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Optimal Allocation of FACTS Devices to Enhance Total Transfer Capability Based on World Cup Optimization Algorithm

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Abstract: In this paper, a new optimization algorithm called world cup optimization is proposed to achieve the optimal allocation of FACTS devices for maximizing the total transfer capability of power transactions between source and sink areas in a power system. World cup optimization algorithm in this study searches for the location and the size of FACTS. Multi-objective OPF with considering penalty function will be performed to solve and handle different inequality constraints. For analyzing the performance of the proposed method, it has been applied on IEEE 14 bus system. Final simulations show that the world cup optimization based method gives good results which may be used for online total transfer capability calculation and even the optimized method could enhance the transfer capability calculation value far more than OPF without FACTS devices.

Keywords: Total Transfer Capability (TTC); Thyristor Controlled Series Compensator (TCSC); world cup optimization algorithm

INTRODUCTION

In the last years, by increasing the competitive market about the electric power systems, electric utilities are forced to operate their facilities at a higher efficiency. Flexible AC Transmission Systems (FACTS) can be utilized in the existing power systems to control improve system dynamics, power flow and increase system reliability [1]. In addition, FACTS devices can be also employed for improving the power system transfer capability [2, 3]. Total Transfer Capability (TTC) is a significant index in power markets which is described as the amount of electric power that can be transferred from one area to another over the interconnected transmission network in a reliable manner based on pre-contingency and post- contingency conditions [4].

For enhancing the open-access of transmission systems, we need to calculate each control area and posted on a public communication system by providing a market signal of the capability of the transmission systems to deliver electric energy [5].

There are great deals of methods which have been developed for achieving TTC. These methods can be categorized into four types including: 1) linear ATC (LATC) method [6] which is based on linear incremental power flow approximation, 2) continuation power flow (CPF) method [7], and repetitive power flow (RPF) method [8], which utilize common loading factor to determine TTC value, and the last is optimal power flow (OPF) based method which can be applied by optimization techniques like sequential quadratic programming (SQP) [8] and transfer based security constrained optimal power flow (TSCOPF) method [9]. For achieving an optimal solution for the presented methods, convexity of the cost function is required.

Although, the OPF problem is generally non-convex, since, many local minima are especially in a highly nonlinear system, when FACTS devices are included in the system [10]. In addition, the parameters FACTS have additional control variables which cannot be calculated by traditional OPF because of making change in the admittance matrix.

Therefore, traditional optimization approaches may converge to a local optimal value in order to its directed search based on local information.

World cup optimization (WCO) algorithm which is introduced by Razmjooy et al. is a new meta-heuristic algorithm based on the human social sport competitions to get the cup (best solution). WCO, like to the other competitive optimization algorithms, starts with an initial population (teams) and the competition among them will be continued until one of them reach the best solution [11].

This algorithm can achieve the global optimal point by moving over hills and across valleys. Because of this, WCO is more robust than the existing direct search methods. Since, in this research, WCO algorithm is utilized for describing the optimal allocation of FACTS devices for maximizing the TTC of power transactions between source and sink areas. In this approach, WCO seeks for FACTS parameters and locations, real power generations except slack bus in source area, real power loads in sink area, and generation bus voltages to achieve the maximum TTC value.

Problem Formulation

For achieving the feasible TTC value of power transactions, OPF with FACTS devices is utilized. The main purpose in this study is to maximize the objective function which is related to the power that can be transferred from a specific set of generators in a source area to loads in a sink area, subject to real and reactive power generation limits, line flow limits, voltage limits, and FACTS devices operation limits.

In this research, thyristor-controlled phase shifter (TCPS), thyristor-controlled series capacitor (TCSC), unified power flow controller (UPFC), and static var compensator (SVC) are employed.

For applying the steady-state studies, mathematical models of the FACTS devices are utilized. Hence, for direct modifying the reactance of transmission lines, the TCSC is modeled. From the [12], injected power model is used to model the UPFC, TCPS and SVC. The final fitness function is considered as follows:

$$Max\ PI = \sum_{i=1}^{ND\_SNK} P_{DI} \tag{1}$$

Subject to:

$$P_{Gi} - P_{Di} + \sum_{k=1}^{m(i)} P_{Pi}(\alpha_{PK}) + \sum_{k=1}^{n(i)} P_{Ui}(V_{Uk}, \alpha_{UK}) - \sum_{j=1}^{N} V_i V_j Y_{ij}(X_S)\cos(\theta_{ij}(X_S) - \delta_i + \delta_j) = 0 \tag{2}$$

$$Q_{Gi} - Q_{Di} + \sum_{k=1}^{m(i)} Q_{Pi}(\alpha_{PK}) + \sum_{k=1}^{n(i)} Q_{Ui}(V_{Uk}, \alpha_{UK}) + Q_{Vi} + \sum_{j=1}^{N} V_i V_j Y_{ij}(X_S)\sin(\theta_{ij}(X_S) - \delta_i + \delta_j) = 0 \tag{3}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max},\ \forall i \in NG, \tag{4}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max},\ \forall i \in NG, \tag{5}$$

$$V_i^{\min} \le V_i \le V_i^{\max},\ \forall i \in N, \tag{6}$$

$$|S_{Li}| \le S_{Li}^{\max},\ \forall i \in NL, \tag{7}$$

$$0 \le X_{Si} \le X_{Si}^{\max} \tag{8}$$

$$\alpha_{Pi}^{\min} \le \alpha_{Pi} \le \alpha_{Pi}^{\max} \tag{9}$$

$$0 \le V_{Ui} \le V_{Ui}^{\max} \tag{10}$$

$$-\pi \le \alpha_{Ui} \le \pi \tag{11}$$

$$Q_{Vi}^{\min} \le Q_{Vi} \le Q_{Vi}^{\max} \tag{12}$$

Where *PI* is the objective (fitness) function and describes the total load in sink area. *PDi* and *QDi* are the real and reactive loads at bus *i*. *PGi* and *QGi* are the real and reactive power generations at bus *i,* respectively. $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the lower and upper limits of real power generation at bus *i* . $Q_{Gi}^{\min}$ and $Q_{Gi}^{\max}$ are the lower and upper limits of reactive power generation at bus *i*. $P_{Pi}(\alpha_{PK})$ and $Q_{Pi}(\alpha_{PK})$ define the injected real and reactive powers of TCPS at bus *i* .

$\theta_{ij}(X_S)$ and $Y_{ij}(X_S)$ are the angle and magnitude of the *ij*th element in bus admittance matrix with TCSC included. $P_{Ui}(V_{Uk}, \alpha_{UK})$ and $Q_{Ui}(V_{Uk}, \alpha_{UK})$ describe the injected real and reactive powers of UPFC at bus i . Q_{Vi} is the fixed injected reactive power of SVC at bus i . Vi and Vj are the voltage magnitudes at bus i and j respectively. δ_i *and* δ_j are the voltage angles of bus *i* and *j* . $V_i^{\min}$ and $V_i^{\max}$ are the lower and upper limits of voltage magnitude at bus *i*. $|S_{Li}|$ and $S_{Li}^{\max}$ are the *i*th line or transformer loading and the *i*th line or transformer-loading limit.

X_{Si} defines the vector of reactance of TCSC. α_{Pi} is the phase shift angle of TCPS at bus *i*. V_{Ui} is the voltage magnitude of UPFC at bus *i* . α_{Ui} is the voltage angle of UPFC at bus *i* . *N* is the total number of buses. *NG* is the number of generators. *NL* is the number of branches, and *ND _ SNK* is the number of load buses in sink area. For providing the inequality constraints in the optimization process, a penalty function is considered as below:

$$h(x_i) = \begin{cases} (x_i - x_i^{\max})^2 & if \ x_i > x_i^{\max} \\ (x_i^{\min} - x_i)^2 & if \ x_i < x_i^{\min} \\ 0 & if \ x_i^{\min} \le x_i \le x_i^{\max} \end{cases} \tag{13}$$

where, x_i has a a penalty function as *h*(*xi*) and $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper bounds of x_i . Since, the final objective function can be considered as follows:

$$Max \ PI = \sum_{i=1}^{ND\_SNK} P_{Di} - h(x_i) \tag{14}$$

World Cup Optimization algorithm

World Cup Optimization (WCO) algorithm is a new Meta-heuristic optimization algorithm which is inspired by the competitions among described teams to become the champion. In this algorithm, based on the rank of competitive teams, they stand in their proper seeds [11]. Indeed, rank has significant impact on the competitions which is achieved for each team according to its fails and wins in the past challenges [13].

By considering the parameter rank, *n* first stronger teams fall into the first seed; the other teams by less strength have been fall into the next seeds, hierarchically. In the first competition, first seed survive from the competition to save and upgrade itself to the higher level. In the following, all the other teams in seeds challenge with each other to achieve more scores to improve its rank and arise into the next stage. After the primary challenge, two high point teams in the seeds arise into the next stage and the rest are omitted.

It should be pointed that if the Play-Off is considered, the third place of each seed can also compete with the rest teams with the same conditions and the highest score of these teams can be arise into the higher level of competition. The challenge will be continued until one of teams achieves the highest score. WCO algorithm can be summarized as the following steps:

Step 1) Initialize and generate random continents and their teams

By considering N dimensional (N_{var}) optimization problem with *M* continents, continents will have an array of $1\times N_{\text{var}}$ as follows:

$$Continent = [country_1, country_2, \ldots, country_{N_{\text{var}}}] \tag{15}$$

$$country_i = [x_1, x_2, \ldots, x_{N_{\text{var}}}] \tag{16}$$

where x_i is the *i*th team in the country. The variable's values ($x_1, x_2, \ldots, x_{N_{\text{var}}}$) describe the floating point number. The rank of the continents can be achieved by considering the rank points f_r in a continent ($x_1, x_2, \ldots, x_{N_{\text{var}}}$) as follows:

$$Rank = f_r(continent) = f_r(x_1, x_2, \ldots, x_{O_{\text{var}}}), \tag{17}$$

$$O = N \times M \tag{18}$$

where *M* is the number of continents and N describes the variables dimension. Initializing in WCO is the best part of this algorithm; in this step, continents consist of different values of random teams by different standard deviation. For improving the convergence time, an interval is selected and gets the random values. Afterwards, it is divided into parts within their continents. This feature makes this algorithm to have a faster convergence rather than the other algorithms. The generated continents are matrices of size $N_{pop} \times N_{\text{var}}$; where N_{var} and N_{pop} are the number of variables in the problem and the number of teams, respectively. A number of random numbers of teams are also exist for the initial continents. Usually, in the real FIFA competitions, there are 5 continents with their teams.

Step 2) Evaluating Fitness Function

After the preliminary competition among teams, the next stage is to achieve the score points. These points are not so clear; because there is may be a continent with some teams which includes the most point (optimum fitness) while the others have weak points in the continents. To solve this problem, is to compute the mean value and the standard deviation of the continents as follows:

$$\overline{X}=\frac{1}{n}\sum_{i=1}^{n}X_i \tag{19}$$

$$\sigma=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i-\overline{X})^2} \tag{20}$$

where *n* is the number of members in *X* , $\overline{X}$ describes the mean value of the continent *X* and S shows the standard deviation of the continent *X*.

Step 3) Ranking stage

In this step, teams are ranked by the following approach:

$$\begin{aligned} &X_1=[X_{11},\dots X_{1n}]^T,\\ &X_2=[X_{21},\dots X_{2n}]^T,\\ &\dots,\\ &X_5=[X_{51},\dots X_{5n}]^T \end{aligned} \tag{21}$$

$$X_{Total}=[X_{11},\dots X_{1n},X_{21},\dots X_{2n},\dots,X_{51},\dots X_{5n}]^T \tag{22}$$

Where *n* is the number of teams for the continents and *T* describes the transpose operator. During this process, two optimal values for the continents have been selected and perched to the other vector (X_{Rank}) for the next competitions and the optimal values of X_{Total} have been selected as the first cup's champion:

$$X_{Rank}=[X_{11},X_{12},X_{21},X_{22},\dots,X_{51},X_{52}]^T \tag{23}$$

$$\begin{aligned} &X_{champion}=\min(X_{Total})=\\ &\min([X_{11},\dots X_{1n},X_{21},\dots X_{2n},\dots,X_{51},\dots X_{5n}]^T) \end{aligned} \tag{24}$$

where, $X_{champion}$ is the minimum value of the solutions.

Step 4) Apply the next stage of challenge among teams

In this part, the next competition will be performed by teams; new continents and teams including them will be regenerated according to the previous championship competitions and their ranking. Here the algorithm does differently from the real FIFA competition. To do this, a vector with two parts can be considered:

$$Pop=X_{total}=[X_{Best},X_{Rand}] \tag{25}$$

where X_{Rand} is a random integer in a definite interval, $Pop(X_{total})$ describes the new generated teams of the size ($N\times M$) and X_{Best} is a vector as follows:

$$L<X_{Best}<U \tag{26}$$

$$U=\frac{1}{2}\times ac\times(Ub+Lb) \tag{27}$$

$$L=\frac{1}{2}\times ac\times(Ub-Lb) \tag{28}$$

where *ac* is a coefficient between L_b and U_b as low and high bounds for the problem, respectively.

Step 5) Applying Exploration and Exploitation

X_{Rand} and X_{Best} describe the exploration and the exploitation operators. X_{Best} describes the process of possession of the formerly search space and X_{Rand} describes the process of generating new random integers in the search space. The size of X_{Best} and X_{Rand} are separated by Cross Point (CP) as follows:

$$\begin{aligned} X_{Rand} &= Pop(1:CP,M) \\ X_{Best} &= Pop(CP+1:N,M) \end{aligned} \tag{29}$$

Upgraded continents in this step are divided into *m* teams of *n* continents as follows:

$$Pop=[X_{Best},X_{Rand}]\rightarrow \begin{array}{l} X_{1new}=[Pop(1:k)] \\ X_{2new}=[Pop(k+1:l)] \\ X_{1new}=[Pop(l+1:r)] \\ X_{1new}=[Pop(r+1:s)] \end{array} \tag{30}$$

Step 6) If the criterion is reached, end the algorithm; otherwise repeat the algorithm.

The Study System and Results

In this study, IEEE 30 bus system has been utilized to demonstrate suitability of the proposed algorithm. Bus and line data can be found in [14]. The simulation studies were carried out on Core i-7, 16 GB of RAM, 2.6 GHZ system in MATLAB 2013 a platform.

Three areas by two generators are included in the system. The limit of voltage and angle for UPFC are in the intervals [0, 0.1](in per unit) and [-π, π] (in radian). The resistance of TCSC is in the interval [0, 0.02] in per unit, phase shifter angle limitation of TCPS is in the interval [0, 0.1] in radian and the reactive power injection limit for SVC is in the interval [0, 11.2] MVAR. Diagram of the IEEE 30-bus system is shown in the Fig. (1).

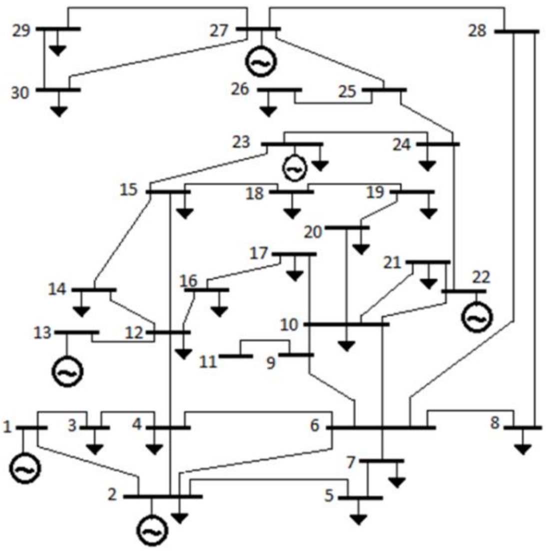

Figure1. Single line diagram of standard IEEE 30 Bus system

Table 1. TTC results from the IEEE 30-BUS system for the proposed method

Transfer		Without Facts		With Facts	
From	To	TTC (MW)	Limit Condition	TTC (MW)	Limit Condition
1	2	103.15	P_{G1}	114.98	Line 27-25
1	3	60.01	P_{G1}	68.23	Line 27-25
2	1	131.83	P_{G13}	135.64	P_{G13}
2	3	73.25	Line 27-30	78.12	P_{G13}
3	1	142.32	Line 22-21	153.11	Line 27-25
3	2	135.07	Line 24-23	141.29	Line 12-15

By using the proposed optimized method without FACTS devices, the load of area 2 increases to 103.15 MW.

The real power loads of area 2 in bus number sequence are [13.75, 0.0, 10.22, 14.06, 8.12, 12.87, 4.27, 13.93, 4.14, 24.56] MW. The generation upper limits at bus 1 form the limiting condition.

Using the proposed optimized method make the TTC value from the transaction from area 1 to area 2 is increased to 114.98 MW during multi-type of FACTS devices are incorporated in the system.

Here, SVC is installed at bus number 7 and TCPS, UPFC and TCSC are installed at line number 13, 11, and 39 respectively. From [14], the parameters of FACTS devices are considered: X_{Si} = 0.001 pu., α_{Pi} = 0.0032 rad, V_{Ui} = 0.003 pu., α_{Ui} = -2.828 rad, and Q_{Vi} = 0.923 MVAR.

CONCLUSION

In this paper, a new optimization algorithm is used to find optimal location and setting of TCSC for maximizing TTC. The paper illustrates step by step procedure for applying the World Cup Optimization algorithm to solve the problem of optimal placement. Matlab program is performed on IEEE 30 bus system. Experimental results show that optimally placed TCSC by WCO could significantly increase TTC, under normal and contingency conditions.

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