01 Nov 2006

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Recommended Citation

R. P. Kalyani et al., "Optimal Placement and Control of Unified Power Flow Control Devices Using Evolutionary Computing and Sequential Quadratic Programming," *Proceedings of the 2006 IEEE Power Engineering Society Conference & Exposition (2006, Atlanta, GA)*, pp. 959-964, Institute of Electrical and Electronics Engineers (IEEE), Nov 2006.
The definitive version is available at https://doi.org/10.1109/PSCE.2006.296442

Optimal Placement and Control of Unified Power Flow Control devices using Evolutionary Computing and Sequential Quadratic Programming

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Abstract— **A crucial factor effecting modern power systems today is power flow control. An effective means for controlling and improving power flow is by installing fast reacting devices such as a Unified Power Flow Controller (UPFC). For maximum positive impact of this device on the power grid, it should be installed at an optimal location and employ an optimal real-time control algorithm. This paper proposes the combination of an Evolutionary Algorithm (EA) to find the optimal location and Sequential Quadratic Programming (SQP) to optimize the UPFC control settings. Simulations are conducted using the classic IEEE 118 bus test system. For comparison purposes, results for the combination of a greedy placement heuristic (H) and the SQP control algorithm are provided as well. The EA+SQP combination is shown to outperform the H+SQP approach.**

I. Introduction

With the ever-increasing complexities in power systems across the globe and the growing need to provide stable, secure, controlled, economic, and high-quality electric power - especially in today's deregulated environment - it is envisaged that Flexible AC Transmission System (FACTS) devices are going to play a critical role in power transmission systems [1]. These devices enhance the stability of the power system both with their fast control characteristics and continuous compensating capability. A FACTS device can control power flow and increase the transmission capacity effectively over an existing transmission corridor by placing the device at an optimal location [1].

There are a variety of methods proposed for optimizing the placement of FACTS devices [2]–[7]. The Unified Power Flow Controller (UPFC) is the most powerful, but also the most expensive, device in the family of voltage-source-converter-based FACTS devices, but there are very few papers that suggest a simple and reliable method [5]–[7] for determining the suitable location of UPFCs for enhancing the loadability of the power system over different topologies. The placement of UPFCs is a very complex problem, even under the consideration of steady-state conditions only (neglecting dynamic controls). An optimal UPFC placement must incorporate not only each possible system topology (line outages, load profiles, etc.) but must also consider the entire range of possible control settings which may themselves be dependent on system topology.

This work was supported in part by the National Science Foundation under grant CNS-0420869.

UPFC placement is a very complex optimization problem for three reasons:

1) Evaluating the quality of a placement is a computationally intensive task.
2) The search space grows combinatorially with the size of the power system and the number of UPFC devices.
3) Non-linear dependencies between the placement of individual UPFC devices result in a search space with many local optima.

The first two reasons combined make exhaustive search infeasible, while the third reason defeats traditional search algorithms. Evolutionary Algorithms (EAs) are appropriate in this case as they are well-suited to finding near optimal solutions in a reasonable amount of time for very large, non-smooth, discontinuous, non-differentiable objective functions. Additionally, the Sequential Quadratic Programming (SQP) [8] has been shown to be an effective approach to determining the optimal power flow control setting for the UPFC [9], [10].

This paper proposes employing the combination of EA and SQP (EA+SQP) for the placement and control setting, respectively, of UPFC devices. The organization of this paper is as follows: Section II defines the problem that must be solved using the EA+SQP approach. Section III describes the UPFC model and Section IV briefly describes the UPFC placement EA specifics. Section V describes the results of the simulations conducted using the proposed approach, while Section VI presents the conclusions and ideas for future work.

II. UPFC Placement and Control

UPFC placement in a bulk power system is a crucial problem as it significantly impacts active power flow. To date, several authors [2], [3] have proposed the placement of this device from an economic perspective, i.e., to reduce the production cost or the installation cost of the device. Other placement algorithms consider only a fixed topology system while determining the power flow control setting necessary for the placement, such that the UPFC placement is suited only to a particular load and generation profile. But in reality, the placement and control algorithm of the UPFC should be able to accomodate any contingency or disturbance. UPFCs, by virtue of their fast controllability, are expected to maintain the stability and security margin of highly stressed power systems. The proposed EA+SQP combination of algorithms provides an approach for placing and determining the steady-state power flow control settings of UPFCs for any contingency in the system.

There are several indices/methods [4], [5] proposed in literature to evaluate the quality of a specific placement of FACTS devices. In this paper, a Performance Index (PI), is used as a metric to determine the optimality of the placement and control setting of the UPFC. The proposed PI is:

$$PI = \sum_{SLC} \sum_{all\ Lines} \left(\frac{S_i}{S_i^{max}} \right)^2 \quad (1)$$

where S_i is the apparent power flow on line i for each Single Line Contingency (SLC) and S_i^{max} is the rating of the line i.

PI index minimizes line overloads as higher overloads incur heavier penalties than lower overloads and minimizes power flow imbalances resulting in a more even utilization of all lines in the system. Fig. 1 shows the PI metric space (interpolation of 21 equidistant control setting samples) for a random contingency on the line between buses 23-32 in the IEEE 118 bus test system [11] with a single UPFC device placed on the randomly selected line 26-30. The allowable power flow control settings for the UPFC are in the range of $\pm$ 20 % of the maximum power flow (P_{max}) value of the line. The PI space for the two randomly selected UPFC placements 5-8 and 26-30 over a sampling of control settings for a single randomly selected SLC 23-32 is shown in Fig. 2. The vertical line in this figure indicates the best UPFC power flow control settings found by SQP. The shape of the control space suggests the absence of local minima. Based on this result, the constrained gradient descent technique SQP [8] was chosen as control algorithm since the gradient descent technique is computationally efficient in the absence of multiple minima. While the results suggest that the PI metric results in a concave surface, further analysis is required to prove that the surface is concave under all operating conditions and placements.

III. UPFC Model

The function of the UPFC in the network is to control the active power flow through a line to a specified value. By controlling the active power through a specified line, the remaining lines in the system adjust their power flow according to the physics of the system. The lossless steady state model of UPFC [12] delivers active power to one of the buses of $Line_{ij}$ and draws a corresponding amount of active power from the other bus of the same line, shown in Fig. 3. It is assumed that the installation of the UPFC may increase or decrease the

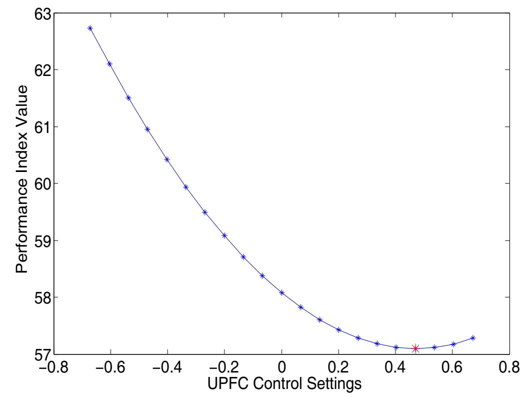

Fig. 1. PI curvature for single UPFC placement 26-30 and SLC 23-32

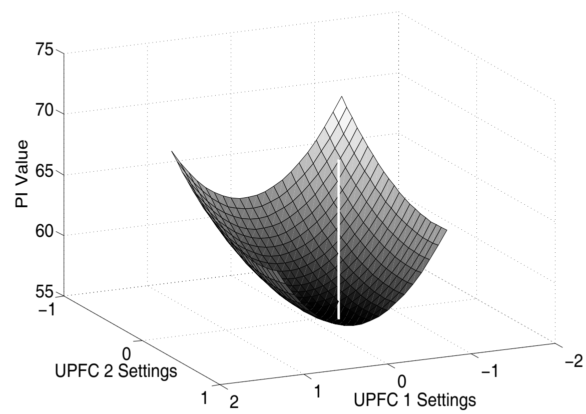

Fig. 2. PI surface for two UPFC placements 5-8, 26-30 and SLC 23-32

active power flow through $Line_{ij}$ by no more than 20% of the line capacity P_{max}.

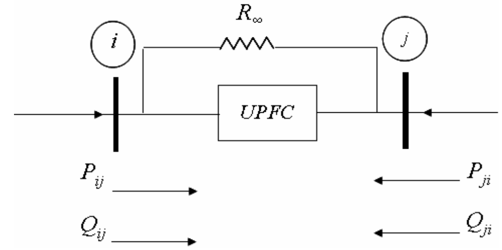

Fig. 3. UPFC injection model

IV. UPFC PLACEMENT EA

EAs are robust search and optimization algorithms based on natural selection in environments and natural genetics in biology [13]. Table I shows the specifications of the EA employed in this work.

TABLE I
SPECIFICATIONS OF EA FOR PLACEMENT OF UPFC

Representation	Fixed size vector of integers
Initialization	70% random, 30% seeded
Parent Selection	Tournament Selection
Recombination	Uniform Crossover
Mutation	Customized
Survivor Selection	Elitist Deterministic Rank Based Steady State
Termination	Fixed Number of Generations

A. Fitness Function

The objective of this optimization problem is to minimize the overloading of the system over all SLCs by optimizing the placement of multiple UPFC devices. In terms of the PI metric (1), this is formulated as a minimization problem. As fitness per definition should be maximized, the fitness function in this case is equal to the negative of the PI metric.

B. Representation

Each individual in a typical EA consists of a set of genes which encode a trial solution to the problem to be solved (i.e., the environment). Here a trial solution consists of a set of UPFC placements, expressed as positive integers, each of which indicates a line in the IEEE 118 bus test system where a UPFC device should be placed. The number of integers (genes) in each individual is fixed to N_{UPFC}, the number of UPFCs to be installed in the IEEE 118 bus power system for decreasing the loadability of the system. For example, for a placement with $N_{UPFC} = 4$, a single individual in the population might be as shown in Fig. 4.

10	27	50	117

Fig. 4. Example UPFC placement individual

C. Initialization

The number of individuals in the population is specified by the parameter μ. The population consists for 70% of randomly initialized individuals, the remaining 30% are seeded from previous runs and heuristics.

D. Parent Selection & Recombination

A mating pool is generated by conducting a tournament among $TournSize$ individuals randomly selected from the population. During each tournament, the two fittest individuals are selected and placed into the mating pool. This process continues until the mating pool is filled, i.e., *NParents* are generated.

The number of offspring that can be generated by recombination is specified by the parameter λ. The parents for the recombination are randomly selected from the mating pool and the offspring are generated depending on the recombination parameter Cross Over Rate (*CORate*). If a random number generated is less than the *CORate*, then two offspring are generated by implementing uniform crossover; otherwise the parents are cloned.

E. Mutation

Each offspring generated by recombination is mutated depending on a mutation probability *MutationRate*. Mutation here reflects the movement of the UPFC to its neighboring lines. This movement acts as neighborhood (local) search for each placement to find better individual. A gene in a placement will be mutated to its neighbor. A line is a neighbor to another line if it has a common bus. Therefore when a UPFC is chosen for mutation depending on *MutationRate*, it is moved from the present line to its neighboring lines. This acts as a local search for finding a better placement in the neighborhood of existing placement [6]. Figures 5 and 6 show a small network with lines 49-53, 53-55, 55-56, 55-58, 55-54 and 54-53 connected to each other.

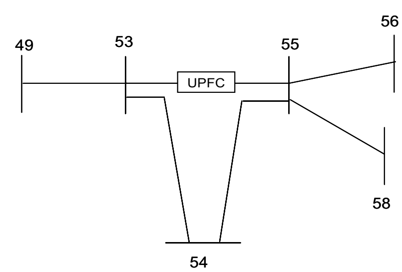

Fig. 5. UPFC initially placed on Line 53-55

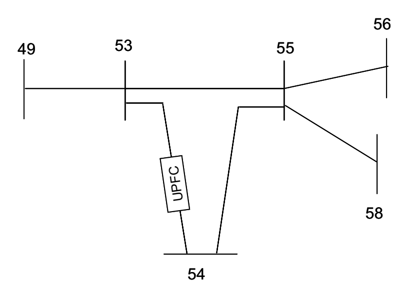

Fig. 6. UPFC moved to the neighbouring Line 53-54 as a result of Mutation

Each of these lines are prone to mutation since the UPFC is initially installed on line 53-55. It shares a common bus with all of the remaining lines. Through the mutation operation mentioned above, the UPFC may be moved from line 53-55 to the neighboring line 53-54.

F. Reproduction Correction

Reproduction correction is an extra stage in the EA to check if any of the line numbers are duplicated in the placement, which is an invalid condition in an actual power system. Fig. 7(a) shows invalid placement and Fig. 7(b) shows its corresponding corrected placement.

10	50	50	117

(a) Invalid Placement

10	50	172	117

(b) Corrected Placement

Fig. 7. Example invalid and valid Placements

In this placement, two UPFC devices are placed on the same line 50 (30-38). This can be corrected by checking the placement after the offspring are generated and moving the device to lines away from the present installation 50 randomly. By implementing validation, every placement is ensured to be unique before it is evaluated for its PI value.

G. Survivor Selection

A steady state EA with rank based elitist is used for survival selection. Steady state refers to the $(\mu+\lambda)$ strategy where $\mu \gg \lambda$. An elitist is used in an attempt to prevent the loss of current fittest member of the population. λ offspring are created and exact same number of least fit individuals are removed from population of $(\mu+\lambda)$ by means of rank based selection. In a rank based selection the total population is sorted according to fitness, and the best μ individuals are selected to survive for the next generation. This deterministic approach is chosen over stochastic approach for faster convergence, as the given fitness function is computationally intensive.

H. Termination Condition

While the theoretical lower bound on the PI metric (1) is zero, the actual minimal value in any given scenario is unknown and cannot therefore be used as a stopping criterion. A more practical issue is the high computational cost of computing the PI metric. To put reasonable bounds on the duration of the experiments, a fixed number of generations is used as the termination condition.

V. Simulation Results

Simulations are conducted on the IEEE 118 bus test system [11] for evaluating the proposed EA+SQP approach. This dataset has 118 buses, 186 lines and 20 generators. Individuals in the EA population encode trial solutions in the form of UPFC placements. The fitness of an individual is computed by having SQP optimize the PI metric (1). The speed and quality of convergence of the EA depends on various EA strategy parameters. In this paper three parameter sets (Table II) are compared in determining the best placement for two to five UPFCs. Each parameter set is run for 100 generations (termination condition based on practical time limitations) and repeated for five runs in order to be able to perform a statistical analysis on the comparison of the difference of two means. Table III shows the mean and standard deviation of highest fitness (*HFit*) over five runs for three parameter sets and different UPFC placements. These sets are further tested for different means by using the Wilcoxon Rank Sum Test (WRST) for two to five placements. WRST performs a two-sided rank sum test of the hypothesis on two independent samples coming from distributions with equal means, and returns the probability value (P) and null hypothesis (NH) [14] from the test.

TABLE II
EA Parameter sets

Parameter set	μ	$TournSize$	λ	NParents	CO Rate	Mutation Rate
PSet1	150	15	10	15	0.7	0.1
PSet2	100	8	10	15	0.7	0.2
PSet3	50	3	5	15	0.9	0.5

TABLE III
Mean and Standard Deviation of $HFit$ over five runs

Number of UPFCs	Parameter Set	Mean	Standard deviation
2	PSet1	-50.6412	0.0894
	Pset2	-50.7295	0.1002
	Pset3	-51.0494	0.2127
3	Pset1	-49.4862	0.0782
	Pset2	-49.6869	0.2037
	Pset3	-49.6997	0.2240
4	Pset1	-48.6331	0.2650
	Pset2	-48.4581	0.1825
	Pset3	-48.7696	0.3052
5	Pset1	-47.4544	0.2513
	Pset2	-48.2087	0.3878
	Pset3	-48.5432	0.4641

For instance, WRST is conducted on every combination of the three parameter sets for two UPFCS as shown in Table IV. The output of the hypothesis and the P-values are as shown in the same table. Based on the hypothesis and mean of *HFit*, parameter set 1 (PSet1) is determined as the one which gives the best promising placement for two UPFCs. This placement is on lines 69 (42-49) and 158 (92-94). Performing similar statistical analysis with the parameter sets shown in Table II, it is determined that PSet1, PSet2 and PSet1 yield best placements for three, four and five UPFCs respectively.

A greedy placement Heuristic(H) [7] in conjunction with SQP (H+SQP) is implemented to compare the results obtained from EA+SQP. This heuristic is a pruned exhaustive search, in which the top fifty best placements found by single UPFC placement search are paired to find the best placement with

TABLE IV
EXPERIMENTAL RESULTS OF WRST ON THREE PARAMETER SETS

Parameter Sets Compared	Alpha Value	P Value from WRST	Conclusion
1 - 2	0.05	0.7222	Accept NH
1 - 3	0.05	0.0317	Reject NH
2 - 3	0.05	0.0215	Reject NH

two UPFCs ($50C_2$ combinations). Similarly for three UPFCs $20C_3$ combinations, for four $10C_4$ combinations and for five $8C_5$ combinations are searched for finding best placement with H+SQP approach.

The number of overloads (NOL) for 118 bus system over all SLCs is 119. The total overloaded power (TOP) is 25.88 p.u and average PI is 56.49 p.u over all SLCs. For finding the best placement of single UPFC, exhaustive search (ES) is conducted with the settings determined by SQP. Table V tabulates N_{UPFC}, NOL, TOP and average PI for placement approaches ES, EA and H while determining the control settings with SQP.

TABLE V
COMPARISON OF ES, EA AND H

Approach	N_{UPFC}	Placement	NOL	TOP	Average PI
ES	1	42-49	119	25.711	52.222
EA	2	42-49, 100-106	113	25.097	50.661
H	2	42-49, 82-83	117	25.5	50.6813
EA	3	42-49, 47-69 100-106	112	24.921	49.112
H	3	42-49, 68-69 82-83	116 116	25.362 25.362	49.553 49.553
EA	4	42-49, 47-69 68-69, 100-106	107	24.748	48.218
H	4	42-49, 68-69 82-83, 103-110	115	25.267	48.4661
EA	5	3-5, 42-49, 47-69 68-69, 100-106	107	24.661	46.752
H	5	3-5, 42-49, 68-69 83-85, 92-94	114	25.154	46.829

Figures 8 through 10 show the comparison plots of the EA+SQP and H+SQP approaches for 0 to 5 UPFCs. It is evident from the plots that as the number of UPFCs increase, NOL, TOP and average PI decrease considerably, also the EA outperforms the heuristic placement approach.

Another advantage of the EA over ES and H is that it is faster, as it executes a loadflow fewer times than the heuristic. For example, the number of loadflow calls for the heuristic (H+SQP) with two UPFCs are $50C_2 \cdot 186 = 227850$ whereas for the EA (for PSet1) it is $(150 + 10 \cdot 100) \cdot 186 = 213900$ calls. With ES the number of loadflow calls will be larger since $186C_2$ combinations have to be run to find the optimal placement. Also as the number of devices increase the heuristic becomes less precise due to restriction on number of combinations that can be searched for finding optimal placement. But for EA, varying selective pressure for the same population size might yield better solutions (placements).

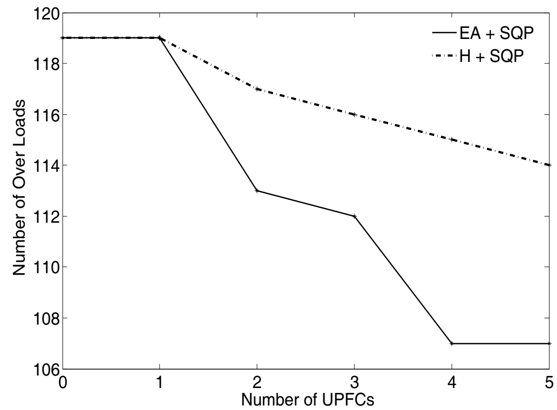

Fig. 8. Comparison of EA and H for NOL

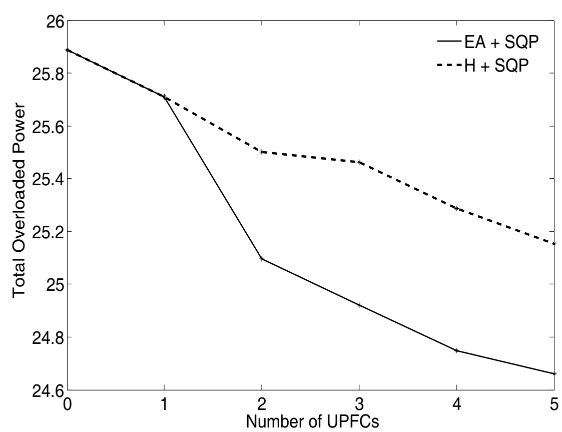

Fig. 9. Comparison of EA and H for TOP

VI. CONCLUSION

This paper proposed and implemented an EA+SQP approach for the placement of UPFCs in a power network. It can be concluded from the results that the loadability of the system increased and better power flow control (during SLCs) was achieved by choosing the optimal placement and control algorithm for UPFCs. Comparison of the EA+SQP and H+SQP approaches demonstrated that robust algorithms such as EAs could find the optimal/near optimal solution for the placement problem at minimum time expense. Also EA+SQP outperformed pruned exhaustive search H+SQP.

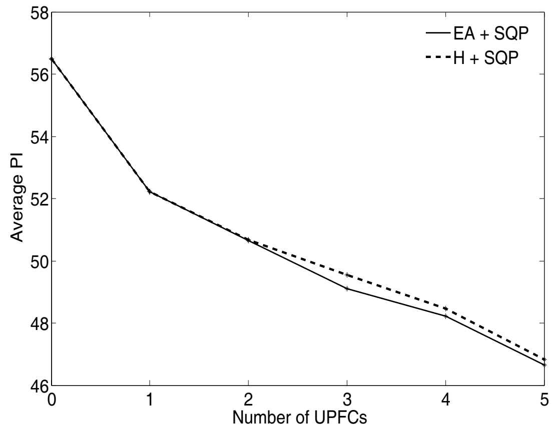

Fig. 10. Comparison of EA and H for average PI

Further studies need to be performed on optimizing the EA strategy parameters as well as employing more sophisticated EAs such as memetic EAs. Another future task is to analyze the placement of the devices from a stability perspective.

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