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Improved PSO Applied to the Optimal Power Flow with Transient Stability Constraints

Stability is an important constraint in power system preventive control against blackouts triggered by transient instability (TS) after a contingency. The Transient Stability Constrained Optimal Power Flow (TSCOPF) has a considerable attention in recent years. In this paper, a novel formulation of Optimal Power Flow (OPF) problem is proposed by incorporating the transient stability constraints into the conventional OPF problem. Improved Particle Swarm Optimizer (IPSO) is developed to solve the TSCOPF. The proposed approach is tested on the Western System Coordinated Council (WSCC) 9-Bus system and IEEE 30-bus system. The results show that the system stability has been greatly enhanced with the proposed formulation

Keywords: Power System Stability, Transient Stability Constrained Optimal Power Flow (TSCOPF), Improved Particle Swarm Optimizer (IPSO), Optimal Power Flow (OPF), Power System Contingencies.

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1. Introduction

Optimal power flow (OPF) is an essential tool for power system operation and planning. The main purpose of an OPF problem is to ensure the economic operation of a power system by setting the control variables such as generator voltages and power outputs, transformer taps, and switchable capacitors. However, the optimal solution obtained from the OPF should ensure the stability of the system under credible contingencies. If the system is transiently unstable under one of the disturbances, the OPF solution must be revised. In the conventional OPF, the solution takes into consideration the static constraints that it is not always powerful in the case of the occurrence of some contingencies. Besides, a large amount of financial loss is due to synchronism in the power system that has been reported in many countries [1].

Recently, due to several blackouts caused by transient instability, dynamic constraints are added into OPF formulation to guarantee the transient stability of the power system against possible contingencies. As a result, OPF formulation presented by adding the transient stability constraints into the conventional OPF problem called transient stability constrained optimal power flow (TSCOPF) [2][1]. It involves the dynamic security and economic operation of power systems, TSCOPF problem which has been extensively investigated and addressed in [3]-[4]. The TSCOPF is considered a nonlinear optimization problem with differential-algebraic equations (DAE) that cannot be solved by employing

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directly the standard mathematical programming methods such as interior point methods (IPM) [5]. Hence, the key issue in the TSCOPF problems is to handle the differential equations from transient stability constraints. These constraints consist of additional equality and inequality constraints, i.e., a set of differential-algebraic equations (DAEs) that describes the dynamic behaviour of rotor angle after undergoing severe disturbances. The widely used stability criterion is the maximum allowable deviation of the rotor angle with respect to the Centre of Inertia (COI). To handle the Transient Stability (TS) equality constraints, a set of DAEs is first converted into numerically equivalent algebraic equations using numerical methods such as modified Euler's method, and then the step-by-step simulation is performed to observe the rotor angle deviation [1]-[6].

In [1] multi-contingency TS constraints are considered in TSCOPF, and both binding and non-binding contingencies are elaborated. In [5], to handle TS constraints, the transcription technique consisting of converting TSCOPF from semi-infinite to a finite optimization problem in Euclidean space is proposed.

Intelligent methods such as differential evolution [7][8], artificial neural network [9][10], evolutionary programming [11], Genetic Algorithm (GA) [12][13] and Particle Swarm Optimisation (PSO) [14]–[15] are population-based stochastic optimisations that do not rely on the derivatives and therefore could handle the non-derivative and non-convex problems. From a practical point of view, PSO, which imitates the social behaviours of birds flocking, is an excellent stochastic optimisation algorithm with only a few parameters need to be tuned [16]. Coupled with the encouraging performance for some hard optimisation problems with faster and stable convergence, PSO has been widely and successfully applied in power system optimisation [17].

Due to the highly non-linear inherence of power system transient stability, the computation of TSCOPF is very difficult. Generally, the difficulties appear in two subproblems:

1) Integrating the transient stability constraints to the conventional OPF model, i.e. how to express the TS limit;

2) Developing a solution methodology for the optimization problem after incorporating the TS constraints

Our objective is to apply IPSO to solve the OPF problem with and without transient stability constraint. The method is applied in WSCC 9 bus and IEEE 30 bus test systems where the main objective function is to minimize the total generation cost. Moreover, for validation purpose, the proposed method is compared with fast optimal power flow (FOPF) method. The results show the effectiveness of the proposed method.

This paper is organized as follows. Section II explains the transient stability assessment Section III gives a brief review of the Improved PSO method (IPSO). Section IV deals with the TSCOPF problem formulation. Section V highlights the main components of the proposed method. Section VI provides the simulation results and discussions. Finally, a conclusion is given in Section VII.

Nomenclature

P_{Di}, Q_{Di} : Active and reactive power loads at bus *i*, respectively;

Q_{Gi} : Reactive power generation at bus *i*;

V_i, V_j : Voltage magnitudes at buses *i* and *j*, respectively;

G_{ij}, B_{ij} : Real and imaginary parts of the *ij-th* element of the admittance matrix *Ybus* , respectively;

θ_{ij} : Difference of voltage angles between buses *i* and *j*;

T_i : Tap setting of the *i-th* transformer;
S_{Li} : Line loading at line *i*;
N : Buses numbers;
NG : Generating units number ;
NL : Lines numbers;
NT : Transformers numbers ;
H_i : Inertia constant;
D_i : Damping coefficient of the *i-th* generator;
δ_{COI} : Position of the centre of inertia (COI);
δ_{MAX} : Maximum allowable deviation of the rotor angle with respect to COI;
ω_R, ω_i : Rated speed and rotor speed, respectively;
P_{mi}, P_{ei} : Mechanical input and electrical output of the *i-th* generator, respectively;

2. TRANSIENT STABILITY CONSTRAINTS

TS is the ability of a power system to maintain synchronism under a severe disturbance such as transmission line outages and loss of generators and loads [18]. After the disturbance, if the generator rotor angle separation between the machines in the system remains within certain bounds, it can be said that the system maintains synchronism. The TS constraints consist of equality constraint i.e. swing equations and inequality constraint i.e. TS limits. The TS analysis of the *i-th* synchronous generator can be done by solving a set of DAEs (swing equation) that describes the motion of rotor angle as follows:

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_R \\ 2H_i\dot{\omega}_i &= \omega_R\left(P_{mi} - P_{ei} - D_i\omega_i\right) \quad i = 1,2,\ldots,NG \end{aligned} \tag{1}$$

Where $P_{ei} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{NG}\left[E_iE_jB_{ij}\sin(\delta_i - \delta_j) + E_iE_jG_{ij}\cos(\delta_i - \delta_j)\right]$

E_i, E_j : Constant voltages behind a transient reactance of the *i-th* and *j-th* generators, respectively.
δ_i, δ_j : Rotor angles of the *i-th* and *j-th* generators, respectively.
H_i : Inertia constant of the *i*-th generator.

To include DAEs into TSCOPF problem, the DAEs in Eq. (1) are converted into numerically equivalent algebraic equations by using the implicit trapezoidal rule as follows:

$$\begin{aligned} \delta_i^{t+\Delta t} &= \delta_i^t + \frac{\Delta t}{2}\left[\omega_i^{t+\Delta t} + \omega_i^t\right] \quad t = t_0, t_0 + \Delta t, \ldots, T \\ \omega_i^{t+\Delta t} &= \omega_i^t + \frac{\Delta t}{2}\left[\frac{\omega_R}{2H_i}\left(P_{mi} - P_{ei}^{t+\Delta t}\right) + \frac{\omega_R}{2H_i}\left(P_{mi} - P_{ei}^t\right)\right] \end{aligned} \tag{2}$$

Where $P_{ei}^t = E_i^2 G_{ii}^t + \sum_{\substack{j=1 \\ j\neq i}}^{NG}\left[E_iE_jB_{ij}^t\sin(\delta_i^t - \delta_j^t) + E_iE_jG_{ij}^t\cos(\delta_i^t - \delta_j^t)\right]$

Δt : Integration step width.
T : Maximum integration period,
$\delta_i^{t_0}, \omega_i^{t_0}$: Rotor angle and rotor speed immediately before the fault occurs, respectively.

The constant mechanical output P_{mi} equals to $P_{ei}^{t_0}$ and E_i could be obtained from load flow solution. In Eq. (2), which forms the equality constraints, the generator rotor angle of time $t+\Delta t$ can be calculated using information at time $t+\Delta t$ and time t. To solve this implicit function, numerical techniques can be applied.

To determine whether the system is stable or not, the maximum allowable deviation of rotor angle with respect to COI is adopted. The position of COI at time t can be expressed as follows:

$$\delta_{COI}^t = \frac{\sum_{i=1}^{NG} H_i \delta_i^t}{\sum_{i=1}^{NG} H_i} \tag{3}$$

The transient stability limit, which is inequality constraints, can be formulated as follows:

$$\left|\delta_i^t - \delta_{COI}^t\right| \le \delta_{MAX} \quad t = t_0, t_0 + \Delta t, ..., T \tag{4}$$

Where δ_{MAX} is the maximum allowable deviation of rotor angle with respect to COI. This stability limit is acceptable and used widely for utility engineers [3].

3. The proposed approach

3.1 Optimal Power Flow (OPF)

The OPF problem is an extension problem of Economic Load Dispatch(ELD). In OPF, the solution is not only power generation, but also other controllable parameters in a power system such as voltages at generator bus, transformer tap settings, and shunt compensations. All additional variable limits in the system are considered as inequality constraints, for instance, voltage limit at load bus, line flow limit, stability limit… etc. Various objective functions can be considered in OPF, for example, fuel cost minimization, system loss minimization, optimal voltage profile, power transfer maximization and load shedding minimization under an emergency condition. Therefore, the OPF problem is a large scale non-linear optimization problem requiring a powerful tool to solve.

In [19], PSO is applied to solve the OPF problem with different objectives such as voltage stability enhancement, voltage profile improvement and fuel cost minimization. The results confirm the potential of PSO and show its effectiveness and superiority over the classical gradient and GA techniques.

3.2 Improved Particle Swarm Optimisation

PSO developed in [16] is an evolutionary computation technique. It was inspired by the social behaviour of fish schooling and birds flocking. It uses a population of individuals, called particles, which fly through the problem hyperspace with some given initial velocities [20].

3.2.1 Basic concept

PSO is employed for optimizing nonlinear functions. At a given iteration a set of solutions or alternatives the (particles). From one iteration to another, each particle X_i moves according to a rule that depends on different factors. In order to understand this rule, one must also keep the record of the best point b_i found by the particle in its past life and the current global best point b_g found by the particle swarm in their past life as shown in Fig.1.

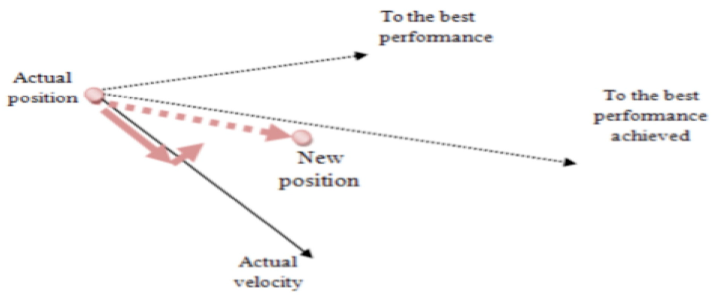

Fig.1. Schematic diagram of the particle displacement by the *PSO* algorithm

$$X_i^{(new)} = X_i + V_i^{new} \tag{5}$$

Where V_i is called the i^{th} particle velocity and is defined by:

$$V_i^{(new)} = w_{i0}V_i + w_{i1}Rnd_1.(pbest_i - X_i) + w_{i2}Rnd_2.(gbest_i - X_i) \tag{6}$$

Where the first term of the summation represents inertia or habit, the second represents memory, and the third represents cooperation or information exchange

The parameters w_{i1} and w_{i2} are weights fixed in the beginning of the process. Rnd_x is random numbers sampled from a uniform distribution in [0, 1]. The following weighting function is usually used in determining w_{i0}:

$$w_{i0} = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}}.iter \tag{7}$$

$w_{\max}, w_{\min}$: Initial and final weights,

$iter_{\max}$: Maximum number of iterations,

$iter$: Current iteration number,

This function supports the speed of the first iterations.

In addition, for the, $w_{\max}, w_{\min}$, w_{i1}, w_{i2} and $iter_{\max}$, the according parameters must be fixed:

N : Number of variables in the function to be optimized.

T_{pop} : Population size,

3.2.2 Modified Particle Swarm Optimization:

In order to speed up convergence and improve the solution quality, the following three modifications are proposed in this work:

Velocity limit of particles

After initializing the positions of particles randomly between their limits, the initial velocities of the particles are randomly selected within [21]:

$$\left(x_j^{\min} - \varepsilon\right) - x_{ij}^0 \le v_{ij}^0 \le \left(x_j^{\max} + \varepsilon\right) - x_{ij}^0 \tag{8}$$

where

ε : a chosen small positive real number.

In addition, at each iteration $k+1$, the velocity limit of the element j of the particle i can be calculated as [22]:

$$V_{ij}^{k+1} = \begin{cases} V_{ij}^{\max} & \text{if } V_{ij}^{k+1} \geq V_{ij}^{\max} \\ V_{ij}^{k+1} & \text{if } -V_{ij}^{\max} \leq V_{ij}^{k+1} \leq V_{ij}^{\max} \\ -V_{ij}^{\max} & \text{if } V_{ij}^{k+1} \leq -V_{ij}^{\max} \end{cases} \tag{9}$$

where

$$V_{ij}^{\max} = \frac{X_j^{\max} - X_j^{\min}}{R} \tag{10}$$

R: is a real number chosen between 5 and 10,

Reducing the search space

In order to accelerate the convergence speed of the method, a strategy to reduce the search space was introduced by reference [23]. In this case, the search space is dynamically adjusted; this will allow us to intensify our research in promising areas. Initially, search limits for the control variable j in the particle i are the minimum and maximum control variables:

$$X_{j\max}^{0} = X_j^{\max} \text{ and } X_{j\min}^{0} = X_j^{\min} \tag{11}$$

At iteration $k+1$, the search limits become:

$$\begin{cases} X_{j\max}^{k+1} = X_{j\max}^{k} - \left(X_{j\max}^{k} - gbest_j^k\right) * \Delta \\ X_{j\min}^{k+1} = X_{j\min}^{k} - \left(gbest_j^k - X_{j\min}^{k}\right) * \Delta \end{cases} \tag{12}$$

where Δ is a chosen step (e.g. = 0.1). The new position of the particle is determined by:

$$X_{ij}^{k+1} = \begin{cases} X_{ij}^{k} + V_{ij}^{k+1} & \text{if } X_{ij,\min} \leq X_{ij}^{k} + V_{ij}^{k+1} \leq X_{ij,\max} \\ X_{ij,\min} & \text{if } X_{ij}^{k} + V_{ij}^{k+1} < X_{ij,\min} \\ X_{ij,\max} & \text{if } X_{ij}^{k} + V_{ij}^{k+1} > X_{ij,\max} \end{cases} \tag{13}$$

Crossover Operation [23]

To ensure the diversity of the population and to speed up the convergence of the method, Park et. al. [23] applied a crossover operation to the conventional PSO algorithm.

At each iteration ($k+1$), the new position of each particle $i\left(X_i^{k+1}\right)$ calculated is replaced by:

$$\tilde{X}_i^{k+1} = \left(\tilde{x}_{i,1}^{k+1}, \tilde{x}_{i,2}^{k+1}, \ldots, \tilde{x}_{i,n}^{k+1}\right) \tag{14}$$

$$\text{With}: \tilde{X}_{ij}^{k+1} = \begin{cases} X_{ij}^{k+1} & \text{if } rand_{ij} \leq C_R \\ pbest_{ij} & \text{otherwise} \end{cases} \tag{15}$$

$rand_{ij}$: is a random number between 0 and 1 inclusive.

C_R is the probability of crossover; the empirically determined optimum value is 0.5

A standard OPF problem can be formulated as expressed in [19] with different objectives.

3.3Objective Function

The main objective of the TSCOPF problem is to minimize the total fuel cost function expressed as follows.

$$F = \sum_{i=1}^{NG} f_i(P_{Gi}) \tag{16}$$

where F is the total fuel cost; $f_i(P_{Gi})$ is the fuel cost function of the *i-th* generator; P_{Gi} is the active power output of the *i-th* generator.

3.4 Constraints

Equality and inequality constraints are defined as follows:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) = 0 \qquad i = 1,2,..., N \tag{17}$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N} V_j \left(G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij} \right) = 0 \qquad i = 1,2,..., N \tag{18}$$

$$P_{Gi,\min} \le P_{Gi} \le P_{Gi,\max} \qquad i = 1,2,..., NG \tag{19}$$

$$Q_{Gi,\min} \le Q_{Gi} \le Q_{Gi,\max} \qquad i = 1,2,..., NG \tag{20}$$

$$V_{i,\min} \le V_i \le V_{i,\max} \qquad i = 1,2,..., N \tag{21}$$

$$T_{i,\min} \le T_i \le T_{i,\max} \qquad i = 1,2,..., NT \tag{22}$$

$$\left| S_{Li} \right| \le S_{Li,\max} \qquad i = 1,2,..., NL \tag{23}$$

$$\begin{aligned} \dot{\delta} &= \omega_i - \omega_R \\ 2H_i \dot{\omega}_i &= \omega_R \left(P_{mi} - P_{ei} - D_i \omega_i \right) \qquad i = 1,2,..., NG \end{aligned} \tag{24}$$

$$\left| \delta_i - \delta_{COI} \right| \le \delta_{MAX} \qquad i = 1,2,..., NG \tag{25}$$

$$\delta_{COI} = \sum_{i=1}^{NG} H_i \delta_i \Bigg/ \sum_{i=1}^{NG} H_i \qquad i = 1,2,..., NG \tag{26}$$

where Eqs (17) and (18) are active and reactive power balance equations; Eqs (19)–(23) are limits of active and reactive power output, voltage magnitude for all generators, transformer tap setting, and line loading respectively; Eq (24) is the swing equation of a synchronous generator; Eq (25) is the transient stability limit.

3.5 Problem Formulation

Generally, the TSCOPF problem is now formulated as follows:
Minimize Eq (16)
Subject to Eqs (17)–(26)

3.6 Constraint Handling Strategies

For the equality constraints, power balance equations expressed in Eqs. (17) and (18) are satisfied by power flow calculation using Newton-Raphson method, and swing equations in Eq. (13) are met by the time domain simulation.
Inequality constraints expressed in Eqs. (21), (23) and (25) will be replaced by a penalty function. The penalty function, for any variable violating its limits, can be expressed mathematically as follows:

$$h(x_i)\begin{cases}(x_i - x_{i,\max})^2 & if \quad x_i > x_{i,\max}\\ (x_{i,\min} - x_i)^2 & if \quad x_i > x_{i,\min}\\ 0 & if \quad x_{i,\min} \le x_i \le x_{i,\max}\end{cases} \tag{27}$$

Where

$h(x_i)$: Penalty functions of variable x_i .

$x_{i,\max}, x_{i,\min}$: The upper and lower limits of the variable x_i , respectively;

Therefore, the original constrained optimization problem is transformed to an unconstrained one as follows:

$$F_{ext} = \sum_{i=1}^{NG} f_i(P_{Gi}) + Rho_1 \sum_{i=1}^{NB} Y(V_{Li}) + Rho_2 \sum_{i=1}^{NL} Y(S_{Li}) + Rho_3 \sum_{i=1}^{Ng} Y(\delta_i - \delta_{COI}) \tag{28}$$

where Rho_1 and Rho_2 are penalty weights of load bus voltage magnitude, and line loading respectively; Rho_3 is a penalty constant for the transient stability limit; $Y(V_{Li})$, $Y(S_{Li})$ and $Y(\delta_i - \delta_{COI})$ are the penalty functions of the related variables. In conclusion, Eq (28) considers all inequality constraints and represents the new objective function to be minimized.

3.7 Implementation of IPSO for TSCOPF Problem

The following flow chart shown in Fig.2 describes the incorporation of IPSO algorithm into the TSCOPF.
The control settings of IPSO method are summarised in Table 1.

Table 1: Control settings of IPSO method

w_{max}	w_{min}	T_{pop}	$Iter_{max}$	w_{i1}	w_{i1}	C_R	ε	R
0.9	0.4	150	15	1.8	2.2	0.4	10e-4	10

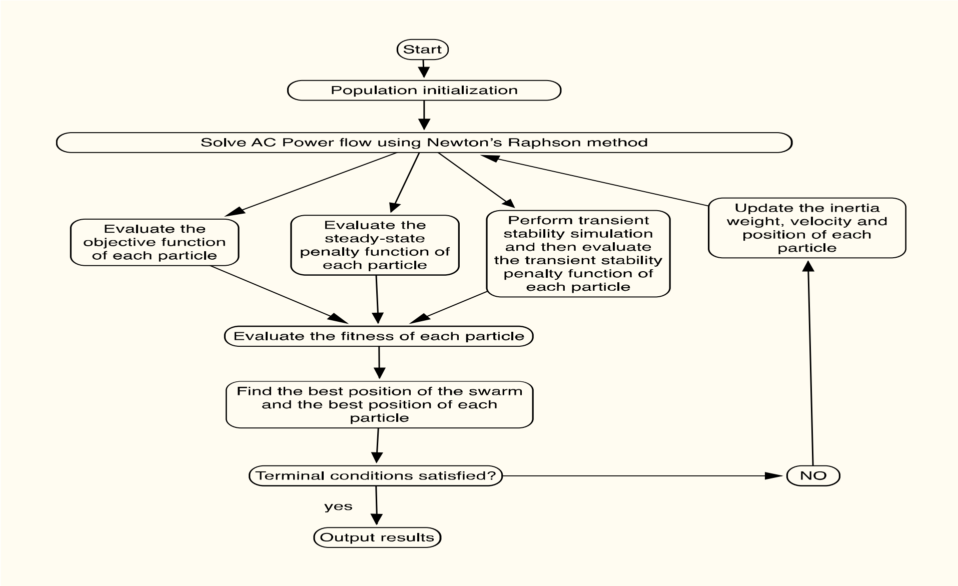

Fig.2. Flowchart of IPSO for TSCOPF calculation

4. Simulation results and discussions

The proposed method is applied on the WSCC 9-Bus and IEEE 30-bus systems. In order to obtain the best results, *PSO* method is applied in two single goals, with and without transient stability constraints. The proposed IPSO method has been applied to the single objective optimisation problem. To verifying the effectiveness of the proposed method, the generation cost function is represented by a quadratic function as fallow:

$$f\left(P_{Gi}\right)=a_i+b_iP_{Gi}+c_iP_{Gi}^2 \quad (\$/\text{hr}) \tag{29}$$

where, a_i, b_i and c_i are the cost coefficients of the *i-th* generators. The prototype program is developed on MATLAB environment and implemented on a personal computer with Intel Core i5 2.6-GHz processor and 8 GB RAM.
Numerical examples are divided into 2 cases as follows:

- ***Case 1***: solve the optimal power flow problem using IPSO without transient stability constraints.
- ***Case 2***: solve the global problem using IPSO with transient stability constraints (TSCOPF)

4.1 WSCC 9-Bus System Case

The 9-Bus system is shown in Fig. 3. The detailed data of the system is given in [24].

Only one contingency was considered in this analysis. The contingency with three-phase grounding fault near bus 7 at the end of line 5-7 at *t*= 0 s is considered. The fault is cleared at *t*= 0.27 s. For time-domain simulation, the integration time step is 0.01 s. The maximum integration time is 2 s, and δ_{MAX} =100 degrees.

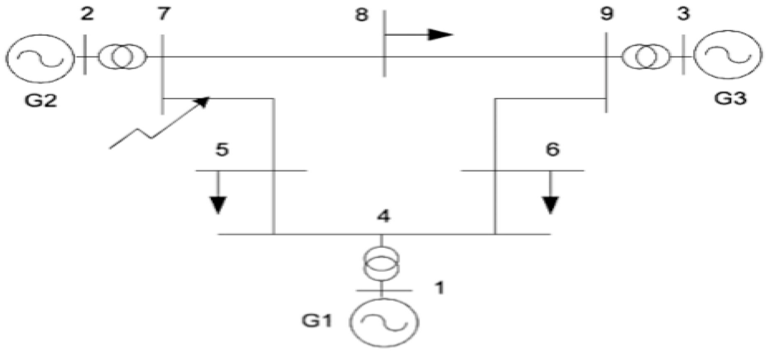

Fig.3. WSCC 3-machine 9-bus test system

Case 1: OPF *Problem*

The optimal settings of the control variables are given in Table 2. Initially, the total fuel cost was 5409.5 ($/hr). The total cost obtained by the proposed technique IPSO is 5280.374($/hr). It is clear that the total fuel cost is reduced.

Case 2: TSCOPF Problem

The proposed IPSO is applied to solve TSCOPF problem on this system. The control variables, the critical clearing time and cost differences based on the best solution between TSCOPF and OPF are also shown in Table 2.

Table 2: OPF and TSCOPF results by IPSO in cases 1 and 2

Result	Case base	Case 1 Without	Case 2 With
P_{G1} *(MW)*	70.56	91.310	98.350
P_{G2} *(MW)*	163	136.490	129.97
P_{G3} *(MW)*	85	95.200	89.88
V_1 *(pu)*	1.04	1.0499	0.9543
V_2 *(pu)*	1.025	0.9845	1.05
V_3 *(pu)*	1.025	0.9871	0.9902
T_1 *(bus 1-4)*	0.920	0.980	0.970
T_2 *(bus 2-7)*	0.921	1.017	0.900
T_3 *(bus 3-9)*	0.940	0.925	0.906
Best cost ($/hr)	5409.5	5280.374	5304.410
Cost diff. ($/hr)	-	24.036	-
CCT (s)	-	0.220	0.255

Also, the cost increased from 5280.374($/hr) to 5304.410($/hr). The rotor angles with respect to COI of all generators based on OPF and TSCOPF solutions are plotted in Figs. 4 and 5, respectively. It is obvious that the operating point from OPF cannot maintain transient stability. In order to guarantee transient stability after the contingency, the operating points have to shift from OPF to TSCOPF solutions leading to the additional cost of 24.036 ($/hr), which is a 0.5% increase. On the other hand, the critical clearing time (CCT) for the OPF without transient stability constraints is equal to 0.220 s comparing with TSCOPF, which equals to 0.255 s that indicates a difference of 35 ms leads to extension of the security margin due to the transient stability constraint.

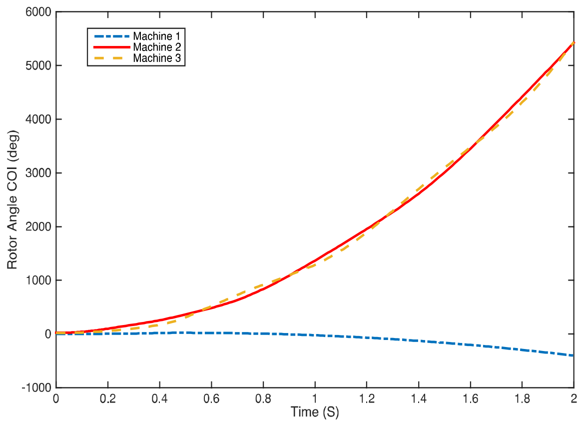

Fig. 4. Rotor angle curves based after OPF solution in WSCC 9-bus system.

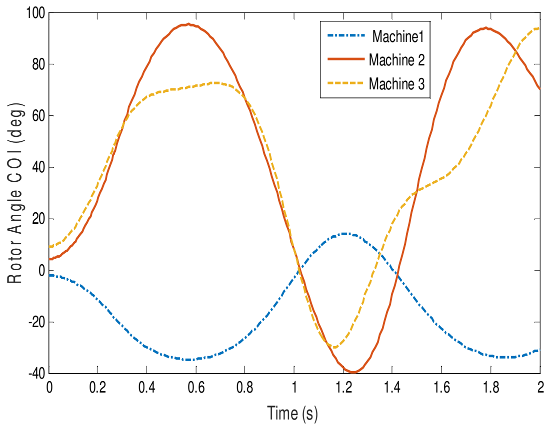

Fig. 5. Rotor angle curves based after TSCOPF solution in WSCC 9- bus system.

In addition, for comparison purpose, the obtained results for WSCC 9 bus system using OPF and Fast Optimal Power flow (FOPF) with and without transient stability are expressed in Table 3.

Table 3: Comparison between WSCC 9 bus system using OPF and FOPF with and without transient stability

Transient stability constraints	**Proposed Approach ($/hr)**	FOPF ($/hr) [25]
Without	**5280.374**	5296.69
With	**5304.410**	5315.35

The proposed TSCOPF procedure and the one presented in [26] have been compared. The proposed technique provides overall better results which confirm the robustness and superiority of the proposed approach.

4.2 IEEE 30-Bus System Case

The IEEE 30-bus system consists of 41 transmission lines, 6 generators, and 4 tap-changing transformers. In this system, shunt VAR compensations are installed at buses 10, 12, 15, 17, 20, 21, 23, 24, and 29. The single-line diagram of the system is shown in Fig.6. The system line and bus data are given in [27] and [28].

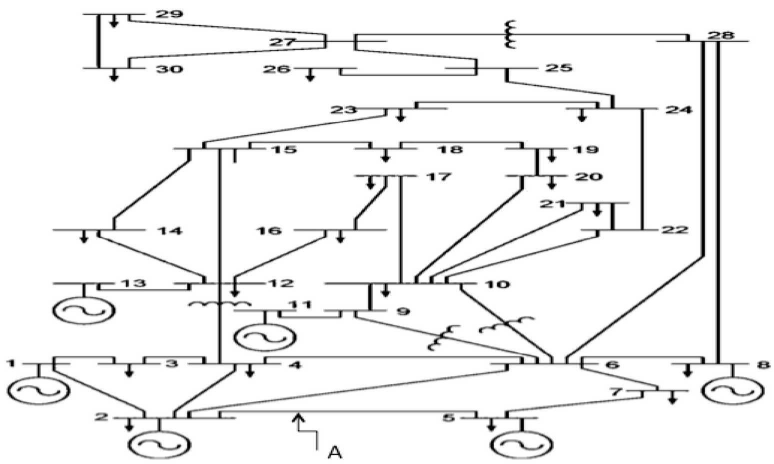

Fig.6. Single-line diagram of IEEE 30-bus system

A single contingency (A) shown in Fig.6 is considered in this problem. The contingency is a three-phase grounding fault occurred near to the bus 2 at t= 0s and cleared by removing the line 2-5 at t=0.350s. TS analysis is based on Time domain (T-D) methods where the non-linear sets of algebraic equations and differential are solved step-by-step using Runge-Kutta. For T-D simulation, the integration step is 0.01 s, the maximum integration time is 1.5 s and δ_{MAX} =120 degrees.

Case 1: OPF Problem

The optimal settings of the control variables obtained are given in Table 4. Initially, the total fuel cost was 901.59 ($/hr). The total cost obtained by the proposed technique (IPSO) is 797.477($/hr).
To assess the potential of the proposed approach, a comparison between the results of fuel cost obtained by the proposed IPSO approach and those reported in the literature has been carried out. The results of this comparison are given in Table 4. The results obtained to validate the proposed method and prove its superior performance in terms of the solution quality.

Table.4: Comparison of fuel cost for different methods.

Methods	**Fuel cost ($/hr)**
Teaching-Learning-Based Optimization TLBO[29]	799.071
Differential Evolution Algorithm [30]	799.289
Biogeography-Based Optimization [31]	799.111
Simulated Annealing [32]	799.450
Adaptive Genetic Algorithm with Adjusting Population Size [33]	799.844
Particle Swarm Optimization-based approach [19]	800.410
Enhanced Genetic Algorithm[34]	802.060
Modified Differential Evolution Algorithm [35]	802.465
Gravitational search algorithm [36]	798.675
Proposed Approach	**797.477**

Case 2: TSCOPF Problem

The effectiveness of IPSO is clarified with more complicated optimization problem. Table 5 shows the best solutions of the critical clearing time, run time in terms of the total generator fuel cost, the control variables and cost differences based on the best solution between TSCOPF and OPF are also given. From this table, the computational times for TSCOPF is highly increased from OPF, since the time domain simulation is performed for every individual during IPSO iterations to calculate the rotor angles of all generators. In addition, the critical clearing time for the OPF without transient stability is equal to 0.238 s comparing with TSCOPF, which equals to 0.300 s that indicates a difference of 62ms leads to a gain of a security margin due to the consideration of transient stability constraints.
Fig. 7 shows the simulation results of all generator rotor angles relative to the COI when TS constraints are not considered, that is, the base case. It is obvious that the system operated at the point suggested by the conventional OPF solutions fails to maintain the transient stability when it is subjected to the credible contingency. As indicated from the TSCOPF results of the IPSO method, the rotor angle curves of all generators are plotted in Fig. 8. It can be seen that the system is transiently stable with the TSCOPF optimal solutions.

After the contingency *A*, the rotor angles with respect to COI of only the generator with the largest swing 5-nd generator in all cases based on TSCOPF and OPF solutions are shown in Fig.9. Obviously, TSCOPF can guarantee system stability after the considered contingency whereas OPF cannot. Where the fuel cost of TSCOPF is obviously higher than the OPF. This is because the additional TS constraints are imposed in the OPF. The solution of OPF is actually unstable in contrast to the solution of TSCOPF that tolerates the disturbance. It is clear that the TSCOPF solution is indispensable in the operation of the power system.

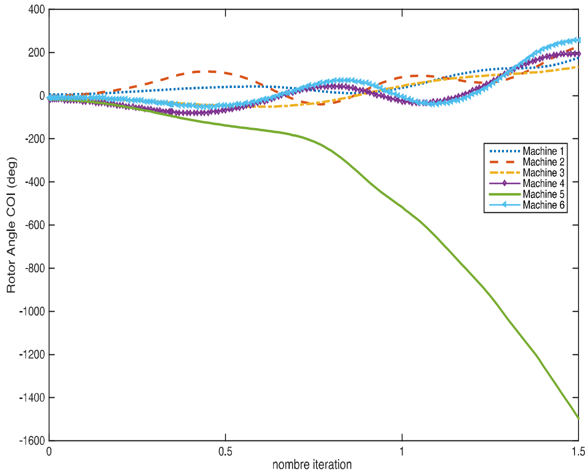

Fig.7. Rotor angle curves with IPSO solution for IEEE 30-bus system

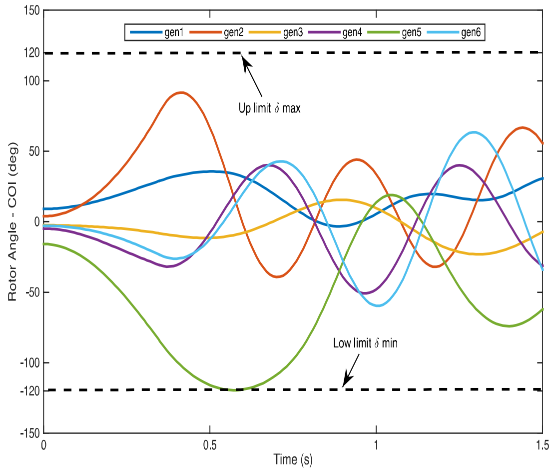

Fig.8. Rotor angle curves with TSCOPF solution case 2.

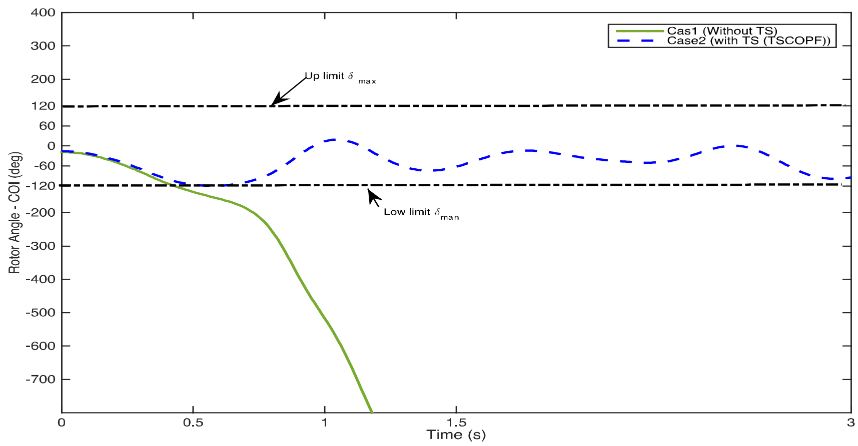

Fig.9. Rotor angle curves for the 5th generator with IPSO and TSCOPF solutions.

5. Conclusion

In this paper, a new formulation of optimal power flow problem has been developed by incorporating the dynamic constraints into the conventional formulation to guarantee the transient stability of the power system after a contingency. A proposed IPSO algorithm was developed and applied to the WSCC-9 bus and IEEE-30 bus test systems.

The problem was formulated as a single objective to minimize the generation fuel cost while satisfying all equality and inequality constraints considered. The findings of this paper can be summarized as follows:

-The TSCOPF using the proposed improved particle swarm optimization is found to be simple, robust and efficient.

- The comparisons with the literature demonstrate the effectiveness and superiority of the proposed approach.

In future, the formulated TSCOPF problems can contain other important constraints as gas emission and voltage stability constraints. Multi-objective problem formulation with novel metaheuristic inspired methods can be also investigated.

Table 5: OPF and TSCOPF results by IPSO in cases 1 and 2

Result	Case 1 Without	Case 2 With
PG1 (MW)	138.63	165.62
PG2 (MW)	46.89	35.02
PG3 (MW)	19.26	34.96
PG4 (MW)	24.15	24.83
PG5 (MW)	12.52	17.17
PG6 (MW)	12.00	12.00
V1 (pu)	1.050	1.0500
V2 (pu)	1.050	1.0060
V5 (pu)	1.050	0.9582
V8 (pu)	1.050	0.9743
V11 (pu)	1.050	1.0161
V13 (pu)	1.050	1.0226
T1 (bus 6-9)	1.078	0.984
T2 (bus 6-10)	1.100	1.053
T3 (bus 4-12)	1.050	0.900
T4 (bus 28-27)	0.906	1.017
QC10 (Mvar)	4.730	2.500
QC12 (Mvar)	5.000	5.000
QC15(Mvar)	0.570	2.000
QC17(Mvar)	2.020	4.000
QC20(Mvar)	5.000	5.000
QC21(Mvar)	5.000	5.000
QC23 (Mvar)	4.680	2.000
QC24 (Mvar)	2.880	4.500
QC29(Mvar)	0.000	3.500
Best cost ($/hr)	**797.477**	**814.451**
Cost diff. ($/hr)	16.974	-
Avg. run time (s)	15,246	110.12
CCT (s)	**0.238**	**0.300**

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