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An Approach for Optimal Placement of UPFC for Power Loss Minimization

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Abstract: - A Unified Power Flow Controller (UPFC) is a member of Flexible AC Transmission System (FACTS) devices which can provide full dynamic control of a transmission line parameters, bus voltage, line impedance and phase angle for improved system security. However, the extent that performance of UPFC can be brought out, it greatly dependent upon the location of this device in the system. The optimal location of the UPFC is determined by the proposed Differential Evolution (DE) technique and tested on an IEEE 14 – bus system. This paper focuses on the steady state operating condition with different real power percentage loading of the system at 100%, 125% and 150% loading respectively. Comparison was made between the power losses with and without UPFC device at the various percentage loadings in an attempt to highlight the merit of the proposed method. The results obtained indicate the proposed algorithm is effective and practical method for optimal location of UPFC device and can significantly enhance the security of power system by reducing system losses.

Keywords: Flexible AC Transmission System (FACTS); Unified Power Flow Controller (UPFC); Differential Evolution, Bus Voltage.

1.0 Introduction

The continued demand in electric power system network has caused the system network to be heavily loaded leading to huge power losses and voltage instability. These necessitates for comprehensive analysis to evaluate the present power system performance and investigate the effectiveness of new devices for improved system security and reliability. FACTS devices are generally known as such new devices emanating from recent innovative technologies that promise to enhance security, capacity and flexibility of an existing power transmission system while maintaining the operating margins necessary for grid stability (Hingorani 1988). The Institute of Electrical-Electronic Engineering (IEEE) defined FACTS as ″ power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability″. As a result, more power can reach consumers with a minimal impact on the environment and at a lower investment cost when compared to the alternative of building new transmission lines. Other broader benefit of FACTS devices can be found in (Paserba 2008, Mubeen, *et al*, 2004). However, to achieve such functionality of UPFC, it is highly important to determine the optimal location of this device in the power system. The following are some factors that can be considered in the selection of the optimal location of UPFC: The stability margin improvement, the power transmission capacity increasing, and the power blackout prevention; Therefore, conventional power flow algorithm should consider one, two, or all of the above-mentioned factors (Puerle-Esquivel & Acha, 1997). In the last decade, new algorithms have been developed for the optimal power flow incorporating with UPFC device as well as for the optimal placement of UPFC. Some of them are: a sensitivity based approach which has been developed for finding suitable placement of UPFC (Singh & Earlich, 2005), a Genetic Algorithm (GA) which proposed for solving the optimal location problem of UPFC (Arabkhaburi *et al* 2006), and a Particle Swarm Optimization (PSO) for optimal location of multi FACTS devices (Haruna et al 2010).

This paper considers power transmission capacity increasing, in other words, enhancing the security of power system by improving transmission capacity through installing UPFC in an optimal location. Steady state stability of a power system refers to the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power changes, (H. Sa'adat, 2004). A system enters a state of voltage instability when a disturbance, or increased in load or change in system condition causes progressive and uncontrollable decline in voltage (Taylor, 2004). One of the shortcomings of those methods only considers the normal state of the system. This paper employ DE algorithm to optimally placed UPFC device on the IEEE 14 bus system for power loss minimization when subjected to different percentage levels of active power loadings.

2.0 Methodology

2.1 Modeling of UPFC and System Losses

In order to investigate the impact of DE on the optimal location of UPFC device on power system effectively, appropriate models of UPFC device are very important. Figure 1 shows the equivalent circuit of a UPFC power flow model, this circuit consists of two coordinated synchronous voltage sources represent the UPFC adequately for the purpose of fundamental steady-state analysis. Mathematical model is constructed by representing the ac output terminal with the two ideal voltage source V_{se} and V_{sh} respectively in series with the reactance X_{se} and X_{sh} denoting the leakage reactance of the two coupling transformer.

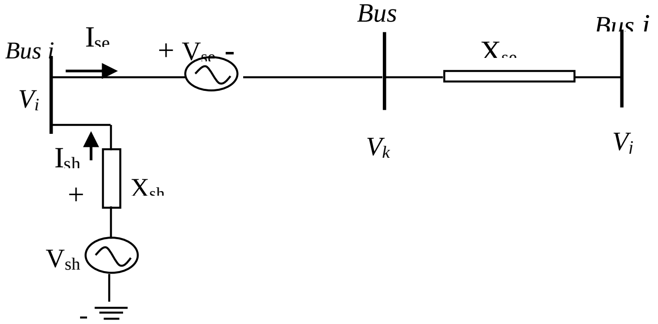

Fig. 1: UPFC Equivalent Circuit Representation Following the approach of (Tumay & Vural 2004)

As seen in the figure two above V_k represent imaginary voltage behind the series reactance X_{se}

$$V_k = V_{se} + V_i \qquad 1$$

The series connected voltage source as developed assumed to be modeled by an ideal series voltage, V_{se} which is controllable in both magnitude and phase as expressed thus;

$$V_{se} = rV_i\ell^{j\gamma} \qquad 2$$

Such that, $0 \le r \le r_{\max}$ and $-\pi \le \gamma \le \pi$

Where, r and γ: are the UPFC value of injected voltage magnitude (p.u) and that of injected voltage angle respectively. Refer to (Vural & Tumay 2004) for detail modeling. Generally, the relationship between power flow P_{ij}, the voltage magnitude V_i, V_j and phase angle between the sending and receiving end voltages δ_i and δ_j is given in equation 3

$$P_{ij} = \frac{V_iV_j}{X_{ij}}.\sin(\delta_i - \delta_j) \qquad 3$$

FACTS device can be applied to control power flow and hence, the system losses by adjusting the variables contained in (3). Since FACTS device can regulate these variables in a very fast and effective way, they are considered suitable for power system dynamic control.

2.2 Objective Function

The main objective of this work is to determine the optimal location of UPFC in the network based on DE technique for improving system security. Therefore, this improvement can be achieved through minimizing the active power losses. The objective function for the optimal location of UPFC device considering the above criteria can be expressed as:

Minimize the objective function

$$F_{Obj} = \sum_{j=1}^{nl} P_{Loss_{ij}} \qquad 4$$

Where nl: Number of lines in the system,

$P_{Loss_{ij}}$: Real power loss on line i-j,

The minimization of the objective function is subject to the constraints.

Real Power generation constraints

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{Max} \quad i = 1 \ldots\ldots\ldots\ldots\ldots Ng \qquad 5$$

Reactive Power generation Constraint

$$Q_{Gi}^{Min} \le Q \le Q_{Gi}^{Max} \quad i = 1 \ldots\ldots\ldots\ldots\ldots Ng \qquad 6$$

Where N_g is the sets generation buses indices respectively.

3.0 Realization of DE Based Tool

3.1. Overview of DE

DE is a parallel direct search method proposed by Storn and Price (1995). DE is a heuristic, population-based optimization method that uses a population of points to search for a global minimum of a function over continuous search space. Basically, DE generates new vectors of parameter by adding the weighted difference between two population vectors to a third one. If the resulting individual provides a smaller objective function value than a predetermined population individual, in the next generation the new individual replaces the one with which it is compared; otherwise, the old individual is retained. There are several variants of DE (Price K. V, 1999). The general notation of DE variants can be expressed as follows:

$$\mathrm{DE/x/y/z} \tag{7}$$

Where x denotes the mutated vector, y is the number of difference vectors and z is the crossover scheme. The advantages of DE are summarized in (Wong and Dong 2005):

3.2. DE Based Optimal Location of UPFC

The location of UPFC in the network is considered as the variable to be optimized, and the location candidates for this variable can be any line in the network, except the lines where the transformers are existed. Because of higher cost of UPFC device, the installation is not recommended to all possible line outage. Hence the aforementioned line contingency screening is carried out by DE algorithm to identify the most critical line during whose UPFC can be positioned and system can be operated under stable condition. However, the computational steps of DE based tools evolved are summarized below:

Step I: Initialize power flow data, and DE-related parameter such as the size of population (NP), the maximum number of iteration or generation (G_{max}), the number of variables to be optimized (D), CR, and F.

Step II: Randomly generate the initial population of NP individuals in the feasible space by:

$$X_{i,k}^{G} = X_{k\,min} + rand\,[0,1] * (X_{kmax} - X_{kmin}) \tag{8}$$

Step III: Evaluate the fitness for each individual in the population according to the objective function in eqn (4).

Step IV: Create a new population by:

` **a. Mutation operation**

$$V_i = X_{r1} + F * (X_{r2} - X_{r3}) \tag{9}$$

With r_1, r_2, $r_3 \in [1, N_P]$ are integers and mutually different, and $F > 0$, is a real constant to control the different variation

$$d_i = X_{r2} - X_{r3}$$

b. Crossover operation

$$U_i(j) = \begin{cases} V_i(j), if\ U_i(0,1) < CR \\ X_i(j), \quad otherwise \end{cases} \tag{10}$$

Where, CR is the cross over rate of DE.

c. Selection operation

$$X_{i,G} = \begin{cases} U_{i,G+1}\ if\ (U_{i,G+1}) < f(X_{i,G}) \\ X_{i,G}, \quad otherwise \end{cases} \tag{11}$$

where, $i \in [1, N_P]$.

Step V: Stop the process and print the best individual (Optimal location and Sizing of UPFC) if the stopping criterion is satisfied, else go back to Step IV.

Table 1, Parameter Initialization of the Implemented DE based UPFC parameters setting adopted to the values reported in the open literature (He, D. K. et al 2008).

Parameters	**Settings**
Number of population (NP)	30
Maximum Number generation, G_{max}	100
No. of variables to be optimized (NV)	3
Length of individual (LI)	3
DE Step-size (F)	0.5
Cross over probability constant CR	0.5
DE Strategy	DE/rand/1/bin
Termination Criteria	$1.e^{-6}$ or G_{max}

4.0 Simulation of Results and Discussion

In order to verify the effectiveness of the proposed method, the modified IEEE 14 bus test system whose data can be obtained from (R. D. Zimmermann, 2005) was used.

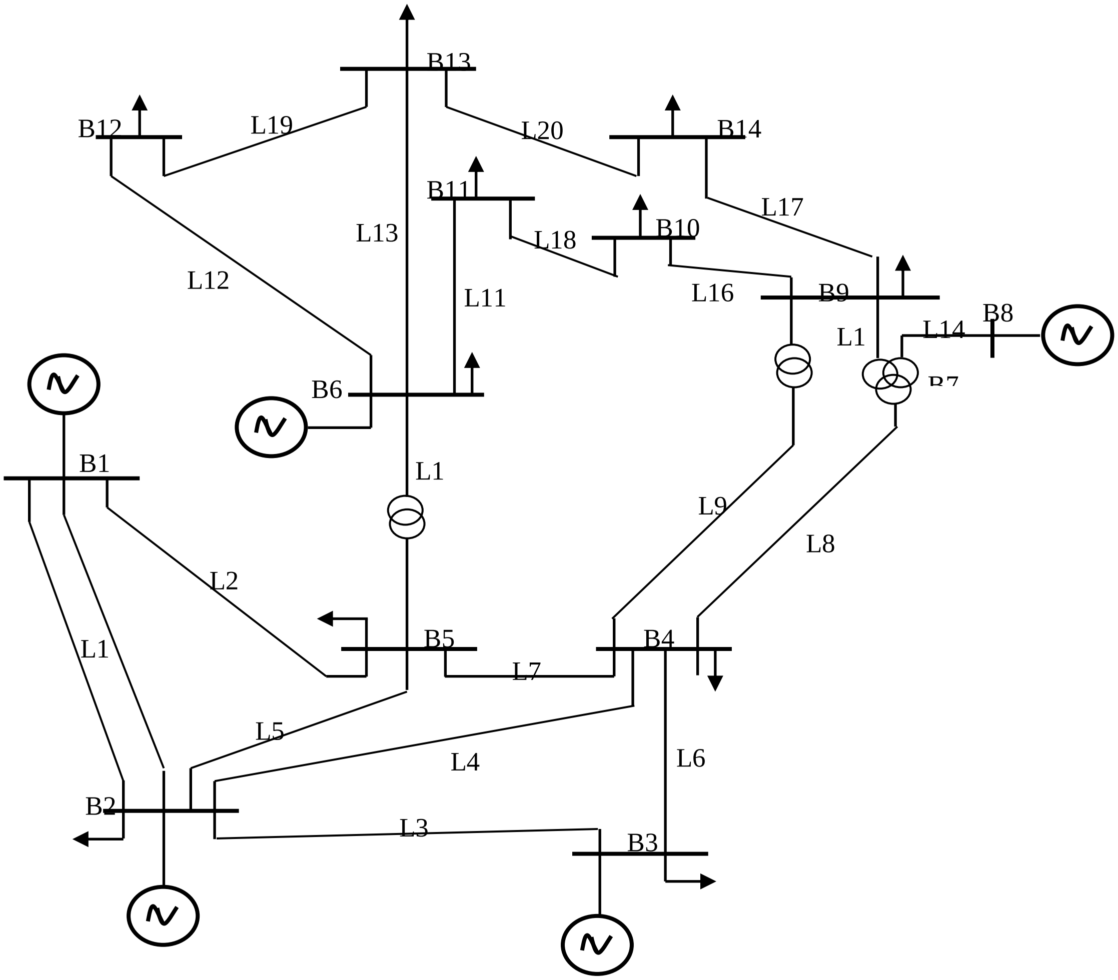

Fig. 2: Standard 14 Bus IEEE Test Network

The test was conducted for the system before and after DE optimal placement of UPFC under 3 different operating conditions. The 3 operating conditions are:

Case1: The system at 100% loading in all the load buses is considered as normal condition, Newton Raphson (NR) load flow is carried out with loading factor value equal to 1.

Case 2: The system loading is increased to 125% loading in all the load buses, NR load flow is carried out with loading of the system at this level result in reasonable real power loss level.

Case 3: The system is increased to 150% loading in all the load buses, loading of the system at this level result with unacceptable real power loss level.

The simulation results before and after UPFC device optimally located on the test system under different percentage loading conditions was demonstrated. Under the above loading conditions, Newton Raphson load flow was used to obtain the initial real power loss in MW (without UPFC). Then, DE technique is applied to produce the optimal location of UPFC device as well as the final power loss values in MW (With UPFC) for the system under same loadings conditions. Lastly, formulation for the percentage real power loss reduction was also set out. The summary of the results is presented in Table 2.

Table 2. Power Flow Results with and without UPFC Located in IEEE 14-Bus Test System Location, Sizing and Network Losses

(%) Loading	Losses Without UPFC (MW)	Rating (MVar)	Losses With UPFC (MW)	Line Location	% Power Loss Reduction
100% loading	34.232	119.4	13.329	20	61.062
125% loading	47.019	108.3	22.325	9	52.520
150% loading	63.822	185.4	34.049	20	48.217

As observed from the above table, it was realized that under 100% and 150% loading condition, DE optimally placed UPFC device on line 20 each respectively while line 9 is considered as the optimal location of UPFC at 125% loading condition. The percentage loss reduction of 61.062%, 52.520% and 48.217% was also established for 100%, 125% and 150% loadings scenarios respectively. Also from the above table, it was deduced that the overall network losses with UPFC installed marginally increases as the system load increases steadily from 100% to 150% loading. Therefore, the efficacy of the UPFC device decreases as the system loading marginally increases. The real power loss (in p.u) convergence characteristics with UPFC against the number of generation on the test system at the different loading conditions is shown in figure 3, 4 and 5 respectively.

4.1 Power Flow Improvement with UPFC

Figure 3 below shows the real power loss convergence characteristics for the optimal location of UPFC by DE technique (DE is made to run for 100 iteration). The convergence of power loss was exhibited for 100% loading at 23th generations to a value of 0.1332(p.u). The result shows the value of power loss (real power loss) has gradually converge to an optimum value of 13.324MW (0.1332p.u) from an initial value of 34.232MW.

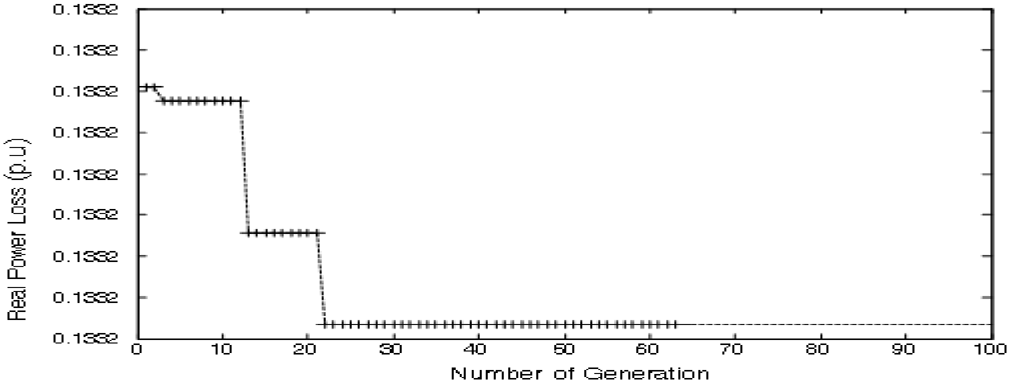

Fig. 3: Convergence Characteristics with UPFC under at 100% loading condition

Figure 4 below also shows the convergence characteristics of UPFC optimal placement by DE technique of real power loss against the number of generation on the test system at 125% loading condition. The convergence reaches a final value of loss reduction at 30th generation to a value of 0.2232p.u (22.325MW). The result is that the value of Ploss converges to a value of 22.325MW from an initial value of 47.019MW.

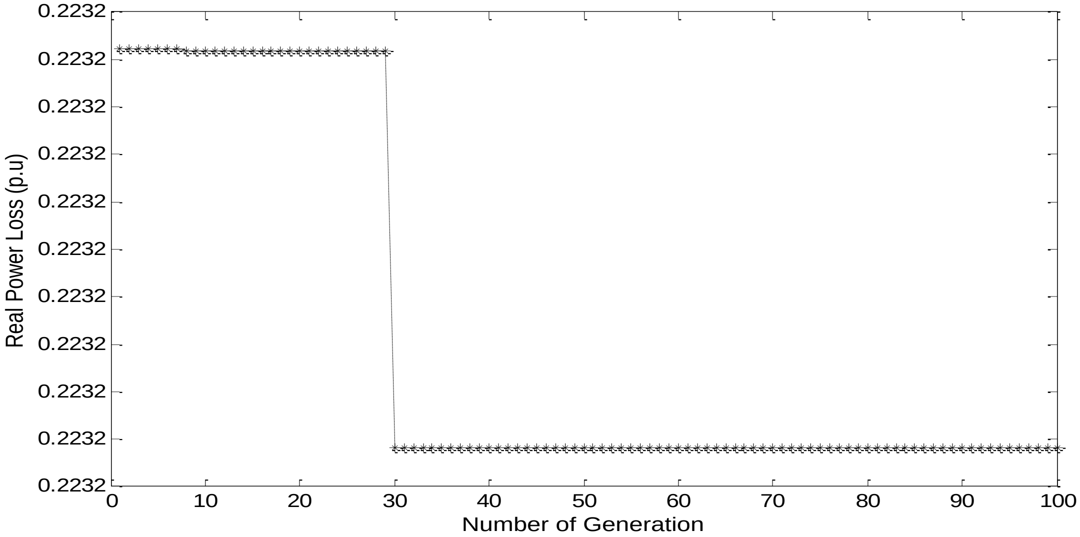

Fig. 4: Convergence Characteristics with UPFC at 125% loading condition

Regarding the 150% loading condition, the convergence characteristics for the optimal location of UPFC by DE technique is shown in figure 5 below. However, fast convergence was exhibited within a few numbers of generations (in less than 5th generation) to reach an optimum value of 0.3405 (34.049MW). The result reveals that the value the value of Ploss converge to a value of 34.049MW from an initial value of 63.822MW

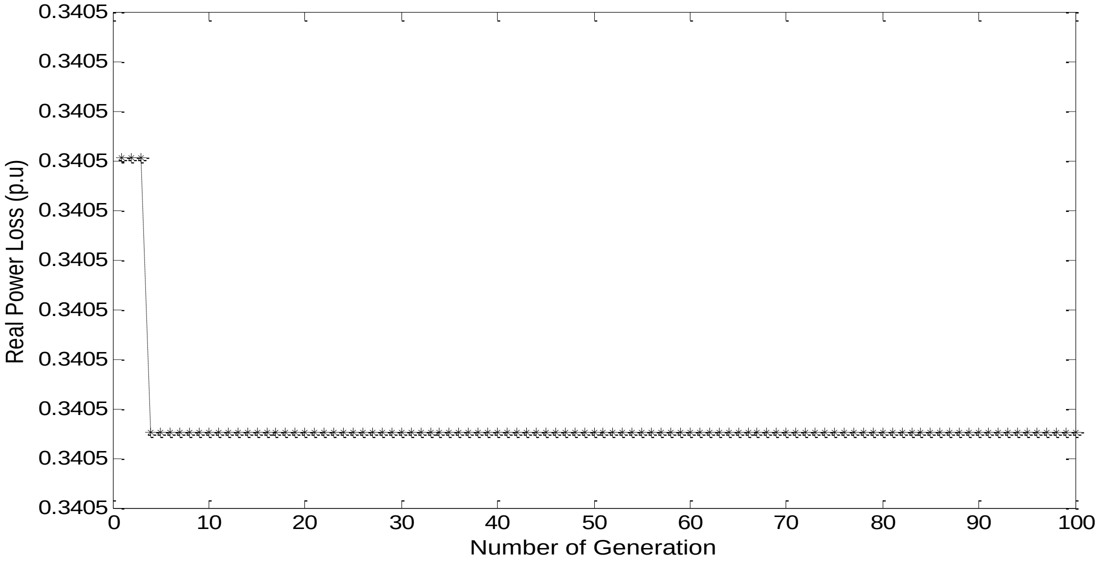

Fig. 5: Convergence Characteristics with UPFC at 150% loading condition

The results as captured in table 2, indicates that the value of loss P_{loss}, which form part of the objective function gradually converges to optimal value of 13.329MW (0.1332p.u) 22.325MW (0.2232p.u) and 33.049MW (0.3405p.u) for 100%, 125% and 150% loading scenarios respectively. It can be observed that the simulation results convergence before the 30th number of generation for all the loading conditions. The effectiveness of this search was seriously influenced by a choice of control parameter values of DE algorithm captured in table 1.

4.0 Conclusion

In conclusion, different system loading scenarios was studied using IEEE 14 bus test system; DE was applied to produce optimal location of UPFC on the test system. Determinations of the severest loading contingency scenarios were performed based on 3 different loading cases of 100%, 125% and 150% loading conditions. The proposed DE technique has been successfully applied to the problem under consideration. It was found that the impact of UPFC on the system real power flow on the optimized location by the applied DE technique has resulted in improved power flow on the system. The proposed DE algorithm is proved to be effective and practical approach for the optimal location and sizing of UPFC on the power system.

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