An Analytical Solution of Electric Power System with Static Compensator

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Abstarct

An analytical solution of power flow equation for a power system with a shunt flexible ac transmission system (FACTS) is presented in this paper. The most commonly used FACTS device is the static synchronous compensator (STATCOM). A formulation of equation using current magnitude in quadrature with the voltage terminal describes the system performance. Non linear dynamics associated with the STATCOM dc-link capacitor voltage, and effective interactions among its variable is validated. The mathematical description is based on the transformation of a threee-phase system into d-q coordinate system. The simulation results show that by the use of the system transmission line with STATCOM can be improved of the transient and steady-state operation.

Keywords: Load Flow Power Transmission, FACTs, STATCOM, Analytical Solution

List of Symbols:

$\bar{V}_s = V_s\angle\delta_s$	: The sending-end Voltage
$\bar{V}_r = V_r\angle\delta_r$	: The receiving-end Voltage
$\bar{V}_{STAT} = V_{stat}\angle\varphi_{stat}$	: The STATCOM rminal Voltage
$\bar{V}_{sh} = V_{sh}\angle\varphi_{sh}$	: The Shunt Voltage
V_{ratio}, and x_{ratio}	: The Voltage and Reactance ratio
$\bar{I}_{sh}$	: The Current injection
V_{abc}, I_{abc}	: The Three-Phase Voltageand
V_{d-q} ,I_{d-q}	: The d-q Voltage and Current
X	: The line impedance
x_1,x_2	: The series inductance of the line

1- INTRODUCTION

The operation of an AC transmission system is generally constrained by the limits of one or more network parameters (such as line impedance) and operatig variables (*such* as voltages currents and the thermal limit). As a result, the power line is unable to direct power flow among generating stations. To achieve those objectives; Increasing the power of transmission systems, minimizes the transmission losses, and supporting a good voltage profile to retain system stability under large disturbances [1-8].

Conventionally, the transmission systems have been designed with fixed or mechanically switched, shunt reactive components. Voltage-regulating and phase-shifting transformer tap-changers are also used to minimize voltage variation, and control power flow under slowly steady state variations of load condition [1-5]

In recent years, a new type of FACTS devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system system stability and to achieve better utilization of existing power systems, to rapid developments in digital processing, fast communication method and power electronic device technologies [9-12].

In this paper, the impact of the shunt compensator on the power flow is analysed. The system constraints and their effects on the STATCOM control are investigated. The operation range of the STATCOM control variables is defined. Furthermore,the paper deals with simulation of STATCOM to control a transmitted active power flow on the transmission line.

2. POWER FLOW TRANSMISSION

For the explanation of the major transmission issues, and for the interaction of relevant FACTS concepts, it is convenient to use an approximate form of short transmission lines. The simplified model neglects the shunt capacitance of the line as shown in Figure(1).

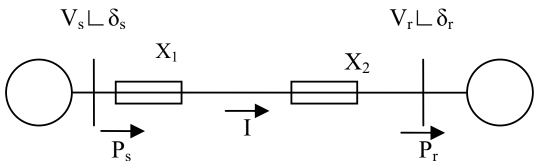

Fig.(1) Simplified Model of the Transmission Line

Where

$$\bar{V}_s = V_s e^{j\delta_s} = V_s(\cos(\delta_s) + j\sin(\delta_s))$$
$$\bar{V}_r = V_r e^{-j\delta_r} = V_r(\cos(\delta_r) - j\sin(\delta_r)) \quad (1)$$

The line current is given by;

$$\bar{I} = \frac{\bar{V}_s - \bar{V}_r}{X} \quad (2)$$

3. CURRENT SOURCE STATCOM

The STATCOM is classified as a shunt compensator. The need for a shunt compensator is to emulate a variable inductive or capacitor in shunt with a transmission line. This emulated inductive or capacitive reactance, in turn, regulate the line voltage at the point of coupling. The basic STATCOM circuit is shown in Figure(2) consists of a voltage source converter (VSC) and a dc storage capacitor, the VSC converts ac voltage to dc voltage on the dc side [1-6].

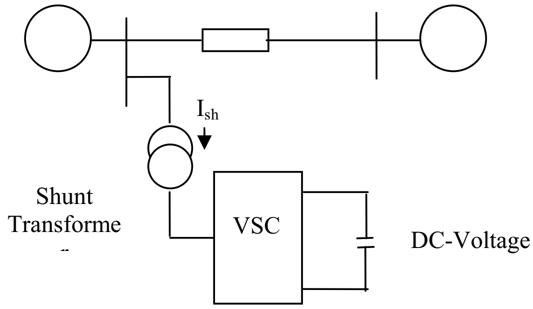

Fig.(2) Basic Scheme of STATCOM

The capacitor voltage can be adjusted by controlling the phase angle between the line voltage and VSC.

From the system point of view STATCOM may be treated as a shunt current source because, in the major part of its operating area the current is independent of the terminal voltage magnitude $V_{STATCOM}$. The STATCOM controllable parameter may therefore be assumed current magnitude equals I_{sh}. When losses are neglected, I_{sh} represents the STATCOM reactive current Phasor which is perpendicular to the terminal voltage Phasor $V_{STATCOM}$.

The network scheme in Fig.(3) shows th model of the transmission line with current source STATCOM

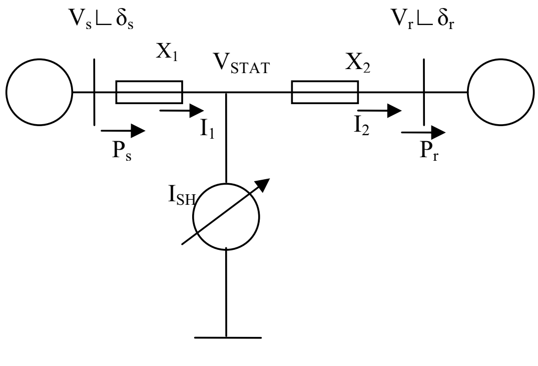

Fig.(3) Model of the Transmission Line with Current Source STATCOM

Refering to Figure(3), the following equation may be written.

$$\bar{V}_{STAT} = \bar{V}_s - j\bar{I}_1 x_1 = \bar{V}_r + j\bar{I}_2 x_1 \quad (3)$$

The Line current is given by:

$$\begin{aligned}\bar{I}_1 &= \bar{I}_{sh} + \bar{I}_2 \\ &= \bar{I}_{sh} + \frac{\bar{V}_{STAT} - \bar{V}_r}{jx_2} \\ &= \bar{I}_{sh} + \frac{\bar{V}_s - j\bar{I}_1 x_1 - \bar{V}_r}{jx_2} \\ &= \bar{I}_{sh}\frac{x_2}{x_1 + x_2} + \frac{\bar{V}_s - \bar{V}_r}{j(x_1 + x_2)}\end{aligned} \quad (4)$$

The terminal STATCOM Voltage is expressed as follows:

$$\bar{V}_{stat} = \bar{V}_s - j[\bar{I}_{sh}\frac{x_2}{x_1+x_2} + \frac{\bar{V}_s - \bar{V}_r}{j(x_1+x_2)}]x_1 \quad (5)$$

Thus, the transmitted active and reactive power without connect STATCOM is expressed as follows;

$$\begin{aligned}P_0 &= \frac{V_s V_r}{x}\sin(\delta) \\ Q_0 &= -\frac{V_s V_r}{x}(1 - \cos(\delta))\end{aligned} \quad (6)$$

Where δ is the angle between the sending-end and receiving-end voltage.

While the transmitted active and reactive power with connect STATCOM is expressed as follows;

$$\begin{aligned}P &= \frac{V_{stat}V_s}{x_1}\sin(\alpha) \\ &= P_0\left(1 + \frac{I_{sh}x_1x_2}{\sqrt{V_s^2x_2^2 + V_r^2x_1^2 - 2V_sV_rx_1x_2\cos(\delta)}}\right)\end{aligned} \quad (7)$$

And

$$Q_0 = \frac{V_{stat}^2}{x_1} - \frac{V_{stat}V_s}{x_1}(1 - \sqrt{1 - \sin(\alpha)^2} \quad (8)$$

Where α is the angle between the sending end voltage and the STATCOM voltage as shown in Figure(4).

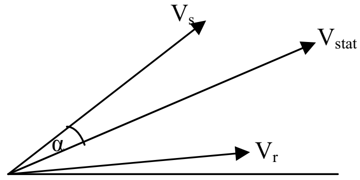

Fig.(4) Phasor diagram of STATCOM

From equation (8), the transmitted active and reactive power is dependent on system terminal voltages V_s,V_r , and the line reactance x_1 , x_2 as well as on transmission angle. In the case the terminal voltages and line reactance are equal to each other, the STATCOM location is in the middle of the system. Figure(5) shows the effect of reactive current on the transmission Characteristic for different values of I_{sh}

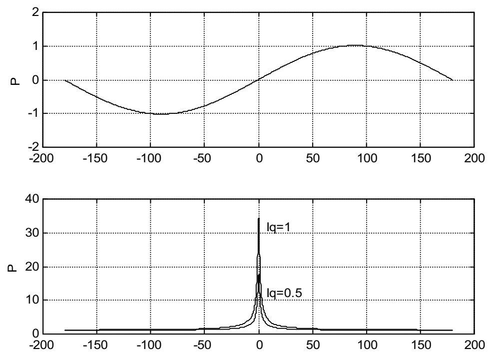

Fig.(5) Effect of reactive corrent on Transmission Characteristic (I_{sh}=0.5,1)

Figure(6) shows the effect of the terminal voltage ratio on the transmission characteristic at constant reactive current and line impedance ratio.

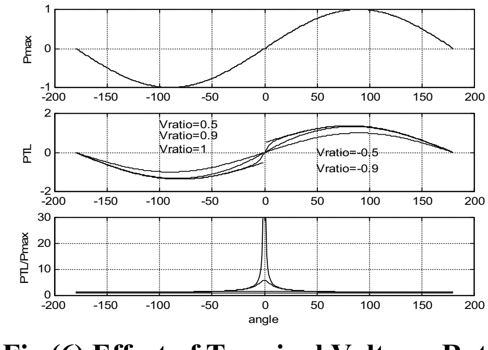

Fig.(6) Effect of Terminal Voltage Ratio on Transmission Characteristic (I_{sh}=1)

The power transfer capacity of a STATCOM equipment system will be limited by its transmission system structure and its location. Fig.(7) shows the effect of transmission ratio on the transmission characteristic at constant reactive current and terminal voltage ratio.

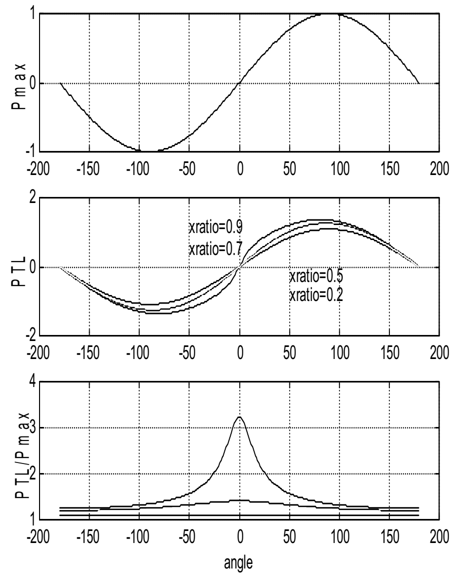

Fig.(7) Effect of Transmission Ratio on Transmission Characteristic (I_{sh}=1)

4. VOLTAGE SOURCE STATCOM

The STATCOM has the ability to either generate or absorb reactive power by suitable control of the shunt voltage $V_{sh}\angle\varphi_{sh}$ with respect to the AC voltage $V_{stat}\angle\varphi_{stat}$ as shown in Figure(8).

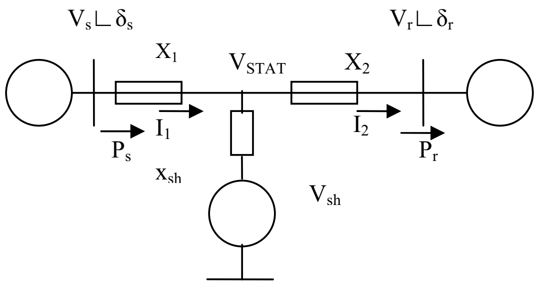

Fig.(8) STATCOM as Voltage Source

In STATCOM with no active power loss, the following reactive power equation is expressed as:

$$Q_{sh} = \frac{V_{s\,tat}^{\;2}}{x_{sh}} - \frac{V_{tats} V_{sh}}{x} \cos(\varphi_{stat} - \phi_{sh}) \quad (9)$$

If the Terminal voltage V_{stat} is greater than the shunt voltage V_{sh}, then the reactive power becomes positive, but if the Terminal voltage V_{stat} is smallerer than the shunt voltage V_{sh}, then the reactive power becomes negative, and if the Terminal voltage V_{stat} is equal to the shunt voltage V_{sh}, then the reactive power becomes zeros[12-16]. As smiliar with the phase angle for the active power, a summary of these conditions are listed in table 1

Table 1 Summary of Power Exchange

Parameter	STATCOM	AC System
$V_{stat}\angle V_{sh}$	Q →	
$V_{sh}\angle V_{stat}$	←	Q
$\varphi_{stat} < \varphi_{sh}$	P →	
$\varphi_{stat} > \varphi_{sh}$	←	P

5. STATCOM in d-q FRAME

Figure(8) shows the Switching Battern of the STATCOM.

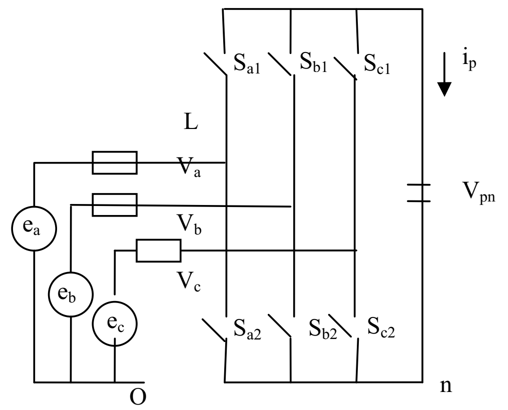

Fig.(9) STATCOM Switching Battern

The equations of the STATCOM shown in Figure(9) in the d-q frame which model the STATCOM are followed as :

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a - e_a \\ v_b - e_b \\ v_c - e_c \end{bmatrix}$$

(10)

By applying Park;s transformation, a three-phase can be transformed into an equivalent d-q system . The transformation matrix for a symmetrical for a symmetrical system is given by :

$$T_{d-q} = \frac{2}{3}\begin{bmatrix} \cos wt & \cos(wt-120) & \cos(wt+120) \\ \sin wt & \sin(wt-120) & \sin(wt+120) \end{bmatrix} \begin{bmatrix} T_{abc} \end{bmatrix} \quad (11)$$

Therfore, the d-q representation of a STATCOM is

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{s_d}{L} \\ -\omega & -\frac{R}{L} & \frac{s_q}{L} \\ \frac{s_d}{C} & \frac{s_q}{C} & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \quad (12)$$

6. COMPUTER SIMULATION

In the following, the data for a power system are given:

$\bar{V}s = 1.055\ \angle 10$, $\bar{V}r = 1\angle 0$

L= 3,8 μH , R=0.02 Ω , C=1000 μF

Figure(10) and Figure(11) show the transient response of the power system with STATCOM to a change in sending-end voltage.

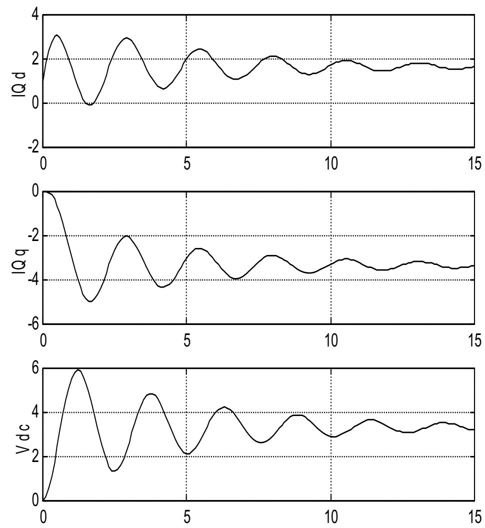

Fig.(10) Transient Response for V_{sd}=1, V_{sq}=0

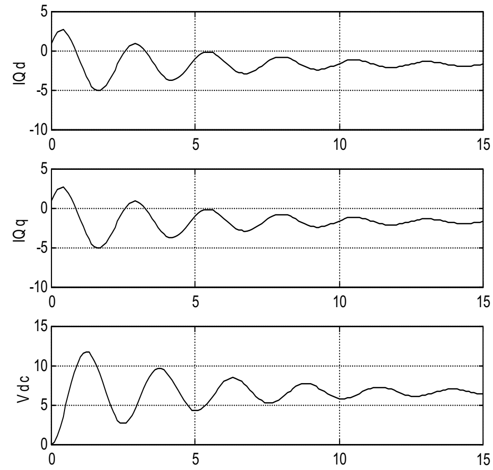

Fig.(11) Transient Response for V_{sd}=1, V_{sq}=1

7. CONCLUSION

This paper illustrates in detail the principle characteristics of STATCOM. The STATCOM may be represented as reactive current source conneceted in parallel with the transmission line. It is evident that the rise in transmission characteristic is in direct proportion to the STATCOM current.

The d-q model used for STATCOM was derived from first principles by neglecting harmonics in the switching functions. The results show that the d-q model is very accurate in predicting the system performance and transient simulation.

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