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Optimal Power Flow Control Using FACTS Devices

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Abstract*—— In any power system, unexpected outages of lines or transformers occur due to faults or other disturbances. These events, referred to as contingencies, may cause significant overloading of transmission lines or transformers, which in turn may lead. Flexible AC Transmission System (FACTS) controllers provide a new facilities, both in steady state power flow control and dynamic stability control. Static VAR controllers control only one of three important parameters (voltage, impedance, phase angle) determining the power flow in the AC power system viz. the amplitude of voltage at selected terminals of transmission line .Overloading Power flow control, in an existing long transmission line, plays a vital role in Power System area. In this the Static Var Compensator (SVC) and Thyrister Controlled Series Capacitor (TSCS) based FACTS device for minimize the losses and power flow in long distance transmission line. The problem of determining the optimal SVC and TCSC parameters is formulated as an optimization problem and a N-R method based approach is applied to solve the Optimal Power Flow (OPF) problem. Simulations are done on IEEE 30 bus system for a few harmful contingencies.

***Index Terms*— FACTS, Optimal Power flow, SVC(Static Var Compensator), TCSC.**

I. INTRODUCTION

In the recent year with the deregulation of the electricity market the traditional concepts and practice of the power system are changed. In this process the existing transmission lines are over loaded and lead to unstable system. Overloading may also due to transfer of chap power from generator bus to load bus ,this lead to the introduction of FACTS such as Static Var Compensator(SVC).This device control the power flow in the network and reduce the flow heavily loaded line there by resulting in an increase load ability low system losses improved stability of the network and reduced cost production[3]. The OPF solution gives the optimal settings of all controllable variables for a static power system loading condition. A number of mathematical programming based techniques have been proposed to solve the OPF problems [4].Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type FACTS device and is connected in series with the transmission line to increase the power transfer capability, improve transient stability, and reduce transmission losses[5].

Optimal power flow (OPF) is an operating condition in which the power flow in an electrical system occurs optimally. It is a power flow problem in which certain controllable variables are adjusted to minimize an objective function such as cost of active power generation or the transmission loss, while satisfying operating constraints.

The type of control that an optimal power flow must be able to statisfied are active and reactive power injections, generator voltages, transformer tap ratios and phase shift angles.

The optimal power flow is problem seeks to find an optimal profile of active and reactive power generations along with voltage magnitudes in such a manner as to minimize the total operating cost of a power system, while satisfying network security constraints.

The main purpose of OPF to schedule power system controls to optimize an objective function while satisfying a set of non-linear equality, and inequality constraints. Mathematically, the OPF problem can be formulated as a constrained non-linear optimization problem. Different solution approaches have been proposed to solve OPF problems [8].

A new N-R method have solved optimal power flow problem incorporating FACTS devices using Newton’s method, leading to highly robust iterative solutions. But it has been noted that the OPF problem with series compensation may be a non- convex problem , which will lead the classical method to be stuck into local minimum.

Voltage control: Applications to optimize bus voltage values. These studies take into account the stability of power system voltages from the maximum and minimum admissible values. Transmission line overloads reduction: Applications to reduce the overload of a specific transmission line. Power system optimization: Applications of FACTS that deal, in general, with power system optimal power flow studies.

Avoidance of generation re-dispatch and Power System Congestion: Applications that use FACTS to reduce congestions and re dispatching of generators. Cost minimization: Applications with the objective of reducing the cost of the power transmission or the FACTS device cost optimization.

Contingency analysis: Applications that deal with power system stability and security have been classified from the contingency analysis studies point of view.

II. BASIC CONCEPTS AND PROBLEM FORMULATION

A.N-R METHOD:

The most widely used method for solving simultaneous nonlinear algebraic equations is the Newton Raphson method (NR). Newton’s method is found to be more efficient and practical. The number of iterations required to obtain a solution is independent of the system size, but more functional evaluations are required at every iteration.

Since in the power flow problem real power and voltage magnitude are specified for the voltage-controlled buses, the power flow equation is formulated in polar form. This equation can be rewritten in admittance matrix as

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j$$

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In the above equation, j includes bus i. expressing this equation in polar form, we have

$$I_i = \sum_{j=1}^{n} |V_j||Y_{ij}| \angle \theta_{ij} + \delta_j$$

The complex power at bus i is

$$P_i + jQ_i = V_i^* I_i$$

Separating the real and imaginary parts

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j)$$
$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j)$$
$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J1 & J2 \\ J3 & J4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}$$

By running the load flow analysis using NR-method we can fine the Power flows in individual lines and loss.

B. Optimal Power Flow Constraints.

OPF Problem Formation:

Basically, OPF problem consists of minimizing the objective function, subject to both equality and inequality constraints, control variable limits and state Variable.

Objective function:

The objective is any one among minimum generation cost, minimum transmission loss etc. The objective function to be minimized is the operating cost, transmission loss etc.

Equality constraints:

Subject to some constraints which are as follows Equality constraints are normal power flow equations i.e g(x,u)=0

Inequality constraints:

The inequality constraints of the OPF limits in the power system as well as the limits created to ensure security. Inequality constraints limits include generators, tap changing transformers, and phase shifting transformers, Active power generation limit, Reactive power generation limit, Voltage limit, Line Flow limits. i.e. $g(x,u) \leq 0$….

Control Variables:

In a power system the operator can only control certain quantities. The most important control variables are the following: Generator active power control, Generator reactive power control, Generator voltage magnitude control, Phase shifter transformer tap position control etc…

General optimization problem is stated as:

Minimize or maximize f(x) (Objective function)

Subject to:

$h(x) = 0$, i=1, 2, ..., n (Equality constraints)

$g(x) \leq 0$, j=1, 2, ..., n (Inequality constraints)

In case of optimal power flow, this optimization problem becomes very large and difficult one because of the involvement of lots of operating conditions in the form of equality and in equality constraints.

Optimal power flow problem is a nonlinear, non convex and highly constrained optimization problem. It is non-convex due to the existence of non-linear AC power flow equations, non-convex fuel cost function (for example quadratic fuel cost function with rectified sine component due to valve point effect, piecewise quadratic function because of multiple fuels) FACTS devices in power system. Almost every mathematical programming approach that can be applied to this problem has been attempted to solve this problem and it has taken several decades to develop it into a successful algorithm that could be applied in everyday use.

III.FACTS DEVICES

The flexible Ac transmission system (FACTS) controllers can play an important role in the power system security enhancement. FACTS devices can regulate the active and reactive power control as well as adaptive to voltage-magnitude control simultaneously because of their flexibility and fast control characteristics.

Controlling the power flows in the network, under normal and abnormal conditions of the network , can help to reduce flows in heavily loaded lines and reduce system power loss.

FACTS Controllers are classified as following

1. Series controllers such as Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulators (TCPAR or TCPST), and Static Synchronous Series Compensator (SSSC).
2. Shunt controllers such as Static Var Compensator (SVC), and Static Synchronous Compensator(STATCOM).
3. Combined series-series controllers and Combined series-shunt controllers such as Interline Power Flow Controller(IPFC), Unified Power Flow Controller(UPFC).

IV. THYRISTOR BASED FACTS CONTROLLER

The thyristor based family uses capacitor and reactor banks with fast solid-state switches in traditional shunt or series circuit arrangements. The thyristor switches control the on and off periods of the fixed capacitor and reactor banks and hence realize a variable reactive impedance.

Except for losses, they cannot exchange real power with the system. Important thyristor based FACTS controllers are:

(i) Static Var Compensator (SVC).

(ii) Thyristor-Controlled Series Capacitor (TCSC).

(A) Static Var Compensator (SVC)

SVC is a shunt connected controller. SVC at a bus is capable of controlling the corresponding bus voltage magnitude during steady state model. It main function is to regulate the voltage at a given bus by controlling its equivalent reactance. It can exchange reactive power only with the connected bus. In EHV transmission line, when the voltage fall in the bus, capacitive vars are injected and when bus voltage become higher, inductive vars are supplied to lower the bus voltage. In conventional methods of shunt compensation, shunt reactors are connected during low loads, and shunt capacitors are connected during heavy loads or low lagging power factor loads. It is largely transient-free, capacitor bank switching and very first operating capability and maintenance is simple. Voltage drops as capacitors in reactive capability is the same degradation.

(B) Thyristor Controlled Series Capacitor (TCSC)

TCSC is a series connected controller. Its major purpose is the increase in steady state power transfer. During steady state, TCSC can be considered as a static reactance .The controllable reactance is directly used as the control variable in the power flow equations Conventional series capacitor is modified by adding the thyristor controlled reactor. A controlled reactor in parallel with series capacitor, enables a continuous and rapidly varying compensator system..

V. MODELING OF FACTS DEVICES

A. Static Var compensator

Static Var Compensator (SVC) is a shunt connected FACTS controller whose main functionality is to regulate the voltage at a given bus by controlling its equivalent reactance. Basically it consists of a fixed capacitor (FC) and a thyristor controlled reactor (TCR). Generally they
are two configurations of the SVC.
A) SVC total susceptance model. A changing susceptance Bsvc represents the fundamental frequency equivalent susceptance of all shunt modules making up the SVC as shown in Fig. 1 (a).
B) SVC firing angle model. The equivalent reactance , which is function of a changing firing angle α, is made up of the parallel combination of a thyristor controlled reactor (TCR) equivalent admittance and a fixed capacitive reactance as shown in Fig. 1 (b). This model provides information on the SVC firing angle required to achieve a given by

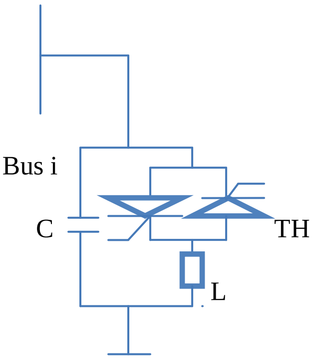


Fig. 1 (a).

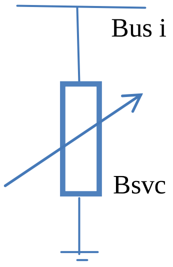


Fig. 1 (b).

The Objective function of the SVC to control the voltage profile of the system. The SVC working range of the SVC is between −100Mvar and +100Mvar. The SVC has been considered as a reactive power sources with the above limit. Thus this SVC should be installed at the centre of the transmission line.
SVC firing angle model is implemented in this paper. Thus, the model can be developed with respect to a sinusoidal voltage, differential and algebraic equations can be written as

$$I_{svc}=-jB_{SVC}V_k$$

The fundamental frequency TCR equivalent reactance

$$X_{TCR}=\frac{\pi X_L}{2(\pi-\alpha)+\sin(2\alpha)}$$

σ and α are conduction and firing angles respectively.
At α=90°. TCR conducts fully and the equivalent reactance X_{TCR} become while at α=180°.TCR is blocked and its equivalent reactance becomes infinite. The SVC effective reactance is determined by the parallel combination of and equivalent reactance becomes infinite.
The SVC effective reactance X_{SVC} is determined by the parallel combination of Xc and X_{TCR}

$$X_{SVC}=\frac{\pi X_L X_C}{X_c[2(\pi-\alpha)+\sin(2\alpha)]-\pi X_L}$$

The SVC equivalent reactance is given by above equations. SVC equivalent sussceptance (BSVC=-1/XSVC) profile, as function of firing angle,
does not present discontinuities.
B. Thyristor Controlled Series Capacitor (TCSC)
Thyristor Controlled Series Capacitor (TCSC) is a series compensator which increases transmission line capacity by decreasing lines' series impedances and increase network reliability.
The TCSC concept is that it uses an extremely simple main circuit. The capacitor is inserted directly in series with the transmission line and the thyristor-controlled
inductor is mounted directly in parallel with the capacitor.
The TCSC equivalent reactance is given as
X_{TCSC}=
$-X_c+K_1(2\sigma+\sin 2\sigma+K_2\cos^2\sigma(\omega\tan\omega\sigma)-\tan\sigma)$
Where
$\sigma=\pi-\alpha$,

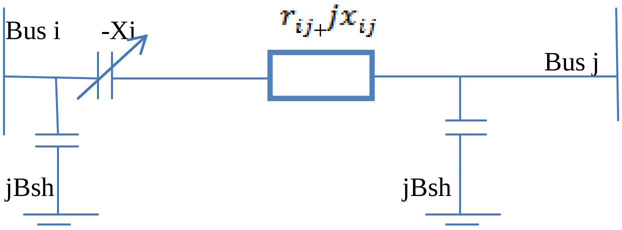
$$\omega=\sqrt{\frac{X_c}{X_L}}$$

$$X_{LC}=\frac{X_C X_L}{X_C-X_L},\quad K_1=\frac{X_C+X_{LC}}{\pi}, K_2=\frac{X_{LC}^{\ 2}}{\pi X_L}$$

Thus no interfacing equipment like for example high voltage transformers is required. The bi-directional thyristor valve is fired with an angle α ranging between 90° and 180° with respect to the capacitor voltage.
This makes TCSC much more economic than some other competing FACTS technologies. Thus it makes TCSC simple and easy to understand the operation. Series compensation will;

i. Increase power transmission capability.
ii. Optimize power flow between parallel lines.
iii. Improve system stability.
iv. Reduce system losses.
v. voltage profile of the lines.

Objective functions of the TCSC minimize the total generation cost, and power loss and reactive power generation limits.
The TCSC has a working range between - 0.8 Xij and 0.2 Xij, where Xij is the reactance of the transmission line, where the TCSC installed.



While selecting inductance, XL should be sufficiently smaller than that of the capacitor Xc . Since to get both effective inductive and capacitive reactance across the device. Suppose if Xc is smaller than the XL , then only capacitive region is possible in impedance characteristics.
In any shunt network, the effective value of reactance follows the lesser reactance present in the branch. So only one capacitive reactance region will appears. Also XL should not be equal to Xc value; or else a resonance develops that result

in infinite impedance an Un acceptable condition and transmission line would be an open circuit. The impedance of TCSC circuit is that for a parallel LC circuit and is given.

VI. RESULT

The total system loss without SVC is 17.599MW, 22.244MVAR, the total system loss with SVC at bus 5 is 17.539MW, 21.777MVAR in IEEE-30 bus system

Table transmission line losses with SVC and TCSC devices for IEEE 30 bus system

Bus	With SVC		With TCSC	
	P MW	Q MVAR	P MW	Q MVAR
1	17.611	22.028	16.936	22.241
2	17.580	21.930	17.256	22.152
3	17.571	21.884	16.235	21.258
4	17.561	21.857	17.564	22.365
5	17.539	21.777	17.558	22.095
6	17.552	21.826	17.652	22.562
7	17.545	21.798	17.523	23.258
8	17.549	21.817	17.528	22.548
9	17.548	21.755	17.658	22.145
10	17.549	21.730	16.895	22.548
11	17.544	21.740	17.589	22.758
12	17.554	21.741	17.528	22.485
13	17.553	21.734	17.524	24.854
14	17.547	22.727	17.685	22.654
15	17.545	22.726	17.547	22.874
16	17.549	22.732	17.541	22.547
17	17.547	21.727	17.987	22.947
18	17.539	21.721	17.351	22.784
19	17.538	21.721	17.582	22.547
20	17.540	21.726	17.874	22.874
21	18.544	21.723	17.547	23.562
22	17.545	21.723	17.589	22.894
23	17.541	21.720	17.489	22.584
24	17.539	21.718	17.847	22.624
25	17.543	21.728	17.541	22.145
26	17.536	22.721	17.247	22.147
27	17.548	22.739	17.247	22.698
28	17.549	21.814	17.547	22.584
29	17.536	21.718	17.658	22.897
30	17.528	21.703	17.558	22.095

The total system loss without TCSC is 17.599MW, 22.244MVAR, the total system loss with TCSC is 17.558MW, 22.095MVAR in IEEE-30 bus System.

VII .CONCLUSIONS

A steady state mathematical model for the SVC and TCSC was proposed. The proposed model can easily be incorporated in existing programs. The capability of SVC and TCSC in optimal power flow applications was demonstrated and compared with losses of a SVC and TCSC. It was shown that a FACTS Devices can be controlled in a power system to satisfy the following objectives simultaneously: Regulating power flow through a transmission line, Minimisation of power losses without generation rescheduling.

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