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Enhancement of power flow and optimal location of Steady State models of TCSC and SVC using intelligent algorithm

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Abstract— **In emergent power system, increased transactions where the systems no longer remains in secure operating region. The paper mainly focused on the application of flexible AC transmission system (FACTS) and use of Differential Evolution (DE) based algorithm for the allocation & coordinated operation of multiple FACTS devices for the improved power transfer capacity and economic operation of an interconnected power system is presented. Both the conventional load flow algorithm (CLFA) and DE based approach is applied on IEEE 30-bus system. The system is reactively loaded starting from base to 200 % of base load and the system performance is observed with and without FACTS devices. Active and reactive power flow in different lines gives an idea in determining the positions of FACTS devices to be placed in the system for the improved performance. Then the CLFA & DE based optimization approach is applied to find the size of the FACTS devices and the comparative analysis between these two techniques are made. This differential evolution (DE) based approach for the installation of FACTS devices found as more beneficial than CLFA based method.**

Index Terms— Conventional load flow algorithm(CLFA,),FACTS devices, Optimal location of FACTS devices, Differential Evolution, Static VAR compensator(SVC), Thyristor Controlled series compensator (TCSC),

I. Introduction to FACTS Devices

Modern power systems are extremely complex and are predictable to full the growing demands of power wherever required, with acceptable quality and costs. The economic and environmental factors necessitate the location of generation at places away from load centers. The restructuring of power utilities has increased the uncertainties in system operation. The regulatory constraints on the expansion of the transmission network has resulted in reduction of stability margins and increased the risks of cascading outages and blackouts. This problem can be effectively tackled by the introduction of high power electronic controllers for the regulation of power flows and voltages in AC transmission networks. This allows 'flexible' operation of AC transmission systems whereby the changes can be accommodated easily without stressing the system. Power electronic based systems and other static equipment that provide controllability of power flow and voltage are termed as FACTS Controllers.[4,5] It is to be noted that power electronic controllers were first introduced in HVDC transmission for not only regulation of power flow in

In 1988, Dr.Narain G. Hingorani introduced the concept of Flexible AC Transmission Systems (FACTS) by incorporating power electronic controllers to enhance power transfer in existing AC

transmission lines, improve voltage regulation and system security without adding new lines. The FACTS controllers can also be used to regulate power °ow in critical lines and hence, ease congestion in electrical networks. FACTS does not refer to any single device, but a host of controllers such as SVC, Thyristor Controlled Series Capacitor (TCSC), Static Phase Shifting Transformer (SPST), and newer controllers based on Voltage Source Converters (VSC) and current source converters (CSC) Static synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC) etc. The advent of FACTS controllers has already made a major impact on the planning and operation of power delivery systems. The concept of Custom Power introduced by Dr.Hingorani in 1995 has extended the application of FACTS controllers for distribution systems with the objective of improving power quality.

A. Benefits of utilizing FACTS devices:

The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows:

- Better utilization of existing transmission
- system assets

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- Increased transmission system reliability
- and availability
- Increased dynamic and transient grid
- stability and reduction of loop flows
- Increased quality of supply for sensitive
- industries
- Environmental benefits

B. Better utilization of existing transmission System assets:

In many countries, increasing the energy transfer capacity and controlling the load flow of transmission lines are of vital importance, especially in de-regulated markets, where the locations of generation and the bulk load centers can change rapidly. Frequently, adding new transmission lines to meet increasing electricity demand is limited by economic and environmental constraints. FACTS devices help to meet these requirements with the existing transmission systems.

C. Increased transmission system reliability and availability:

Transmission system reliability and availability is affected by many different factors. Although FACTS devices cannot prevent faults, they can mitigate the effects of faults and make electricity supply more secure by reducing the number of line trips. For example, a major load rejection results in an over voltage of the line which can lead to a line trip. SVC’s or STATCOMs counteract the over voltage and avoid line tripping.

D. Increased quality of supply for sensitive Industries:

Modern industries depend upon high quality electricity supply including constant voltage, and frequency and no supply interruptions. Voltage dips, frequency variations or the loss of supply can lead to interruptions in manufacturing processes with high resulting economic losses. FACTS devices can help provide the required quality of supply.

E. Environmental benefits

FACTS devices are environmentally friendly. They contain no hazardous materials and produce no waste or pollutants. FACTS help distribute the electrical energy more economically through better utilization of existing installations thereby reducing the need for additional transmission lines.

II. FACTS devices

Basic power flow equation

A. Modelling of FACTS devices

For the steady state analysis it is necessary to model the FACTS devices mathematically.Thyristor controlled swithced capacitors (TCSC) and Static VAr Compensators (SVC) are used as FACTS devices in the transmission network in this approach.

B. TCSC:

TCSC acts as either inductive or capacitive compensator by changing the line reactance. The maximum value of the capacitance is fixed at $-0.8X_{Line}$ and $0.2X_{Line}$ is the maximum value of the inductance. When a TCSC is connected to a particular line, its admittance can be written as

$$G_{TCSC} + jB_{TCSC} = \frac{1}{R_{Line} + j(X_{Line} + X_{TCSC})} \quad \text{.....(1)}$$

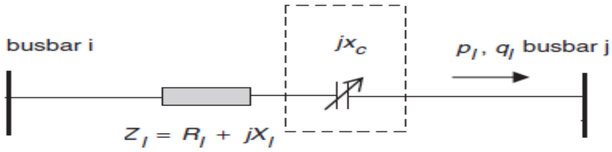

Fig 1. Mathematical Model of TCSC

TCSC allows faster changes of transmission line impedance. Fig. 1 shows the mathematical model of TCSC connected with transmission lines.

$X_{ij} = X_{Line} + X_{TCSC}$

$X_{TCSC} = rTCSC \times X_{Line}$

$Z_{Line} = R_{Line} + jX_{Line}$

C. SVC:

In this, SVC considered as simple reactive power injection model as shown in Fig.2.

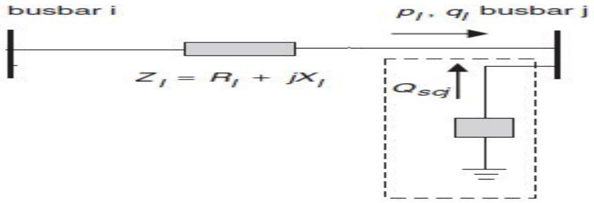

Fig.2.Reactive power injected model of SVC

The SVC's effective reactance X_{SVC} is determined by parallel combination of X_C & X_L and is given by

$$X_{SVC} = \frac{\Pi X_C X_L}{X_C[2(\Pi - \alpha) + 2\sin\alpha] - \Pi X_L} \quad \text{....(2)}$$

The SVC model is shown in fig.3

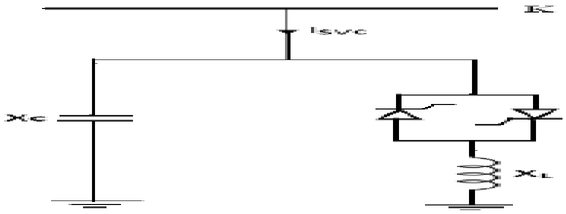

Fig.3 SVC firing angle model

FACTS devices Cost Function:

TCSC:

$C_{TSCS}=0.0015(OR)^2-0.7130(OR)+127.38(US\$/kVar)$

SVC:
C_{svc}=0.0003(OR)^2-0.2691(OR)+188.22 (US$/kVar)

Here,(OR) is the operating range of the FACTS Devices.

III. Optimal Placement FACTS devices

The installation of FACTS devices in a power system depends upon the following factors such as types of devices, location at which it is to be installed and its capacity. The decision where they are to be placed is largely dependent on the desired effect and the characteristics of the specific system. SVCs are mainly used to provide the voltage support at a particular bus and to inject reactive power flow in the adjacent lines. Power flow through the lines can also be changed by modifying the line reactance with the help of TCSC. For increasing the system ability to transmit power, FACTS devices are placed in such a way that it can utilize the existing generating units. That is why FACTS devices are placed in the more heavily loaded lines to limit the power flow in that line. This causes more power to be sent through the remaining portions of the system while protecting the line with the device for being overloaded. Reactive power flow in a line can be reduced by placing a TCSC in a line or by installing a SVC at the end of the line that also increases the active power flow capacity of the line simultaneously.

IV. The Proposed Approach

Here the main objective is to minimize the total operational cost under different loading conditions by installing FACTS devices at proper locations of the transmission network. Costs of the FACTS devices are to be taken into account while minimizing the operational system cost. Installation costs of various FACTS devices and the cost of system operation, namely, energy loss cost are combined to form the objective function to be minimized. Minimization of transmission loss is nothing but a problem of reactive power optimization that can be done by controlling transformer tap setting positions, by controlling reactive generations of the generating units and by adding shunt capacitors at weak buses. But with the help of FACTS devices, active and reactive power flow pattern can be changed significantly and also the desired effects can easily be obtained. The optimal allocation of FACTS Devices can be formulated as:

$C_{TOTAL}= C_1 (E) + C_2 (F)$

Subject to the nodal active and reactive power balance

$$P_{ni}^{\min} \le P_{ni} \le P_{ni}^{\max}$$

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

Voltage magnitude constraints: $V_i^{\min} \le V_i \le V_i^{\max}$

And the existing nodal reactive capacity constraint

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

The power flow equations between the nodes i-after incorporating FACTS devices would appear as

TCSC:

$$P_{Gi} - P_{Di} + P_i - \sum_{j=1}^{N-1} V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0$$

$$Q_{Gi} - Q_{Di} + Q_i - \sum_{j=1}^{N-1} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0$$

$$P_{Gj} - P_{Dj} + P_j - \sum_{j=1}^{N-1} V_i V_j (G_{jj} \cos\theta_{jj} + B_{jj} \sin\theta_{jj}) = 0$$

$$Q_{Gj} - Q_{Dj} + Q_j - \sum_{j=1}^{N-1} V_i V_j (G_{jj} \sin\theta_{jj} - B_{jj} \cos\theta_{jj}) = 0$$

SVC:

$$Q_{Gi} - Q_{Di} + Q_{iL(inj)} - \sum_{j=1}^{N-1} V_i V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0$$

These changes in the power flow equations are taken into consideration by appropriately modifying the admittance bus matrix for execution of load flow in evaluating the objective function for each individual population of generation both in the cases of DE & PSO based algorithmic methods. In this present work, first the locations of FACTS devices are obtained by calculating power flow in the lines. The TCSC positions are selected by choosing the lines carrying largest reactive power. Lines 25th,41th 28th & 5th are found as the lines for TCSC placement and simultaneously series reactance of these lines are controlled. SVC's are installed at 21st, 7th, 17th & 15th buses, where necessary reactive power injection and voltage support is required.

A. DE Technique in brief*:*

Differential Evolution (DE) developed by Storm & Price is very similar to Genetic Algorithm (GA) in the sense that it also uses the cross-over, mutation and the selection procedure in a different way than performed in the GA. Initial populations are created randomly that are represented by strings where the variables inside string is shown in fig 3. In DE, each vector in the population becomes a target vector. Each target vector is combined with a donor vector and a random vector differential in order to produce a trial vector. If the cost of the trial vector is less than the target, the trial vector replaces the target in the next generation. The donor vector is selected such that its cost is either less than or equal to the target vector. Mutation in GA is generally performed by generating a random value utilizing a predefined probability density function. In DE the differential vector, where the contributors are the target, the donor and two other randomly selected vectors perform the mutation. The objective function is calculated for all the individual of the new generation and the procedure is repeated till the final goal is achieved.

Table 1 Locations of different FACTS devices in the transmission network

TCSC in lines	SVC in Buses
25, 41, 28, 5	21, 7, 17, 15

Table 2: Comparative analysis of active power loss Using CLFA & DE

Reactive Loading	Active Power Loss without FACTS (p.u)	Active Power Loss with FACTS using DE (p.u)
100%	0.0711	0.0406
150%	0.0742	0.0434
175%	0.0765	0.0458
200%	0.0795	0.0576

Table 3: Comparative analysis of operating cost using DE approach

Reactive Loading	Operat-ing cost due to the energy loss (in $) (A)	Operating Cost with FACTS devices using DE (in $)x10^6 (B)	Cost of FACTS devices Using DE (in $)	Net Saving Using DE (in $) (A-B)
100%	3737016	2.1770	43064	1560016
150%	3899952	2.3470	65896	1552952
175%	4020840	2.4933	86052	1527540
200%	4178520	3.1118	90544	1060520

Table 4 Comparative study of reactive power flow in line with DE

Lines	For base reactive loading of 150% (before) In p.u	For base reactive loading of 150% (By the DE based approach) In p.u	For reactive loading of 200% (before) In p.u	For base reactive loading of 200% (By the DE based approach) In p.u
5	0.0387	0.0391	0.0384	0.0387
25	0.0553	0.0265	0.0664	0.0512
28	0.0650	0.0179	0.0883	0.0180
41	0.0581	0.0520	0.0751	0.0833
9	0.0884	0.0416	0.1032	0.0667
18	0.0930	-0.1022	0.1365	0.0067
26	0.0735	-0.0058	0.0860	-0.0350
27	0.1430	0.0346	0.1925	0.0295

V. Test Results & Discussion

The proposed approach for the placement of FACTS devices is applied on IEEE 30 Bus system. The power system is loaded (reactive loading is considered) and accordingly FACTS devices are placed at different locations of the power system. The power system is loaded up to the limit of 200% of base reactive load and the system performance is observed with and without FACTS devices. Table 1 shows the locations of different FACTS devices in the transmission network. Table 2 shows the comparative analysis of active power loss using DE & CLFA approach. A comparative study of the operating cost of the system with FACTS devices using DE & CLFA technique is shown in Table 3 & Table 4. The change in reactive flow pattern in the lines where FACTS devices are connected for 150% and 200% base reactive loading is shown in Table 5 & Table 6 by using DE & CLFA technique. From Table 1 it is observed that SVC's are connected at the buses 21st, 7th, 17th & 15th those are at the finishing ends of the lines 27th, 26th, 9th & 18th respectively because these are the four lines carrying highest, second highest, third and fourth highest reactive power respectively. After connecting SVC's at theses buses reactive power flow reduces greatly in the lines 27th, 26th, 9th & 18th in each case of loading. TCSC's are placed in the lines 25th, 41st, 28th & 5th.

From Table 2, 3 & 4 we observe that transmission loss as well as operational cost reduced significantly in all cases of loading with FACTS devices as compared to without such devices. Significant economic gain is obtained even at a loading of 200% of base reactive loading which is also evident from Table 3 & Table 4. The economic gain obtained is much higher than the installation cost of FACTS devices in every cases of loading. From table 2 it is clear that the active power loss in DE based approach is considerably less compared to CLFA based technique in all cases of loading. Also the overall saving using the DE based approach is found as much better than CLFA based technique that is observed from table 3 & 4 i.e. DE is found as more economical approach than CLFA based approach. Reactive power flow in lines reduced significantly at different loading conditions in both the DE and CLFA based techniques as observed from table 5 & 6 respectively.

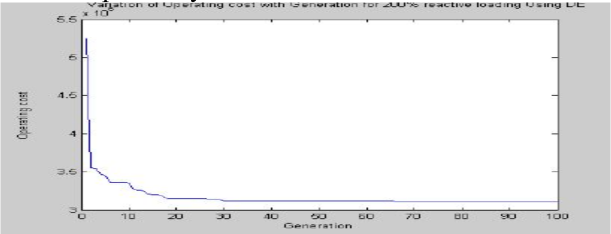

Fig. 4. Variation of operating cost with Generation for 200% of base reactive loading using DE

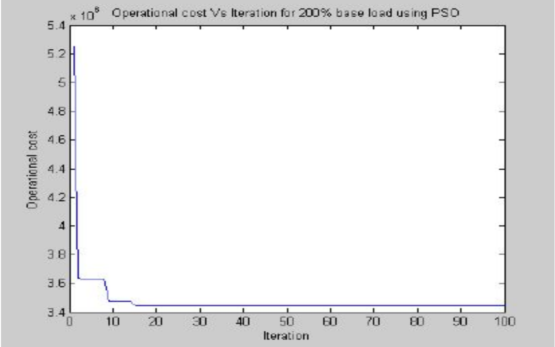

Fig. 5. Variation of operating cost with Generation for 200% of base reactive loading using DE.

Conclusions

In this approach, CLFA (Conventional Load flow algorithm) & DE (Differential Evolution) based optimal placement of FACTS devices in a transmission network is presented for the increased load ability of the power system as well as to minimize the total operating cost. DE based algorithmic approach is found advantageous over CLFA based approach in minimizing the overall system cost. Cost of FACTS devices are very less compared to the benefits in terms of the system operating cost for each cases of loadings that are clearly observed. Two different types of FACTS devices are considered. It is clearly evident from the results that effective placement of FACTS devices using suitable optimization technique can significantly improve system performance. After comparative analysis between the DE & PSO based approach, DE based method is found as more advantageous from the economic point of view and can be used as a suitable optimization method for the proper placement of FACTS devices in the transmission network.

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