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Optimal congestion management in an electricity market using particle swarm optimization with time-varying acceleration coefficients

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ABSTRACT

This paper proposes an optimal congestion management approach in a deregulated electricity market using particle swarm optimization with time-varying acceleration coefficients (PSO-TVAC). Initially, the values of generator sensitivity are used to select redispatched generators. PSO-TVAC is used to determine the minimum redispatch cost. Test results on IEEE 30-bus and 118-bus systems indicate that the PSO-TVAC approach could provide a lower rescheduling cost solution compared to classical particle swarm optimization and particle swarm optimization with time-varying inertia weight.

1. Introduction

In a deregulated electricity environment, transmission congestion management is a function and responsibility of independent system operators (ISOs). There are several system operating limits to be observed including thermal, voltage and stability limits.

A number of the congestion management approaches are presented in [1]. In [2–4], the technique called transmission congestion distribution factors (TCDFs) is discussed. The zones are divided by active and reactive power flow sensitivity indexes. Nevertheless, when all buses are considered, this technique requires a huge computational effort. In [5], an optimal power flow (OPF)-based approach for minimizing cost of congestion and service costs are expressed. In [6], OPF for coordination between generation companies and the ISOs using the Benders cuts is discussed. In [7], OPF is used to adjust the power injection in the least cost manner and optimal curtail transactions due to voltage instability and thermal overload. In [8], relative electrical distance (RED) concept is introduced to mitigate the transmission overload by real power generation rescheduling. The method minimizes the system losses and maintains the voltage profile. However, the rescheduling cost is not considered by this method. In [9], the optimal generation rescheduling approach considering the rescheduling cost minimization based on particle swarm optimization (PSO) is proposed. Although PSO is an efficient solution approach for non-convex optimization problems, the statistical results should be investigated to confirm searching performance of the optimizer.

In this paper, the congestion management approach based on particle swarm optimization with time-varying acceleration coefficients (PSO-TVAC) is proposed. The redispatch cost of participating generators is minimized satisfying power balance, generator operating limit and line flow limits constraints. PSO-TVAC is compared to classical particle swarm optimization (CPSO) and particle swarm optimization with time-varying inertia weight (PSO-TVIW) in searching for optimal congestion management solutions on the IEEE 30 and 118-bus systems.

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Nomenclature

The notations used in this paper are given below.

g	Participating generator.
N_g	Number of participating generators.
IC_g	Incremental and decremental cost of generator g.
ΔP_g	Active power adjustment at bus g.
$\Delta P_g^{\min}$	Minimum adjustment limit of generator g.
$\Delta P_g^{\max}$	Maximum adjustment limit of generator g.
P_g	Active power output.
$P_g^{\min}$	Minimum generation limit of generator g.
$P_g^{\max}$	Maximum generation limit of generator g.
F_l^0	Power flow caused by all contracts requesting the transmission service.
$F_l^{\max}$	Power flow limit of line l.
n_l	Number of transmission lines in the system.
ΔP_{ij}	Changed in active power flow on the line connected between buses i and j.
ΔP_{G_g}	Changed in active power of generator g.
n	Number of all the buses in the system.
V_i, V_j	Voltage magnitude at buses i and j.
θ_i, θ_j	Phase angle at buses i and j.
G_{ij}	Conductance of the line connected between buses i and j.
B_{ij}	Susceptance of the line connected between buses i and j.
k	Current iteration number.
C	Constriction factor.
w	Inertia weight.
c_1	Cognitive acceleration coefficient.
c_2	Social acceleration coefficient.
rand_i	Random numbers between 0 and 1, $i = 1, 2$.
$w_{\min}$	Minimum inertia weight.
$w_{\max}$	Maximum inertia weight.
$k_{\max}$	Maximum number of iterations.
c_{1i}, c_{1f}	Initial and final values of c_1.
c_{2i}, c_{2f}	Initial and final values of c_2.

2. Problem formulation

The optimal congestion management minimizing redispatch cost can be expressed as [9]

$$\text{Min} \sum_{g}^{Ng} IC_g\left(\Delta P_g\right) \cdot \Delta P_g \tag{1}$$

subject to:

power balance constraint

$$\sum_{g=1}^{Ng} \Delta P_g = 0 \tag{2}$$

operating limit constraints

$$\Delta P_g^{\min} \le \Delta P_g \le \Delta P_g^{\max}; \quad g = 1, 2, \ldots, N_g \tag{3}$$

where $\Delta P_g^{\min} = P_g - P_g^{\min}$ and $\Delta P_g^{\max} = P_g^{\max} - P_g$
line flow constraints

$$\sum_{g=1}^{Ng} \left(\mathrm{GS}_g^{ij} \cdot \Delta P_g\right) + F_l^0 \le F_l^{\max}; \quad l = 1, 2, \ldots, n_l. \tag{4}$$

3. Selecting redispatched generators

The generator sensitivity (GS) technique indicates the change of active power flow due to change in active power generation. The GS value of generator g on the line connected between buses i and j can be written as [9]

$$\mathrm{GS}_g^{ij} = \frac{\Delta P_{ij}}{\Delta P_{G_g}} = \frac{\partial P_{ij}}{\partial \theta_i} \cdot \frac{\partial \theta_i}{\partial P_{G_g}} + \frac{\partial P_{ji}}{\partial \theta_j} \cdot \frac{\partial \theta_j}{\partial P_{G_g}}. \tag{5}$$

The power flow equation on congested lines can be calculated by

$$P_{ij} = -V_i^2 \cdot G_{ij} + V_i \cdot V_j \cdot G_{ij} \cdot \cos(\theta_i - \theta_j) + V_i \cdot V_j \cdot B_{ij} \cdot \sin(\theta_i - \theta_j). \tag{6}$$

The differentiations of (6) with respecting to θ_i and θ_j are in (7) and (8) as

$$\frac{\partial P_{ij}}{\partial \theta_i} = -V_i \cdot V_j \cdot G_{ij} \cdot \sin(\theta_i - \theta_j) + V_i \cdot V_j \cdot B_{ij} \cdot \cos(\theta_i - \theta_j) \tag{7}$$

$$\frac{\partial P_{ij}}{\partial \theta_j} = +V_i \cdot V_j \cdot G_{ij} \cdot \sin(\theta_i - \theta_j) - V_i \cdot V_j \cdot B_{ij} \cdot \cos(\theta_i - \theta_j) = -\frac{\partial P_{ij}}{\partial \theta_i}. \tag{8}$$

The active power injected at a bus-s which refers to any bus in the system can be calculated as

$$\begin{aligned} P_s &= |V_s| \cdot \sum_{t=1}^{n} \{(G_{st} \cdot \cos(\theta_s - \theta_t) + B_{st} \cdot \sin(\theta_s - \theta_t)) \cdot |V_t|\} \\ &= |V_s|^2 \cdot G_{ss} + |V_s| \cdot \sum_{\substack{t=1 \\ t\neq s}}^{n} \{(G_{st} \cdot \cos(\theta_s - \theta_t) + B_{st} \cdot \sin(\theta_s - \theta_t)) \cdot |V_t|\}. \end{aligned} \tag{9}$$

Further calculation can be linked by differentiating (9) as

$$\frac{\partial P_s}{\partial \theta_t} = |V_s| \cdot |V_t| \cdot \{G_{st} \cdot \sin(\theta_s - \theta_t) + B_{st} \cdot \cos(\theta_s - \theta_t)\} \tag{10}$$

$$\frac{\partial P_s}{\partial \theta_s} = |V_s| \cdot \sum_{\substack{t=1 \\ t\neq s}}^{n} \{(-G_{st} \cdot \sin(\theta_s - \theta_t) + B_{st} \cdot \cos(\theta_s - \theta_t)) \cdot |V_t|\}. \tag{11}$$

The relation between the change in active power at each bus and voltage phase angles can be written as

$$[\Delta P]_{n\times 1} = [H]_{n\times n} \cdot [\Delta\theta]_{n\times 1} \tag{12}$$

$$[H]_{n\times n} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial \theta_2} & \cdots & \frac{\partial P_1}{\partial \theta_n} \\ \frac{\partial P_2}{\partial \theta_1} & \frac{\partial P_2}{\partial \theta_2} & \cdots & \frac{\partial P_2}{\partial \theta_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \theta_1} & \frac{\partial P_n}{\partial \theta_2} & \cdots & \frac{\partial P_n}{\partial \theta_n} \end{bmatrix}_{n\times n}. \tag{13}$$

$$\text{Given } [M] = [H]^{-1}. \tag{14}$$

$$\text{Thus } [\Delta\theta] = [M] \cdot [\Delta P]. \tag{15}$$

Since bus 1 is the reference bus, the first row and first column of $[M]$ can be eliminated. Therefore, the modified $[M]$ is written as

$$[\Delta\theta]_{n\times 1} = \begin{bmatrix} 0 & 0 \\ 0 & [M_{-1}] \end{bmatrix}_{n\times n} \cdot [\Delta P]_{n\times 1}. \tag{16}$$

In (16), the modified $[M]$ represents the values of $(\partial\theta_i)/(\partial P_{G_g})$ and $(\partial\theta_j)/(\partial P_{G_g})$ in (5) to calculate GS values. Large GS generators will be selected for redispatch since they are more influential on the congested line.

4. PSO schemes

PSO is an efficient population-based optimization technique [10]. During a search, all particles keep their personal best positions, $p\mathrm{best}_p = (p_{p1}, p_{p2}, \ldots, p_{pd})$, and their global best position, $g\mathrm{best}_g = (g_{g1}, g_{g2}, \ldots, g_{gd})$, to adjust their velocities. Velocity of particle p, $V_p = (v_{p1}, v_{p2}, \ldots, v_{pd})$, determines searching directions of the particle. A position of particle p, $X_p = (x_{p1}, x_{p2}, \ldots, x_{pd})$, is updated using its velocity. In the optimal congestion management problem, a particle position represents the amount of redispatch power generation shown in Fig. 1. X_p^{k+1} is the updated position at iteration $k+1$ of a particle p. Each dimension of particle position could be updated by different PSO schemes described below.

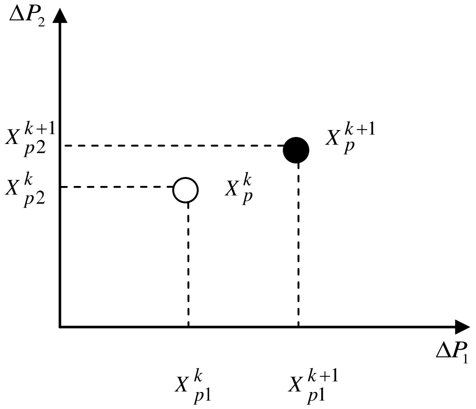

Fig. 1. Particle positions representing and redispatch power generation.

4.1. Classical PSO (CPSO)

CPSO is mathematically defined as [10]

$$v_{pd}^{k+1} = w \cdot v_{pd}^{k} + c_1 \cdot \mathrm{rand}_1 \cdot \left(\mathrm{pbest}_{pd} - x_{pd}\right) + c_2 \cdot \mathrm{rand}_2 \cdot \left(\mathrm{gbest}_{gd} - x_{pd}\right) \tag{17}$$

$$x_{pd}^{k+1} = x_{pd} + v_{pd}^{k+1}. \tag{18}$$

In (17), a velocity updating equation of CPSO is shown. A particle position will be updated by (18).

4.2. PSO with time-varying inertia weight (PSO-TVIW)

The main concept of PSO-TVIW is similar to CPSO in which the Eqs. (17)–(18) are used. However, for PSO-TVIW the velocity update equation is modified by the constriction factor C and the inertia weight w is linearly decreasing as iteration grows [11]

$$v_{pd}^{k+1} = C\left\{w \cdot v_{pd}^{k} + c_1 \cdot \mathrm{rand}_1 \cdot \left(\mathrm{pbest}_{pd} - x_{pd}\right) + c_2 \cdot \mathrm{rand}_2 \cdot \left(\mathrm{gbest}_{gd} - x_{pd}\right)\right\} \tag{19}$$

$$w = (w_{\max} - w_{\min}) \cdot \frac{(k_{\max} - k)}{k_{\max}} + w_{\min}. \tag{20}$$

$$C = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}, \quad \text{where } 4.1 \le \varphi \le 4.2. \tag{21}$$

4.3. PSO with time-varying acceleration coefficients (PSO-TVAC)

PSO-TVAC is extended from PSO-TVIW. All coefficients including inertia weight and acceleration coefficients are varied with iterations. The velocity updating equation of PSO-TVAC can be expressed as [12]

$$\begin{aligned} v_{pd}^{k+1} = C \Bigg\{ & w \cdot v_{pd}^{k} + \left(\left(c_{1f} - c_{1i}\right)\frac{k}{k_{\max}} + c_{1i}\right) \cdot \mathrm{rand}_1 \cdot \left(\mathrm{pbest}_{pd} - x_{pd}\right) \\ & + \left(\left(c_{2f} - c_{2i}\right)\frac{k}{k_{\max}} + c_{2i}\right) \cdot \mathrm{rand}_2 \cdot \left(\mathrm{gbest}_{gd} - x_{pd}\right)\Bigg\}. \end{aligned} \tag{22}$$

5. PSO-TVAC procedure

The procedure of PSO-TVAC for the congestion management problem is described as follows.

Step 1: Line and bus data are input to obtain power flow analysis solution.
Step 2: GS values at generator buses are determined and redispatched generators are selected.
Step 3: PSO parameters such as inertia weight, acceleration coefficients, and number of particles and iterations are specified.
Step 4: Particles' positions are randomly initialized and the iteration counter is set as 1.
Step 5: Particles' fitness is evaluated by the objective function in (1).

Step 6: Particle positions and velocities are updated by (18) and (22), respectively.
Step 7: If the maximum PSO iteration is reached, the optimal solution is the position of the global best particle. Otherwise increase the iteration counter by 1 and go to Step 5.

The PSO-TVAC procedure could be summarized in Fig. 2.

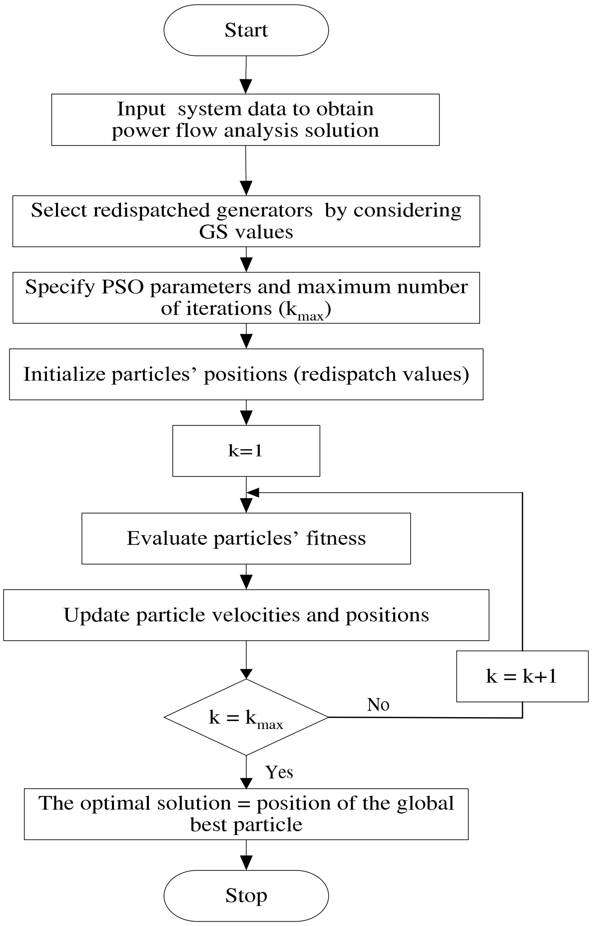

Fig. 2. Flowchart of the PSO-TVAC for congestion management.

6. Numerical results

The proposed congestion management approach based on PSO-TVAC is tested on the IEEE 30-bus and 118-bus systems and compared with the CPSO and PSO-TVIW approaches. In Table 1, PSO parameters are given.

Table 1
Parameters of PSO.

Parameters	CPSO	PSO-TVIW	PSO-TVAC
C	–	$\varphi = 4.1$	$\varphi = 4.1$
w	0.5	$w_{\min} = 0.4$ $w_{\max} = 0.9$	$w_{\min} = 0.4$ $w_{\max} = 0.9$
c_1	2	2	$c_{1i} = 2.5$, $c_{1f} = 0.2$
c_2	2	2	$c_{2i} = 0.2$, $c_{2f} = 2.5$

6.1. IEEE 30-bus system

Here, the IEEE 30-bus system with 6 generators and 41 lines is used. The system configuration is shown in Fig. 3 and the system data can be found in [13]. Bus 1 is assigned as the reference bus. A congested line between buses 1 and 2 exists as shown in Table 2. The maximum number of iterations and particles are set as 500 and 70, respectively.

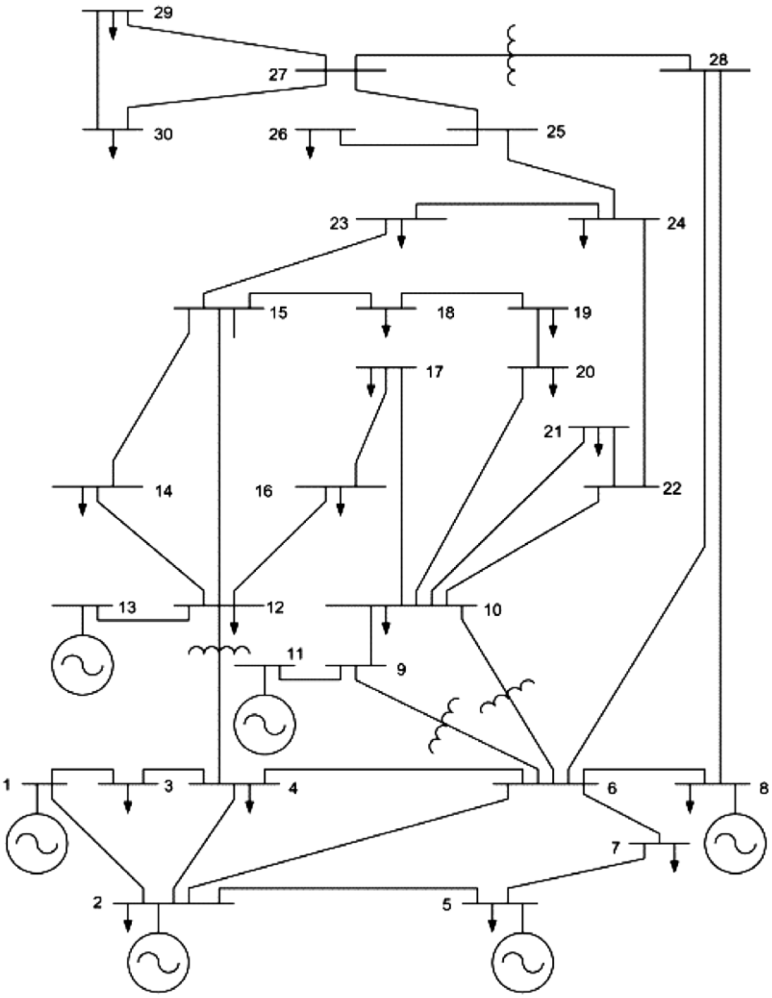

Fig. 3. The IEEE 30-bus system configuration.

Table 2
A congested line on the IEEE 30-bus system.

Congested line	Active power flow (MW)	Line limit (MVA)	Overload (MW)
1 to 2	170	130	40

The GS values of 6 generation units in the IEEE 30-bus system are shown in Table 3. Considering GS values, all generators are selected for redispatch.

In the IEEE 30-bus system, the GS of all 6 generators are high. This implies that all generators should be used to relieve the congested line. For a larger system, selected group of generators having the largest GS values may be used to save the computational effort.

Table 3
Generation sensitivity of 6 units on the IEEE 30-bus system.

Gen no.	1	3	5	8	11	13
GS 1–2	0	−0.8908	−0.8527	−0.7394	−0.7258	−0.6869

In Fig. 4, the average active power adjustment and GS values of each generator are shown. With 50-trial simulation, statistical results with different PSO approaches are compared in Table 4. PSO-TVAC provides the minimum redispatch cost solution of $ 237.9/h, whereas CPSO and PSO-TVIW provide $ 240.3/h and $ 239.2/h, respectively. In addition, the solutions of PSO-TVAC have the lowest standard deviation compared to the other PSO.

Table 4
Comparison of PSO solutions on the IEEE 30-bus system.

MW	ΔP_1	ΔP_2	ΔP_5	ΔP_8	ΔP_{11}	ΔP_{13}	Total ΔP	Cost ($ /h)
CPSO								
Max	−66.1	28.9	23.3	18.1	6.2	3.7	146.3	403.1
Min	−47.9	18.6	16.5	11.3	2.8	0.1	97.2	240.3
Mean	−55.9	22.6	16.2	10.5	5.6	2.6	113.2	287.1
SD	8.3	7.6	3.5	3.3	3.2	3.3	15.9	48.2
PSO-TVIW								
Max	−58.5	16.7	13.0	11.8	8.6	5.7	114.2	288.0
Min	−47.3	20.1	14.5	10.5	4.8	0.5	97.7	239.2
Mean	−50.1	18.9	13.2	9.2	5.9	4.1	101.4	253.1
SD	2.8	3.5	5.4	3.3	3.5	6.1	13.3	3.8
PSO-TVAC								
Max	−51.1	22.0	14.7	8.8	6.2	1.0	103.8	254.9
Min	−47.3	25.1	16.0	7.6	0.6	0.0	96.7	237.9
Mean	−49.3	17.5	14.0	9.9	6.8	3.0	100.5	247.5
SD	0.8	2.1	2.1	2.2	2.3	2.4	4.6	1.6

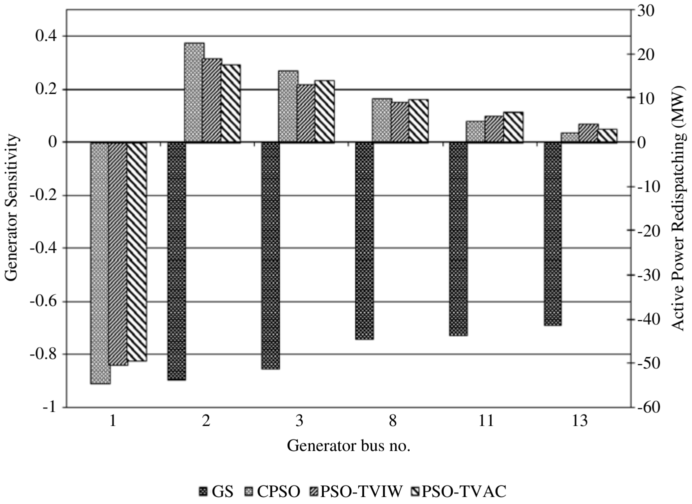

Fig. 4. GS values and generation redispatch on the IEEE 30-bus system.

In Fig. 5, the convergence characteristics of different PSO schemes are shown. The proposed PSO-TVAC could converge to a better solution than CPSO and PSO-TVIW.

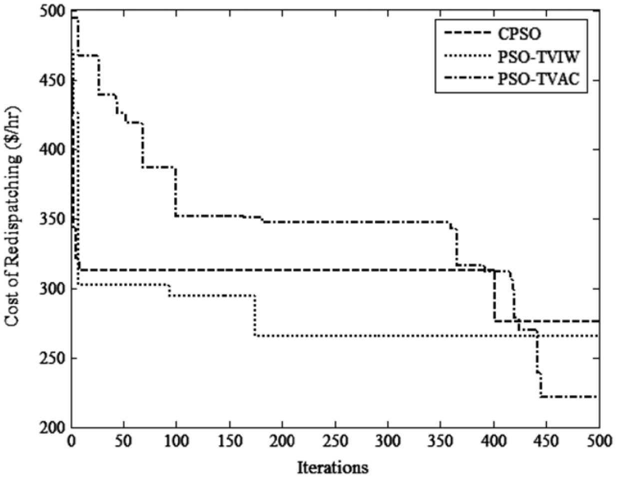

Fig. 5. Convergence characteristics of PSO schemes on the IEEE 30-bus system.

6.2. IEEE 118-bus system

The IEEE 118-bus system with 54 generators and 186 lines [14–17] is used here. Bus 1 is assigned as the reference bus. The congested line data is shown in Table 5.

Table 5
A congested line on the IEEE 118-bus system.

Congested line	Active power flow (MW)	Line limit (MVA)	Overload (MW)
89 to 90	260	200	60

In Fig. 6, the illustration of GS values is shown. GS values of all generator buses are compared in Table 6. The generator buses 85, 87, 89, 90, and 91 are among the largest magnitude of GS. This implies that these generators could significantly affect to the congested line. Thus, they are chosen as redispatched generators.

Using the largest GS values, only 6 generators out of 54 are used for redispatching by PSO, requiring a much less computational effort.

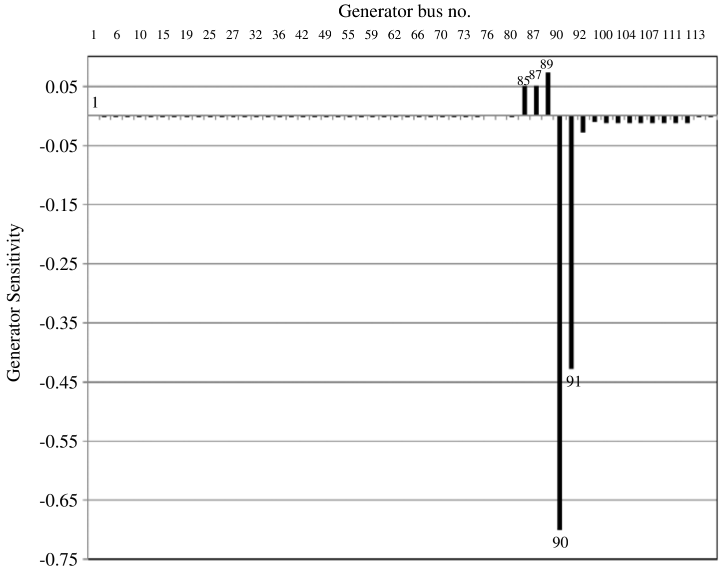

Fig. 6. GS values of 54 units on the IEEE 118-bus system.

Table 6
GS values of 54 generators on the IEEE 118-bus system.

Gen no.	GS (10^{-3})	Gen no.	GS (10^{-3})	Gen no.	GS (10^{-3})
1	**0**	42	−0.0375	80	−0.9250
4	−0.0005	46	−0.0242	**85**	**50.068**
6	−0.0001	49	−0.0460	**87**	**50.654**
8	−0.0014	54	−0.0838	**89**	**74.455**
10	−0.0014	55	−0.0871	**90**	**−701.15**
12	0.0004	56	−0.0854	**91**	**−427.90**
15	0.0021	59	−0.1100	92	−28.411
18	0.0051	61	−0.1160	99	−9.391
19	0.0046	62	−0.1130	100	−12.915
24	0.1350	65	−0.1350	103	−12.737
25	0.0484	66	−0.0983	104	−12.854
26	0.0337	69	0.2120	105	−12.772
27	0.0451	70	0.3690	107	−12.202
31	0.0339	72	0.2326	110	−12.274
32	0.0477	73	0.3400	111	−12.07
34	−0.0323	74	0.5410	112	−11.747
36	−0.0329	76	0.8650	113	0.0110
40	−0.0343	77	0.0012	116	−0.1750

With 50-trial simulation, the solutions from different PSO approaches are shown in Table 7. From the results, PSO-TVAC provides the lowest redispatch cost of $ 829.5/h, while CPSO and PSO-TVIW provide the minimum $ 875.0/h and $ 853.8/h, respectively. Mean and standard deviation values of PSO-TVAC are also lower than the other PSO.

Table 7
Comparison of PSO solutions on the IEEE 118-bus system.

MW	ΔP_1	ΔP_{85}	ΔP_{87}	ΔP_{89}	ΔP_{90}	ΔP_{91}	Total ΔP	Cost ($ /h)
CPSO								
Max	−5.1	−6.4	−8.6	−122.9	117.8	18.9	279.8	1604.5
Min	−5.1	−27.3	−27.5	−28.9	68.1	25.9	182.7	875.0
Mean	−5.9	−15.3	−31.5	−62.0	85.1	26.8	226.6	1183.8
SD	4.4	8.4	11.4	17.5	23.2	14.6	30.5	196.4
PSO-TVIW								
Max	−2.7	−13.8	−23.4	−97.7	121.4	10.4	269.4	1497.8
Min	3–6.8	−18.2	−28.2	−33.1	78.3	8.9	173.5	853.8
Mean	−5.5	−12.1	−28.2	−59.8	76.4	29.8	211.7	1088.4
SD	4.3	6.7	10.7	16.9	21.1	13.5	26.3	165.8
PSO-TVAC								
Max	−5.9	−6.2	−6.5	−96.2	80.1	30.5	225.5	1229.6
Min	−0.8	−12.1	−13.9	−52.3	81.6	3.3	163.8	829.5
Mean	−4.4	−10.3	−22.0	−58.5	69.4	24.7	189.3	970.7
SD	2.9	5.0	10.0	15.1	9.8	16.1	16.5	94.5

Fig. 7 shows the relationship between power redispatch and GS values. As the GS at bus 85, 87, and 89 are positive, the generation output at these buses is reduced. By contrast, the generators at bus 90 and 91 have negative GS values, thus the generation is increased. Moreover, the GS magnitude affects the amount of active power adjustment. The reference bus is used to maintain the power balance.

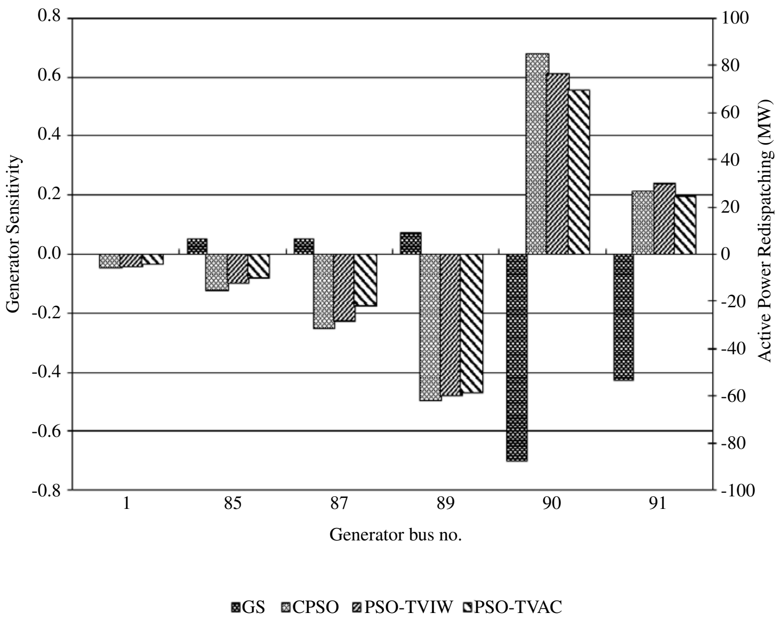

Fig. 7. GS values and power redispatch on the IEEE 118-bus system.

In Fig. 8, convergence characteristics of CPSO, PSO-TVIW, and PSO-TVAC are shown. The maximum iteration limit is set to 1000. PSO-TVAC could converge to a lower redispatch cost than CPSO and PSO-TVIW.

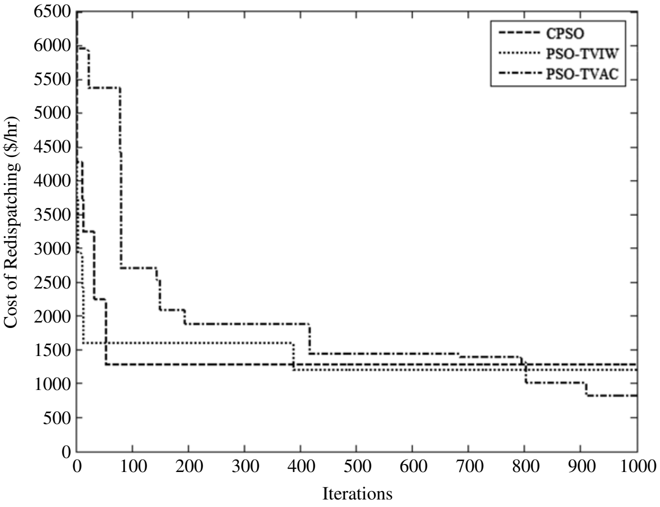

Fig. 8. Convergence characteristics of PSO schemes on the IEEE 118-bus system.

7. Conclusion

In this paper, the optimal congestion management approach based on PSO-TVAC is efficiently minimizing redispatch cost. Redispatched generators are selected based on the large magnitude of GS. Test results on the IEEE 30-bus and 118-bus systems indicate that PSO-TVAC is superior to CPSO and PSO-TVIW in providing the optimal congestion management. The proposed approach is useful for ISOs in managing the transmission congestion in a deregulated electricity environment.

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