International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-6, March 2020

Critical Line based Optimal Allocation of UPFC to improve Voltage Stability of the system

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Abstract**: *This paper proposes critical line based optimal allocation of Unified Power Flow Controller (UPFC) in network to improve voltage stability through which finest power flow (PF) control can be obtained with proposed approach. A Genetic Algorithm based Upgraded Differential Evolutionary (UDE) approach is programmed with optimal allocation of UPFC at critical lines to enhance voltage stability. Critical lines can be obtained with severity of buses connected. Ranking Index(RI) is proposed to obtain critical lines in priority manner. UPFC device can be allocated at most priority line flow obtained from the proposed Ranking Index (RI).The constraints are modeled and programmed to make better voltage profiles of various bus networks. IEEE-5bus, 14bus, 30bus system are tested under MATLAB programming environment. The proposed strategy is compared with and without UPFC placement to show its effectiveness.***

Keywords **: *Critical buses, Critical lines Differential Evolution, Voltage Limits, Unified Power Flow Controller.***

I. INTRODUCTION

With development and increase in utilization of various infrastructure in the world, there is in need to give power supply adequately to the consumers. Day by day, with increase in power demand, utilization factor increases. beyond this, there are line contingency, power congestion and over load problems in power system network. In power system there are three criteria's to be considered 1) economic criteria, 2) Technical and 3) reliability.

Increase of transmission lines to a long distance for consumers may increase the economic prospective. Instead of establishment of new transmission lines which increases economic cost, it is convenient to locate any FACTS devices to enhance the voltage stability of the system. Research to allocate FACTs devices in transmission line with various techniques is being carried. Identification of suitable location for deployment of FACTs devices like UPFC which has unified PF characteristics is more important to obtain voltage stability of the system. Due to sudden load changes in network, either heavy load conditions or light load conditions, the voltage deviates from the limits leading to collapse of the network causing blackout. Identification of critical lines or sensitive PF lines is important to protect power system from blackouts. The author in [1] described many FACTS devices and modeling of components of devices with their characteristics. Author in [2] presented a new hybrid PSO based on evolutionary cultural algorithm for tuning of UPFC parameters and optimal deployment of UPFC in network. The author in [3] proposed performance Index and Ranking Index based on sensitivity of line flows for optimal deployment of UPFC and IPFC devices in Network. The author in [4] proposed WCA for optimal deployment of UPFC. The pareto optimal set is obtained using this algorithm. The author in [5] proposed DE-GWO as dual controller to multi machine arrangement for signal stability evaluation. The author in [6] presented two evolutionary algorithms such as CMAES, and NSGA-II are proposed for optimal deployment and configuring of UPFC. The author in [7] proposed GSA to obtain OPF with multiple UPFC devices. The author in [8] presented multi objective GA to solve voltage constrained OPF. Two control strategies are followed to improve voltage stability of network. The author in [9] proposed self-adaptive DE algorithm for enhancing OPF UPFC considering security constraints. The author in [10] proposed sensitive analysis based on load flow for optimal deployment of devices in network. The author in [11] presented critical bus analysis which defines severity of the stresses on the buses with more number of lines flows connected.

Research is carried out for optimal deployment based on sensitive indices values but the problem is lagging at formulation of suitable index for finding critical lines in network. Connecting more number of lines to single bus increases more stress on bus. At light load conditions the voltage may increase in lines and at heavy load conditions the voltage may decrease so in order to maintain voltage stability of network UPFC is to be allocated between two highly stresses buses.

In this paper, severe critical buses are analyzed and framed through proposed RI Index. An upgraded differential evolution (UDE) algorithm with UPFC allocated at critical bus is formulated to obtain voltage in p.u within the limits preserving stability of network

Manuscript received on February 10, 2020.
Revised Manuscript received on February 20, 2020.
Manuscript published on March 30, 2020.
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II. PROBLEM FORMULATION

A. Problem Formulation

The OPF is formulated as :

$$Minimize \quad (C(x)) \tag{1}$$

$$\text{Subject to} \quad \begin{matrix} r(x)=0 \\ s(x)\le 0 \end{matrix} \tag{2}$$

Where $C(x)$ is Cost function, $r(x)$ is equality constraints, $s(x)$ is inequality constraints and x is control vector. active and reactive power is P_G , Q_G and voltage magnitude of generation bus V_g and T is Transformer tap setting.

$x=[P_G, Q_{G,} V_G, T....]$

B. Objective Function

The OPF problem is formulated to minimize real power cost for production i.e., specified by quadratic function of generator output power as shown

$$C(x)=\sum_{k=1}^{ng}(a_k + b_k P_{Gk} + c_k P_{Gk}^2) \tag{3}$$

Where

$C(x)$ shows fuel cost

a_k , b_k , c_k are coefficients of real power

k denote corresponding generator (1,2…. n_g)

P_{Gk} is active generator power at bus k

n_g is sum of generators and slack bus

C. Equality and Inequality Constraints

Equality constraints are considered as PFs constraints that presents active and reactive powers injections of i^{th} bus, defined as

$$P_{Gk}-P_{Dk}=V_k\sum_{l=1}^{N}V_l(g_{kl}\cos\delta_{kl}+b_{kl}\sin\delta_{kl}) \quad (4)$$

$$Q_{Gk}-Q_{Dk}=V_k\sum_{l=1}^{N}V_l(g_{kl}\sin\delta_{kl}+b_{kl}\cos\delta_{kl}) \quad (5)$$

Where P_{Gk} , Q_{Gk} , P_{Dk} , Q_{Dk} are active and reactive power generation and power demand at bus k .

V_k , V_l are voltage magnitudes at bus (k,l) .

$g_{kl,}\, b_{kl}$ are real and imaginary part of admittance (Y_{kl}),

δ_{kl} is phase angle in between k and l buses.

N is number of buses.

The inequality constraints are formed to ensure network security which are presented as follows [15]

Constrained Limits on generator active PF buses:

$P_{Gk}^{\min} \le P_{Gk} \le P_{Kl}^{\max}$

Constrained Limits on generator reactive PF buses:

$Q_{Kl}^{\min} \le Q_{Kl} \le Q_{Kl}^{\max}$

Constrained Limits on transformer positions

$T^{\min} \le T \le T^{\max}$

Constrained Limits on phase angles

$\delta_k^{\min} \le \delta_k \le \delta_k^{\max}$

Constrained Limits on transmission line loading

$S_{Lk}{}^{\min} \le S \le S_{Lk}{}^{\max}$

Constrained Limits on Facts controllers

$y^{\min} \le y_{FACTS} \le y^{\max}$.

D. Critical Line Analysis

Fig. 1 shows Schematic diagram of 14-bus network. In 14-bus network [10], Bus-1, 2 are generator buses, bus 3,6,8 have compensating devices, remaining buses are load buses. To find critical line flows in system network, consider the number of line flows connected to every bus. The bus with more than 4 line flows is considered as critical bus. The bus with more line flows connected is bus-4. The line flows (branches) connected are 4-7, 4-5,4-9,4-2, 4-3. Total 5 branches are connected to bus-4. Buses that are connected to generator or compensator are considered as strong buses.

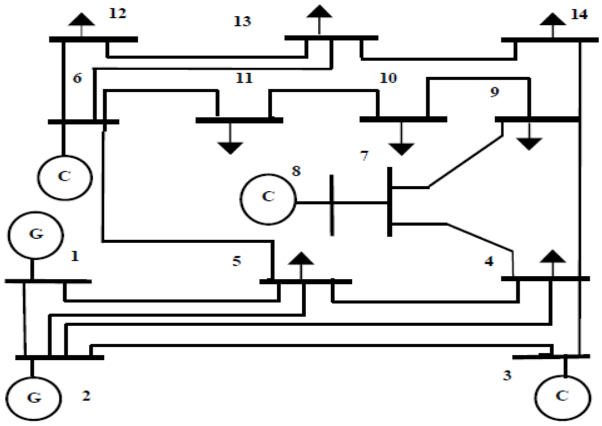

Fig.1. Schematic diagram of 14-bus network

Bus-4, 5 and 9 are considered as critical or weak buses in priority. The line flows between two critical buses is considered as most critical line flows i.e., 4-5, 4- 9, 4-7 are critical line flows arranged in prior in the network. critical line flows for 5bus, 14-bus and 30 bus network are shown in Table I.Ranking Index decides severity of line flow in descending order. suppose in 14 bus network line 4-5, is more severe compared to line 4-9, and line 4-9 is more stressed line compared to 4-7. Schematic diagram of 14-nus network is presented in Fig.1.

Table I. Critical Line flows based on RI

Test case systems	Critical line flows based on RI
5-bus system	3-4
14-bus system	4-5,4-9,4-7
30-bus system	6-10,12-15, 6-4

III. MODELING OF FACTS DEVICES 'UPFC'

Among obtainable FACTS devices, UPFC is best multipurpose one that can be utilized to increase voltage stability of network.

The UPFC can autonomously control many constraints since it is arrangement of STATCOM and SSSC. These devices suggest another mean to diminish oscillations in network [15].

UPFC equivalent circuit in Figure 2 encloses voltage source connected in shunt and series and constrained active power equation, which couples 2-voltage sources. 2- voltage sources are coupled to AC network through reactance signifying VSC transformers.

Voltage sources of UPFC are E_{vr} and E_{cR} which are represented as[14]

$$E_{vr} = V_{vr}(\cos\delta_{vr} + j\sin\delta_{vr}) \quad (6)$$

$$E_{cR} = V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \quad (7)$$

$$\begin{aligned} V_{vR\min} \le V_{vR} \le V_{vR\max} \\ 0 \le \delta_{vR} \le 2\pi \end{aligned} \quad (8)$$

Where V_{vr} and δ_{vr} are constrained magnitude and phase angle of voltage signifying shunt converter.

$$\begin{aligned} V_{cR\min} \le V_{cvR} \le V_{cR\max} \\ 0 \le \delta_{cR} \le 2\pi \end{aligned} \quad (9)$$

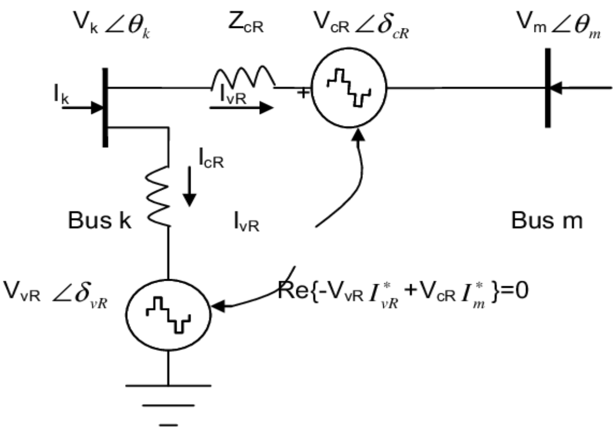

Fig 2. Equivalent circuit of UPFC

V_{cR} and δ_{cR} are constrained magnitude and phase angle of voltage source signifying series converter.

Active and reactive PFs are shown as

$$\begin{aligned} P_K = V_k^2 G_{kk} + V_k V_m[G_{km}Cos(\theta_k - \theta_m) + B_{km}Sin(\theta_k - \theta_m)] \\ + V_k V_{cR}[G_{km}Cos(\theta_k - \delta_{cR}) + B_{km}Sin(\theta_k - \delta_{cR})] \\ + V_k V_{vR}[G_{vR}Cos(\theta_k - \delta_{vR}) + B_{vR}Sin(\theta_k - \delta_{vR})] \end{aligned} \quad (11)$$

$$\begin{aligned} Q_K = -V_k^2 G_{kk} + V_k V_m[G_{km}Cos(\theta_k - \theta_m) - B_{km}Sin(\theta_k - \theta_m)] \\ + V_k V_{cR}[G_{km}Cos(\theta_k - \delta_{cR}) - B_{km}Sin(\theta_k - \delta_{cR})] \\ + V_k V_{vR}[G_{vR}Cos(\theta_k - \delta_{vR}) - B_{vR}Sin(\theta_k - \delta_{vR})] \end{aligned} \quad (12)$$

$$\begin{aligned} P_m = V_m^2 G_{mm} + V_m V_k[G_{km}Cos(\theta_m - \theta_k) + B_{km}Sin(\theta_m - \theta_k)] \\ + V_m V_{cR}[G_{mm}Cos(\theta_m - \delta_{cR}) + B_{km}Sin(\theta_{mk} - \delta_{cR})] \end{aligned} \quad (13)$$

$$\begin{aligned} Q_m = -V_m^2 G_{mm} + V_m V_k[G_{mk}Cos(\theta_m - \theta_k) - B_{mk}Sin(\theta_m - \theta_k)] \\ + V_m V_{cR}[G_{mm}Cos(\theta_m - \delta_{cR}) - B_{km}Sin(\theta_m - \delta_{cR})] \end{aligned} \quad (14)$$

Active and reactive PF of series converter

$$\begin{aligned} P_{cR} = V_{cR}^2 G_{mm} + V_{cR} V_k[G_{mk}Cos(\delta_{cR} - \theta_k) + B_{mk}Sin(\delta_{cR} - \theta_k)] \\ + V_{cR} V_m[G_{mm}Cos(\delta_{cR} - \theta_m) + B_{mm}Sin(\delta_{cR} - \theta_m)] \end{aligned} \quad (15)$$

$$\begin{aligned} Q_{cR} = -V_{cR}^2 B_{mm} + V_{cR} V_k[G_{mk}Cos(\delta_{cR} - \theta_k) - B_{mk}Sin(\delta_{cR} - \theta_k)] \\ + V_{cR} V_m[G_{mm}Cos(\delta_{cR} - \theta_m) - B_{mm}Sin(\delta_{cR} - \theta_m)] \end{aligned} \quad (16)$$

Active and reactive PF of shunt converter

$$P_{vR} = -V_{cR}^2 G_{vR} + V_{vR} V_k[G_{vR}Cos(\delta_{vR} - \theta_k) + B_{vk}Sin(\delta_{vR} - \theta_k)] \quad (17)$$

$$Q_{vR} = V_{vR}^2 B_{vR} + V_{vR} V_k[G_{vR}Sin(\delta_{vR} - \theta_k) - B_{vk}Cos(\delta_{vR} - \theta_k)] \quad (18)$$

IV. UDE ALGORITHM FOR OPF

DE is evolutionary strategy suggested by Price and Storn [12]-[13] for optimization in uninterrupted domain. DE is modest and robust. Simple design of UDE is to accustom search throughout evolutionary process. It is similar to direct search (DS) method that engages ' $NP - D$ dimensional' parameter vectors $i = 1, 2, ...NP$ as population for every G-generation. NP do not vary in period of optimization method. The primary population is selected arbitrarily and would wrap complete constraint space. At initiate of development, agitations are bulky since parental inhabitants are distant away from each other.

A. Initialization

The primary step in DE strategy is to generate a primary population of candidate solution by allocating arbitrary value to every result parameter of each independent of population. A population N_p is created in arbitrary way so that values lies in possible bounds $y_j^{\min}$ and $y_j^{\max}$ of decision variable,

$$y_{ij} = y_j + rand \times (y_j^{\max} - y_j^{\min}) \quad (19)$$

Where $i = 1, 2, ...n$ is individual's population

$j = 1, 2, ….,n$ implies D-dimensional search space position

$y_j^{\min}$ = lower bound

$y_j^{\max}$ = upper bound

$rand$ = random number varies between 0 to 1 which is uniformly distributed .

B. Mutation

A new mutant population is created whose size is same as that of initial population NP. Among several methods utilized for mutation in DE, accumulation of subjective modification variable between two population members to third member is adopted. Here three different population namely y_{r1} y_{r2} and y_{r3} are chosen from current population. Then change among any two of these population is ascended by scalar number F known as scaling factor, added to third population number.. The value of F is in between 0.4 and 1.

If finest variable for mutant individual is exterior of domain search, then this variable is replaced by its lower bound or its upper bound so that every individual can be constrained to remain within search domain. In every generation, a donor vector path is generated to change population vector. Thus j^{th} member of donor vector $V_{ij}(t)$ is formulated as

$$V_{ij}^{(t+1)} = y_{r1}(t) + F * (y_{r2}j(t) - y_{r3}j(t)) \quad (20)$$

C. Crossover

A new population vector is created by suitably merging parent and mutant population. The strategy of crossover is based on C_R which is in range (0, 1). Binomial crossover technique is used which can implement on all D variables and can be presented as:

$$U_{i,j}^{t+1} = V_{i,j}^{t+1} \quad if \quad rand\ (0,1) < C_R \qquad (21)$$
$$U_{i,j}^{t+1} = P_{i,j}^{t+1} \quad else$$

Where $U_{ij}(t)$ is child vector which is attained after crossover technique

where i = 1,2, ... Np, j = 1,2, ... D. Here, *rand* concludes newly generated vector is different from both $V_{ij}(t)$ and $y_{ij}(t)$.

D. Selection

After computing cost function or main objective function $C(t)$ considering D-variables for using initial and crossover population vector, a new population vector with least objective function is obtained for next generation. This is given by

$$y_i^t = \begin{cases} U_i^{i+1}, if \ f(U_i^{t+1}) \le f(y_i^t) \\ y_i^t \qquad\qquad otherwise \end{cases} \qquad (22)$$

The global finest searching ability and convergence of DE are susceptible to select of control constraints N_P, F and C_R. Crossover rate is between [0.3, 0.9]. Mutation Factor F is supposed to be greater than definite value to avoid early convergence.

Verification of stopping criteria:

Set generation number for t=t+1. Recurrence mutation, recombination (crossover) and selection process still a stopping criterion come across i.e., generally with a maximum number of iterations. The ending criterion can be subject to type of a problem.

E. Upgraded Differential Strategy

The proposed UDE strategy procedure is shown in Fig3. In this mutation strategy, mutant vector can be created according to following equation from arbitrarily selected base vector.

$$V_{ij}^t = y_{R1j}^t + F(P_{R2j}^t - y_{R2j}^t)(i = 1,2.....NG; i \ne d; j = 1,2,....L) \qquad (23)$$

Where t is time

$y_i^t = [y_{i1}^t, y_{i2}^t, ...y_{iNG}^t]^T$ Signifies location of i individual of inhabitants of real values in NG-dimensional.

$V_i^t = [V_{i1}^t, V_{i2}^t, ...V_{iNG}^t]^T$ Signifies location of i^{th} individual of mutual vector. $R1$, $R2$ *and* $R3$ are equally unlike integers that are also dissimilar from running index, i is arbitrarily selected with uniform distribution from set {1, 2, i-1, i+1,..L}. F is mutation factor and F >0 is real constraint.

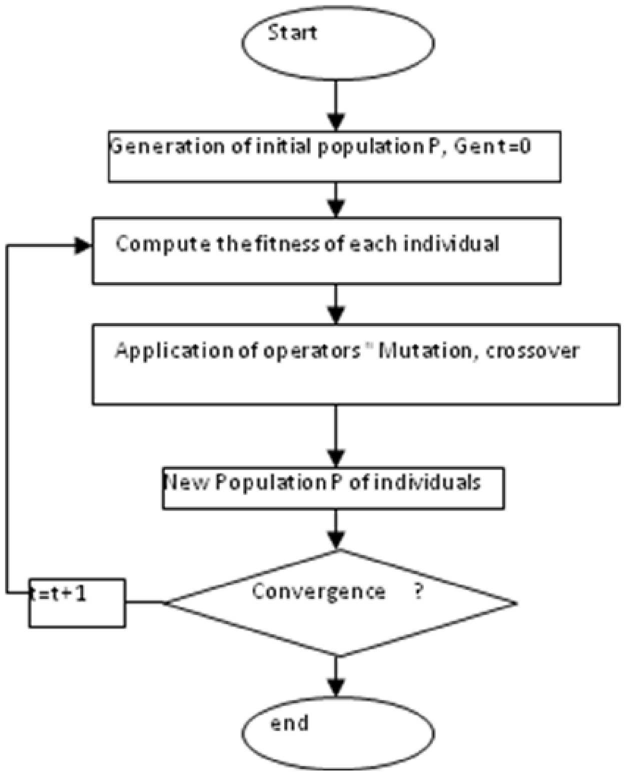

Fig 3. Flow chart for UDE algorithm

V. RESULTS AND ANALYSIS

In OPF problem every vector in UDE, population signifies a candidate solution. The vector of that solution consists of output power produced by a generation unit. The objective is to decrease, total fuel cost subjected to constraints by running UDE and inequality constraints by summing a quadratic penalty function. Table II presents UDE Algorithm parameters. The control constraints of UPFC are showed in Table III.

Table II. UDE Algorithm Parameters

DE Parameters	
Population Size NP	20
Maximum number of generations G_{max}	100
Crossover Constant CR	0.5
Weighting Factor	0.9

Table III. UPFC Parameters

No UPFC	$X_{cr}(p.u)$	$X_{vr}(p.u)$	Q_{max} $(MVAR)$	Q_{min} $(MVAR)$
1	0.1	0.1	35	-35

The OPF with UPFC device using UDE approach is developed and executed utilizing MATLAB. validity of proposed UDE strategy is tested on 5-bus , 14-bus and 30-bus system.

To validate effectiveness of UDE approach two cases to be discussed:

Case 1: presents solution of OPF using UDE without UPFC device allocated. In this case control vector constraints include only generated active power P_{gi}

Case 2: presents solution of OPF using UDE with one UPFC device allocated. The control vector constraints include generated active power (P_{gi}), shunt and series voltage source of UPFC (V_{cR}, V_{vR}) .

$$x = [P_{g2}, P_{g5}, P_{g8}, P_{11}, P_{g13}, V_{cR}, V_{vR}]$$

The upper and lower bounds on shunt and series voltage source of UPFC are set as

$$0.95 \le V_{vR} \le 1.10\, p.u \qquad 0.95 \le V_{cR} \le 1.10\, p.u$$

IEEE Test Case 1: 5-bus network:

Table IV. Power generation limits and cost coefficients for IEEE 5-bus system.

Gen	$P_{gi(\min)}$ (MW)	$P_{gi(\max)}$ (MW)	A_i $(\$/h)$	$B_i 10^{-2}$ $(\$/MWh)$	$C_i 10^{-4}$ $(\$/MW^2h)$
G1	37.5	150	0.008	10	200
G2	45	180	0.00745	10	240

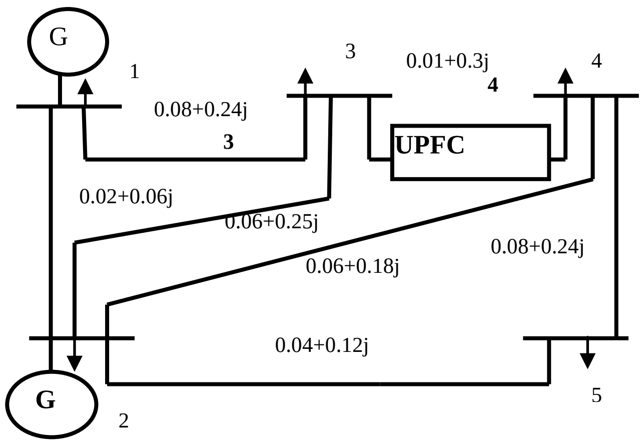

Fig 4: Five-Bus network

The line data of 5-bus network is given in Fig 4.The active power generating constraint limits and unit costs of all generators of 5-busnetwork are given in Table IV. The obtained results as shown in Fig 5 shows that upper and lower bounds of generator and load buses are maintained between 0.9 and 1.1p.u. voltage values.

Figure 4 presents voltage profile of 5 bus network obtained with and without UPFC considering UDE algorithm. From Fig.4 we can observe that voltage profile at bus 4 and 5 and line 4-5, 3-4 is improved.

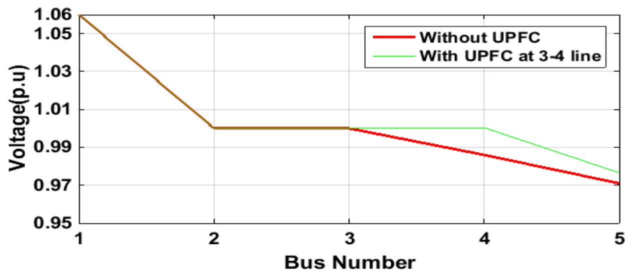

Fig 5. Voltage Profile of all 5-buses

Test case 2: 14-bus network:

The schematic diagram of 14 bus network is presented in Fig 1. The optimal placement of UPFC which is achieved through critical line is (from bus 4 to bus 5). For UDE technique, best value considered for F is 0.5 and for C_R it is 0.5. The power and cost coefficients for 14-bus network is shown in Table V. from critical analysis we know that line 4-5 is most critical line according to proposed analysis. The UPFC is deployed at line 4-5 in 14-bus network.

Table VI presents voltage in p.u obtained with and without UPFC considering UDE strategy. from the table 6 it can be observed that voltage values at bus-4,5,9 are within limits. The upper and lower bounds of generator and load buses are maintained between 0.9 & 1.1p.u and phase angles are maintained between -14 and 0°.

Table V Power generation limits and cost coefficients for IEEE 14-bus system.

Gen	$P_{gi(\min)}$ (MW)	$P_{gi(\max)}$ (MW)	A_i $(\$/h)$	$B_i 10^{-2}$ $(\$/MWh)$	$C_i 10^{-4}$ $(\$/MW^2h)$
G1	10	160	0.05	2.45	105.000
G2	20	80	0.05	3.510	44.100
G3	20	50	0.05	3.890	40.600

Table VI. Voltage p.u with and without UPFC

Bus No	Without UPFC	With UPFC
1	1.06	1.060
2	1.045	1.045
3	1.010	1.010
4	1.013	1.019
5	1.016	1.020
6	1.070	1.070
7	1.045	1.062
8	1.080	1.090
9	1.030	1.056
10	1.029	1.051
11	1.046	1.057
12	1.053	1.055
13	1.046	1.050
14	1.019	1.036

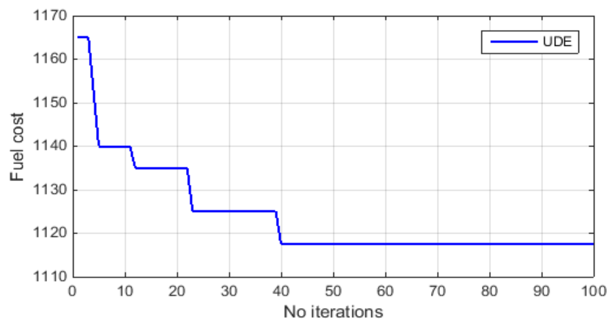

Fig 6. Convergence Characteristics of UDE algorithm with UPFC

The fuel cost($/hr) obtained for UDE with UPFC allocated at critical lines at base case is 1116.5($/hr) as shown in Fig.6.

Test case 3: 30 bus Network:

The active power constraint limits and unit costs of all generators of 30-bus test network are shown in Table VII.

Table VII. Power generation limits and cost coefficients for IEEE 30-bus system.

Gen	$P_{gi(\min)}$ (MW)	$P_{gi(\max)}$ (MW)	A_i $(\$/h)$	$B_i 10^{-2}$ $(\$/MWh)$	$C_i 10^{-4}$ $(\$/MW^2h)$
G1	50	200	0.0	200	37.5

G2	20	80	0.0	175	175.0
G5	15	50	0.0	100	625.0
G8	10	35	0.0	325	83.0
G11	10	30	0.0	300	250.0
G13	12	40	0.0	300	250.0

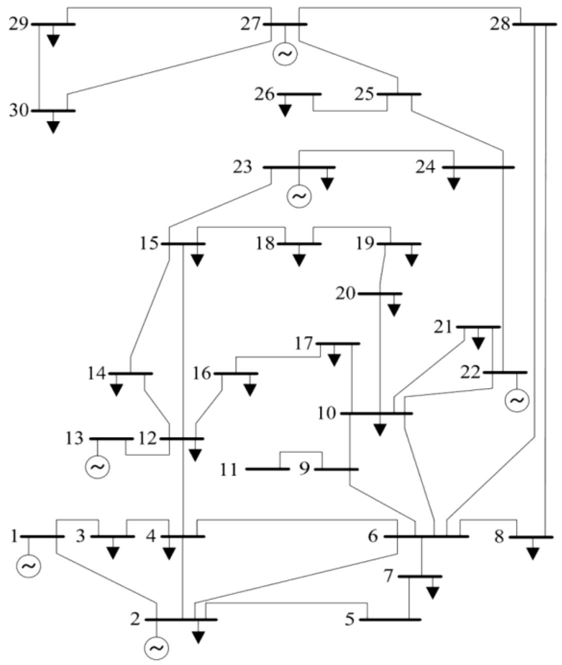

Fig 7. Schematic Line diagram of 30- bus network

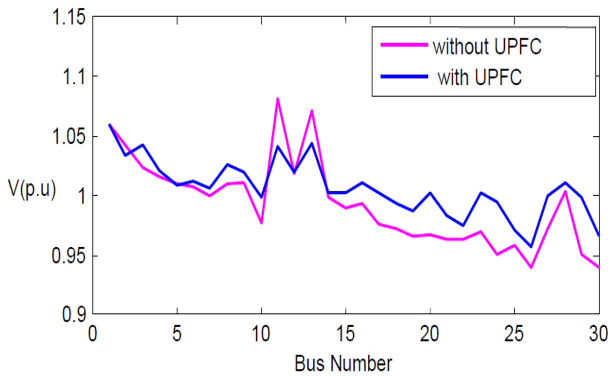

Fig.7 Voltage profile of all buses for 30-Bus with & without UPFC.

The upper and lower bounds of generator and load buses are maintained between 0.9 and 1.1p.u as shown in Fig 7. From Fig. 7, voltage profile before and after UPFC is clearly identified that all voltage magnitude profiles are within constraint limit. The fuel cost($/hr) obtained for UDE with UPFC allocated at critical line at base case is 562($/hr) as presented in Fig.8.

The proposed UDE with FACTS devices is applied on 5bus 14bus and 30-bus network systems. UPFC devices are allocated at line 3-4 in 5-bus network, between line4-5 in 14 bus network and line 6-10 in 30-bus network. performance is observed with and without UPFC device. The results of voltage magnitude and convergence characteristics of all bus networks are described with figures.

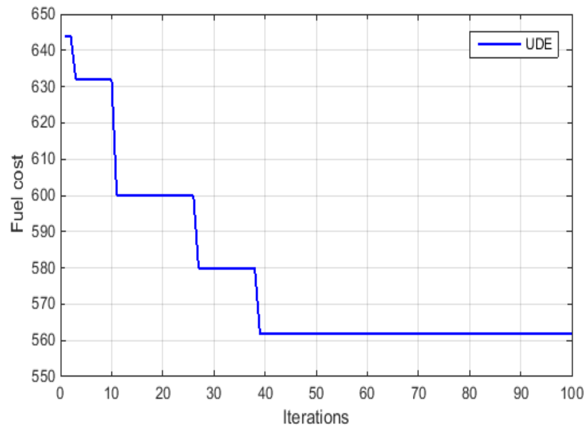

Fig 8. Convergence Characteristics of UDE algorithm with UPFC for 30-bus network

VI. CONCLUSION

This paper presented Upgraded Differential Evolution (UDE) strategy to obtain voltage stability with UPFC. The critical line based optimal deployment of UPFC device improves the voltage stability of network. proposed ranking index considers priory the most concentrated or stressed lines in descending order for deployment of UPFC. UDE is programmed considering with and without UPFCs are compared to show its effectiveness of UPFC. UPFC is one of finest OPF control device which enhances stability with voltage control. The convergence characteristics with fuel cost minimization is obtained for 14-bus and 30 bus networks. This paper describes UDE strategy with effect of UPFC to enhance dynamic stability improving voltage profile. IEEE 5 bus 14 bus and 30-bus network are considered for testing the proposed UDE strategy.

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