STATCOM STEADY STATE PERFORMANCE

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ABSTRACT

This paper deals with a modern approach of controlling the power flow in AC transmission lines. The control and distribution of power flow in two parallel transmission lines will be implemented by applying one of the flexible AC Transmission System (FACTS) which is STATic COMpensator (STATCOM) device. The STATCOM device is installed on one line of the two parallel transmission lines to investigate the effect of power flow control (active and reactive power) in one line on the other. The paper deals with mathematical modeling, analysis and simulation of a PWM based on STATCOM. By using STATCOM device the power flow distribution and line voltage can be controlled by varying the modulation index. The power flow and voltage controls are investigated at different installation position of the device over the transmission line. In addition, the optimum installation operating position for such FACTS device will be discussed.

Keywords: Modeling, FACTS, STATCOM, Modulation Index, and Steady-State Analysis.

INTRODUCTION

The application of power electronics, microelectronics, microprocessors and communications in the power distribution and transmission plays an important role to make the system more reliable, more controllable and more efficient [5]. The flexible AC Transmission System (FACTS) becomes an ever increasingly popular solution to our over extended electric power distribution and transmission systems. Because of the flexibility of the system the transmission line can function closer to its thermal limit. The STATCOM is one of the FACTS devices, which can compensate the reactive power in an efficient fast way [3]. It is also called advanced Static VAR Compensator (STATCOM) [8] or STATic CONdenser STATCON [8]. The STATCOM is a shunt FACýTS, which consists of a solid state three-phase source inverter, and it is used as a reactive power compensator. Its power electronic structure is illustrated in Figure 1 [7].

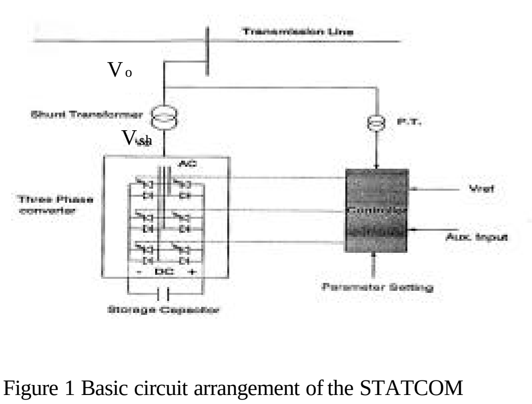


Figure 1 Basic circuit arrangement of the STATCOM

The STATCOM can either absorb or supply reactive power whose capacitive or inductive output current can be controlled independent of the ac line voltage as indicated in the static characteristic in Figure 2, line voltage versus reactive current. The device is connected to one of two parallel transmission line through a transformer as illustrated in Figure 3.

This paper deals with mathematical modeling and analysis of the open loop PWM based STATCOM implemented on parallel transmission lines. The steady state performance simulation results of the system are carried out using Matlab package program [2] at different installation position and operating conditions. In addition, the optimum installation position for the device will be discussed and determined.

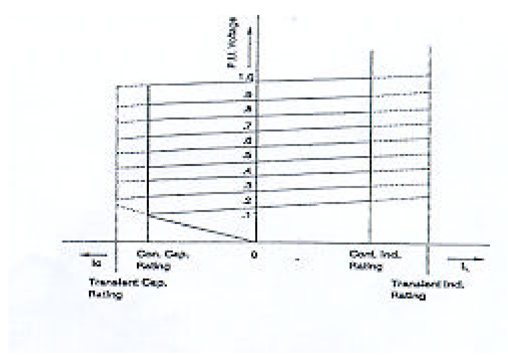


Figure 2 V-I static characteristics of STATCOM

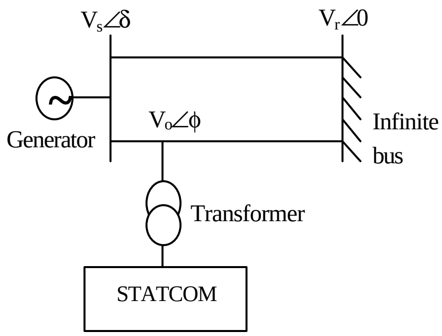


Figure 3 Schematic diagram of system

STATý COM MATHEMATICAL MODEL

Figure 3, shows a single line of the power circuit of the system and a STATý COM. The STATCOM is composed of a three-phase GTO based voltage source inverter, shunt transformer and a dc voltage storage source [4].

A mathematical model for the STATý COM with parallel transmission lines is illustrated in Figure 4. A synchronous machine feed the active power P_1 and reactive power Q_1 to an infinite busbar via a two parallel transmission lines. It is decided to place the STATCOM in the first quarter of the line closer to the generation side. V_s is the sending end voltage and V_r is the receiving end voltage which is the reference voltage. δ is the load transmission angle before the compensation and X_2, X_3 and X_4 are the transmission lines impedances and X_{sh} is the leakage reactance of the shunt transformer which are assumed pure inductive for simplicity. The voltage injected by the STATCOM is V_{sh} and it has a phasor angle β with respect to V_r. V_o is the transmission line voltage at which the device is connected with a phasor angle ϕ with respect to V_r.

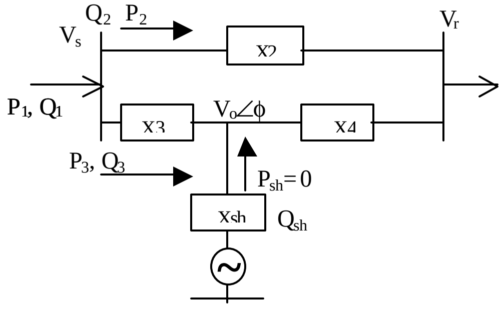


Figure 4 Basic mathematical model for STATCOM.

Whereas, if the total complex power supplied at the sending end before injection $I_{sh}=0$ is

$$S_1=V_s I_s^* = P_1 + j Q_1 \quad (1)$$

$$I_s=(V_s - V_r)/ jX \quad (2)$$

$$\text{Where } X= X_2 \,//\, (X_3 + X_4) \quad (3)$$

Therefore, it can be proved easily that

$$P_1=(V_r V_s \sin \delta) / X \quad (4)$$

$$Q_1=(V_s^2 - V_r V_s \cos \delta) / X \quad (5)$$

The active and reactive power is distributed in the two parallel lines as follows

$$P_2=(V_r V_s \sin \delta) / X_2 \quad (6)$$

$$Q_2=(V_s^2 - V_r V_s \cos \delta) / X_2 \quad (7)$$

$$P_3=(V_r V_s \sin \delta) / (X_3 + X_4) \quad (8)$$

$$Q_3=(V_s^2 - V_r V_s \cos \delta) / (X_3 + X_4) \quad (9)$$

The voltage at the connection point of the device is

$$V_o=A + jB \quad (10)$$

$$A = [1 - \{X_3 / (X_3 + X_4)\}] V_s \cos \delta + \{X_3/(X_3+X_4)\} V_r \quad (11)$$

$$B= [1 - \{X_3 / (X_3 + X_4)\}] V_s \sin \delta \quad (12)$$

$$\phi=\tan^{-1} (B/A) \quad (13)$$

$$\delta= \sin^{-1} (P1X / V_r V_s) \quad (14)$$

After the injection ($I_{sh} \neq 0$), the line will be under control of STATCOM. The reactive power is supplied or absorbed from the line, which will effect the power flow in the whole system. The total complex power supplied at the sending end in the line, which is connected to the STATCOM, is

$$S_3=V_s I_3 \quad (15)$$

$$I_3= (V_s - V_o) / jX_3 \quad (16)$$

Therefore, it can be proven that

$$P_3=\{V_o V_s \sin (\delta' - \phi)\} / X_3 \quad (17)$$

$$Q_3= \{ V_s^2 - V_o V_s \cos(\delta' - \phi) \} / X_3 \quad (18)$$

Where δ' is the load transmission angle after the injection $I_{sh} \neq 0$).

Since P_1 is constant, therefore P_2 changes as P3 changes
Therefore,

$$P_2 = P_1 - P_3 \quad (19)$$

$$Q_2 = (V_s^2 - V_r V_s \cos \delta') / X_2 \quad (20)$$

The complex power at the point of connection of the device is

$$S_{sh} = V_{sh} I_{sh}^* \quad (21)$$

$$I_{sh} = (V_{sh} - V_o) / jX_{sh} \quad (22)$$

$$P_{sh} = \{V_{sh} V_o \sin(\beta - \phi)\} / X_{sh} \quad (23)$$

$$Q_{sh} = \{(V_{sh}^2 - V_{sh} V_o) \cos(\beta - \phi)\} / X_{sh} \quad (24)$$

Hence, the STATCOM device is operated to compensate the reactive power only, there must be no active power provided by the device. And, the active power losses are neglected. Therefore, $P_{sh} = 0$ means ($\beta = \phi$) Vo and V_{sh} are in phase, and the reactive power is

$$Q_{sh} = (V_{sh}^2 - V_o V_{sh}) / X_{sh} \quad (25)$$

The magnitude of injected voltage by the inverter [6] is

$$V_{sh} = 0.35 M_\beta V_{dc} \quad (26)$$

And it is related to the V_o (before injection) in the following equation,

$$V_{sh} = K V_o \quad (27)$$

Where, K is a compensation factor controlled by the modulation index M_β. K determines the control percentage of the transmission line voltage that reflects the VAR compensation. By substitution of (27) in (25)

$$Q_{sh} = K V_o^2 (K-1) / X_{sh} \quad (28)$$

So, the STATCOM device compensates the reactive power according to the value of K. If K=1 means the reactive power is neither supplied nor absorbed from the system. And, if the K > 1 means the device supplies reactive power to the system. Whereas, if K < 1 the STATCOM device absorbs the reactive from the system. In general, the device can compensate the reactive power by changing the modulation index M_β as shown in (28), where K is a function of M_β.

Equation (17), (18), (19) and (20) show that the distribution of the active power in each line is controlled by changing M_β.

It can be proved that:

$$(X_t * V_o - V_{sh}) * \cos\phi - (X_{sh}/X_3) * Vs * \cos\delta' - (X_{sh}/X_4) * V_r = 0 \quad (29)$$

$$(X_t * V_o - V_{sh}) * \sin\phi - (X_{sh}/X_3) * Vs * \sin\delta' = 0 \quad (30)$$

$$X_3 * V_r * Vs * \sin\delta' + X_2 * V_o Vs * \sin(\delta' - \phi) - P_1 * X_2 * X_3 = 0 \quad (31)$$

$$\text{Where, } X_t = (1 + X_{sh}/X_3 + X_{sh}/X_4) \quad (32)$$

By solving the system of nonlinear equation (29), (30) and (31) for the three variables V_o, ϕ and δ by using Newton-Raphson method, the steady state can be simulated.

SIMULATIONS RESULTS

The open loop STATCOM is modeled and simulated by using Matlab package program. The steady state performance results of the parallel two-transmission lines system have been tested. An active power supplied to the grid by the machine P_1= 40 MW, reactive power Q_1= 11.9 MVAR, sending end voltage V_s = 66.9 kV and receiving end voltage V_r= 65.4 kV. It was decided that if $0<M_p<50\%$ the STATCOM will absorb the reactive power from the transmission line. Nevertheless, if $50\%<M_\beta<100\%$ the STATCOM will supply the reactive power to the transmission line. Whereas at $M_\beta=50\%$ there will be no effect for the STATCOM on the transmission line power flow.

The steady-state performance results have been tested by varying the compensation factor K from 80% to 120%. First, the device is connected at the mid-point of the transmission line. Then, it is connected at different installation positions over the transmission line.
It was decided that if K <100% the STATCOM will absorb the reactive power from the transmission line. Nevertheless, if K>100% the STATCOM will supply reactive power to the transmission line. Whereas at K=100% the STATCOM will have no effect on the transmission line power flow. Figure 5 indicates that, the reactive power in the line connected to the STATCOM is highly sensitive to the change of modulation index. Whereas, the reactive power of the other line is just slightly sensitive the change of modulation index. Nevertheless, the STATCOM device compensates the reactive power. The STATCOM supplies Q_{sh} reactive power as K > 100% and it absorbs the reactive power when K<100%.

The terminal line voltage at the point of connecting the FACTS device is controllable within ± 20 % of the line rated voltage as indicated in Figure 6. Practical constrains determine the percentage of line voltage control. The device is superior to other devices in providing voltage support.

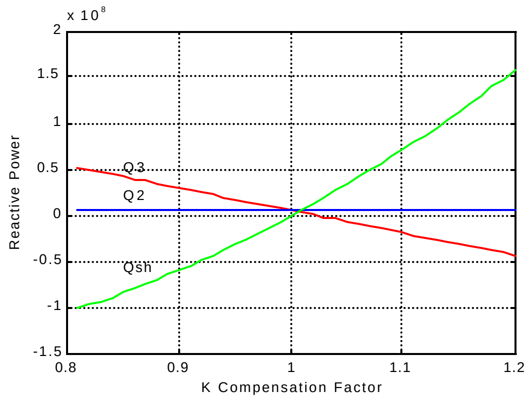
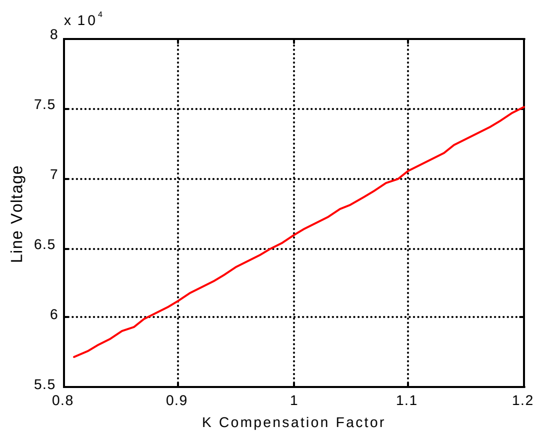


Figure 5 Reactive power flow in the system as function of compensation factor when STATCOM installed at the



middle of the line.

Figure 6 The terminal line voltage as function of compensation factor when STATCOM installed at the middle of the line.

In addition, it was found that, the STATCOM could control the distribution of the active power in both lines in a very limited range simply by varying the modulation index of the inverter as presented in Figure 7. This is due to the limited range of changing the load transmission angle as indicated in Figure 8. Note all the simulated active power, reactive power and voltage are measured in Watt, VAR and Voltage respectively.

The STATCOM device has been installed over ten different position of the transmission line. The active power flow P_2 and P_3 can be controlled in both transmission lines to a limited percentage as shown in Figures 9 and 10. That is due to the limited range of changing to the load transmission angle as indicated in Figure 11. The reactive power Q_3 is highly sensitive to the variation of the compensation factor over different installation positions and especially in the first half of the transmission line as indicated in Figure 12. On the other hand, the reactive power Q_2 is slightly sensitive to the change of the compensation factor over a wide range as shown in Figure 13. The STATCOM device compensates the reactive power. The STATCOM supplies Q_{sh} the reactive power as K> 100% and it absorbs the reactive power when K <100% over different installation positions as indicated in Figure 14. The line terminal voltage at the point of connection of the STATCOM device to the line can be controlled over a wider range under different compensation factors over the transmission line as illustrated in Figure 15. The optimum installation position for the device is at the middle of the transmission line where a wider range of voltage control can be achieved.

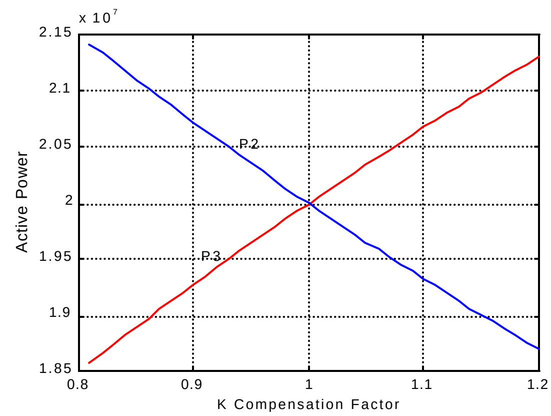


Figure 7 Active power flow in the system as function of compensation factor when STATCOM installed at the middle of the line.

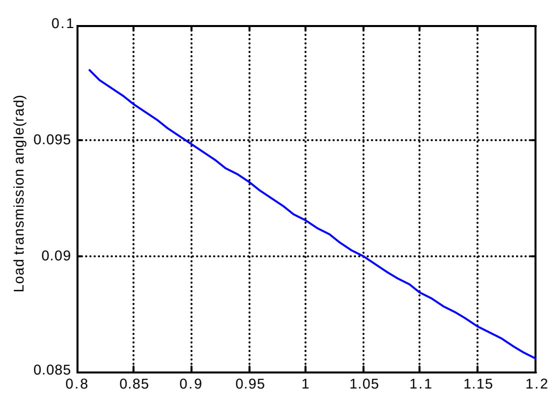


Figure 8 The load transmission angle as function of compensation factor when STATCOM installed at the middle of the line.

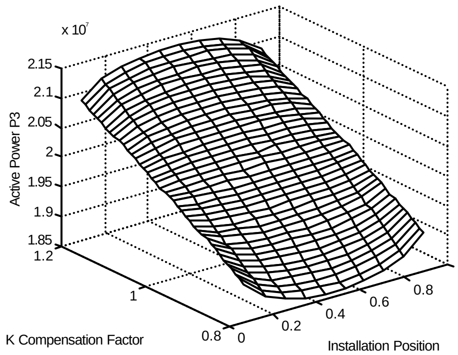


Figure 9 Active power flow P3 as function of compensation factor when STATCOM installed at different positions over the line.

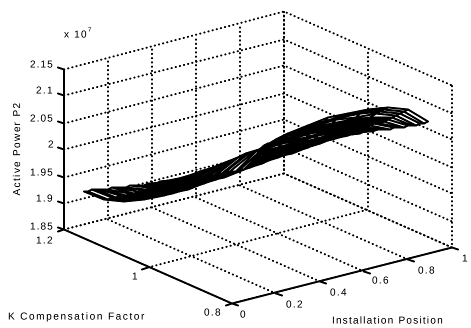


Figure 10 Active power flow P2 as function of compensation factor when STATCOM installed at different positions over the line.

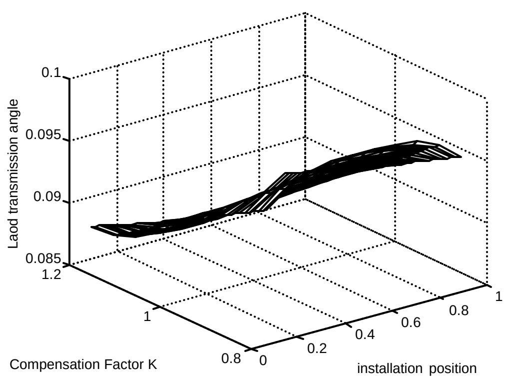


Figure 11 Load transmission angle as function of compensation factor when STATCOM installed at different positions over the line.

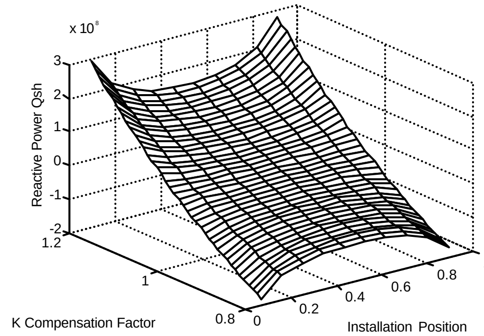


Figure 12 Reactive power flows Q3 as a function of compensation compensation factor when STATCOM installed at different positions over the line.

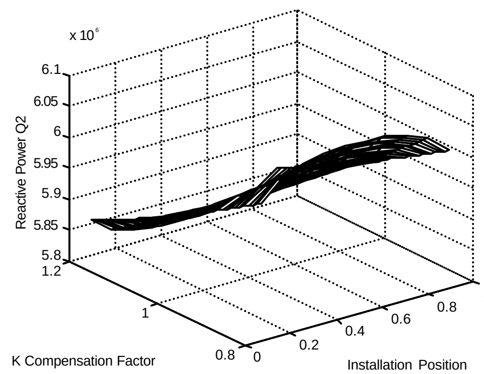


Figure 13 Reactive power flows Q2 as a function of compensation compensation factor when STATCOM installed at different positions over the line.

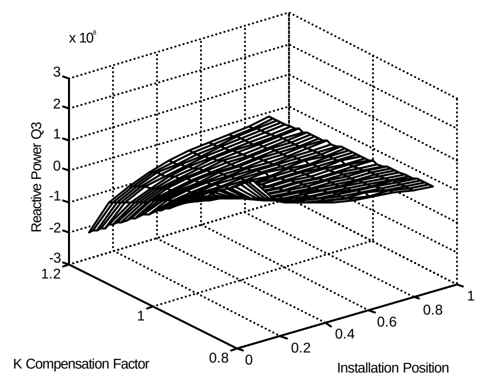


Figure 14 Reactive power flows Q2 as a function of compensation compensation factor when STATCOM installed at different positions over the line.

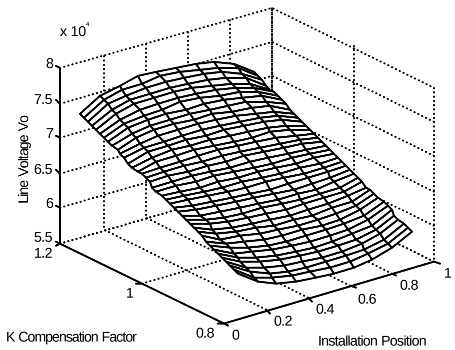


Figure 15 Line Voltage V_o as a function of compensation compensation factor when STATCOM installed at different positions over the line

CONCLUSION

The STATCOM has been analyzed with two parallel transmission lines. The system has been modeled and simulated by using MATLAB program package. In this case a PWM scheme has been used to control the operation of the inverter of the STATCOM. It has been found mathematically that the STATCOM can supply or absorb the reactive power to or from the transmission line. It has been found also that, by varying the modulation index the active power flow distribution in the parallel transmission lines can be controlled. In addition, the simulation results have shown that the reactive power is highly sensitive in the line connected to the device and slightly sensitive to the other. Furthermore, it was found that the finest position to install the device is that at the middle point of the transmission line, where wide range of terminal line voltage can be controlled.

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