Research on Effect of Renewable Energy Power Generation on Available Transfer Capability

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***Abstract*—Renewable energy power generation could increase the uncertainties of power system with intermittent and stochastic performance, which has significant effect on Available Transfer Capability (ATC). With the rapid development of renewable energy power generation technology as well as the gradual maturity of power market, it has become essential to research the effect specially. The wind generator was simulated by applying the PX model based on the induction generator principle, and the solar power generator was regarded as PQ node. According to the above, the Optimal Power Flow (OPF) model to calculate the ATC was established, which could reflect the characteristics of wind and solar power.The intermittent and stochastic output and load wave, state uncertainty of the system equipment were simulated by applying Monte Carlo simulation. The Differential Evolution algorithm was improved to solve the OPF on ATC. Simulation could be made by improved IEEE118 system involving wind and solar power, the results show that with the algorithm the ATC can be calculated rapidly and accurately, in addition, the influence on ATC can be estimate effectively.**

***Index Terms*—available transfer capability, renewable energy power generation, Monte Carlo simulation, differential evolution algorithm**

I. INTRODUCTION

Renewable energy power generation can reduce human dependence on fossil fuels and environment and climate issues. It is an important part of the world power industry development to vigorously promote the new energy power generation. Wind power and solar power, which represent new energy power generation industry developed rapidly. In recent years, global wind power installed capacity of an average annual increase 30%, and solar photovoltaic power generation more than 40%.

With the development of renewable energy power generation technology [1-2] and increase of power load demand, renewable energy power generation can not only service specific users outside power grid, but also can massively incorporate into the power grid. Renewable energy power generation has many unique advantages, but the intermittent and stochastic of output may have influence on Available Transfer Capability (ATC) [3] when massive incorporated into power grid. There are a few researches about this area at present. Previous studies have reported ATC assessment of the large wind farm [4-5]. In addition, the transmission capability of including large scale solar a large-scale solar power system has also been calculated [6]. The above studies put forward their own unique perspectives and methods on the transmission capability with renewable energy power generation. However, they focus on the uncertainties of wind power and solar power in transmission capacity, and do not pay more attention to the impact on transmission capability from the uncertainties of renewable energy power generation. So, it is worthy of study the impact on ATC of the equipment location, penetration rate, and uncertainties of renewable energy power generation, and quantitative analysis the extent of the impact.

Based on a typical new energy power generation, namely wind power and solar power generation, this paper studies the effect on ATC of renewable energy power generation. ATC can be calculated by applying the established Optimal Power Flow (OPF) model with the PX model to describe wind generator and the PQ node to regard as the solar power generator. The intermittent, stochastic and error to forecast load of renewable energy power generation can be described by normal distribution probability model. The system state can be determined by Monte Carlo simulation. For a large number of ATC calculation sampled, this paper put forward to make an

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evolution by improved Differential Evolution (DE), which can ensure speed and accuracy of the calculation. In addition, through comparing many cases, the impact on ATC can be analyzed of uncertainties of renewable energy power generation, the position of power generation equipment, and penetration rate. The research can provide valuable reference for the power system operation and renewable energy power generation planning.

II. ATC MODEL BASED ON OPF

Uncertainties have been considered to impact the transfer capability, so ATC calculation will not consider transmission reliability margin alone. This calculation uses load factor to reflect the growth degree of load of sink area. The starting value of sink area is P_{Di}^0 and at this time $\lambda = 0$ corresponding to the existing transmission case; when each node of sink area grows according to the active proportion K_{Pi} of the existing load, λ will be maximum. That is to say, when $P_{Di}(\lambda_{\max}) = P_{Di}^0 + K_{Pi}\lambda_{\max}$, transfer capability will be the maximum. Therefore, we only need to calculate λ reaches its maximum value $P_{Di}(\lambda_{\max})$ and ATC can be calculated as

$$P_{ATC} = \sum_{i=1}^{\sin k} P_{Di}(\lambda_{\max}) - \sum_{i=1}^{\sin k} P_{Di}^0 - P_{CBM} \qquad (1)$$

where, $P_{Di}(\lambda_{\max})$ is the load maximum value of node i in sink area; $\sin k$ is set of all the nodes in sink area; P_{CBM} is the margin of capacity benefit, this paper take 5% of the maximum transfer capability.

The load factor reaching the biggest is an optimization problem, and this paper solve it by using OPF, the model is expressed as

$$\left.\begin{array}{l} \min -\lambda \\ s.t. \\ G(x,\lambda) = 0 \\ H(x,\lambda) \geq 0 \end{array}\right\} \qquad (2)$$

where, $G(x,\lambda)$ is equality constraints, namely power flow equation of system; $H(x,\lambda)$ is inequality constraints, including voltage amplitude constraints of a node, the generator capacity constraints, and the line thermal stability constraints.

III. RENEWABLE ENERGY POWER GENERATION TURBINE MODEL

A. Wind Turbine Model

Regarding wind turbine model as PQ node [4] will affect the accuracy of calculation, as wind turbine uses induction generator, the active power of its output depends on wind speed, and consumption of reactive power is related with generator voltage, the output of active power, as well as slip. So this paper simplifies equivalent circuit by PX model in Figure 1. V is the generator voltage; r_s is the stator resistance; x_s is the stator reactance.

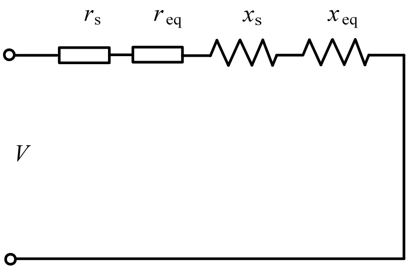

Figure 1. Simplified equivalent circuit of induction generator

Equivalent resistance r_{eq} and equivalent reactance x_{eq} can be respectively expressed as:

$$r_{eq}(s) = \frac{r_r x_m^2 / s}{(r_r/s)^2 + (x_m + x_r)^2} \qquad (3)$$

$$x_{eq}(s) = \frac{(r_r/s)^2 x_m + x_m x_r (x_m + x_r)}{(r_r/s)^2 + (x_m + x_r)^2} \qquad (4)$$

where, x_m is magnetizing reactance; s is slip coefficient; r_r is rotor resistance; x_r is rotor reactance

When $r(s) = r_s + r_{eq}(s)$, $x(s) = x_s + x_{eq}(s)$, the active power outputted to system by generator and reactive power demand of the generator can be expressed as:

$$P_G(V,s) = \frac{V^2}{r^2(s) + x^2(s)} r(s) \qquad (5)$$

$$Q_G(V,s) = \frac{V^2}{r^2(s) + x^2(s)} x(s) \qquad (6)$$

From equivalent circuit of generator and mathematical model, it can be seen that wind turbine has three unknown parameters, namely terminal voltage, reactive power demand and slip coefficient. These parameters can be solved by the augmented power flow equations. If $F_{Pi}(\delta,V)$ and $F_{Qi}(\delta,V)$ respectively are active and reactive power equation of the ordinary flow, then corresponding i node flow equation connecting wind turbine is

$$f_{Pi} = F_{Pi}(\delta,V) - P_{Gi}^s + P_{Di} = 0 \qquad (7)$$

$$f_{Qi} = F_{Qi}(\delta,V) + Q_{Di} + Q_{Gi}(V_i, s_i) = 0 \qquad (8)$$

where, P_{Di} and Q_{Di} are respectively active and reactive power load; $Q_{Gi}(V_i, s_i)$ is reactive power demand of wind turbine which is connected to i node. P_{Gi}^s is active power outputted to the system by wind turbine, which depends on wind speed. The purpose of this paper is to research the impact of the uncertainties of renewable energy power generation, so the time sequence changing characteristic of the speed is not considered. Despite, based on normal distribution, P_{Gi}^s reflects the uncertainties as a given value by Monte Carlo simulation sampled.

In the above model added a variable sliding coefficient, for the solution of flow equations an equation should be added, namely active power outputted to the system $P_{Gi}(V_i, s_i)$ should equal to above given value P_{Gi}^s, which can be expressed as:

$$f_{PGi}(V_i, s_i) = -P_{Gi}(V_i, s_i) - P_{Gi}^s = 0 \tag{9}$$

If N_G wind turbines are connected to the system, then N_G variables and additional active power equation are added. These additional connect with ordinary flow equations to augmented power flow equation, and unknown variables can be solved by Newton-Raphson. The augmented power flow equation is formula (10).

Wind turbine can be easily introduced into OPF shown in formula (2) by PX model. Compared with no wind turbine, additional active power formula (9) is added in the equality constraint.

$$\begin{bmatrix} \frac{\partial f_P}{\partial \delta} & \frac{\partial f_P}{\partial V} & \frac{\partial f_P}{\partial s} \\ \frac{\partial f_Q}{\partial \delta} & \frac{\partial f_Q}{\partial V} & \frac{\partial f_Q}{\partial s} \\ \frac{\partial f_{PG}}{\partial \delta} & \frac{\partial f_{PG}}{\partial V} & \frac{\partial f_{PG}}{\partial s} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \\ \Delta f_S \end{bmatrix} = \begin{bmatrix} \Delta f_P \\ \Delta f_Q \\ \Delta f_{PG} \end{bmatrix} \tag{10}$$

B. Solar Generator Turbine Model

Solar power (photovoltaic) generation transfers solar energy to electric energy by solar panels. Its power generation efficiency depends on weather conditions, so it is possible that generating capacity deviates from predicted values in a specific period of time. In this paper, solar generator turbine is to simulate by PQ nodes. Based on normal distribution, the output intermittent and stochastic is to simulate by Monte Carlo simulation sampled.

IV. MONTE CARLO SIMULATION

The uncertainties of renewable energy power generation system are mainly reflected in three aspects, namely system status, load, and renewable power generation output. Assessment of transmission capability is based on above three parameters and the predictive value. In order to more accurate assessment, some documents considered the characteristics of parameters time sequence changing, such as speed change of renewable energy power generation [4], load fluctuation [7], the state of system components [4,7] and so on. This paper attempts to study the uncertainties of renewable energy power generation, so it does not consider the time sequential variation of parameters, but simulate uncertainties of system by Monte Carlo simulation sampled.

Normal distribution probability model is used in renewable energy power generation output and the simulation process of load uncertainties. Its normal distribution probability density function is

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \tag{11}$$

where, μ is the average of predictive value, σ reflects standard deviations of the forecast error. x is Monte Carlo simulation sample values, which is determined as

$$x = x_\mu + \sigma Z \tag{12}$$

where, Z is random numbers of normal distribution, which can be determined by Box-Muller method.

System state uses a two-state model, that is to say, it considers normal operation and failure of generating units and transmission lines. Based on failure probability of equipment got from historical experience, corresponding network status of every sample can be determined by Monte Carlo simulation, specific operating process was carried out according to Reference [8].

V. ATC PROBABILITY ASSESSMENT INDICATORS

In order to study the impact on ACT of renewable energy power generation, the expected value and variance of ATC needs to be compared under different circumstances. Their assessment values $E_{ATC}(x_i)$ and $V_{ATC}(x_i)$ are respectively calculated as

$$E_{ATC}(x_i) = \frac{1}{N}\sum_{i=1}^{N} F_{ATC}(x_i) \tag{13}$$

$$V_{ATC}(x_i) = \frac{1}{N}\sum_{i=1}^{N} \left[F_{ATC}(x_i) - E_{ATC}(x_i)\right]^2 \tag{14}$$

where, $F_{ATC}(x_i)$ is an ATC sample value under a certain sampled state; N is number of the simulation samples.

VI. IMPROVEMENT AND APPLICATION OF DIFFERENTIAL EVOLUTION ALGORITHM

OPF described in this paper is a nonlinear optimization problem. At present, intelligent algorithms have been used in it and have obtained some research achievements, such as interior point method [9-14], sequential quadratic programming (SQP) [15-18], and particle swarm optimization (PSO) [19-26]. The traditional algorithms to solve this large-scale optimization problem of ATC with nonlinearity and many constraints have certain defects: the poor robustness; single search mechanism was used, so it was difficult to jump out of local optimal solutions and find global optimal solutions, which made the calculation results are too conservative to achieve the purpose of optimization calculation, even could cause serious waste in transmission resources. In the process of dealing with such problems, intelligent algorithms have excellent performances: the better robustness; parallel random search strategy is used, so the global optimal solution can be found and its value is more coincident with the factual data. This paper will use the Differential Evolution (DE) to solve ATC.

A. Algorithm Introduction

DE makes direct search in the search space parallel through N_P (population size) D-dimensional parameter vector $\boldsymbol{x}_{ij}(i=1,2,\cdots, N_P, j=1,2,\cdots, D)$, D is the number of decision variable. There are 3 basic operation of DE: mutation, crossover and selection, the basic strategy of DE was performed according to previous reports [27-28].

B. Mutation Strategy

The most basic mutation of DE is the difference vector of the parent. With each target vector $\boldsymbol{x}_i^t$, mutation strategy is improved as

$$\boldsymbol{v}_i^{t+1}=\alpha \boldsymbol{x}_{r_5}^t+(1-\alpha)\boldsymbol{x}_{gbest}^t+F[(\boldsymbol{x}_{r_1}^t-\boldsymbol{x}_{r_2}^t)+(\boldsymbol{x}_{r_3}^t-\boldsymbol{x}_{r_4}^t)] \quad (15)$$

$$\alpha=(T-t)/T \quad (16)$$

where, r1~r5 are different index number in groups; $\boldsymbol{x}_{gbest}^t$ is the best individual with fitness value. F is scaling factor, $F\in$ [0, 2]; T is the maximum number of iteration, and t is the current number of iteration; α is simulated annealing factor, $\alpha\in$ [0, 1]. In the process of research, α gradually changes from 1 to 0, then $\boldsymbol{x}_{r5}^t$weight decreases and $\boldsymbol{x}_{gbest}^t$ weight increases. As a result, it ensures that algorithm not only has strong global search capability, but also has fast convergence speed and accuracy.

C. Crossover Strategy

This paper puts forward a solution including time-varying crossover probability constant

$$C_R=C_{R\min}+(C_{R\max}-C_{R\min})\frac{t}{T} \quad (17)$$

where, $C_{R\max}$ and $C_{R\min}$ are maximum and minimum crossover probability respectively. This method makes C_R from small to big with the increase of iteration number. Therefore, in the initial stage of algorithm search, $\boldsymbol{x}_i^t$ makes contribution to $\boldsymbol{u}_i^{t+1}$, which improve the global search capability. While in the latter part, $\boldsymbol{v}_i^{t+1}$ makes contribution to $\boldsymbol{u}_i^{t+1}$, which improve the local search ability.

D. Establishment of Fitness Function

By flow calculation, this paper eliminates equality constraint to reduce problem dimension, and deals with inequality constraints by penalty function [20]. If there are n inequality constraints, $H_i(x,\lambda)\ge 0$ is the number of i , fitness function is

$$F_{itness}(x)=\begin{cases} f(x) & x\in H(x,y)\ge 0 \\ f(x)+\Delta(t,x) & other \end{cases} \quad (18)$$

where, $\Delta(t,x)$ is penalty function, this paper uses adaptive penalty function. Penalty value depends on the value of penalty factor $\left|H_i(x,\lambda)\right|$ and evolution generation t. The specific structure is

$$\Delta(t,x)=h(t)\sum_{i=1,i\notin H(x,y)\ge 0}^{n}\theta_i\times\left|H_i(x,\lambda)\right|^{\alpha_i} \quad (19)$$

where, $h(t)$ and θ_i are penalty coefficient; α_i is punishment force; $h(t)=t\sqrt{t}$; θ_i and α_i depend on penalty factor. In this paper, they are selected as follows

$$\alpha_i=\begin{cases} 1, penlty\ factor\le 1 \\ 2, other \end{cases} \quad (20)$$

$$\theta_i=\begin{cases} 10, penlty\ factor\le 0.001 \\ 20, penlty\ factor\le 0.01 \\ 100, penlty\ factor\le 1 \\ 300, other \end{cases} \quad (21)$$

E. Evaluation Criterion of Relative Merits of Individual

The optimal solution of a lot of the constrained optimization problem is located in or near the boundary constraints, that is to say, all or most of inequality constraints are equal in the optimal point. For this kind of problem, when the objective function is continuous, fitness value of infeasible solution nearby optimal solution may be superior to fitness value of a feasible solution within feasible region. DE is a kind of population search strategies, from the point of view of improving optimization efficiency, part of infeasible solutions to close to boundary can be compared with feasible solutions according to their fitness value in order to keep a certain amount of infeasible individuals, which are very beneficial. In this paper, a comparison strategy to test infeasible solution according to the constant proportion is put forward, the standards are as follows:

(1) When target individual x and experimental individual x' are all feasible, their fitness $F(x)$ and $F(x')$ are calculated to select the individual of smaller fitness of both.

(2) When target individual x and experimental individual x' are all infeasible, their value of penalty function $\Delta(x)$ and $\Delta(x')$ are calculated to select the individual of smaller value of penalty function of both.

(3) When one is feasible and another is infeasible in both of target individual and experimental individual, value of penalty function of infeasible individuals are calculated and they are arranged with increasing sequences, the front η% of infeasible individuals have opportunities to compare with corresponding target individuals or experimental individuals, individual of the smaller fitness will be selected.

VII. NUMERICAL EXAMPLE

Simulation study can be made by IEEE118 node test system. The system is divided into two regions, as in Figure 2. In order to make comparable research, 4 kinds

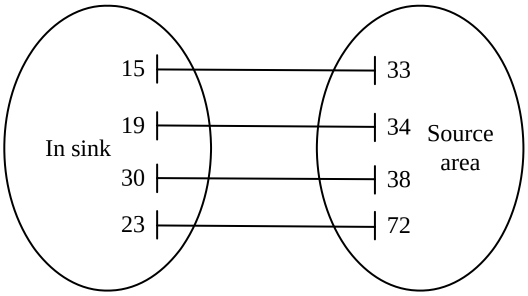

Figure 2. Diagram of the sectionalized test system

of penetration level of renewable energy power generation are set, as

Penetration level 1: There is no wind or solar power in system;

Penetration level 2: In sink area 2 wind farms and a solar station are added. Each wind farm has 50 wind turbines, and each unit is rated at 1.7MW, which is installed on the nodes 13 and 14. Each solar station has 20 solar generator sets whose rated power is 5MW, which is installed on the node 22.

Penetration level 3: In sink area 4 wind farms and 2 solar stations are added. Wind farms are installed on the node 13, 14, 16, 17; solar stations are installed on node 22 and 23.

Penetration level 4: In sink area 6 wind farms and 4 solar stations are added. Wind farms are installed on node 13, 14, 16, 17, 20, 115; solar stations are installed on node 22, 23, 29, 114.

The average of each wind turbine and solar generating unit is predicted at 1.3MW and 4MW. In order to assess the impact on system of renewable energy power generation and load, 6 study cases are considered in experiment, as in TABLE I.

A. Impact on ATC of Different Penetration Levels

Figure 3 shows value of ATC expectations under different penetration levels for the corresponding case 6. It can be seen from the data in the TABLE I, regional ATC is gradually increasing with the improvement of penetration level. In fact, renewable energy power provides power support for it near load, so the load between regions reduces and transmission capacity increases.

TABLE I.
PARAMETER OF CASES

Standard deviation	Case					
	1	2	3	4	5	6
σ_D %	0	15	0	0	0	15
σ_W %	0	0	50	0	50	50
σ_S %	0	0	0	50	50	50

where, σ_D 、 σ_W 、 σ_S *are respectively load, wind power, and the standard deviation of solar power output prediction.*

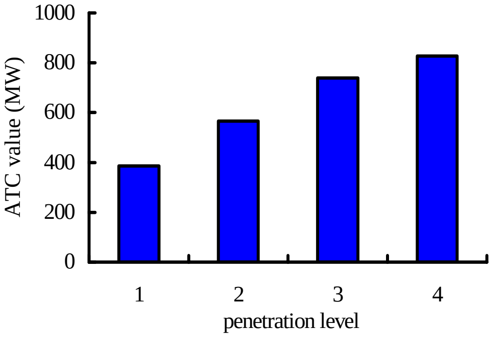

Figure 3. ATC under different penetration level (MW)

B. Impact on ATC of Uncertainties of Renewable Energy Power Output

In order to reflect the impact on ATC volatility of uncertainties of renewable energy power generation based on ATC calculation between sink and source area, different penetration and the corresponding ATC variance are calculated, as in TABLE II.

From TABLE II, we can see that under the same penetration level, not only load fluctuations can make impact on ATC, but also the intermittent and stochastic of wind power and solar power output enlarge ATC fluctuations. In addition, we can see that with the improvement of penetration level, ATC fluctuations in each case increases gradually, which is due to the increase of system uncertainties with the improvement of penetration level.

C. Impact on ATC from Installation Location of Renewable Energy Power Generation Equipment

Corresponding to case 6, wind farms and solar station under penetration level 2, 3, 4 are transferred from sink area to source area, and ATC between the two areas and its variance are calculated. The results are shown in TABLE III.

It can be seen from TABLE III that before relative transfer, ATC value after transfer and its variance have little change under different penetration level, which instructs that different impacts on ATC are brought by renewable energy power generation incorporated system in different locations. The impact on ATC will be greater when incorporating system in sink area, while it is opposite in source area. Therefore, from the point of view to improve ATC, renewable power generation should be

TABLE II.
ATC VARIANCES OF DIFFERENT STATUS (MW2)

Penetration level	Case					
	1	2	3	4	5	6
2	309	993	589	466	785	1367
3	410	1120	823	716	1200	1801
4	563	1269	921	835	2201	2969

TABLE III.
ATC (MW) AND VARIANCES UNDER DIFFERENT STATUS (MW2)

Compared value		Penetration level		
		2	3	4
Before transfer	ATC	566	739	827
	variance	1367	1801	2969
After transfer	ATC	328	350	367
	variance	422	361	408

chosen to incorporate system in sink area to system planning.

D. Study on DE Calculation Efficiency

In order to verify the advancement of improved DE (IDE) based on case6 and penetration level3 of simulation experiment, IDE compare with DE, PSO [19] under the same operating environment of the same computer. The results are tested through MATPOWER of MATLAB are shown in TABLE IV.

It can be seen from TABLE IV that IDE and the corresponding ATC values are close to MATPOWER, which reflects its good global search capability. In addition, from the view of average evolution generation and run-time, IDE has strong local search capacity, high speed and efficiency, which instructs that the calculation used in this paper and improved strategy are effective.

VIII. CONCLUSIONS

ATC calculation of renewable energy power incorporated system needs to consider a large number of uncertainties, ATC calculation including wind power and solar power, and assessment model are established based on Monte Carlo simulation. ATC calculation uses improved DE, which has high speed and accuracy. The impact on ATC of renewable energy power generation incorporated system is assessed by uncertainties of simulation power system and the corresponding ATC calculation. Simulation example verifies the effectiveness of proposed models and methods. The results achieved can provide evidence for the planning and operation of renewable energy power generation.

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REFERENCES

[1] G. G. Chen, H. T. Lei, H. B. Fang, J. Xu, “Solving DOPF in VSWGs Integrated Power System Using Improved Evolutionary”, *Journal of Computers*, vol. 6, no. 3, pp. 556-563, 2011.

[2] X. S. He, C. F. Gao, B. Wang, Z. Y. Luo, “A Novel Control Algorithm for Maximum Power Point Tracking of Photovoltaic”, *Journal of Computers*, vol. 7, no. 4, pp. 959-964, 2012.

[3] NERC, “Available transfer capability definition and determination: a reference document prepared by TTC task force”, New Jersey: North American Electric Reliability Council, 1996.

[4] Paensuwan Nattawut, Yokoyama Akihiko, Verma S.C., Nakachi Yoshiki, “Investigation of Impact of Renewable Energy Penetration on System Total Transfer Capability at Risk”, *IEEJ Transactions on Power and Energy*, vol. 129, no. 12, pp. 1523-1531, 2009.

[5] C. S. Wang, W. Sun, X. G. Wang, “Total transfer capability calculation of power system including large-scale wind farm”, *Automation of Electric Power Systems*, vol. 31, no. 2, pp.17-21, 2007.

[6] M. Wang, M. Ding, “Probabilistic calculation of total transfer capability including large scale solar park”, *Automation of Electric Power Systems*, vol. 34, no. 7, pp.31-35, 2010.

[7] G. Y. LI, Y. J. GAO, M. ZHOU, “Sequential Monte Carlo simulation approach for assessment of available transfer capability”, *Proceedings of the CSEE*, vol. 28, no. 25, pp. 74-79, 2008.

[8] C. S. Wang, X. G. Wang, P. Zhang, “Fast calculation of probabilistic total transfer capability considering static voltage stability constraints and the probability of device contingencies”, *Proceedings of the CSEE*, vol. 28, no. 10, pp.8-13, 2008.

[9] Y. Xia, K. W. Chan, M. B. Liu, “Calculation of available transfer capability with transient stability constraints”, *Proceedings of the 2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, pp. 128-132, 2004.

[10] Yin Li, B. M. Zhang, H. B. Sun, W. C. Wu, “Security constrained optimal power flow based on nonlinear interior point method part one theory analysis”, *Automation of Electric Power Systems*, vol. 31, no. 19, pp. 7-13, 2007.

[11] F. Liu, W. Yan, G. Y. Xu, “Dynamic optimal power flow with decomposed predictor-corrector interior point

TABLE IV.
CONTRAST FOR ALGORITHM EFFICIENCY

Compared Project	Algorithm category			
	DE	IDE	PSO	MATPOWER
ATC(MW)	757.6	735.9	780.1	740.1
Average evolutionary generations	39	21	42	—
Running time (s)	135	128	141	138

method", *Automation of Electric Power Systems*, vol. 31, no. 14, pp. 38-42, 2007.

[12] L. Xie, Chiang Hsiao-Dong, "Weighted multiple predictor-corrector interior point method for optimal power flow", *Electric Power Components and Systems*, vol. 39, no. 2, pp. 99-112, 2011.

[13] Yamin H.Y., "Dynamic optimal power flow using interior point method and benders decomposition considering active and reactive constraints", *Electric Power Components and Systems*, vol. 34, no. 12, pp. 1377-1393, 2006.

[14] Sousa Andréa A., Torres Geraldo L., Cañizares Claudio A., "Robust optimal power flow solution using trust region and interior-point methods", *IEEE Transactions on Power Systems*, vol. 26 no. 2, pp. 487-499, 2011.

[15] Shaaban Mohamed, W. X. Li, Z. Yan, Y.X. Ni, F. F. Wu, "Calculation of total transfer capability incorporating the effect of reactive power", *Electric Power Systems Research*, vol. 64, no. 3, pp.181-188, 2003.

[16] Sivasubramani S., Swarup K.S., "Sequential quadratic programming based differential evolution algorithm for optimal power flow problem", *IET Generation, Transmission and Distribution*, vol. 5, no. 11, pp.1149-1154, 2011.

[17] Vovos P.N., Bialek J.W., Harrison G.P., "Optimal generation capacity allocation and network expansion signaling using OPF", *39th International Universities Power Engineering Conference*, pp. 1327-1331, 2004.

[18] Nejdawi Imad M., Clements Kevin A., Davis Paul W., "Efficient interior point method for sequential quadratic programming based optimal power flow", *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp.1179-1183, 2000.

[19] C. H Zhang, R. F. Sun, C. X. Liu, Y. Fan, S. B. Niu, Y. H. Song, "Improved particle swarm optimization algorithm and its application in power system transfer capability calculation", *Automation of Electric Power Systems*, vol. 31, no. 7, pp.20-24, 2007.

[20] H. T. Huang, H. Zhen, L. Z. Zhang, "Study of available transfer capability based on improved particle swarm optimization", *Proceedings of the CSEE*, vol. 26, no. 20, pp.45-49, 2006.

[21] AlRashidi M.R., AlHajri M.F., El-Hawary M.E., "Enhanced particle swarm optimization approach for solving the non-convex optimal power flow", *World Academy of Science, Engineering and Technology*, vol. 62, no. 2, pp.651-655, 2010.

[22] W.B. Liu, M. Li, X. J. Wang, "An improved particle swarm optimization algorithm for optimal power flow", *2009 IEEE 6th International Power Electronics and Motion Control Conference*, pp. 2448-2450, 2009.

[23] Umapathy Prabha, Venkataseshaiah Chinthakunta, Arumugam Muthukumarasamy S., "An efficient particle swarm optimization algorithm for optimal power flow solution", *Recent Patents on Electrical Engineering*, vol. 3, no. 2, pp.144-151, 2010.

[24] Hazra J., Sinha A.K., "A multi-objective optimal power flow using particle swarm optimization", *European Transactions on Electrical Power*, vol. 21, no. 1, pp.1028-1045, 2011.

[25] AlRashidi M.R., AlHajri M.F., El-Hawary M.E., "Enhanced particle swarm optimization approach for solving the non-convex optimal power flow", *World Academy of Science, Engineering and Technology*, vol. 62, no. 2, pp. 651-655, 2010.

[26] Mohamed Khalid H., Rao K.S.Rama, Hasan Khairul Nisak Bt Md, "Optimal parameters of interline power flow controller using particle swarm optimization", *Proceedings 2010 International Symposium on Information Technology-Engineering Technology*, pp. 727-732, 2010.

[27] K. Price, "Differential evolution: a fast and simple numerical optimizer", *Biennial Conference of the North American Fuzzy Information Processing Society*, pp. 524-527, 1996.

[28] S. Rainer, and K. Price, "Differential evolution-a simple and efficient heuristic for global optimization over Continuous Spaces", *Journal of Global Optimization*, vol. 11, no. 4, pp.341-359, 1997.

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