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Voltage Stability Enhancement in Power System using STATCOM based on Specific Coefficient Algorithm (SCA)

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Abstract - **The countries like India with increasing demand of electric power day by day it is difficult to expand the existing transmission system due to difficulties in right of way and cost problem in transmission network expansion. So, we need power flow controllers to increasing transmission capacity and controlling power flows Increased demands on transmission, absence of long-term planning, and the need to provide open access to generating companies and customers, all together have created tendencies toward less security and reduced quality of supply. Due to increase in demand, the transmission system becomes more stressed, which in turn, makes the system more vulnerable to voltage instability. Voltage stability plays an important role in the operation of the power system and there are major concerns about it for better utilizations of the system. Improvement in power system performance can be obtained using flexible AC transmission systems (FACTS). FACTS devices are capable of the simultaneous control of the bus voltage and real and reactive power flow in transmission systems independently; but because of excessive cost, the number and the location of these devices should be indicated optimally. This paper proposes a method of optimization of STATCOM allocation based on specific coefficients algorithm (SCA) to specify the number, location and input values by minimizing the voltage indices of system buses. The proposed SCA noticeably improves the accuracy and performance of traditionally used optimization processes especially in large scale networks. This method is applied to the 14-bus IEEE standard system. The results of ordinary and new optimization algorithm have shown the great improvement in optimization process using SCA.**

Keywords: **FACTS, STATCOM, SCA, MATLAB**

I. INTRODUCTION

Due to increase in demand, the transmission system becomes more stressed, which in turn, makes the system more vulnerable to voltage instability. Voltage stability has become an increasingly important phenomenon in the operation and planning of the present day power systems.

Voltage collapse is a process in which the appearance of sequential events together with the voltage instability in a large area of system can lead to the case of unacceptable low voltage condition in the networkThe increase in power demand has forced the power system to operate closer to its stability limit. It is very important to analyze the power system with respect to voltage stability. So, we need power flow controllers to increasing transmission capacity and controlling power flows. Voltage stability plays an important role in the operation of the power system and there are major concerns about it for better utilizations of the system [1]. Voltage stability has become an increasingly important phenomenon in the operation and planning of the present day power systems. Voltage collapse is known as a process in which the appearance of sequential events together with the voltage instability in a large area of system can lead to the case of unacceptable low voltage condition in the network. Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load changes occur continually; the system must be able to adjust to the changing conditions and operate satisfactorily [2]. Load increasing can lead to excessive demand of reactive power, system will show voltage instability. If there are not sufficient reactive power resources and the excessive demand of reactive power can lead to voltage collapse. The FACTS technology is essential to alleviate some but not all of these difficulties by enabling utilities to get the most service from their transmission facilities and enhance grid reliability.

FACTS controllers are high power electronic controllers, which can be applied individually or collectively in power system, to control the line parameters like series and shunt impedances effectively. A Flexible Alternating Current Transmission System is a system composed of static equipment used for the AC transmission of electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power electronics-based system.

Flexible AC Transmission System (FACTS) was first introduced by Narain G. Hingorani in the United States of America in the year of 1988. FACTS is a system composed of static equipment used for the AC transmission of electrical energy. The FACTS controller is defined by the Institution of Electrical and Electronics Engineers (IEEE) as “a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability” [3]. There are three main categories in FACTS controller, which are namely series, shunt, shunt-series FACTS controller with every category having its own functions.

In general, FACTS Controllers can be divided into four categories:

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Series Controllers: The series controller could be variable impedance, such as capacitor, reactor, etc., or power electronics based variable source of main frequency, subsynchronous and harmonic frequencies (or a combination) to serve the desired need [4]. In principle, all series controllers inject voltage in series with the line. The series connected FACTS controller uses the basic principle of the cancellation of a portion of the reactive line impedance could increase the transmittable power. This is due to the fact that AC power transmission over long lines was primarily limited by the series reactive impedance of the line. The series connected FACTS controller could improve the voltage stability limit; increase the transient stability margin, power oscillation damping and sub-synchronous oscillation damping. Some examples of the series FACTS devices are Thyristor Switched Series Capacitor (TSSC), Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC).

Shunt Controllers: As in the case of series controllers, the shunt controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt controllers inject current into the system at the point of connection. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. The shunt connected FACTS devices uses the basic principle of the steady state transmittable power and the voltage profile along the line could be controlled by appropriate reactive shunt compensation. The shunt connected FACTS devices could be used to improve the voltage profile of a specific bus, improve the transient stability and power oscillation damping. Some examples of the shunt connected FACTS devices are Static VAR Compensator (SVC) and the Static Synchronous Compensator (STACOM).

Combined Series-series Controllers: This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. or it could be a unified controller, in which series controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series controller, referred to as Interline Power Flow Controller, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term “unified” here means that the de terminals of all controller converters are all connected together for real power transfer.

Combined Series-shunt Controllers: This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner or a Unified Power Flow Controller with series and shunt elements. In principle, combined shunt and series controllers inject current into the system with the shunt part of the controller and voltage in series in the line with the series part of the controller. However, when the shunt and series controllers are unified, there can be a real power exchange between the series and shunt controllers via the power link. The combinational shunt-series connected FACTS devices combine the main principles of the series and shunt connected FACTS devices. It is able to control, simultaneously or selectively, all the parameters affecting the power flow in the transmission line, such as impedance, voltage and the phase angle. The shunt-series connected FACTS devices provides multifunctional flexibility required to solve many of the problems faced by the power delivery industry. Some examples of shunt-series connected FACTS devices are Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC).

Placing a FACTS device in the system for the purpose of increasing the system's ability to transmit power, thereby allowing for the use of more economical 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. This method which sites the devices in the heavily loaded line is the most effective [5].

II. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

STATCOM is a Static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage. STATCOM is one of the key FACTS Controllers. It can be based on a voltage sourced or current-sourced converter. As mentioned before, from an overall cost point of view, the voltage-sourced converters seem to be preferred, and will be the basis for presentations of most converter-based FACTS Controllers. STATCOM can be designed to also act as an active filter to absorb system harmonics [3].

STATCOM as defined above by IEEE is a subset of the broad based shunt connected Controller which includes the possibility of an active power source or storage on the de side so that the injected current may include active power. Such a controller is defined as: Static Synchronous Generator (SSG): A static self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multiphase output voltages, which may be coupled to an ac power system for the purpose of exchanging independently controllable real and reactive power.

Clearly SSG is a combination of STATCOM and any energy source to supply or absorb power. The term, SSG, generalizes connecting any source of energy including a battery, flywheel, superconducting magnet, large de storage capacitor, another rectifier/inverter, etc. An electronic interface known as a "chopper" is generally needed between the energy source and the converter.

This is a solid-state synchronous condenser connected in shunt with the AC system. The output current is adjusted to control either the nodal voltage magnitude or the reactive power injected at the bus [4]. The STATCOM is one of the important shunt connected 'Flexible AC Transmission system' controllers to control the power flow and make better transient stability. A STATCOM is a controlled reactive power source. It provides voltage support by generating or absorbing capacitors banks. It regulates the voltage at its terminals by compensating the amount of reactive power in or out from the power system [1].

When the system voltage is low the STATCOM injects the reactive power to and when the voltage is high it absorbs the reactive power [9]. The reactive power is fed from the Voltage Source Converter (VSC) which is connecting on the secondary side of a coupling transformer as shown in the Fig 1. The power electronic based source generates three phase supply with proper frequency. By varying the magnitude of the output voltage the reactive power exchange can be regulated between the convertor and AC system. STATCOM is such a device in which the modern power electronic converters have been employed. These converters are capable of generating reactive power with no/very little need for large reactive energy storage elements.

This can be achieved by making currents circulate through the phase of an AC system with the assistance of fast switching devices. The most advanced solution to compensate reactive power is the use of a Voltage Source

Converter (VSC) incorporated as a variable source of reactive power. These systems offer several advantages compared to standard reactive power compensation solutions. Compared to other solutions, a voltage source converter is able to provide continuous control, dynamic behavior due to fast response times and with single phase control also, compensation of unbalanced loads is made possible. The ultimate aim is to stabilize the grid voltage.

A. OPERATING PRINCIPLE

The STATCOM generates a balanced 3-phase voltage whose magnitude and phase can be adjusted rapidly by using semiconductor switches. The STATCOM is composed of a voltage-source inverter with a dc capacitor, coupling transformer, and signal generation and control circuit.

Let V_1 be the voltage of power system and V_2 be the voltage produced by the voltage source (VSC). During steady state working condition, the voltage V_2 produced by VSC is in phase with V_1(i.e. =0) in this case only reactive power is flowing. If the magnitude of the voltage V_2 produced by the VSC is less than the magnitude of V_1, the reactive power is flowing from power system to VSC (the STATCOM is absorbing the reactive power). If V_2 is greater than V_1 the reactive power is flowing from VSC to power system (the STATCOM is producing reactive power) and if the V_2 is equal to V_1 the reactive power exchange is zero. The amount of reactive can be given as

$$Q = \frac{V_1(V_1 - V_2)}{X} \tag{1}$$

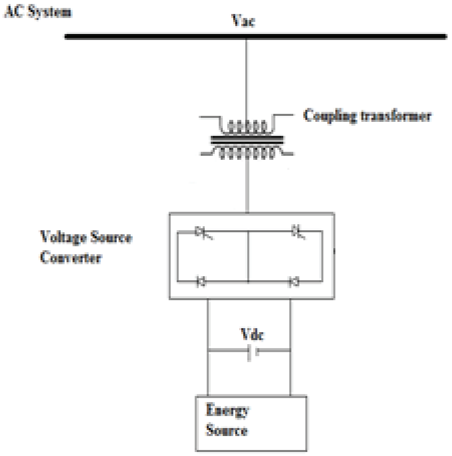

Fig. 1 Functional block diagram of STATCOM

B. V-I CHARACTERISTICS OF STATCOM

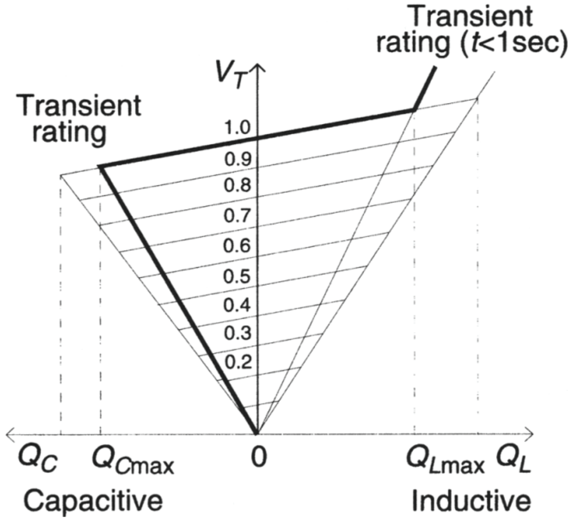

Fig. 2: V-I Characteristics of STATCOM

From Fig 2, STATCOM exhibits constant current characteristics when the voltage is low/high under/over the limit. This allows STATCOM to delivers constant reactive power at the limits compared to SVC. Since SVC is based on nominal passive components, its maximum reactive current is proportional to the network voltage. While for STATCOM, its reactive current is determined by the voltage difference between the network and the converter voltages and therefore, its maximum reactive current is only limited by the converter capability and is independent of network voltage variation.

C. ADVANTAGES OF STATCOM

There are many technical advantages of a STATCOM, these are primarily considered

- It has fast response.
- It requires less space as passive elements are eliminated.
- Inherently modular and re-locatable.
- It can be interfaced with real power source viz. battery.
- It has superior performance during low voltage condition as the reactive current can be maintained constant.

III. SPECIFIC COEFFICIENTS ALGORITHM (SCA)

The Specific Coefficient Algorithm (SCA) is used in order to get optimal location of the FACTS devices [1]. The objective function defined in this paper is based on SCA which considers voltage indices (VI) for each bus:

$$J = \sum_{i=1}^{n} \left[\left(A_i \frac{VI_i^{comp} - VI_i^{init}}{VI_i^{init}} \right) \right] + \frac{n}{N} \quad ; n < n_{max}$$

Where,

VI_i^{comp} = Voltage index of bus i, calculated after compensation.

VI_i^{init} = Voltage index of bus i, calculated before compensation.

n = The number of FACTS devices which is used for compensation of power network initial state.

N = The number of possible places for locating FACTS devices.

A_i = Individual coefficient

The purpose is to minimize this objective function to find the optimal place of STATCOM in power system. The maximum possible amount for "n" i.e. n_{max} is determined by power system designers and operators based on their budget. The V_i can be calculated using Newton Raphson method and by using that V_i we get the voltage index VI. The traditional methods for the optimization of above mentioned objective functions are usually summing of different terms with limited coefficients. Here a new algorithm is applied to automatically determine the importance of each term of objective function. In the objective function the coefficient A_i is multiplied in the main percent of improvement formula. A_i is constructed by the multiplication of two different coefficients. One of them is called "individual coefficient" and is based on the importance of the VI_i term used in objective function. The term VI_i is more important.

The aim of this optimization is to improve the critical terms of objective function. The individual coefficient depends on the ratio of the VI of each bus to the summation of the VIs. So, the importance of the VI of each bus can be considered differently in optimization process. This method of optimization with the consideration of individual coefficients is known as SCA. However, the level coefficient depends on the limits defined for three levels of VI, namely the desired area (e.g.$0<VIi<0.05$), critical area (e.g.$0.05<VIi<0.1$) and unfeasible area (e.g.$0.1<VIi$). The VI values that stand in the unfeasible area, has got a more significant weight that is the level coefficient; hence it will be minimized drastically in optimization process. So we should prefer the desired area.

C. IMPLEMENTATION ALGORITHM OF SCA

Step 1: Assume a suitable solution for all buses except the slack bus. Let V_p =1+j0.0 for p=1,2….n,p $\neq$s,V_s=a+j0.0.

Step 2: Set convergence criterion = ϵ i.e. if the largest of absolute of the residues exceeds ϵ the process id repeated, otherwise it is terminated.

Step 3: Set iteration count K=0.

Step 4: Set bus count p=1.

Step 5: Check if p is a slack bus. If yes, go to step 10.

Step 6: Calculate the real and reactive powers P_p and Q_p respectively using

$$P_p = \sum_{q=1}^{n} \{ e_p \left(e_q G_{pq} + f_q B_{pq} \right) + f_p \left(f_q G_{pq} - e_q B_{pq} \right) \}$$

$$Q_p = \sum_{q=1}^{n} \{ f_p \left(e_q G_{pq} + f_q B_{pq} \right) - e_p \left(f_q G_{pq} - e_q B_{pq} \right) \}$$

Step 7: Evaluate $\Delta P^k_p = P_{sp} - P^k_{p.}$

Step8: Check if the bus is a generator bus. If yes, compare Q^k_p with the limits. I it exceeds the limit, fix the reactive power generation to the corresponding limit and treat the bus as a load bus for that iteration and go to next step. If the lower limit violated set $Q_p = Q_{p\ min}$. If the limit is not violated evaluate the voltage residue and go to step 10.

Step 9: Evaluate $\Delta Q^k_p = Q_{sp} - Q^k_{p..}$

Step10: Advance the bus count by 1, i.e. p=p+1 and check if all the buses have been accounted if not, go to step 5.

Step 11: Determine the largest of the absolute value of the residue.

Step 12: If the largest of the absolute value of the residue is less than, go to step 17.

Step 13: Evaluate elements for Jacobian matrix.

Step 14: Calculate voltage increments Δe^k_p and Δf^k_p .

Step 15: Calculate new bus voltages $e_p^{k+1} = e^k_p + \Delta e^k_p$ and $f_p^{k+1} = f^k_p + \Delta f^k_p$. Evaluate cosδ and sinδ of all voltages.

Step 16: Advance iteration count K=K+1 and go to step 4.

Step 17: Evaluate bus and line powers, voltages and print the results.

Step 18: Find the Voltage Index from the load flow analysis.

$$VI_i = 1 - V_i$$

Step 19: Find individual coefficient, A_i

$$A_i = \frac{VI}{\Sigma VI}$$

Step 20: Calculate the objective function,

$$J = \sum_{i=1}^{n}\left[\left(A_i \frac{VI_i^{comp} - VI_i^{init}}{VI_i^{init}}\right)\right] + \frac{n}{N};\ n < n_{max}$$

Step 21: Check whether the voltage index, VI <0.05. If no go to step 18 otherwise go to next step.

Step 22: Minimize optimization function by minimizing VI.

IV. RESULTS AND DISCUSSIONS

The simulation result of the FACT device like STATCOM is carried out by using MAT lab programming. Here the voltage profile of an IEEE 14 bus system is evaluated with and without the use of compensating devices. The Newton Raphson method is carried out inorder to find the V_i of the system and thus the voltage index is calculated. By minimizing the value VI we can minimize the objective function.

From the simulation result we minimize the value of the objective function as 0.14254. For STATCOM the location and reactance is found and is as shown in Table I. From the table we can understand that the STATCOM should be connected in between the buses 7 and 9 because the reactance is very less here. In Table II voltages of each bus and its power using STATCOM is mentioned.

In Fig.3 results by using STATCOM is discussed. From the simulation result the STATCOM is to be placed in between bus 7 and bus 9 and the voltage profile with and without STATCOM is discussed. Without STATCOM the voltage in p.u is less than 1p.u. and by using STATCOM it is maintained to be 1p.u.

TABLE I LOCATION OF STATCOM

LOCATION	X_{TCSC}
2-5	-0.2
4-9	-0.2
5-6	-0.740509
7-9	-0.8

TABLE II VOLTAGE COMPENSATION USING STATCOM

BUS NO	VOLTAGE BEFORE COMPENSATION P.U	VOLTAGE AFTER COMPENSATION P.U	POWER AT THE BUS	
			MW	MVAR
1	1.06	1.0345	2.3270	-0.1218
2	1.045	1	0.1830	-0.2079
3	1.02	1	-0.9420	0.2952
4	1.01302	1.0046	-0.4780	0.0444
5	1.016	1	-0.0589	0.0237
6	1.07	1.0256	-0.1120	-0.0155
7	1.0443	1	0.0000	0.0000
8	1.08	1.0541	0.0000	0.0191
9	1.02763	1	-0.2950	-0.1660
10	1.02518	1.0134	-0.0900	-0.0580
11	1.03714	1.037137	-0.0350	-0.0180
12	1.05312	1.053119	-0.0610	-0.0160
13	1.04611	1.046111	-0.1350	-0.0580
14	1.01735	1.017353	-0.1490	-0.0500

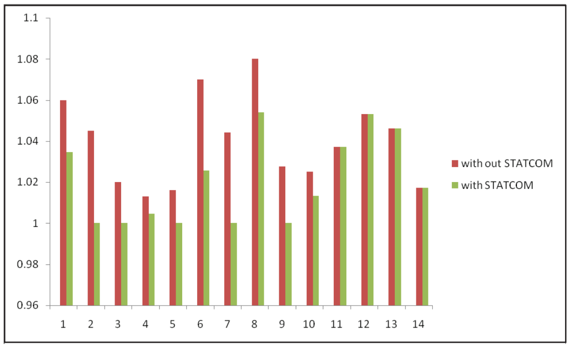

Fig. 4 Voltage profile with and without TCSC

V. CONCLUSION

FACTS devices provide enormous opportunity for optimized usage of existing infrastructure with usage of power system near its stability limit. FACTS devices are helpful for maintaining voltage stability during load variation, for increasing loadability of power system as a whole and to maintain stability of power system. With ever increasing demand of power, optimum use of existing power infrastructure is must.

Traditionally, ordinary objective function was defined to optimize different parameters of power networks with a limit consideration of different terms importance. In this paper, a novel approach based on SCA was introduced to improve the accuracy, speed of convergence and performance of optimization process.

The intention of paper is just to highlight the optimization of proper location of FACTS devices. This paper has immense potential for further studies corresponding to placement of series and shunt FACTS devices for improving voltage profile of power system.

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