Reliability Contingency Analysis by Static Synchronous Series Compensator in Optimal Power Flow

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Abstract—One of the best innovated Flexible A.C Transmission system (FACTS) devices is the static synchronous series compensator (SSSC). This device is effective to alter power system parameter in order to increase power transfer capacity, stabilize system. This paper shows how it may reduce the generation cost. These FACTS devices enable a continuous and wear resistance control of reactive power flows as well as voltage control. The incorporation of the control capabilities provided by FACTS devices into an optimal power flow opens up an unused potential for reducing power losses as well as cost for power transmission of power system operator.

Index Terms— FACTS, Optimal Power Flow (OPF), Static Synchronous Series Compensator (SSSC)

I. INTRODUCTION

Recent developments in semiconductor technology have made the Flexible A.C Transmission system (FACTS) devices [5], [6] of special interest to power system operation and transmission providers. Their operation is realized using advanced power electronics components which make them respond quickly to the control inputs, and their instant response grants a high ability for power system dynamic stability enhancement in addition to control of steady-state power flow [5]-[15].

Utilizing the powerful FACTS devices may help interconnected systems have increased power transfer capability for the existing power transmission lines due to the constantly increasing loads the power networks are required to serve. The optimization tasks in a competitive environment comprise in particular cost minimizing including different aspects of the procurement and transmission of electrical energy or the reduction of power losses. Alternatively the optimization aims at maximization of the available transmission capacity.

A SSSC offers a fast series compensation offer flexible power system control [6], therefore, it can be utilized to control line active and reactive power, achieve more power transfer capability, and so significantly improved power system stability. As the SSSC is capable of controlling power system parameters.

These papers review the structure of SSSC and derive the exact Pi-model of the SSSC embedded transmission lines from which the injection model using two port network is presented. These of SSSC also review some of the possible

uses and advantages of SSSC in power system operations. The generalized formulation of an optimal power flow including exact model of SSSC. Because the unified power flow controller is the most versatile FACTS-device which allows the independent influence of active and reactive power flows as well as a control of the voltage profile at the same time.

Unified power flow controller (UPFC) is a combination of STATCOM (Static Synchronous Compensator) and SSSC which are coupled via a common dc link to allow bidirectional flow of power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. These are controlled to provide concurrent real and reactive series line compensation without an external energy source.

The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently and selectively, the transmission line voltage, impedance and angle or alternatively the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation. A UPFC as shown in fig (1). This is a complete controller for controlling active and reactive power control through the line, as well as line voltage control.

Fig.(1) UPFC voltage source model

II. STRUCTURE, MODULING OF SSSC

1) Structure of SSSC

Fig (2) represented a SSSC inserted in the line connecting i & j.

A SSSC is basically consisting of converter with semiconductor devices having turn off capability, a coupling transformer and a capacitor [16]-[18]. A converter is connected to a power system through the coupling transformer. The DC capacitor provides a DC voltage support for the converter operation and functions as an energy storage element. The SSSC injects a voltage in series with transmission line through the series transformer.

Fig(2). Schematic diagram of SSSC inserted transmission line.

Two part model of SSSC-Embedded line Fig(3) represented as SSSC circuit model.

The SSSC is located between i and m. The equivalent circuit includes both the two port steady state model of the SSSC and the two port Pi model of the transmission line connected in cascade. The converter is represented by a voltage source in series impedance, where Z_{se} (Y_{se}) is the impedance (admittance) associate with the series converter, Where $Y_{se} = G_{se} + jB_{se}$. The complex voltage V_{se} is the controllable voltage inserted from the converter, and V_i and V_j are the complex voltage at voltage at node I and j, respectively.

$$V_i = V_i < \theta_i, \quad V_j = V_j < \theta_j, \quad V_{se} = V_{se} < \theta_{se} \quad (1)$$

Fig(3) Representing the SSSC Model

From the circuit of fig(3). We can write the following relation.

$$\begin{bmatrix} V_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & Z_{se} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_m \\ I_m \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_{se} \quad (2)$$

Let $V_L = G_L + jB_L$ and $Y = jB$ are the admittance of the two port network of Pi-equivalent circuit of a transmission line in fig (3). The transmission line is described by the following equation.

$$\begin{bmatrix} I_m \\ I_j \end{bmatrix} = \begin{bmatrix} (Y_L + Y) & Y_L \\ Y_L & (Y_L + Y) \end{bmatrix} \begin{bmatrix} V_m \\ V_j \end{bmatrix} \quad (3)$$

From three we can express I_m and I_j in term of V_m and V_j as follows

$$\begin{bmatrix} I_m \\ I_j \end{bmatrix} = \begin{bmatrix} (Y_L + Y) & Y_L \\ Y_L & (Y_L + Y) \end{bmatrix} \begin{bmatrix} V_m \\ V_j \end{bmatrix} \quad (4)$$

Let $Y_T = Y_{se} + Y_L + Y$, then for the circuit of fig (3), we can express I_i and I_j in terms of V_i and V_j , and V_{se} in matrix form follows:

$$\begin{bmatrix} I_i \\ I_j \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{ij} \\ Y_{ji} & Y_{jj} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} + \begin{bmatrix} b_i \\ b_j \end{bmatrix} V_{se} \quad (5)$$

Where $Y_{ij} = Y_{ji} = -Y_{se} (Y_L / Y_T)$

$$Y_{ii} = G_{ii} + jB_{ii} = (Y_{se} Y_T - Y_{se}^2) / Y_T \quad (6)$$

$$= Y_{se} Y_L / Y_T + (Y_{se} Y) / Y_T = -Y_{ij} + Y_{jo} \quad (7)$$

$$Y_{jj} = Y_{se} Y_L / Y_T + Y (Y_{se} + 2Y_L + Y) / Y_T = -Y_{ij} + Y_{jo} \quad (8)$$

$$b_i = G_{bi} + jB_{bi} = Y_{se} (1 - Y_{se} / Y_T) = Y_{se} (Y_L + Y) / Y_T \quad (9)$$

$$b_j = G_{bj} + jB_{bj} = -Y_{se} Y_L / Y_T = Y_{ji} \quad (10)$$

Note that we decomposed each of Y_{ii} and Y_{jj} into two parts, i.e,

$Y_{ii} = -Y_{ij} + Y_{io}$ and $Y_{jj} = -Y_{ij} + Y_{jo}$, where;

$$Y_{ii} = G_{ii} + jB_{ii} = -Y_{se} Y_L / Y_T \quad (11)$$

$$Y_{jo} = G_{jo} + jB_{jo} = -Y_{se} Y_L / Y_T \quad (12)$$

$$Y_{jo} = G_{jo} + jB_{jo} = Y (Y_{se} + 2Y_L + Y) / Y_T \quad (13)$$

Equation (5) and (6)-(10) can be represented by the circuit in fig (4). The fig. represents modeling of the SSSC embedded line using current source and modified admittances.

Fig(4) SSSC model using current source.

III. LOAD FLOW EQUATION OF PI-MODEL.

The complex power injection Pi-model of the SSSC embedded line, which is derived from fig(4), is show in fig (5). The complex power S_i^{se} at bus i and S_j^{se} at bus j represents complex power associated with the current source show in fig (4). To derive the complex power injections and flows of the Pi-model of the SSSC embedded line, the withdrawals due to SSSC at bus i and j are calculated as

$$S_i^{se} = V_i (b_i V_{se})^* \text{ and } S_j^{se} = V_j (b_j V_{se})^* \quad (14)$$

$$S_i^{se} = P_i^{se} + jQ_i^{se} = V_i < \theta_i ((G_{bi} + jB_{bi}) V_{se} < \delta)^* \quad (15)$$

From equation (14) and (15), we can write

$$P_i^{se} = V_i V_{se} [-B_{bi} \cos(\theta_i - \delta) + G_{bi} \sin(\theta_i - \delta)] \quad (16)$$

$$Q_i^{se} = V_i V_{se} [G_{bi} \cos(\theta_i - \delta) + B_{bi} \sin(\theta_i - \delta)]$$

$$P_j^{se} = V_j V_{se} [G_{bj} \cos(\theta_j - \delta) + B_{bj} \sin(\theta_j - \delta)] \quad (17)$$

$$Q_j^{se} = V_j V_{se} [-B_{bj} \cos(\theta_j - \delta) + G_{bj} \sin(\theta_j - \delta)]$$

Fig(5) The injection Pi-model of the SSSC Embedded line.

The current I_{ij} and I_{ji} and complex power S_{ij} ($S_{ij} = V_i I_{ij}^*$) and S_{ji} ($S_{ji} = V_j I_{ji}^*$) flowing out of buses in the line i-j can be expressed as

$$I_{ij} = (V_i - V_j) Y_{ij} + V_i Y_{io} = (V_i - V_j) (G_{ij} + jB_{ij}) + V_i (G_{io} + jB_{io}) \quad (18)$$

$$I_{ji} = (V_j - V_i) Y_{ji} + V_j Y_{jo} = (V_i - V_j) (G_{ij} + jB_{ij}) + V_j (G_{jo} + jB_{jo}) \quad (19)$$

$$S_{ij} = G_{ij} [V_i^2 - V_i V_j \cos(\theta_i - \theta_j)] - B_{ij} [V_i V_j \sin(\theta_i - \theta_j)] + G_{io} V_i^2$$

$$-j\{B_{ij}[V_i^2 - V_i V_j \cos(\Theta_i - \Theta_j)] + G_{ij}[V_i V_j \sin(\Theta_i - \Theta_j)] + B_{io} V_i^2\} \quad (20)$$

$$S_{ji} = G_{ij} [V_j^2 - V_j V_i \cos(\Theta_j - \Theta_i)] - B_{ij} [V_j V_i \sin(\Theta_j - \Theta_i)] + G_{jo} V_j^2 \\ -j\{B_{ij}[V_j^2 - V_j V_i \cos(\Theta_j - \Theta_i)] + G_{ij}[V_j V_i \sin(\Theta_j - \Theta_i)] + B_{jo} V_j^2\} \quad (21)$$

Let R_i is set of buses connected to bus i , P_i^G/Q_i^G is the active/reactive power generated at bus i , P_i^D/Q_i^D is the active/reactive power demanded at bus i , and P_i^o/Q_i^o is the net active/reactive power flowing out bus i , then for $i, j = 1, 2, \dots, NB$, Where NB is the number of buses, the load flow balance equations can be expressed as follows .

$$\begin{aligned} P_i^G - P_i^D &= P_i^{se} + P_i^o \\ Q_i^G - Q_i^D &= Q_i^{se} + Q_i^o \end{aligned} \quad (2)$$

$$Q_i^o = -V_i^2 b_{ii} \sum_{j \in R_i} V_j [b_{ij} \cos(\theta_i - \theta_j) + g_{ij} \sin(\theta_i - \theta_j)] \quad (23)$$

The current I_m in the fig.(3) can be found using any of the following equation .

$$I_m = Y_{se} [(Y + Y_L)(V_i + V_{se}) - Y_L V_j] / (Y + Y_L + Y_{se}) \quad (24)$$

IV. OPTIMAL POWER FLOW

Optimal power flow expresses as follows:

$$f(x) = f(P^G, Q^G, V, \theta, V_{se}, \delta) \quad (25)$$

Subject to

Equality constraints:

$$\begin{aligned} P_i^G - P_i^D &= P_i^{se} + P_i^o \\ Q_i^G - Q_i^D &= Q_i^{se} + Q_i^o \\ P_j^G - P_j^D &= P_j^{se} - P_j^o \\ Q_j^G - Q_j^D &= Q_j^{se} - Q_j^o \end{aligned} \quad (26)$$

Inequality constraints:

$$\begin{aligned} P_{ij}^{\min} &\leq P_{ij} \leq P_{ij}^{\max}, p_{ji}^{\min} \leq P_{ji} \leq P_{ji}^{\max} \\ P_i^{G,\min} &\leq P_i^G \leq P_i^{G,\max} \\ Q_i^{G,\min} &\leq Q_i^G \leq Q_i^{G,\max} \\ V_i^{\min} &\leq V_i \leq V_i^{\max} \\ V_{se}^{\min} &\leq V_{se} \leq V_{se}^{\max} \\ \delta^{\min} &\leq \delta \leq \delta^{\max} \end{aligned} \quad (27)$$

V. TEST RESULT

Input IEEE-14 data has been taken from M A PAI[18]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1		21.38	-16.90	0.00	0.00	-4.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	-16.9		33.7	-5.05	-5.67	-5.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3														
4														
5														
6														
7														
8														
9														
10														
11														
12														
13														
14														

3	4	5	6	7	8	9	10	11	12	13	14
0.00	0.00	-4.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	-5.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-5.05	-5.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.8	-5.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-5.84	42.0	-23.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	-23.7	38.24	-4.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	-4.26	20.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	19.66	-5.68	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	-5.68	5.68	-9.09	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	26.48	-11.8	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	-11.8	17.04	-5.21	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.23	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.91	-5.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.55	-2.87
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.57

B-bus Matrix

VI. CONCLUSION

The presented approach combines suitable linear models for facts-devices with a powerful optimization model including security constraints which are of major importance when optimizing existing power systems within the new frame work.

The SSSC offers a fast series compensation and grant flexible power system control by adjusting the basic power system parameters on which system performance depends. Therefore, it can be utilized to control line active and reactive power flows achieve more power transfer capability for the existing power network.

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