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Optimal siting and sizing of unified power flow controller using sensitivity constrained differential evolution algorithm

Karri Manoz Kumar Reddy[1], Kailasa A. Rao[2], Rayapudi Srinivasa Rao[3]
[1]Department of Electrical and Electronics Engineering, Aditya College of Engineering, Surampalem, India
[2]Department of Electrical and Electronics Engineering, Pragati engineering College, India
[3]Department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University, Kakinada, India

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ABSTRACT

This paper presents Sensitivity constrained placement of unified power flow controller (UPFC) considering active-power flow sensitive index (APFSI) and static voltage stability index (STATIC-VSI) to minimize active-power losses and to improve power transmission capacity. The sensitive factors are derived with respect to voltage, phase angle and current to formulate APFSI. Transmission line impedance parameters along with active and reactive-power flow measurements are considered to formulate static-VSI. Sensitivity constrained differential evolutionary (SCDE) algorithm is proposed for parameter setting through which power control and minimization of losses in system can be achieved. Testing is performed on IEEE-5, 14 and 30-bus networks in MATLAB and results indicate that SCDE is robust optimization technique compared to conventional method and genetic algorithm (GA).

Corresponding Author:

Karri Manoz Kumar Reddy
Department of Electrical and Electronics Engineering, Aditya College of Engineering
Surampalem, India
Email: kmkreddyy@gmail.com

1. INTRODUCTION

The demand of power on load side is increasing day by day. The capacity limits of transmission line changes with increase in load. This leads to power congestion problems that result in sag and swell of voltages which can lead to voltage collapse or blackouts in power system [1]. The introduction of flexible alternating current transmission system (FACTS) devices like unified power flow controller (UPFC) offers a unified power flow (PF) distribution, relieving congestion problems by minimizing power losses [2]. The problem here is to site the UPFC at suitable location and size parameters of the device to reduce power losses and achieve unified PF.

From the recent work carried out by researchers it is observed that, Acharjee [3] proposed self-evolution algorithm for controlling and maintaining the power flow using UPFC. Chen *et al.* [4] presented hybrid intelligent algorithm for locating and sizing of UPFC. Esmaili *et al.* [5] presented a novel coordinated design of UPFC for power system stability considering culture-PSO-co evolutionary (CPCE) algorithm. Reddy *et al.* [6] proposed optimal allocation of UPFC critical based to enhance the voltage stability of system considering genetic algorithm based upgraded differential evolution algorithm In recent days, evolutionary algorithms [7] such as artificial algae algorithm (AAA) [8], modified particle swarm optimization (M-PSO) [9], imperialist competitive algorithm [10], dolphin echolocation optimization [11], Cuckoo search algorithm and chemical reaction optimization [12], genetic algorithm [13], sine-cosine algorithms [14] are proposed for optimal placement of UPFC for unified PF control. The studies [15], [16] proposed power congestion control strategy to increase the stability of the network. Suliman and Al-Khayyat [17] proposed power flow in parallel transmission lines with UPFC. Several studies [18], [19] focused on fuzzy logic controller to allocate UPFC in optimal places. Indices such as fast voltage stability index (FVSI) [20], network branch index (NBI) [21], and ranking index (RI) [22] are proposed to find the weakest locations of network for siting of UPFC.

Various Congestion [23], line contingency [24] and transient stability [25], [26] problems can be minimized with optimal siting of UPFC at weakest line in network. In this paper two sensitive Indices are formulated to find weakest line in transmission network for siting of UPFC. Sensitive factors are designed to formulate APFSI and Impedance and PF parameters are considered to formulate static-VSI. UPFC located at weakest line and parameter tuning can minimize active power losses in the system.

2. THE PROPOSED METHOD

2.1. Overview of sensitivity constrained differential evolutionary (SCDE)

DE is an evolutionary technique suggested in [27], [28] for optimization in uninterrupted domain. It is analogous to direct search (DS) method that involves $'NP - D$ 'dimensional' parameter vectors $i = 1,2 \dots, NP$ as population for all G-generation. NI will not vary in period of optimization technique.

2.1.1. Initialization

The first step in sensitivity constrained differential evolutionary method is to produce first population of candidate solution by assigning random value to each outcome parameter of every independent population. A population N_p is formed in arbitrary process so that values lie in $z_j^{min}$and z_j^{max} boundaries of decision variable. It is defined as (1):

$$z_{ij} = z_j + rand \times \left(z_j^{max} - z_j^{min}\right) \tag{1}$$

2.1.2. Mutation

A novel mutant population is generated whose size is similar to initial population NI. From several strategies used in differential evolution, accretion of subjective variation variable in between two and three members is considered. Population members z_{r1}, z_{r2} and z_{r3} are considered from current population. Then amendment between these two is ascended by Scalar Factor F, which is added to population number third. F value is between 0.4 and 1. Thus j^{th} member of donor vector $v_{ij}(t)$ is defined as (2).

$$V_{ij}^{t+1} = z_{r1}(t)F * \left(z_{r2}j(t) - z_{r3}j(t)\right) \tag{2}$$

2.1.3. Crossover

A novel population vector is produced by inclusion of mutant and parent population. The process of crossover is considered with C_R which lies between (0, 1). Binomial crossover strategy is considered which can be applied on D variables and it is defined as (3):

$$\begin{aligned} U_{i,j}^{t+1} &= V_{i,j}^{t+1} \quad if \;\; rand \; (0,1) < C_R \\ U_{i,j}^{t+1} &= P_{i,j}^{t+1} \quad else \end{aligned} \tag{3}$$

where, $U_{ij}(t)$ is child vector obtained after crossover technique.

2.1.4. Selection

Cost objective $C(t)$ suggesting D-variables for utilizing initial and crossover population vector a novel population vector with objective function is attained for the next generations. This defined as (4).

$$z_i^t = \begin{cases} U_i^{i+1}, if \; f\left(U_i^{t+1}\right) \le f(z_i^t) \\ \quad z_i^t \qquad\quad otherwise \end{cases} \tag{4}$$

The global premium searching ability and convergence of DE are prone to select of control constraints N_p, F and C_R.

2.1.5. Stopping criteria

The stopping criterion is max iteration attained. Recurrence of mutation, recombination (crossover) and selection process still a stopping criteria is met. The output results are obtained at minimum convergence value.

3. METHOD

3.1. UPFC model

Two voltage-source converters (VSC) of UPFC are connected along with DC link and Figure 1 presents two ideal voltage-sources between two buses. Z_{se} and Z_{sh} are impedances of 2-coupling transformers associated in series and shunt between UPFC and line. The voltage-sources of UPFC can be defined as (5) and (6).

$$\mathrm{V_{se}} = \mathrm{V_{se}}\ (\cos\theta_{se} + \mathrm{j}\ \sin\theta_{se})$$

$$V_{se} = V_{se}(cos\theta_{se} + j\ sin\theta_{se}) \tag{5}$$

$$V_{sh} = V_{sh}\ (cos\theta_{sh} + j\ sin\theta_{sh}) \tag{6}$$

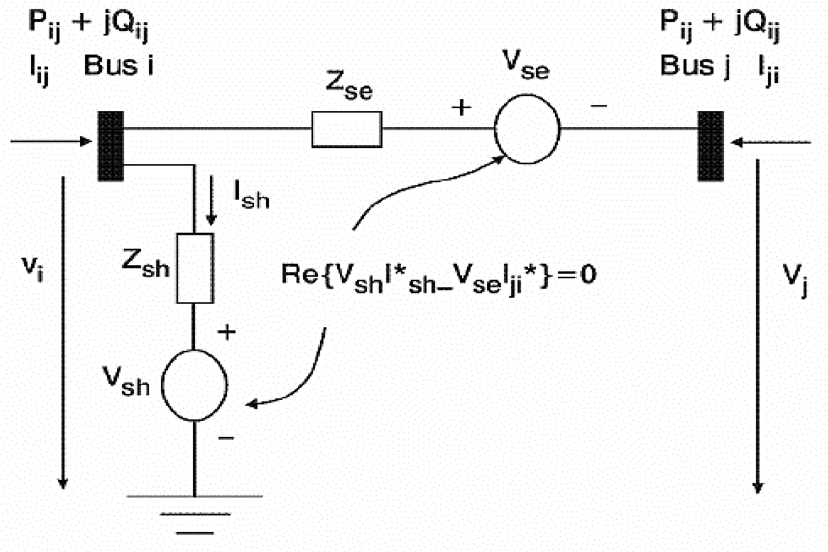

Figure 1. Voltage-source circuit of UPFC

3.2. Function definition

Diminishing losses of active and reactive-power in networks has considered as a significant issue in planning and operation of power systems [29], [30]. UPFC should be sited at optimal place by tuning the parameter settings to minimize these losses as much as possible. The function is defined as (7):

$$min\ F = \sum_1^n PQ_{\mathrm{kloss}} \tag{7}$$

where, F is function, n is lines in network, PQ_{kloss} are losses in network.

3.2.1. Equality constraints

The equality constraints can be written as:

At bus k: $P_k(v,\theta) + P_{dk} - P_{gk} = 0$
$Q_k(v,\theta) + Q_{dk} - Q_{gk} = 0$

At bus m: $P_m(v,\theta) + P_{dm} - P_{gm} = 0$
$Q_m(v,\theta) + Q_{dm} - Q_{gm} = 0$

where: P_k and P_m are active-powers at bus-k and bus-m, respectively; Q_k and Q_m are reactive-powers at bus-k and bus-m, respectively; P_{dk} and Q_{dk} are load active and reactive-power at bus-k, P_{dm} and Q_{dm} are load active and reactive-power at bus m, P_{gk} and Q_{gk} are generation active and reactive-power at bus-k, P_{gm} and Q_{gm} are the generation active and reactive-power at bus m.

3.2.2. Inequality constraints

The inequality constraints can be written as:

$$P_{gk}{}^{min} \leq P_{gk} \leq P_{gk}{}^{max}$$
$$Q_{gk}{}^{min} \leq Q_{gk} \leq Q_{gk}{}^{max}$$
$$V_k{}^{min} \leq V_k \leq V_k{}^{max}$$
$$\delta_k{}^{min} \leq \delta_k \leq \delta_k{}^{max}$$
$$V_{sh}{}^{min} \leq V_{sh} \leq V_{sh}{}^{max}$$
$$V_{se}{}^{min} \leq V_{se} \leq V_{se}{}^{max}$$

3.3. Optimal siting of UPFC

Optimal location of UPFC can be determined by following active-power flow sensitivity index (APFSI) and static-VSI. APFSI is given by (8):

$$\sum_{1}^{n} PQ_{kloss} \quad PI = \sum_{m=1}^{N_l} \frac{W_m}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right)^{2n} \tag{8}$$

where W_m is real positive weight coefficient, P_{lm} is active PF of line-m, P_{lm}^{max} = rated-capacity of line-*m*, N_l = number of network lines.

PI will be small if line is under loaded and high if line is over loaded. This work is done with n=2.0 and W_m =1.0. In case of UPFC, the PI sensitivity factors are derived as:

$$c_1^u = \left.\frac{\partial PI}{\partial V_T}\right|_{V_T=0} = \text{PI sensitivity w.r.t } V_T$$

$$c_2^u = \left.\frac{\partial PI}{V_T \partial \delta_T}\right|_{\delta_T=0} = \text{PI sensitivity w.r.t } \delta_T$$

$$c_3^u = \left.\frac{\partial PI}{\partial I_q}\right|_{I_q=0} = \text{PI sensitivity w.r.t } I_q$$

where $V_{T,}$ δ_T and I_q are tunable parameters of UPFC that can control PF

Generally, UPFC is located in $line - k$ which has highest sensitivity. UPFC is located in $line - k$ which has highest absolute measure of sensitivity w.r.t to phase-angle. Device are not suggested to be inserted in line with PV buses, even if sensitivity is highest. Static-VSI is given by:

$$Static - VSI = \frac{\sqrt[2]{({R_{ij}}^2 + {X_{ij}}^2)({P_j}^2 + {Q_j}^2)}}{{V_i}^2 - 2(P_j R_{ij} + Q_j X_{ij})}$$

where Z means line impedance, S means apparent power P_j and Q_j represents active and reactive-power at receiving end, θ is impedance angle and V_i is sending end voltage.

The line exhibiting *Static-VSI* close to 1.00 means that it is reaching instability point. If *Static-VSI* exceeds 1.00 the buses to connected line will face an abnormal voltage drop resulting in voltage collapse. The transmission line with highest value of *Static-VSI* is taken as weakest line and device can be located.

3.4. Parameter setting and power control by SCDE

The variables considered in SCDE for parameter setting are as:

- UPFC Siting in system is first variable parameter considered, and siting individual for this tunable parameter can be any line, excluding lines where generators or transformers present.
- UPFC series voltage magnitude (V_{se}) is second variable parameter to be considered for optimization, and range considered is (in p.u.) between 0.001 and 0.2.
- The UPFC series voltage phase-angle (θ_{se}) is third variable parameter considered for optimization, and range considered is between 0 and 2п.

- The UPFC shunt voltage magnitude (V_{sh}) is fourth variable parameter considered for optimization, and range considered (in p.u.) is in between 0.9 and 1.1.
- The UPFC shunt voltage phase angle (θ_{sh}) is fifth variable parameter considered for optimization, and range considered is between 0 and 2π.

These variables are considered for optimization to minimize active and reactive-power loss in network. The implementation of SCDE algorithm is presented as follows:

Step 1: Initialize PF data and SCDE parameters i.e, size of population (NP), maximum number of generation (G_{max}), number of parameter individuals to be optimized (D), and DE control parameters C_R, and F.

Step 2: At random generate, initial population of NP individuals in feasible solution space by below equation considering variables that has to be optimized (parameters of UPFC)

$$X_i(G_o)=X_{imin}+rand_i[0,1]\ (X_{imax}-X_{imin})$$

Step 3: Evaluate, fitness for every individual population w.r.to objective function.

Step 4: Generate new population by mutation, crossover and selection.

Step 5: Stop process and observe best parameter setting and PF if stopping criterion is fulfilled, else move to Step 4.

4. RESULTS AND DISCUSSION

Consider the IEEE 5-bus network as presented in Figure 2 and slack bus is presented by bus 5 and bus 1, 2 are load buses and buses 3, 4 are generator buses. Bus data and line data are considered as per IEEE standards. Sensitivity and stability indices are presented in Tables 1 and 2 respectively. Generally, flexible AC transmission systems device is located where APFSI is high and static-VSI is low hence line 3 are considered as sensitive line. Sensitivity index for line 3 is high w.r.t phase angle as presented in Table 3, hence device is located in line 3.

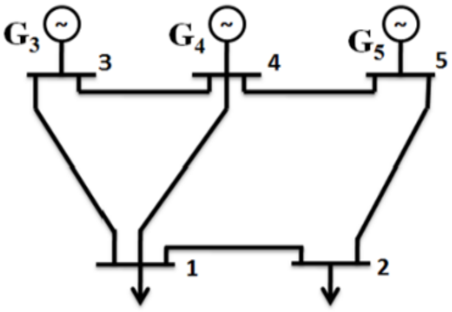

Figure 2. IEEE 5-bus test system

Table 1. Active power flow sensitivity index (APFSI)

Line-k		Active power flow sensitivity Index		
No	i-j	C_1^u	C_3^u	C_3^u
1	1-2	-0.6257	-2.3363	0.0
2	1-3	-0.0357	-1.0725	0.0
3	1-4	0.9474	**4.0746**	0.0
4	2-5	-0.4095	-2.4411	0.0
5	3-4	-0.2321	-1.2537	0.0
6	4-5	0.5042	2.5421	0.0

Table 2. Static voltage stability index (STATIC-VSI)

S. No	Lines	Static-VSI
1	1-2	0.1297
2	1-3	0.5473
3	1-4	**0.2663**
4	2-5	0.2417
5	3-4	0.5428
6	4-5	0.2021

Table 3. Optimal UPFC parameters considered in SCDE

V_{sh}	θ_{sh} in radians	V_{se}	θ_{se} in radians
1	-0.0768	0.085	0.5589

As presented in Table 2, device can be located in line 3 whose STATIC-VSI is 0.2663 because line 2, 5 consists of generator buses. So, line 3 is considered as sensitive line for optimal siting of UPFC. Optimal parameter setting of UPFC by SCDE is presented in Table 3.

In Table 4, real power loss is decreased from 0.23 to 0.1850 p.u and real power is controlled to 8.0 p.u by using sensitivity constrained differential evolution (SCDE) method. Similar process is carried out for IEEE -14 bus system and UPFC is located in line 2(5-1) according to calculated indices and line power is controlled from 0.7549 to 1.1388 p.u and also power loss to 0.0715 p.u as shown in Table 5. Obtained line power and power loss in IEEE 5 and 14 bus networks for proposed SCDE method is compared with genetic algorithm (GA) and power loss is less using SCDE method as shown in Table 6. Similarly, process is implemented for IEEE -30 bus system and device can be located in between bus 12-15.

Table 4. Active power flows and loss without, with UPFC and also using SCDE for IEEE 5 bus system

S. No	Lines	N-R method without UPFC P_{line}	N-R method without UPFC P_{loss}	N-R method with UPFC in line-3, P_{line}	N-R method with UPFC in line-3, P_{loss}	Proposed method (SCDE method) P_{line}	Proposed method (SCDE method) P_{loss}
1	1-2	0.9634	0.0021	0.5734	0.0016	0.5734	0.0016
2	1-3	-6.9911	0.221	-7.5733	0.2302	-7.5733	0.2302
3	1-4	**-8.9722**	**0.2300**	**-8.0000**	**0.1852**	**-8.0000**	**0.1850**
4	2-5	-4.0386	0.1008	-4.4281	0.0933	-4.4281	0.0932
5	3-4	2.7874	0.0290	2.1963	0.0181	2.1963	0.0181
6	4-5	1.056	0.0041	1.4931	0.0084	1.4931	0.0084

Table 5. Active power flows and loss without, with UPFC and also using SCDE for IEEE 14 bus system

S. No	Lines	N-R method without UPFC P_{line}	N-R method without UPFC P_{loss}	N-R method with UPFC inline-2, P_{line}	N-R method with UPFC in line-2, P_{loss}	Proposed method (SCDE method) P_{line}	Proposed method (SCDE method) P_{loss}
1	5-1	-0.7549	0.0276	-1.1388	0.0717	-1.1388	0.0715

Table 6. Comparison of proposed SCDE method with other method GA for IEEE 5, 14, 30 bus system

S. No	system	Proposed method (SCDE method), P_{line}	Proposed method (SCDE method), P_{loss}	GA, P_{line}	GA, P_{loss}
1	5	-8.0000	0.1850	8.0000	0.1855
2	14	-1.1388	0.0715	-1.1388	0.0718
3	30	0.17853	0.00216	0.17852	0.00217

5. CONCLUSION

In power system, siting and sizing of parameters of UPFC device is main step to decrease losses and proper power control. This paper presented APFSI and static-VSI Indices to find weakest line for UPFC siting to minimize power losses of power system. The parameters are tuned in such a way to minimize power losses. The proposed sensitivity constrained differential evolution method is successfully applied to considered problem for IEEE 5, 14 and 30 bus system and obtained better results when compared to conventional N-R method and GA method.

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BIOGRAPHIES OF AUTHORS

Karri Manoz Kumar Reddy obtained his B.Tech degree in electrical and electronics engineering in 2002 and he obtained his M.Tech degree in power systems high voltage engineering in 2005 from JNTU Kakinada. He is a life member of ISTE. Presently he is working as associate professor, Electrical and Electronics department in Aditya college of engineering, Surampalem, A.P, India and he is having 14 years teaching experience. Email kmkreddyy@gmail.com.

Kailasa A. Rao has graduated from IIT, Kharagpur in Electrical Engineering. He took his M.Tech degree in Power Systems from JNTU, Hyderabad and obtained Ph.D., from IIT, Kharagpur in Control Systems. He has Published 13 research papers, all in International Journals currently; he is a Director of Pragati Engineering College, Surampalem, Andhra Pradesh, India. Email akailasarao60@gmail.com.

Rayapudi Srinivasa Rao has graduated from SV University, Tirupati, in Electrical Engineering. He took his M.E degree from IISC, Bangalore and obtained Ph.D. from JNTU Hyderabad. He has Published 43 research papers, in various national, international conferences and journals. Currently, he is working as professor in JNTU Kakinada, Andhra Pradesh, India. Email srinivas.jntueee@gmail.com.