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Optimal Power flow with FACTS devices using Genetic Algorithm

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Abstract— Increasing demands for reliable and most economic operation of transmission and distribution systems has been met by the use of FACTS devices. The paper incorporates Optimal power flow with FACTS device embedded in transmission line that constitute a valuable tool in operations of meeting these high demands. Optimal power flow with FACTS devices belong to a class of nonlinear constrained optimization problem with generation cost and system losses as the objective functions. The genetic algorithm approach is used to achieve optimal power flow in power system incorporating FACTS device. Genetic algorithm determines the control parameters of power flow constraints with FACTS devices. The various parameters considered are the location of Facts devices, their type and rating. Static power flow models are developed for Static Var Compensator (SVC), Thyristor Controlled Series Compensator (TCSC), and Unified Power Flow Controller (UPFC) using Power injection method. These equations are embedded into normal Newton Raphson equations to form extended Newton Raphson Power flow with FACTS devices. In the paper Genetic algorithm is coupled with full ac power flow equations which selects best regulation to minimize total generation cost keeping power flow within limits. MATLAB coding is developed for simulation .The algorithm is being applied to an IEEE 30 bus system.

Index Terms— FACTS, SVC, TCSC, UPFC, Genetic Algorithm, load flow, MATLAB, Newton Raphson method, Optimal power flow, Power injection method.

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1 INTRODUCTION

IN the present day scenario private power producers are increasing rapidly to meet the increase demand of electricity. In this process, the existing transmission lines are overloaded and lead to unstable system. It becomes more and more important to control power flow along the transmission line thus to meet the needs of power transfer.

Optimal power flow is a nonlinear constrained optimization problem and is getting difficult to solve. This has led to the introduction to Flexible AC Transmission systems devices. The main benefits of these devices include improvement of system dynamic behavior and enhancement of system reliability. They control power flow in the network, reduces the flow in heavily loaded lines thereby resulting in an increased loadability and low system losses [1].

2 STATIC MODELING OF FACTS DEVICES

2.1 FACTS devices

In this paper, three typical FACTS devices have been considered: SVC (Static Var Compensator), TCSC (Thyristor Controlled Series Compensator) and UPFC (Unified Power Flow Controller).

Among these devices,SVC can be used to control the reactive power compensation, TCSC change the reactance of the line and the UPFC is the most powerful and versatile FACTS device due to the fact that the line impedance, terminal voltages and the voltage angle can be controlled by it simultaneously[6]. The power flow Pij through the transmission line i-j is a function of line impedance Xij, the voltage magnitude Vi, Vj and the phase angle between the sending and receiving end voltages θij.

$$P_{ij} = \frac{V_i V_j \sin\theta_{ij}}{X_{ij}} \tag{1}$$

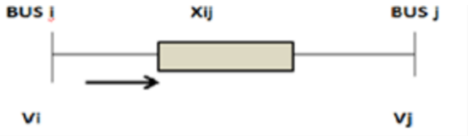

Fig. 1. Power flow between bus i and j.

2.2 Mathematical Modeling

The mathematical models of FACTS device are developed to perform steady state research. TCSC is modeled to modify the reactance of transmission line directly.SVC and UPFC are modeled by power injection method. For TCSC and UPFC their mathematical model is integrated into the model of transmission line.SVC model is incorporated into the sending end as a shunt element of transmission line.

2.2.1 Static Var Compensator

A changing Susceptance B_{SVC} represents the fundamental frequency equivalent Susceptance of all shunt modules making up the SVC. The SVC consists of a group of shunt-connected capacitors and reactors banks with fast control action by means of thyristor switching circuits. Depending on the nature of the equivalent SVC's reactance, i.e., capacitive or inductive, the SVC draws either capacitive or inductive current from the

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network. Suitable control of this equivalent reactance allows voltage magnitude regulation at the SVC point of connection. The most popular configuration for continuously controlled SVC's is the combination of either fix capacitor and thyristor controlled reactor or thyristor switched capacitor and thyristor controlled reactor.

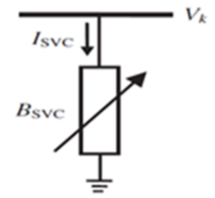

Fig. 2. Variable Susceptance model of SVC.

The circuit shown in Fig. 2 is used to derive the SVC's nonlinear power equations and the linearised equations required by Newton's load flow method. In general, the transfer admittance equation for the variable shunts compensator

$$I_{SVC} = jB_{SVC}V_k \tag{2}$$

The Reactive power equation is

$$Q_{SVC} = -V_k^2 B_{SVC} \tag{3}$$

This changing Susceptance value represents the total SVC Susceptance which is necessary to maintain the nodal voltage magnitude at the specified value (1.0 p.u.).

2.3 Thyristor Controlled Series Compensator

The TCSC can serve as capacitive or inductive compensation by modifying the reactance of transmission line. Reactance of transmission line can be adjusted by adjusting the TCSC directly. The rated value of TCSC is a function of reactance of transmission line where TCSC is located[2].

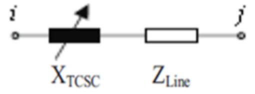

Fig. 3. Mathematical model of TCSC.

$$X_{ij} = X_{Line} + X_{TCSC} \tag{4}$$

$$X_{TCSC} = r_{TCSC} * X_{Line} \tag{5}$$

where

X_{Line} = Reactance of the transmission line
X_{TCSC} = Reactance of TCSC.

r_{TCSC} is coefficient which represents the compensation degree of TCSC To avoid overcompensation the working range of TCSC is chosen to be between -0.7 X_{Line} to 0.2 X_{Line} , r_{TCSC}(min) = -0.7 and r_{TCSC}(max) = 0.2.

The TCSC power flow model presented is based on the simple concept of a variable series reactance, the value of which is adjusted automatically to constrain the power flow across a branch to a specified value. The amount of reactance is determined efficiently using Newton's method. The changing reactance X_{TCSC}, represents the equivalent reactance of all the series-connected modules making up the TCSC, when operating in either the inductive or the capacitive regions[6].

The active and reactive power equations at a bus k are:

$$P_k = V_k V_m \sin(\theta_k - \theta_m) \tag{6}$$

$$Q_k = -{V_k}^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m) \tag{7}$$

For the power equations at bus m, the subscripts k and m are exchanged in "(6)" and "(7)".In Newton–Raphson solutions these equations are linearised with respect to the series reactance. For the conditions shown in "(6)"and "(7)", where the series reactance regulates the amount of active power flowing from bus k to bus m at a value P_{km}^{reg}, the set of linearised power flow equations is:

$$\Delta X_{TCSC} = X_{TCSC}^{i} - X_{TCSC}^{I-1} \tag{8}$$

is the incremental change in series reactance and $P_{km}^{XTCSC,CAL}$ is the calculated power as given by "(9)".

The state variable X_{TCSC} is updated as

$$X_{TCSC}^{i} = X_{TCSC}^{i-1} + \left(\frac{\Delta XTCSC}{XTCSC}\right)^{i} X_{tcsc}^{i-1} \tag{9}$$

2.4 Unified Power flow Controller (UPFC)

UPFC is a combination of series and shunt controllers. It has three controllable parameters namely magnitude of the boosting injected voltage (U_T), phase of this injected voltage ρ_T and the exciting transformer reactive current (Iq).Figure consists of an UPFC is installed in the power system with exciting transformer directly connected to bus i. The unified power flow controller consists of two switching converters. These converters are operated from a common link provided by a dc storage capacitor.

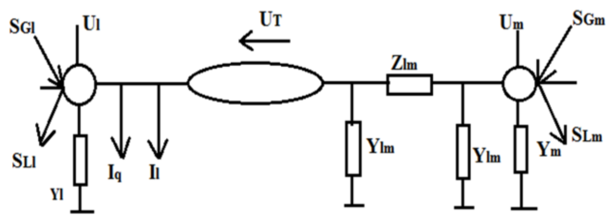

Fig. 4. Representation of UPFC connected between bus l-m
Z_{lm} denotes series impedance between bus l and bus m
Y_{lm} denotes shunt admittance between bus l and bus m

2.5 Voltage Source Model

In the following section, a model for UPFC which will be referred as UPFC injection model is derived.[3] This model is helpful in understanding the impact of the UPFC on the power system in the steady state. Furthermore, the UPFC injection model can easily be incorporated in the steady state power flow model.

The two-voltage source converters of UPFC can modeled as two ideal voltage sources one connected in series and other in shunt between the two buses. The output of series voltage magnitude V_{cR} controlled between the limits $V_{cR}min \le V_{cR} \le V_{cR}max$ and the angle $\boldsymbol{\delta}_{cR}$, $0 \le \boldsymbol{\delta}_{cR} \le 2\Pi$. The shunt voltage magnitude V_{vR} controlled between the limits $V_{vR}min \le V_{vR} \le V_{vR}max$ and the angle $\boldsymbol{\delta}_{vR}$, $0 \le \boldsymbol{\delta}_{vR} \le 2\Pi$, Z_{cR} and Z_{vR} are considered as the impedances of the two transformers one connected in series and other in shunt between the transmission line and the UPFC as shown in the figure which is the UPFC equivalent circuit [3].

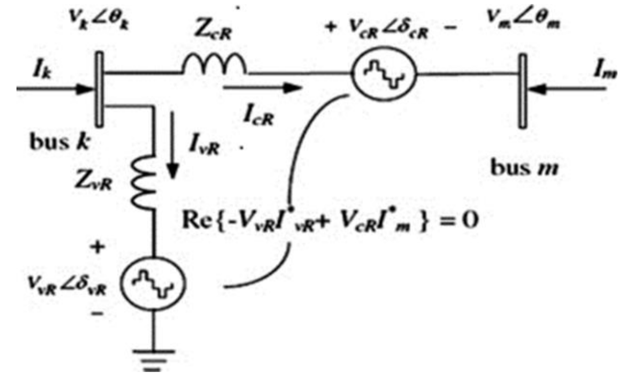

Fig. 5. Voltage Source model for UPFC

The UPFC Voltage sources are

$$E_{vR} = V_{vR}(\cos\delta_{vR} + j\sin\delta_{vR}) \quad (10)$$

$$E_{cR} = V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \quad (11)$$

The phase angle of the series-injected voltage determines the mode of power flow control. If **δ_{cR}** is in phase with the nodal voltage angle θ_k, the UPFC regulates the terminal voltage If **δ_{cR}** is in quadrature with respect to θ_k(bus voltage angle), it controls active power flow, acting as a phase shifter. If **δ_{cR}** is in quadrature with the line current angle then it controls active power flow, acting as a variable series compensator. At any other value of **δ_{cR}**, the UPFC operates as a combination of voltage regulator, variable series compensator, and phase shifter. The magnitude of the series-injected voltage determines the amount of power flow to be controlled[8].

Assuming loss-less converter valves, the active power supplied to the shunt converter, P_{vR}, equals the active power demanded by the series converter, P_{cR}.

$$P_{vR}+P_{cR}=0 \quad (12)$$

Furthermore, if the coupling transformers are assumed to contain no resistance then the active power at bus k matches the active power at bus m. Accordingly

$$P_{vR} + P_{cR} = P_k + P_m \quad (13)$$

3 COST FUNCTIONS

The main objective of this paper is to find the optimal locations of FACTS devices to minimize the overall cost function consisting of generation costs and FACTS devices investment costs[5].

3.1 Generation Cost Function

The generating cost function has been approximated as a quadratic function in US$/Hour given by.

$$C_1(P_G) = aP_G^2+bP_G+c \quad (14)$$

3.2 FACTS Device Cost Function

(i)The cost function for SVC is:

$$C_{ISVC} = 0.0003S^2-0.3051S+127.38 \text{ (US\$/kVar)} \quad (15)$$

(i)The cost function for TCSC is:

$$C_{ITCSC}=0.0015S^2-0.7130S+153.75\text{(US\$/kVar)} \quad (16)$$

(i)The cost function for UPFC is:

$$C_{IUPFC} = 0.0003S^2 - 0.2691S+ 188.22 \text{ (US\$/kVar)} \quad (17)$$

Total investment cost function of FACTS devices is

$$C_2(f) = C_{IUPFC} + C_{ITCSC} + C_{ISVC} \quad (18)$$

4 OPTIMAL FACTS ALLOCATION

The overall cost function C_{TOTAL} consist of generation cost and FACTS devices investment costs[5].

$$C(Total)= C_1(P_G) +C_2(f) \quad (19)$$

The objective function to be minimized CTOTAL is given as

$$\textbf{Min (C Total)= Min(C1(PG))+ Min(C2(f))} \quad (20)$$

Subject to

$$E(f,g)=0 \ \&$$
$$B1(f)<b1,\ B2(g)<b2$$

Where C_{TOTAL} is the overall cost objective function that includes average investment cost of FACTS devices $C_2(f)$

$C_1(P_G)$ is the Generation cost.

E(f,g) is the conventional power flow equations.

B1(f) and B2(g) are inequality constraints for FACTS devices and conventional power flow respectively.

f and P_G are the vectors that represent variables of FACTS devices and the active power outputs of the generators.

g represents operating state of power system.

5 GENETIC ALGORITHM(GA) IMPLEMENTATION

Based on the mechanism of natural selection and genetics Genetic algorithms are global search techniques. They can search several possible solutions simultaneously and do not require any prior knowledge or special properties of objective function. Moreover they produce quality solutions and are excellent methods for searching optimal solution in a complex problem[7].The GA's start with random generation of initial population and their selection, Crossover and Mutation are proceeded until best population is generated. Particularly GA's are practical algorithms easy to be implemented in power system analysis. In the paper the Genetic Algorithm tool (GA Tool) in MATLAB 7.5 is used to formulate the problem. Here optimization is performed by GA tool.

5.1 GA Solution Representation,coding and decoding

For the problem considered the genetic string should represent allocation of variable number of FACTS devices in a network. In the representation chosen genetic string consists of kmax number of positions for location of FACTS devices. The objective is to find the optimal locations for the FACTS devices within the equality and inequality constraints. Therefore, the configuration of FACTS devices is encoded by three parameters[4]:

1. The Location
2. Type
3. Rated value of FACTS devices

5.1.1 Rating of FACTS device

After decision and location and type of FACTS device the rating of Device should be decided. As already mentioned 'r_f' is the variable that is used to find rating of FACTS device. The value of r_f is between -1 and +1.The rating of each FACTS device can be calculated as follows[2]:

SVC: The working range of SVC is between -100MVar and 100MVar.Then rf is converted into real compensation value using

$$r_{SVC} = r_f * 100 \text{ (MVar)} \tag{21}$$

TCSC: It has a working range between $-0.7X_{Line}$ and $0.2\ X_{Line}$ where X_{Line} is the reactance of transmission line where TCSC is installed for the system

$$r_{TCSC} = (r_f * 0.45 - 0.25)\ X_{Line} \tag{22}$$

UPFC: The inserted voltage of UPFC VUPFC has a maximum magnitude of 0.1Vm where Vm is the rated voltage of transmission line where UPFC is installed. The angle of V_{UPFC} can be varied from -180 to +180 therefore rf is converted into the working angle r_{UPFC} by the equation

$$r_{UPFC} = r_f * 180 \text{(degrees)} \tag{23}$$

6.2 Fitness Calculation

Fitness is defined as follows in the algorithm.

$$\text{Fitness} = C_{TOTAL} \tag{24}$$

where C_{TOTAL} is the objective function of the problem. Because the GA TOOL can only find the minimum positive value of objective function, the objective function is directly proportional to the fitness.

6.3 Reproduction

Reproduction is a process where individual is selected to move to a new generation according to their fitness .The Roulette wheel selection is employed[1].

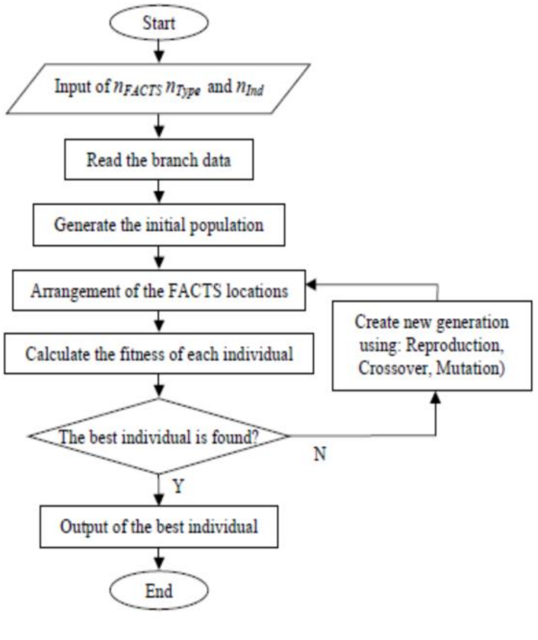

Fig. 6. Flowchart For Optimal Power Flow With FACTS Devices

6.4 Crossover

The main objective of crossover is to reorganize the information of two different individuals and produce a new one. A two point crossover is applied. Although one point crossover is used mostly, two point crossover is used to enhance diversity in population.

6.5 Mutation

It introduces some sort of artificial diversification in the population to avoid premature convergence to local optimum. In this paper adaptive feasible mutation is employed.

7 CASE STUDY AND RESULTS

To verify the effectiveness of the proposed method IEEE 30 bus system is used. Different operating conditions are considered for finding optimal location and choice of FACTS controller.

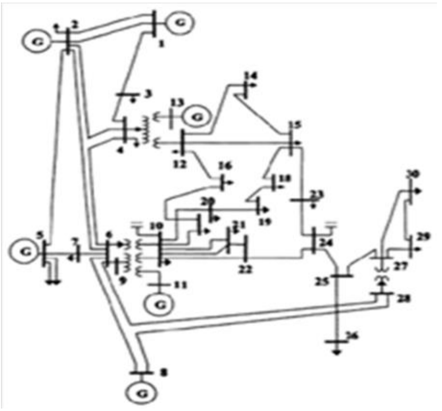

Fig. 7. Single line diagram of an IEEE 30 Bus System

Case 1 Normal loading of IEEE 30 Bus system
Case 2 Loading at bus 2 increased
Case 3 Loading at bus 15 increased
Case 4 Loading at bus 4,7,20 increased simultaneously

Case 1

In this case no FACTS controllers are required and the generator outputs are 178.37 MW, 48.54 MW, 21.68 MW, 12.96 MW, 12.87 MW, 12.57 MW.

Case 2

In this case SVC is selected at line 36. The rating of SVC is 73.38MVar. The generators outputs are 201.46 MW, 49.76 MW, 22.27 MW, 13.97 MW, 11.05 MW and 17.42 MW respectively.

Case 3

In this case the TCSC is selected at line 10. The rating of TCSC is 72.90 MVar. The generators outputs are 199.73 MW, 50.16 MW, 19.71 MW, 11.48 MW, 12.97 MW and 12.94 MW respectively.

Case 4

In this case the UPFC is selected at line 23. The rating of UPFC is 8.74MVar. The generators outputs are 213.63 MW, 44.72 MW, 20.04 MW, 12.18 MW, 10.32 MW and 12.49 MW respectively.

From the above results it is proved that the total losses are reduced when appropriate FACTS device is chosen with optimal location, type and rating of the device.

TABLE 1
OPTIMAL TYPE, LOCATION AND RATING OF FACTS DEVICES

Bus No	Normal loading (MW)	New Loading (MW)	Selected device type	Device Rating	Location of FACTS
-	As per IEEE data	No Change	No Device	-	-
2	21.7	51.7	SVC	73.38	Line 36
4	7.6	37.6	SVC	94.7	Line 34
14	6.2	36.2	TCSC	30.4	Line 25
15	8.2	28.2	TCSC	186.7	Line 10
17	9.0	39.0	SVC	82.43	Line 21
18	3.2	18.2	SVC	91.49	Line 12
26	3.5	7.0	TCSC	263.44	Line 14
2 4	21.7 7.6	36.7 22.6	SVC	65.04	Line 34
4 7 18	7.6 22.8 3.20	19.6 27.8 13.2	TCSC	57.6	Line 12
4 7 20	7.6 22.8 2.20	19.6 27.8 12.2	UPFC	8.74	Line 23
4 7 23	7.6 22.8 3.2	19.6 27.8 13.2	UPFC	4.3	Line 32

MW = megawatt.

TABLE 2
MINIMIZATION OF TOTAL COST AND LOSSES AFTER INCORPORATION OF FACTS CONTROLLERS

Bus No	Device selected	Total Cost ($/h)	Total Demand (MW)	Total Generation (MW)	Total Loss (MW)
--	None	781.24	283.4	287.0	2.95
2	SVC	881.8	313.4	315.93	2.53
4	SVC	883.6	313.4	316.65	3.06
14	TCSC	882.3	313.4	316.12	2.72
15	TCSC	849.4	303.4	307.0	2.95
17	SVC	884.6	313.4	316.8	2.55
18	SVC	831.0	298.4	301.35	2.95
26	TCSC	792.6	286.9	290.5	3.83
2 4	SVC	868.4	308.4	312.23	3.83
4 7 18	TCSC	874.5	310.4	313.95	3.55
4 7 20	UPFC	879.4	310.4	313.37	2.90
4 7 23	UPFC	871.8	310.4	313.46	3.06

h=hour,MW=megawatt

The graph below shows the Variation of fitness value along with number of generations. It is seen that the fitness curve increases initially and saturates from 80th generation onwards.

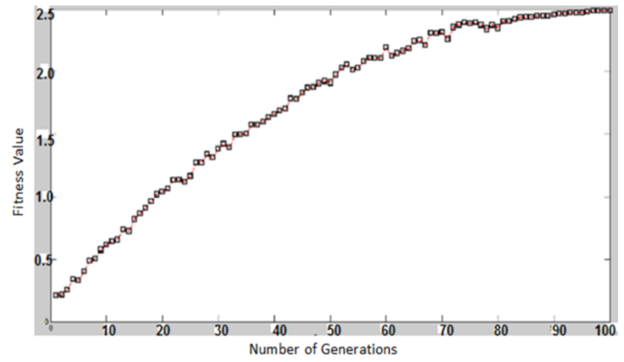

Fig. 8. Graph Fitness Value Vs Number of generations

7 CONCLUSION

In this paper a Genetic algorithm based optimal power flow approach is proposed to determine the suitable type of FACTS controllers, its optimal location and rating of the devices in power systems and also to simultaneously determine the active power generation for different loading condition .The overall system cost which includes generation cost of power plants and the investment cost of FACTS controllers are employed to evaluate the system performance .A MATLAB coding is developed for Genetic Algorithm. Simultaneous optimization of the locations of the FACTS devices, their types and rated values is a very complicated optimization problem in large power systems. The proposed algorithm in suitable to search several possible solutions simultaneously. It always produces high quality solutions and it is faster than the traditional optimization methods in large power system researches. The proposed algorithm is an effective and practical method for the allocation of FACTS controllers.

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