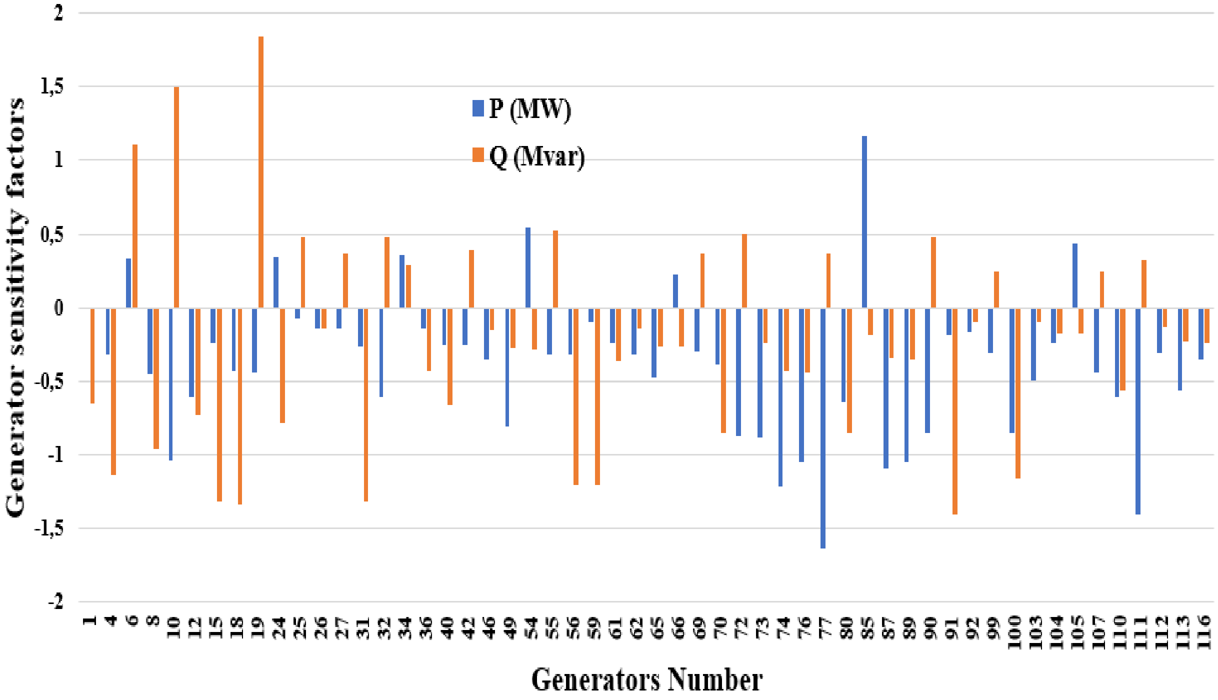


FIGURE 19. IEEE 118-bus generator's sensitivity factors for the congested line 264.

rescheduling of active and reactive power of the generators, and cost of rescheduling were the performance metrics considered. The simulation was carried out using MATLAB 2022a.

A. CASE 1: IEEE 14-BUS SYSTEM NETWORK

The network data were acquired from [34]. The network comprises 14 buses, 20 interconnected lines, and 5 generators. Fig. 3 depicts its single-line diagram.

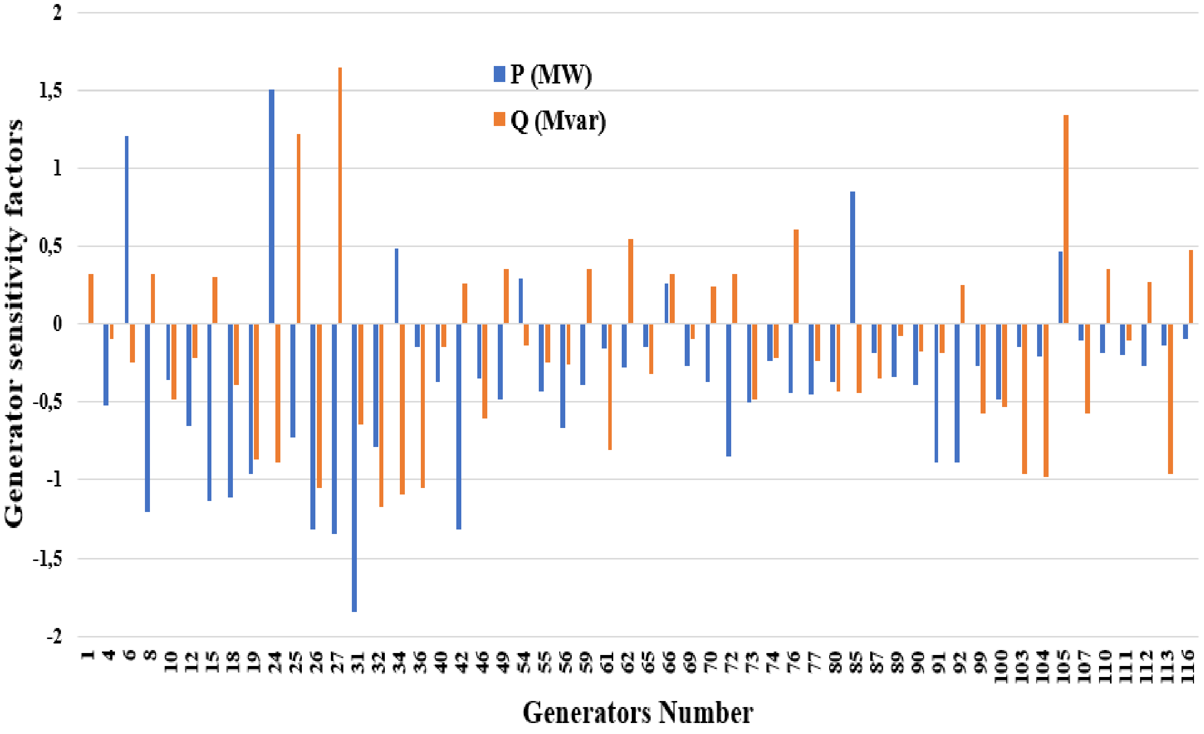


FIGURE 20. IEEE 118-bus generator's sensitivity factors for the congested line 331.

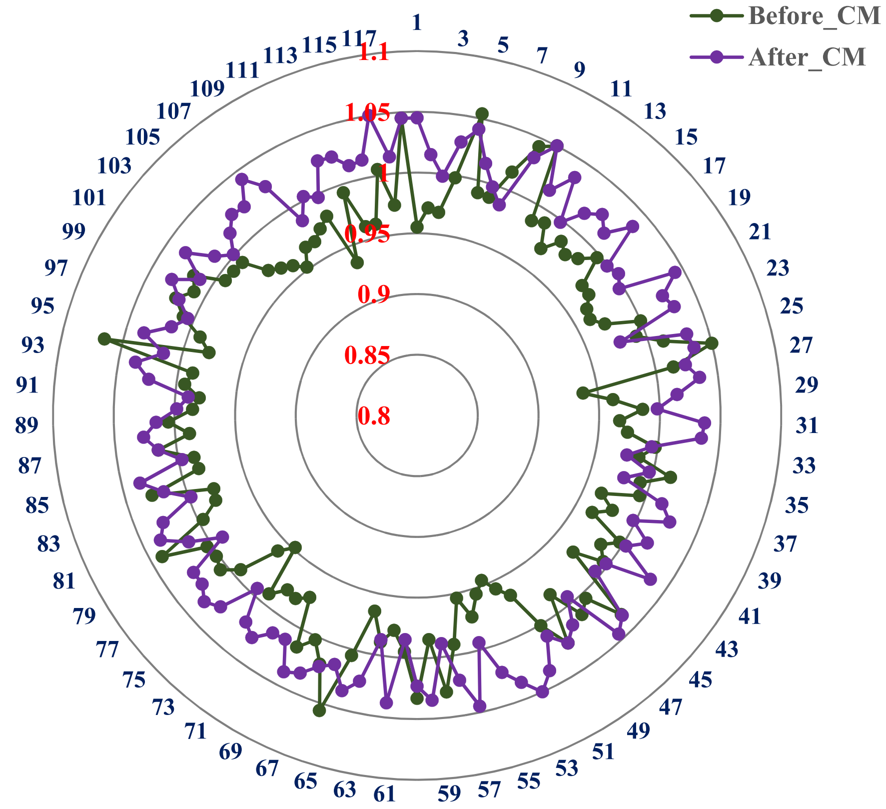


FIGURE 21. IEEE 118-bus voltage profile improvement before and after CM.

According to the power flow results, line number 6 (between buses 2 and 5) was identified as the congested line. Table 2 shows the detailed result for the power flow of the congested line. Fig. 4 also shows the detailed results of

TABLE 7. Active power rescheduling for ieee 118-bus system.

Active power rescheduling (MW)					
Active power rescheduling cost ($/day)				7.88E+04	
Total active power rescheduling (MW)				3711	
Total active power demand (MW)				3668	
ΔP_1	68.716	ΔP_{42}	63.314	ΔP_{80}	50.409
ΔP_4	12.427	ΔP_{46}	34.16	ΔP_{85}	0
ΔP_6	0	ΔP_{49}	38.25	ΔP_{87}	64.685
ΔP_8	30.337	ΔP_{54}	0	ΔP_{89}	59.5
ΔP_{10}	44.097	ΔP_{55}	60.361	ΔP_{90}	104.107
ΔP_{12}	72.413	ΔP_{56}	52.387	ΔP_{91}	19.75
ΔP_{15}	8.875	ΔP_{59}	58.128	ΔP_{92}	58.99
ΔP_{18}	8.839	ΔP_{61}	39.904	ΔP_{99}	92.19
ΔP_{19}	47.403	ΔP_{62}	39.432	ΔP_{100}	48.125
ΔP_{24}	0	ΔP_{65}	38.451	ΔP_{103}	13.284
ΔP_{25}	26.076	ΔP_{66}	0	ΔP_{104}	92.342
ΔP_{26}	14.776	ΔP_{69}	42.88	ΔP_{105}	0
ΔP_{27}	37.079	ΔP_{70}	36.209	ΔP_{107}	73.464
ΔP_{31}	84.863	ΔP_{72}	251.353	ΔP_{110}	43.526
ΔP_{32}	27.541	ΔP_{73}	41.127	ΔP_{111}	43.981
ΔP_{34}	0	ΔP_{74}	9.636	ΔP_{112}	15.409
ΔP_{36}	113.461	ΔP_{76}	12.27	ΔP_{113}	12.132
ΔP_{40}	75.897	ΔP_{77}	27.902	ΔP_{116}	145.859

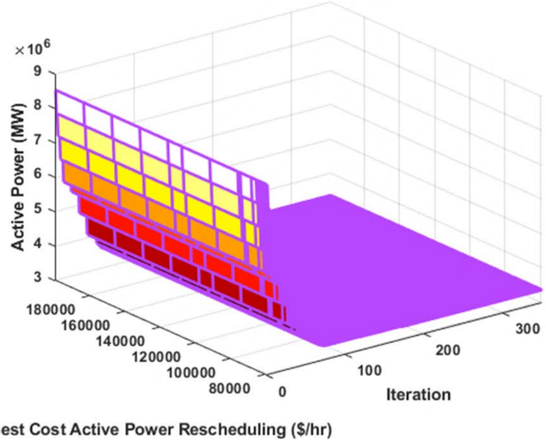


FIGURE 22. PSO-based active power convergence characteristic for IEEE 118-bus system.

generator sensitivity factors, which were utilized to identify any generators that are or are not participating in congestion. Any generator with a negative sensitivity factor for both active and reactive power indicates that increasing the generation of such a generator reduces the power flow in congested lines. Also, positive values of sensitivity factor for both active and reactive power of the generator indicate an increase in the power flow in a such generator.

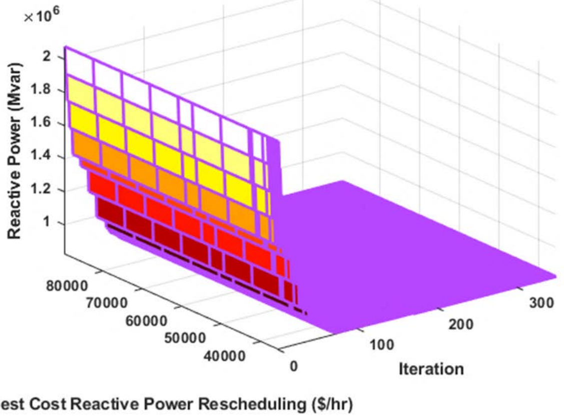


FIGURE 23. PSO-based reactive power convergence characteristic for IEEE 118-bus system.

As can be seen in Fig. 4, generators 1, 2, 6, and 8 are the generators that would help to alleviate congestion on the congested line. Therefore, to alleviate congestion, the output power of the generators was optimally rescheduled using the PSO Algorithm. The detailed results of PSO optimally rescheduling the output power of the partaking generators to alleviate congestion are shown in Table 3.

Generator rescheduling for congestion mitigation can sometimes result in significant or low load bus voltage deviation. To address the issue of voltage deviation on the load buses, generator voltages were rescheduled to maintain voltages at all load bus within allowable boundaries. In addition, reactive power rescheduling significantly improves the voltage profile of all load buses and protects the system from voltage collapse. The Pre-CM and Post-CM voltage profile improvement is shown in Fig. 5. Fig. 6 and 7 also depict the convergence characteristics of the PSO-based active and reactive power rescheduling cost for the test system network. As shown in Figures 6 and 7, the cost of rescheduling both active and reactive powers for IEEE 14 bus system decreases as the converge characteristics (iteration number) increases.

B. CASE 2: IEEE 30 BUS SYSTEM NETWORK

The network data were obtained from [36]. The network comprises 30 buses, 41 interconnected lines, and 6 generators. Fig. 8 depicts its single-line diagram.

According to the power flow results, lines 1 and 5 are the most congested. The detailed result for the power flow of the congested line is shown in Table 4 below. In addition, Fig. 9 and 10 show the detailed results of generator sensitivity factors (GSF), which were used to identify any generators contributing to congestion on lines 1 and 5.

Based on the GSF principle explained in sub-section IV (A) of case 1 above, generators 1, 2, 5, 8, and 13 are the generators that would participate in alleviating congestion from the congested line. In addition, the generator output powers have

TABLE 8. Reactive power rescheduling for ieee 118-bus system.

Reactive power rescheduling (MVar)					
Cost of reactive power rescheduling ($/day)				3.54E+04	
Total reactive power rescheduling (MW)				1477	
Total reactive power demand (MVar)				1438	
ΔQ_{1}	20.569	ΔQ_{42}	50.798	ΔQ_{80}	148.507
ΔQ_{4}	37.658	ΔQ_{46}	53.667	ΔQ_{85}	0
ΔQ_{6}	0	ΔQ_{49}	59.363	ΔQ_{87}	39.66
ΔQ_{8}	114.135	ΔQ_{54}	0	ΔQ_{89}	81.288
ΔQ_{10}	49.625	ΔQ_{55}	10.049	ΔQ_{90}	32.464
ΔQ_{12}	20.1	ΔQ_{56}	15.69	ΔQ_{91}	136.635
ΔQ_{15}	75.848	ΔQ_{59}	46.818	ΔQ_{92}	49.938
ΔQ_{18}	69.789	ΔQ_{61}	78.305	ΔQ_{99}	20.964
ΔQ_{19}	16.328	ΔQ_{62}	35.134	ΔQ_{100}	4.912
ΔQ_{24}	0	ΔQ_{65}	26.333	ΔQ_{103}	58.679
ΔQ_{25}	159.157	ΔQ_{66}	0	ΔQ_{104}	14.672
ΔQ_{26}	85.224	ΔQ_{69}	21.847	ΔQ_{105}	0
ΔQ_{27}	44.038	ΔQ_{70}	65.115	ΔQ_{107}	135.659
ΔQ_{31}	17.373	ΔQ_{72}	67.407	ΔQ_{110}	41.318
ΔQ_{32}	12.527	ΔQ_{73}	20.133	ΔQ_{111}	17.624
ΔQ_{34}	0	ΔQ_{74}	20.087	ΔQ_{112}	21.743
ΔQ_{36}	49.319	ΔQ_{76}	43.094	ΔQ_{113}	34.265
ΔQ_{40}	23.678	ΔQ_{77}	44.05	ΔQ_{116}	14.59

been optimally rescheduled using the PSO Algorithm to reduce congestion. The detailed results of PSO optimally rescheduling the output power of the partaking generators to alleviate congestion are shown in Table 5.

Also, to conquer the hassle of voltage deviation at the load buses, generator voltages were rescheduled to hold load bus voltages within acceptable boundaries. Reactive power rescheduling helps enhance the voltage stability in all load buses and ensures the system out of voltage collapse point. Fig. 11 shows the before and after voltage profile improvement. Also, Fig. 12 and 13 describe the convergence characteristics of PSO-based active and reactive power rescheduling costs for the test network.

As shown in Figures 12 and 13, the cost of rescheduling both active and reactive powers of the IEEE 30 bus system decrease as the converge characteristics (iteration number) increases.

C. CASE 3: IEEE 118 BUS SYSTEM NETWORK

Ref [39] describes the system in detail. The system has 118 buses, 179 interconnected lines, and 54 generators. Its single-line diagram is shown in Fig. 14 below. The detailed power flow result of the congested lines is shown in Table 6 below. Fig. 15 to 20 show the details of the generator sensitivity factors (GSF) for each congested line. Table 7 and 8 show the details of PSO optimally rescheduling the output active and reactive power of the participating generators to reduce congestion. According to the tables, only generators 6, 24, 34, 54, 66, 85, and 105 are not involved in congestion. Table 9 also provides a detailed summary of both active and reactive power loss before and after congestion management. The diagrammatic representation of voltage profile improvement before (Pre) and after (Post) congestion management is shown in Fig. 21. Fig. 22 and 23 also depict the convergence characteristics of PSO-based active and reactive power rescheduling costs for the test network.

TABLE 9. Summary of power loss for all the cases considered.

		Proposed method		Reported in [30]		Reported in [38]	
		Before	After	Before	After	Before	After
Case 1 [IEEE 14]	P (MW)	13.55	12.91	×	×	×	×
	Q (MVar)	55.56	53.52	×	×	×	×
Case 2 [IEEE 30]	P (MW)	17.59	15.65	21	15	×	17.76
	Q (MVar)	17.87	15.12	×	×	×	20.93
Case 3 [IEEE 118]	P (MW)	91.39	81.46	140	137	×	×
	Q (MVar)	87.89	77.07	×	×	×	×

As shown in Figures 22 and 23, the cost of rescheduling both active and reactive powers of the IEEE 118 bus system decrease as the converge characteristics (iteration number) increases.

V. CONCLUSION

This research presented a novel generator rescheduling approach for transmission system network congestion control. The rescheduled generators were identified based on their sensitivity to the congested line, as shown by their active and reactive power characteristics. Then, to save money, a PSO-based algorithm was employed to restrict the divergence of the rescheduled generation's active and reactive power from the scheduled generator. This approach's applicability was examined utilizing IEEE 14, 30, and 118 standard network buses. The simulation results prove that after rescheduling the cost of both active and reactive powers is less expensive. The active power losses for each of the considered IEEE 14, 30, and 118 cases are 4.7%, 11.03%, and 10.87% respectively, while the reactive power losses are 3.67%, 15.39%, and 12.31% respectively. The results suggest that decreasing the divergence of active and reactive power of rescheduled generators from planned generators can minimize the total cost of congestion management. Furthermore, attaining enhanced voltage stability and voltage profile while reducing the transmission system operation cost. The future researchers work to develop a classical method and compare the exiting heuristics method TCM solutions, secondly apply parallel computing approaches for the solution of transmission congestion control as part of the future study.

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