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Optimal Placement of Unified Power Flow Controllers in Electrical Power Systems for Maximize the Loadability of Transmission Lines Using Chaotic Optimization Algorithm

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Abstract: This paper presents a Modified Shuffled Frog Leaping Algorithm to obtein the optimal number and location of FACTS devices in a power system. Unified Power Flow Controller (UPFC) has great flexibility that can control the active and reactive power flow and bus voltages, simultaneously. Decoupled model of the UPFC is applied to maximize the system loadability subject to the transmission line capacity limits and specified voltage level. Chaotic Optimization Algorithm (COA) is a new memetic meta heuristic algorithm with efficient mathematical function and global search capability. The objective is to maximize the transmission system loadability subject to the transmission line capacity limits and specified bus voltage levels. Using the proposed method, the location of UPFCs and their parameters are optimized simultaneously. The proposed approach is examined and tested on IEEE 14-bus system. The results show that the steady state performance of power system can be effectively enhanced due to the optimal location and parameters of the UPFC.

Key words: Unified Power Flow Controller (UPFC); Maximize the Loadability of Transmission Lines; Chaotic Optimization Algorithm (COA).

INTRODUCTION

Recently, the steady state performance of power system has become a matter of grave concern in system operation and planning. As the power system becomes more complex and more heavily loaded, it can be operated in unstable or insecure situations like the cascading thermal overloads, the frequency and voltage collapse. For a secure operation of the power system, it is essential to maintain the required level of security margin (Hao, *et al*., 2004; Hingorani, *et al*., 1999). Then, power system controllability is required in order to utilize the available network capacitance adequately. The development of FACTS devices based on the advance of semiconductor technology opens up new opportunities for controlling the load flow and extending the loadability of the available transmission network. The UPFC is one of the family members of FACTS devices for load flow control, since it can either simultaneously or selectively control the active and reactive power flow along the lines (Nabavi-Niaki, *et al*., 1996; Noroozian; *et al*., 1997). Several papers have been published about finding the optimal location of the UPFC with respect to different purposes and methods (Fang, *et al*., 1999; Gerbex, *et al*., 2001). In (Fang, *et al*., 1999), augmented Lagrange multiplier method is applied to determine the optimal location of the UPFC to be installed. Although multi operating conditions can simultaneously be taken into consideration, the operating condition must be preassigned. (Gerbex, *et al*., 2001) provides the genetic algorithm to optimize three parameters of the multi-type FACTS devices including TCSC, TCPST, TCVR and SVC: the location of the devices, their types and their values, but another kind of FACTS device -UPFC has not been considered.

The main objective of this paper is to develop an algorithm for finding and choosing the optimal location of the UPFC in order to maximizing the system loadability while simultaneously satisfying system operating constraints including transmission line capacity and voltage level limits.

In this paper, an optimization-based tuning algorithm is proposed to optimal location problem Problem. This algorithm optimizes the total system performance by means of COA method. Chaos is a kind of characteristic of non-linear systems which is a bounded unstable dynamic behavior, which exhibits sensitive dependence on initial conditions and include infinite unstable periodic motions. The COA is based on ergodicity, stochastic properties and regularity of chaos. It is not like some stochastic optimization algorithms that escape from local minima by accepting some bad solutions according to a certain probability but COA searches on the regularity of chaotic motion to escape from local minima.

The optimal location problem of a given number of FACTS is converted to an optimization problem which is solved by the Chaotic Optimization Algorithm that has a strong ability to find the most optimistic results. In the following, the main results of tests on the IEEE 14-bus for the proposed COA method are shown to demonstrate the effectiveness of the proposed method.

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Upfc Equivalent Circuit:

In this paper, a simplified equivalent circuit of UPFC given in (Hao *et al*., 2004) used and is shown in Figure 1.

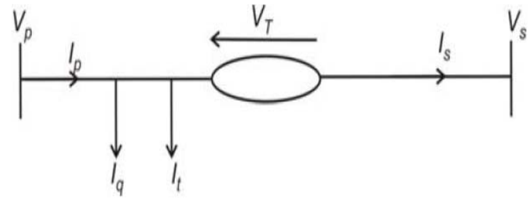

Fig. 1: Equivalent circuit of UPFC.

The three controllable parameters of UPFC are V_T, φ_T and I_q. V_T denotes the magnitude of the voltage injected in series with the transmission line through the series transformer. φ_T is the phase angle of this voltage. I_q is the shunt reactive current of UPFC. The UPFC parameters V_T, φ_T and I_q are chosen within a range due to physical and economic limitations.

$$V_T \in [V_{T\min}, V_{T\max}], \phi_T \in [0, 2\pi]$$

$$I_q \in [-I_{q\max}, I_{q\max}]$$

The limits of UPFC parameters are taken from (Fang, *et al*., 2005).

UPFC Power Equations:

The equivalent circuit of UPFC embedded in transmission line i-j is shown in Figure 2. The two power injections ($P_{i(inj)}$, $Q_{i(inj)}$) and ($P_{j(inj)}$, $Q_{j(inj)}$) of the UPFC are calculated according to the following expressions (Fang, *et al*., 2005):

$$P_{i(inj)} = -G_{ij}(e_i e_T + f_j f_T) + B_{ij}(f_j e_T - e_j f_T) + 2G^{'}(e_i e_T + f_i f_T) \quad (1)$$

$$Q_{i(inj)} = G^{'}(f_i e_T - e_i f_T) - B^{'}(e_i e_T + f_i f_T) - V_i I_q \quad (2)$$

$$P_{j(inj)} = -G_{ij}(e_i e_T + f_j f_T) - B_{ij}(f_j e_T - e_j f_T) \quad (3)$$

$$Q_{j(inj)} = G_{ij}(e_i f_T - f_j e_T) + B_{ij}(e_j e_T + f_j f_T) \quad (4)$$

Where:

$P_{i(inj)}$, $P_{j(inj)}$: the active power injections at bus *i* and *j*, respectively;
$Q_{i(inj)}$, $Q_{j(inj)}$: the reactive power injections at bus *i* and *j*, respectively;
e_i , f_i : real part and imaginary part of voltage at bus i;
e_j , f_j : real part and imaginary part of voltage at bus j;
e_T , f_T: real part and imaginary part of voltage of series voltage source, respectively and $e_T = V_T \cos(\varphi T)$, $f_T = V_T \sin(\varphi T)$
V_i : the voltage magnitude of bus *i* ;
G_{ij}, B_{ij}, g_{ij}, b_{ij} : the parameters of line $i - j$

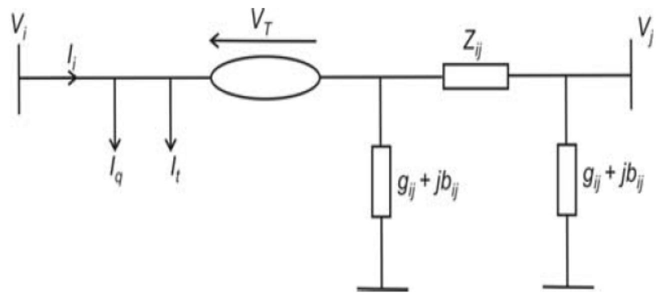

Fig. 2: Equivalent circuit of UPFC embedded branch.

Chaotic Optimization Algorithm (COA):

Chaos often exists in nonlinear systems. It is a kind of highly unstable motion of deterministic systems in finite phase space. An essential feature of chaotic systems is that small changes in the parameters or the starting values for the data lead to vastly different future behaviors, such as stable fixed points, periodic oscillations, bifurcations, and periodicity. This sensitive dependence on initial conditions is generally exhibited by systems containing multiple elements with nonlinear interactions, particularly when the system is forced and dissipative. Sensitive dependence on initial conditions is not only observed in complex systems, but even in the simplest logistic equation (Coelho, 2007). The application of chaotic sequences can be an interesting alternative to provide the search diversity in an optimization procedure. Due to the non-repetition of chaos, it can carry out overall searches at higher speeds than stochastic argotic searches that depend on probabilities (Liu, *et al*., 2005). The design of approaches to improve the convergence of chaotic optimization is a challenging issue. The simple philosophy of the COA includes two main steps: firstly mapping from the chaotic space to the solution space, and then searching optimal regions using chaotic dynamics instead of random search (Liu, B., Wang, *et al*. 2005). This chaotic map involves also non-differentiable functions which difficult the modeling of the associate time series. The Lozi map is given by (Coelho, 2007):

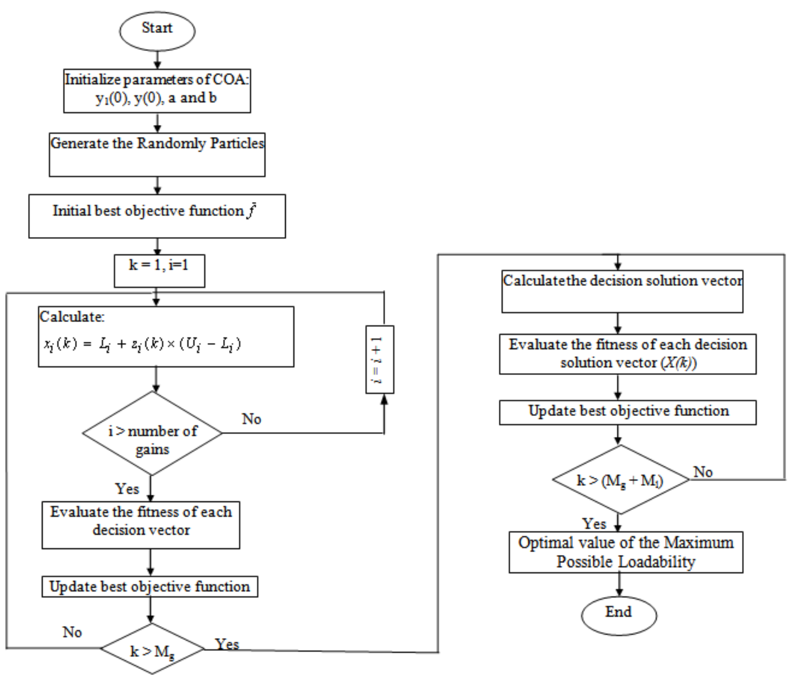

Fig. 3: Flowchart of the proposed COA.

$$y_1(k) = 1 - a \times |y_1(k-1)| + y(k-1) \tag{5}$$

$$y(k) = b \times y_1(k-1) \tag{6}$$

$$z(k) = \frac{y(k) - \alpha}{\beta - \alpha} \tag{7}$$

Where, k is the iteration number. In this work, the values of y are normalized in the range [0,1] to each decision variable in n-dimensional space of optimization problem. Therefore, y_1 ε [-0.6418, 0.6716] and [α, β] = (-0.6418, 0.6716). The parameters used in this study are a = 1.7 and b = 0.5, these values suggested by (Caponetto, R, *et al*. 2004). Many, unconstrained optimization problems with continuous variables can be formulated as the following functional optimization problem.
Find X to minimize $f(X)$, X= [x_1, x_2, …, x_n].

Where, f is the objective function, and X is the decision solution vector consisting of the n variables, x_i, bounded by lower (L_i) and upper limits (U_i). Figure 1 shows the flowchart of the proposed chaotic search procedure based on the Lozi map.

Where f is the objective function, and X is the decision solution vector consisting of n variables, x_i, bounded by lower (L_i) and upper limits (U_i). M_g and M_L are maximum number of iterations of chaotic Global search and maximum number of iterations of chaotic Local search, respectively. In this paper λ is step size in chaotic local search and linearly decreases from 0.1 to 0.01. Also, $\bar{f}$ and $\bar{X}$ are best objective function and best solution from current run of chaotic search, respectively.

Problem Formulation:

The aim of the optimization is to perform a best utilization of the existing transmission lines. In this respect, UPFC device is located in order to maximize the system loadability while observing thermal and voltage constraints. In other words, it was tried to increase the power transmitted by power system as much as possible to the costumers with holding power system in security state in terms of branch loading and voltage levels. The objective function is made in order to penalize configurations of the UPFC which lead to overload transmissions lines and over or under voltage at busses. The objective function is defined as the sum of two terms. The first one is related to the branch loading which penalizes overloads in lines. This term is called LF and is computed for all lines of the power system, if branch loading is less than 100% its value is equal to 1; otherwise, it decreases exponentionally with respect to the overload. To accelerate the convergence, product of values for all objective functions is calculated. The second part of the objective function is for voltage levels that are named BF. This function is calculated for all buses of power system. For voltage levels between 0.95 and 1.05, values of the objective functions is equal to 1. Outside this range, value decreases exponentionally with the voltage deviations. Therefore, for a configuration of UPFCs, objective function is given as:

$$LF = \begin{cases} 1 & , BL < 100 \\ \exp[0.0461(100 - BL)] & , BL \geq 100 \end{cases} \quad (8)$$

$$BF = \begin{cases} 1 & , 0 \leq V_L \leq 100 \\ \exp[-23.0259|1 - V_L| - 0.05] & , 1.05 \leq V_L \leq 1.25 \\ & or\, 0.75 \leq V_L \leq 0.95 \end{cases} \quad (9)$$

$$Objective\,Function \quad OF = \prod_{i=line} LF_i + \prod_{j=buses} BF_i \quad (10)$$

Where, LF is the line flow index and BL is the Branch Loading (Percentage of the line flow with respect to the line capacity rate). BF is bus voltage index and V_L is per unit value of the bus voltages. In this paper, all loads are increased in the same proportion and it is assumed that the increase in real power generation due to this increase in load is met by the generator connected to slack bus.

Numerical Results:

To verify the effectiveness and efficiency of the proposed COA based loadability maximization approach, the IEEE 14-bus power system is used as the test systems. The numerical data for IEEE 14-bus system is taken from [university of Washington Archive]. The simulation studies are carried out in MATLAB environment.

IEEE 14-bus system:

Table I gives the optimal location and parameters of UPFCs for different loading factors for IEEE 14-bus system. From the results, it is observed that the loadability has been increased to 114.1% by installing an UPFC between buses 1 and 5. The maximum loadability with 2 UPFCs without violating the thermal and voltage constraints is 129.1 % . For this load factor, the UPFCs are embedded in lines connecting buses 2,4 and 2,5. From Figure 4, it is evident that, there is a maximum number of devices beyond which the efficiency of the network cannot be further improved. According to the used optimization criterion, for IEEE 14 bus system, the maximum number of UPFCs beyond which the loadability cannot be increased is 3. Table II summarizes the results as obtained by the three methods for the IEEE14-bus system using their proposed methodologies. The results show that the optimal solutions determined by COA lead to increased loadability of the lines with less number of UPFCs, which confirms that COA based present approach is capable of determining global optimal or near global optimal solution.

Table 1: Optimal location and parameters of UPFCs for different load factors for IEEE 14-bus system.

No. of UPFCs	Loading Factor	Location (Bus No -Bus No)	UPFC parameters		
			V_T (p. u.)	φ_T (deg)	I_q (p. u.)
1	1. 148	1-5	0.147	82.241	0.0610
2	1.329	2-4	0.102	68.415	0.0633
		2-5	0.169	99.894	-0.0527
3	1.752	2-4	0.113	85.131	0.0208
		2-5	0.221	153.314	0.0406
		6-7	0.371	99.025	-0.0489

Table 2: Comparison of simulation results of IEEE 14-bus system.

Compared Algorithm	Maximum Possible Loadability
EP based Method	1.559
PSO based Method	1.671
COA based Method	1.752

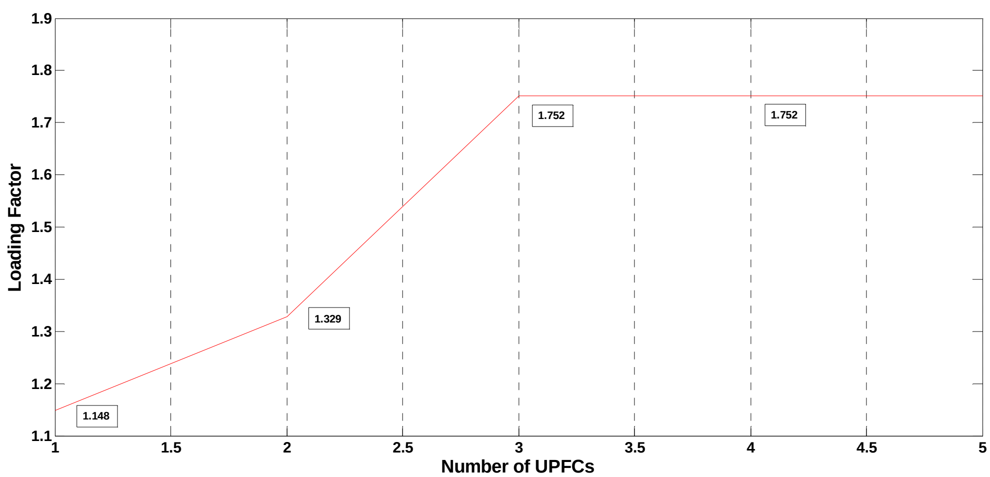

Fig. 4: Maximum loading factor with respect to given number of UPFCs for IEEE 14-bus system.

Conclusion:

In this paper, the optimal UPFC placement on an unstable power system because of load increasing has been investigated. A mathematical model for simultaneously optimizing location and parameters of the UPFCs is presented in this paper. A Modified Shuffled Frog Leaping Algorithm is used to solve this nonlinear programming problem. The case study of the IEEE 14-bus system has confirmed that the developed algorithm is correct and effective. The system loadability was employed as a measure of power system performance. Simulation results validate the efficiency of this new approach in maximizing the loadability of the system. Furthermore, the location of UPFCs and their parameters are optimized simultaneously. The performance of the proposed method demonstrated through its evaluation on the IEEE 14-bus power system shows that COA is able to undertake global search with a fast convergence rate and a feature of robust computation. The proposed algorithm is an effective and practical method for the allocation of UPFCs in large power systems.

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