Available Transfer Capability Determination for the Electricity Market using Cuckoo Search Algorithm

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Abstract—**In the electricity market, power producers and customers share a common transmission network for wheeling power from generation to consumption points. All parties in this open access environment may try to produce energy from cheaper sources for greater profit margin, which may lead to transmission congestion, which could lead to violation of voltage and thermal limits, threatening the system security. To solve this, available transfer capability (ATC) must be accurately estimated and optimally utilized. Thus, accurate determination of ATC to ensure system security while serving power transactions is an open and trending research topic. Many optimization approaches to deal with the problem have been proposed. In this paper, Cuckoo Search Algorithm (CSA) is applied for determining ATC problem between the buses in deregulated power systems without violating system constraints such as thermal, voltage constraints. The suggested methodology is tested on IEEE 14 and IEEE 24-bus for normal and contingency cases. The simulation results are compared with the corresponding results of EP, PSO, and GWO and show that the CSA is an effective method for determining ATC.**

Keywords-CSA; ATC; congestion; electricity market

I. INTRODUCTION

One of the key features of the competitive electricity market is fair and open transmission access of the network to all users which may result to the frequent overloading of transmission system facilities. Assessment of available transfer capability for the economic utilization of the available system components with regard to system security plays a vital role in operational planning and real time operation of a system. With the development of renewable energy power generation technology and the increase of power load demand, renewable energy power generation can not only service specific users outside the power grid, but also can be massively incorporated into the power grid. Renewable energy power generation has many advantages, but its intermittent and stochastic output may influence the power system. Renewable energy power generation could increase the uncertainties of the power system which has significant effects on the transfer capability of the transmission system. Hence, transmission congestion management problem and analysis of the impacts of renewable energy has become an important challenge [1-4].

Secure and reliable operation of transmission network requires the Independent System Operators (ISO) to determine and update ATC at regular intervals for its optimal commercial use [5]. The ATC of a transmission network is the unutilized transfer capability of the network for the transfer of power for further commercial activity, over and above the already committed usage [6]. Essentially, ATC is a measure of the extra transmission capability above the base case power transfer for the purpose of power marketing. ATC value can be derived by considering various parameters relating to transfer capabilities such as Total Transfer Capability (TTC), Transmission Reliability Margin (TRM), and Capacity Benefit Margin (CBM). TTC is the summation of all the network transfers (base case and commercial transfers) including the margins for system security and reliability, and existing transmission commitments (ETC). TRM is the network margin reserved for system uncertainties whereas CBM is the network margin reserved for external generation in case of emergency generation outages. It is measured by the loss of load expectation. Adequate ATC is needed to ensure all economic transactions, while sufficient ATC is needed to facilitate electricity market liquidity. It is necessary to maintain economical and secure operation over a wide range of system operating conditions and constraints. An accurate value of ATC can be used in forecasting future upgrading of the transmission network. The precise calculation of ATC should include system constraints such as voltage limit, thermal limit, real and reactive power generation limit, and system uncertainties.

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Several approaches have been proposed for ATC computation including linear approximation methods (LAMs) [7], Repetitive Power Flow (RPF) [8], Continuation Power Flow (CPF) [9], Optimal Power Flow (OPF) [10], and Artificial Intelligence (AI) techniques [11]. Different AI techniques have been used to solve various optimization problems [12-14]. Applying meta-heuristic algorithms for determining the ATC have been proposed recently: Genetic Algorithm (GA) [15], Bee Algorithm (BA) [16], Particle Swarm Optimization (PSO) [17], and Evolutionary Programming (EP) [18-19]. AI approaches are employed to avoid local optimal solutions associated with conventional optimization techniques, especially for highly nonlinear systems.

Authors in [20] have developed a new meta-heuristic algorithm called Cuckoo Search Algorithm (CSA) which is inspired from the obligate brood parasitic behavior of some cuckoo species. A cuckoo bird will choose a random nest of other species and lay and dump its egg in it. An egg is either hatched and carried over to the next generation or abandoned by the host bird. It is an efficient meta-heuristic algorithm that balances between the local search strategy (exploitation) and the whole space (exploration) [21]. In each generation, there are two new populations created using the Levy flight and discovering alien egg mechanisms. The first mechanism helps CSA to explore the search space while the second mechanism supports CSA to exploit the search space, ensuring that the obtained results from CSA have better quality compared to others. In addition, there is only one control parameter for CSA in the search process, which makes it more reliable for applying to the optimal problem. The CSA algorithm has been proposed for solving power system security in [22]. In this paper, CSA is applied for determining the ATC of power transactions between sources and sink areas in a deregulated power system considering thermal and voltage limits. The proposed approach is demonstrated on the IEEE 14-bus and the IEEE 24-bus test systems.

II. OBJECTIVE FUNCTION

The main objective of this work is to determine the available power that can be transferred from a specific set of generators of a source area to loads in a sink area, subject to real and reactive power generation limits, voltage limits, and line thermal limits. The ATC is determined by starting from an initial point and then increasing the load by a factor λ until a system limit is reached [15]. The details of ATC computation are given below:

$$F_{obj}^{ATC} = \sum_{i=1}^{load} P_{Di}(\lambda_{\max}) - \sum_{i=1}^{load} P_{Di}^{0}(\lambda_0) \quad (1)$$

Subject to:

- The real and reactive power balance equations:

$$\sum_{\forall j} P_{ij,c} + (1+\lambda)P_{Dio} = P_{Gio} + P_{Gi} \quad (2)$$

$$\sum_{\forall j} Q_{ij,c} + (1+\lambda)Q_{Dio} = Q_{Gio} + Q_{Gi} \quad (3)$$

- The power generation limits:

$$0 \le P_{Gio} + P_{Gi} \le P_{Gi}^{\max} \quad (4)$$

$$0 \le Q_{Gio} + Q_{Gi} \le Q_{Gi}^{\max} \quad (5)$$

- The voltage limits:

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (6)$$

- The apparent power flow limit:

$$\left|S_{ij}\right| = \sqrt{P_{ij,c}^2 + Q_{ij,c}^2} \le S_{ij}^{\max} \quad (7)$$

To effect the generation and load changes, the active power generation and the active and reactive loads in the source and sink areas, respectively, need to be modified using the scalar parameter λ.

$$P_{Gi}(\lambda) = P_{Gi}^{0} \,.\, (1+\lambda) \quad (8)$$

$$P_{Di}(\lambda) = P_{Di}^{0} \,.\, (1+\lambda) \quad (9)$$

$$Q_{Di}(\lambda) = Q_{Di}^{0} \,.\, (1+\lambda) \quad (10)$$

where P_{Gio}, P_{Dio} and Q_{Gio}, Q_{Dio} are the active and reactive power respectively of bus i in the base case. λ=0 corresponds to no transfer (base case) and $\lambda=\lambda_{max}$ corresponds to the largest value of transfer power that causes no limit violations. $P_{Di}(\lambda_{max})$ is the sum of load in sink area when $\lambda=\lambda_{max}$ while P_{Dio} refers to the sum of load when λ=0.

III. APPLICATION OF CSA ON ATC PROBLEM DETERMINATION

The steps of determining the ATC problem using the proposed CSA are presented below.

Step 1: Read the power system data and set associated parameters such as the host nests size n, the probability of an alien egg in a nest of a host bird to be discovered $Pa \in [0, 1]$, the number of variables to be optimized d, the maximum number of iterations *Itmax*.

Step 2: Initialize n host nests {Xi (i=1, 2, …, n)}. Each of these nests is concatenated of two strings and represents a feasible solution to the optimization problem.

Step 3: Evaluate the fitness function of the initial n host nests based on the results of power flow analysis, choose the best value of each nest $Xbesti$ (i=1, 2, ⋯ , n) and the global best nest among all nests *Gbest* which is corresponding to the best fitness function, store the fitness values and the best fitness value.

$$\begin{aligned} F_f = F_{obj} - k_P \sum_{i=1}^{NB} (P_{gi} - P_{gi}^{\lim})^2 - k_q \sum_{i=1}^{NB} (Q_{gi} - Q_{gi}^{\lim})^2 \\ -k_V \sum_{i=1}^{NB} (V_i - V_i^{\lim})^2 - k_S \sum_{i=1}^{NL} (s_{li} - S_{li}^{\max})^2 \end{aligned} \quad (11)$$

Step 4: Get cuckoos (new solutions) randomly based on the previous best nest via Lévy flights. The new solution for each nest is calculated using (12) and (13):

$$X_i^{new} = Xbest_i + \alpha \times rand_1 \times \Delta X_i^{new} \quad (12)$$

where $\alpha>0$ is the updated step size, $rand_1$ is a normally distributed stochastic number, and the increased value ΔX_i^{new} is determined by:

$$\Delta X_i^{new} = \frac{rand_u}{\left|rand_v\right|^{1/\beta}} \times \frac{\sigma_u}{\sigma_v} \times \left(Xbest_i - Gbest \right) \quad (13)$$

where $rand_u$ and $rand_v$ are two normally distributed stochastic variables with standard deviation σ_u and σ_v given in (14).

$$\begin{cases} \sigma_u = \left\{ \dfrac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta 2^{(\beta-1)/2}} \right\}^{1/\beta} \\ \sigma_v = 1 \end{cases} \quad (14)$$

where β is the distribution factor ($0.3\leq\beta\leq1.99$).

Step 5: Evaluate the new solutions' fitness function based on the results of power flow analysis, determine the newly best value of each nest $Xbest_i$ and the global best nest *Gbest* by comparing the stored fitness values in Step 3 with the newly calculated ones, update the best value of each nest $Xbest_i$ and the global best nest *Gbest*, store the fitness values and the best fitness value.

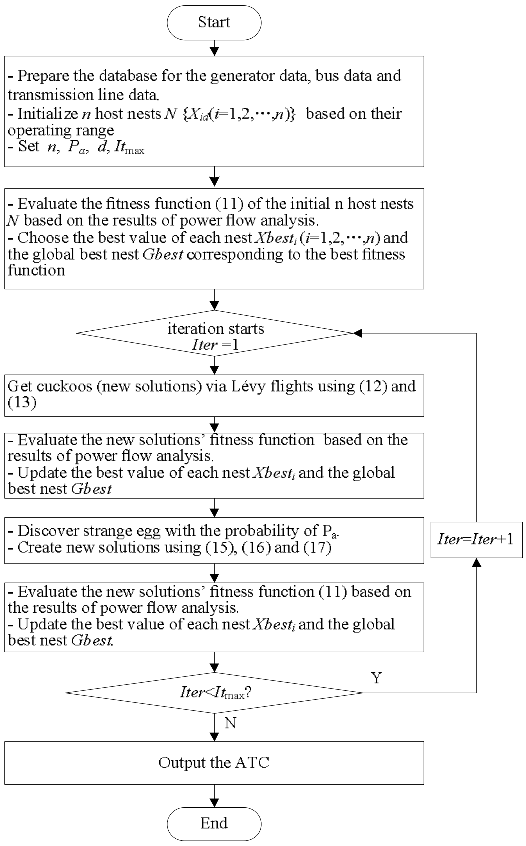

Fig. 1. The flowchart of the proposed process of applying the CSA to determine ATC

Step 6: Discovering an alien egg in a nest of a host bird with the probability of *Pa* creates a new solution for the problem similar to the Lévy flights. The new solution because of this action is calculated by (15), (16) and (17):

$$X_i^{disc} = Xbest_i + C \times \Delta X_i^{disc} \quad (15)$$

$$C = \begin{cases} 1 & if\ rand_2 < P_a \\ 0 & otherwise \end{cases} \quad (16)$$

$$\Delta X_i^{disc} = rand_3 \times [randp_1(Xbest_i) - randp_2(Xbest_i)] \quad (17)$$

where $rand_2$ and $rand_3$ are the distributed random numbers on the interval [0, 1], $randp_1(Xbest_i)$ and $randp_2(Xbest_i)$ are the random perturbation for positions of nests in $Xbest_i$.

Step 7: Evaluate the new solutions' fitness function based on the results of power flow analysis, determine the newly best value of each nest $Xbest_i$ and the global best nest *Gbest* by comparing the calculated fitness function from this new solutions with the stored fitness values in Step 5, update the best value of each nest $Xbest_i$ and the global best nest *Gbest*, store the fitness values and the best fitness value.

Step 8: If the predefined maximum number of iterations *Itmax* is reached, the computation is terminated and the results are displayed, else go to Step 4.

The flowchart of the proposed process is shown in Figure 1.

IV. NUMERICAL RESULTS

The ATC for each of the stipulated source to sink power transfers on two IEEE systems (IEEE 14-bus and IEEE 24-bus) reliability is tested. The IEEE 14-bus system consists of 5 generators and 20 lines as shown in Figure 2, while there are 41 lines and 11generators in the IEEE 24-bus system as shown in Figure 3. The network and load data are given in [23]. Based on experimental results, the optimal control parameters of CSA have been selected for the 14-bus and 24-bus systems as: The number of nests for the two systems is 20 and 25 respectively. The rate of detection of alien eggs and the maximum number of iterations are 0.25 and 100 respectively for both systems.

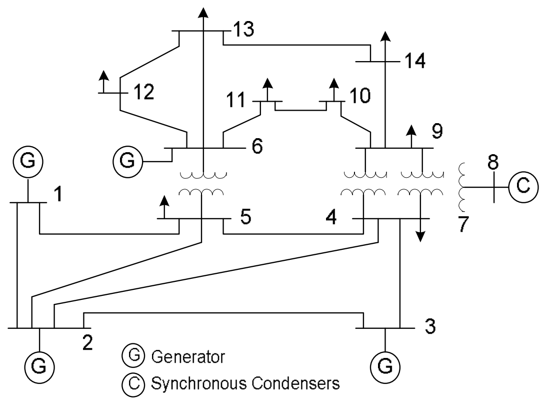

Fig. 2. The IEEE 14-bus system

In order to apply the proposed methodology in security studies and in congestion management, ATC values are computed in selected line outages. In the studies, the ATC margin is limited by bus voltage magnitude in the range of 0.95-1.15pu. The variation in ATC over the base state for both systems is studied with line outages, in line 16 (bus 13 to bus 14) in the IEEE 14-bus system and in line 8 (bus 4 to bus 9) in the IEEE 24-bus system.

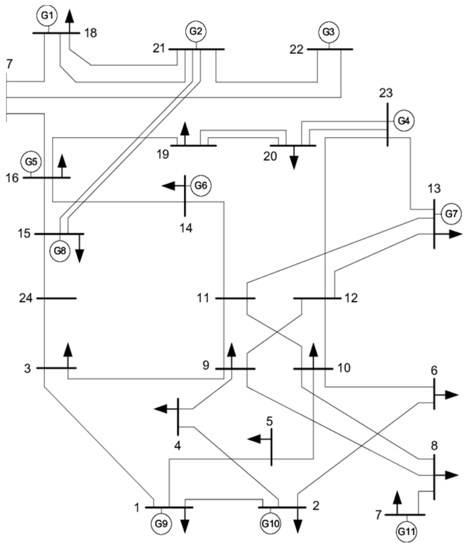

Fig. 3. The IEEE 24-bus RTS system

The ATC results for each of the stipulated source to sink power transfers on the IEEE 14-bus and 24-bus systems with and without line outage are tested by CSA, EP, GWO and PSO algorithms. From the results in Tables I-IV and Figures 4-9 it can be seen that CSA has the ability to converge quickly while achieving better ATC compared to EP, GWO and PSO while the power on the branches and the voltage at the buses also meet the allowable limits as shown in Figures 3 and 4.

TABLE I. ATC WITH NORMAL TOPOLOGY IEEE 14-BUS SYSTEM

Source/sink bus no	ATC			
	EP	GWO	PSO	CSA
1/9	54.2131	54.6663	54.6714	55.4486
1/10	43.7002	44.5024	44.3598	44.8332
1/12	28.9543	29.1568	29.0006	29.0220
1/13	28.8554	29.0571	29.3684	29.5996
1/14	38.5578	38.4526	39.1232	39.4719
1/4	213.0554	214.1656	213.9675	215.3233
1/3	149.1062	152.4437	152.9997	153.1253

TABLE II. ATC WITH NORMAL TOPOLOGY IEEE 24-BUS SYSTEM

Source/sink bus no	ATC			
	EP	GWO	PSO	CSA
23/15	790.9801	794.8945	794.9189	797.3823
22/9	375.4146	375.5291	377.2215	377.5662
22/5	249.8510	249.0834	251.1657	252.8519
21/6	65.3891	65.5217	65.9981	65.9995
18/5	250.2302	251.4353	251.9639	252.8634

The analysis results show that the CSA algorithm is able to solve the nonlinear optimization problem of handling ATC of power transactions between sources and sinks with equality and inequality constraints in the deregulated power system considering both thermal and voltage limits, and the ability of the algorithm to converge.

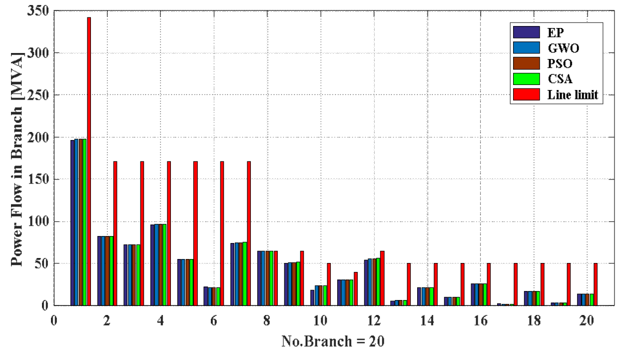

Fig. 4. Power flow branch of the IEEE 14-bus system without line outage

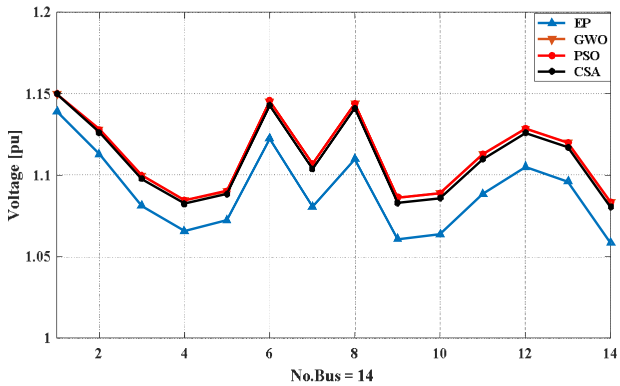

Fig. 5. Bus voltage profile of the IEEE 14-bus system without line outage

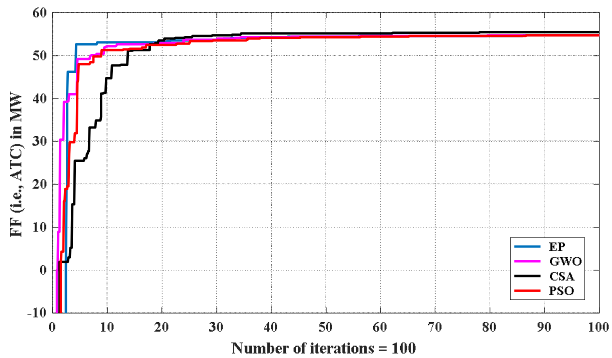

Fig. 6. Convergence characteristics of CSA compared to EP, GWO, and PSO for the IEEE 14 bus system without line outage

TABLE III. ATC WITH LINE OUTAGE TOPOLOGY FOR THE IEEE 14-BUS SYSTEM

Source/sink bus no	ATC			
	EP	GWO	PSO	CSA
1/9	46.8778	48.7042	48.7277	50.0297
1/10	46.7321	49.9837	48.7654	50.8314
1/12	30.8796	34.1418	34.1167	34.1631
1/13	26.9986	32.4435	31.9989	33.8311
1/14	37.5423	38.2378	35.2742	38.6285
1/4	206.751	209.8131	207.324	210.365
1/3	148.903	150.778	150.228	151.770

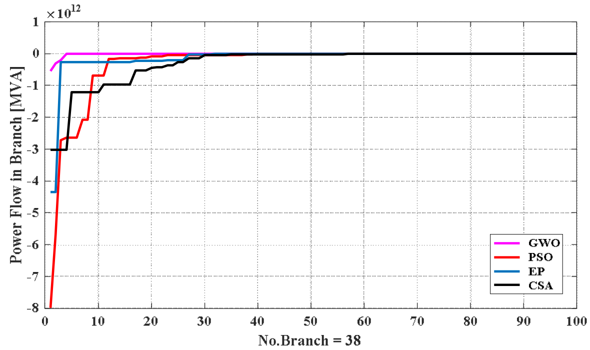

Fig. 7. Convergence characteristics of CSA compared to EP, GWO, and PSO for the IEEE 24-bus system without line outage

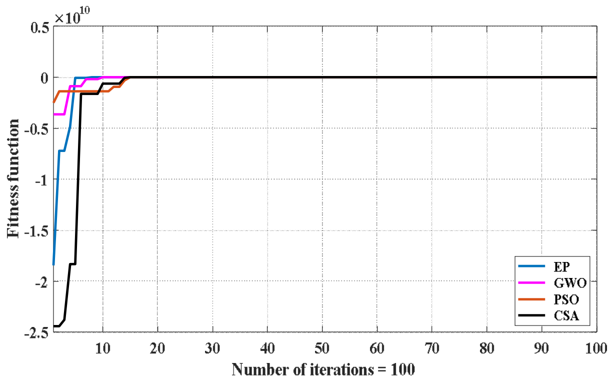

Fig. 8. Convergence characteristics of CSA compared to EP, GWO, and PSO for the IEEE 14-bus system with line outage

TABLE IV. ATC WITH LINE OUTAGE TOPOLOGY FOR THE IEEE 24-BUS SYSTEM

Source/sink bus no	ATC			
	EP	GWO	PSO	CSA
23/15	781.342	793.135	794.381	795.014
22/9	372.625	371.950	372.768	376.399
22/5	227.914	226.261	226.823	227.259
21/6	49.9771	51.0006	50.5363	51.1782
18/5	228.763	228.724	227.561	229.852

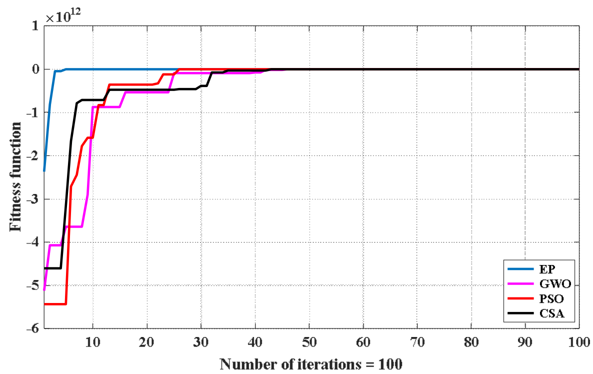

Fig. 9. Convergence characteristics of CSA compared to EP, GWO, and PSO for the IEEE 24-bus system with line outage

V. CONCLUSIONS

Accurate ATC determination in order to ensure system security while serving power transactions is one of the most challenging tasks in the electricity market. This paper has presented an implementation of the Cuckoo Search Algorithm to solve the problem which is formulated as a nonlinear optimization problem with equality and inequality constraints for handling the ATC of power transactions between sources and sinks in a deregulated power system considering both thermal and voltage limits. The results for the two systems have proved that the proposed CSA has remarkable robustness in maximizing the ATC. In all cases, the available transfer capability obtained by using CSA is much higher than that of EP, GWO, and PSO. Thus, CSA is one of the most effective methods for determining ATC in an electric power system.

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