AN INTELLIGENT RULE BASE ADAPTIVE CONTROLLER FOR PWM BASED SSSC TO ENHANCE DYNAMIC PERFORMANCE OF POWER SYSTEMS

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ABSTRACT

The Static Synchronous Series Compensator (SSSC) is a FACTS device which allows rapid and continuous changes in the transmission line impedance so that the active power flow along the compensated transmission line can be controlled within a specified range under a range of operating conditions and can help to improve the dynamic performance of power systems.

This paper presents an intelligent rule based controller for the SSSC. The power flow oscillation stabilizer action can be adjusted on line using automatic gain scheduling criteria. The analysis of the dynamic performances of a PWM based Static Synchronous Series Compensator (SSSC) with the proposed controller and its interaction with a representative two-area EHV network is presented. The detailed switching-level SSSC device as well as the power systems models were developed in SimPowerSystems (MATLAB), which was used to evaluate the static and dynamic performances of the series compensated system. Various control strategies were evaluated and an adaptive PI controller was developed. Study results show a substantial improvement in the response of the network to system disturbances, with minimum harmonic distortion.

I. INTRODUCTION

Electric utilities are operating in an increasingly competitive market due to the deregulation. At the same time, economic and environmental pressures limit their possibilities to expand their transmission facilities. With interconnected systems, particularly in the de-regulated environment, it becomes increasingly important to be able to control power flow on individual transmission lines, and to this end, FACTS devices are becoming increasingly used in high voltage transmission system.

The improvement of voltage and current limits of power electronics devices has lead to very fast development of FACTS devices in the last decade: for example the development of high power GTOs led to the development of STATCOMs which offer significant advantages over the thyristor-controlled SVCs in common use. In the coming future it is likely that high power IGBTs will make PWM controlled FACTS devices feasible for transmission applications. These devices will offer improved speed of response and cause less distortion on the network.

Flexible AC transmission systems (FACTS) devices using high-power power electronic based inverter can be divided into four main categories: Shunt controllers, series controllers, combined series-shunt controllers and combined series-series controllers. The functions and their basic operation principles are shown in the Table 1:

Shunt controllers	Series controllers	Combined series-shunt controllers	Combined series-series controllers
SVC, STATCOM	TCSC, SSSC	UPFC	IPFC
Inject current into the system at the point of connection	Inject voltage in series with the line	Combined of separate shunt and series controllers	Combined of separate series controllers
The injected current is in phase quadrature with the line voltage	The injected voltage is in phase quadrature with the line current	Inject current into the system with the shunt part and Inject voltage in series with the series part	Provide independent series active and reactive compensation for each individual lines

Table 1

In this paper the basic working principle, control strategy and dynamic performance of the SSSC is presented. Furthermore, an adaptive PI controller is added to the SSSC controller in order to improve the performances of the SSSC. Finally, the transient performance of the SSSC with the adaptive controller is presented with a representative interconnected two areas network.

II. BASIC PRINCIPLE OF THE SSSC

A schematic diagram of a SSSC is shown in Fig. 1. The SSSC is connected in series with a simple transmission line between Bus 1 and Bus 2 where Vs and Vr are the sending end voltage source and receiving end voltage source respectively. The SSSC consists of a three phase 24-pulse full-wave bridge inverter which is controlled by the SSSC controller to inject a three-phase synchronous voltage in series with the line so as to control the active and reactive power flow through the transmission line.

Consider the simple transmission system shown in Figure 1.

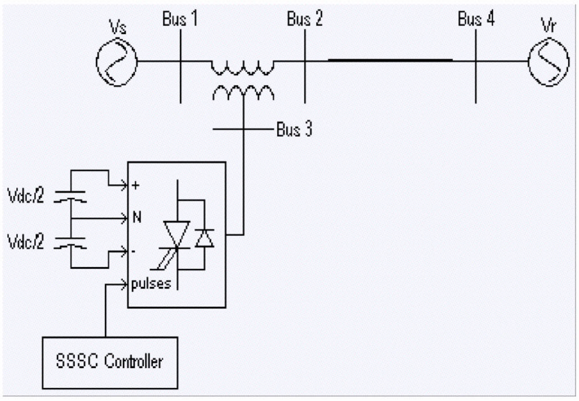

Fig. 1 A simple transmission system with SSSC

The real and reactive power (P&Q) flow at the receiving-end can be expressed as:

$$P=\frac{V_sV_r}{X_L}\sin(\delta_s-\delta_r)=\frac{V^2}{X_L}\sin\delta$$

and **(1)**

$$Q=\frac{V_sV_r}{X_L}(1-\cos(\delta_s-\delta_r))=\frac{V^2}{X_L}(1-\cos\delta)$$

The SSSC introduces a virtual compensating reactance, X_q, (both inductive and capacitive) in series with the transmission line inductive reactance, X_L The expression for the power flow will become:

$$P_q=\frac{V^2}{X_{eff}}\sin\delta=\frac{V^2}{X_L(1-\frac{X_q}{X_L})}\sin\delta$$

and **(2)**

$$Q_q=\frac{V^2}{X_{eff}}(1-\cos\delta)=\frac{V^2}{X_L(1-\frac{X_q}{X_L})}(1-\cos\delta)$$

where, $X_{eff,}$ is the effective reactance of the transmission line, including the emulated variable reactance inserted through the injected voltage source supplied by the SSSC. The compensating reactance X_q is defined to be negative when the SSSC is operated in an inductive mode and positive when the SSSC is operative in a capacitive mode. Therefore, by controlling the value of X_q, the power flow of the line can be controlled. [1][2]

III. BASIC OPERATING MODES FOR THE SSSC

There are several possible control strategies:

- Constant Voltage Injection Mode: In this mode the SSSC generates a three phase voltage with respect to a reference input. The direct voltage injection mode is used to provide purely reactive series compensation where the injected voltage is always kept in quadrature with the line current.
- Constant Impedance Emulation Mode: This control mode provides a opportunity for operator to control the total line impedance, which can be specified by the reference input. The series injected voltage will create, via the series transformer, a virtual impedance seen by the transmission line.
- Constant Power Control Mode: Under this mode, the injected voltage can be variable in magnitude and phase angle in order to control the power flow to be constant. This control mode can also be used for improving system transient stability. [1] [2]

IV. SSSC CONTROLLER

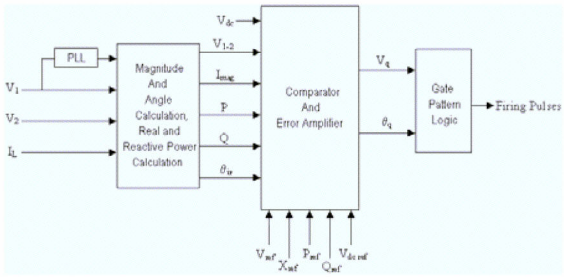

Fig. 2 Simplified control block diagram of the SSSC

Figure 2 shows the simplified control block diagram of the SSSC. An instantaneous 3-phase set of line voltages, V_1, at the transmission line is used to calculate the reference angle, θ, which is phase-locked to the red phase of the line voltage, V_{1R}. An instantaneous 3-phase set of line currents, I, is measured and the amplitude and the relative angle, θ_{ir}, of the line current with respect to the phase-locked-loop angle , θ are calculated by using Park's Transformation.

In the Constant Impedance Emulation Mode, the calculated magnitude of the line current, I_{mag}, is multiplied by the compensating reactance reference, X_{ref}, and the result is the injection voltage magnitude, V^*_{ref}. The phase angle of the line current, θ_i, is then added to the phase angle of the line voltage, θ_v, and the result, θ_{ir}, is used to calculate θ_q. The phase angle, θ_q, of the injected voltage is either θ_{ir} + 90 if the required compensating reactance is inductive or θ_{ir} - 90 if the required compensating reactance is capacitive. The compensating reactance demand, X_{ref}, is either negative if the SSSC is emulating an inductive reactance or positive if it is emulating a capacitive reactance.

In Constant Voltage Injection Mode, the insertion voltage amplitude demand, V_{ref}, may be specified and the SSSC will inject the desired voltage almost in quadrature with the line current.

In Constant Power Control Mode, the calculated instantaneous power is P are compared to the active power reference, P_{ref}, so as to control the injected voltage magnitude and phase angle. [1] [2]

V. AN ERROR DRIVEN INTEGRATOR FOR STATIC SYNCHRONOUS SERIES COMPENSATOR

The effectiveness of SSSC is determined largely by the control strategy. SSSCs are utilized in applications including current control, damping oscillations, improving transient and dynamic stability, as well as voltage stability. In order to improve the static and dynamic performances of the SSSC, an intelligent error driven integrator for Static Synchronous Series Compensator was developed and is presented in this paper. The intelligent error driven integrator is based on the concept of the error excursion plane where the stabilizing action is scaled by the magnitude of the power error signal, voltage error signal and the reactance error signal in order to ensure adequate compensation. [5] The proposed rule based design is robust and tolerates system parameter variations as well as modeling inaccuracies, since the control level (Gain of the PI controller) is only scaled by the input error signal.

The PI regulator inside the SSSC controller is used to control the output magnitude of the compensated voltage of the Static Synchronous Series Compensator. In order to shorten the response time of the SSSC, prevent undesired oscillation of the output voltage and improve the power system stability, an intelligent error driven integrator was developed applied to the SSSC controller.

Intelligent error driven integrator

The intelligent error driven integrator is based on the concept of the on-line gain scheduling and adjustment based on the magnitude of the input error signal and its rate of change [5]. Figures 3 show the structure and the detailed block diagram of the intelligent error driven integrator. The control equations are shown as following:

$$
\begin{aligned}
P_{er} &= K_1 \frac{P_e}{P_{ref}} \, p.u. \\
P_{e'} &= P_{er} + P_e \\
P_1 &= (F(s) \times P_e)^2 \qquad \textbf{(3)} \\
P_2 &= (K_2 P_e)^2 \\
K_g &= K_3 \sqrt{P_1^2 + P_2^2}
\end{aligned}
$$

where P_e is the input Power error signal of the controller, P_{ref} is the reference power, K_1, K_2 and K_3 are the selected modulation gain the intelligent integrator, and F(s) is a transfer function which is used to calculate the rate of change of the error signal and perform the filter effect of the error signal by a second order filter to avoid undesired hunting, oscillation and instability of the system due to the unsuitable output of the intelligent integrator.

At any sampling time instant t:

$$P_{in}(t) = K_g(t) P_{e'}(t) \qquad \textbf{(4)}$$

where P_{in} (t) is the input signal of the integrator at any sampling time (t).

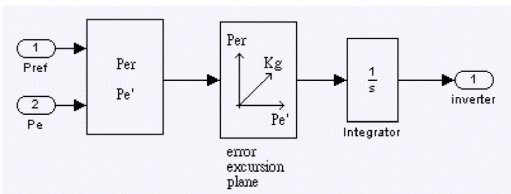

Fig. 3 Structure of the intelligent error driven Integrator

VI. VITAL SIMULATION OF APPLING SSSC TO IMPROVING TRANSIENT STABILITY

i. Interconnected areas network

The dynamic performances of the SSSC with conventional PI controller and intelligent error driven integrator were evaluated by using a representative two areas system shown in Figure 4. The system consists of two individual areas interconnected by a 300 km tie-line. During normal operating conditions, the interconnecting tie-line carries 680 MW from area 1 to area 2. [3] [4]

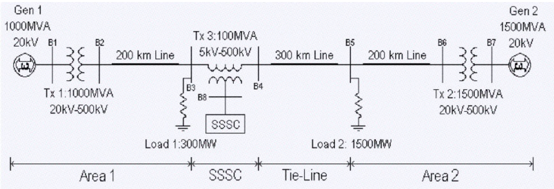

Fig. 4 A representative interconnected areas network

An SSSC is installed between bus 3 (B3) and bus 4 (B4) (at the line end of the tie-line). In normal operation, the SSSC will inject constant voltage into the system in order to maintain constant power flow through the tie-line.

The SSSC consists of a PWM based three phase 24-pulse full-wave bridge inverter which is controlled by the SSSC controller to inject a three-phase synchronous voltage in series with the line so as to control the active and reactive power flow through the tie-line. The inverter consists of two three-phase three-level PWM voltage source converters connected in twin configuration. The inverter injects voltage to the system through a three-phase series inverter. The results of the injected three phase voltage of the 24-pulse full-wave bridge inverter in the simulation are shown in Fig. 5

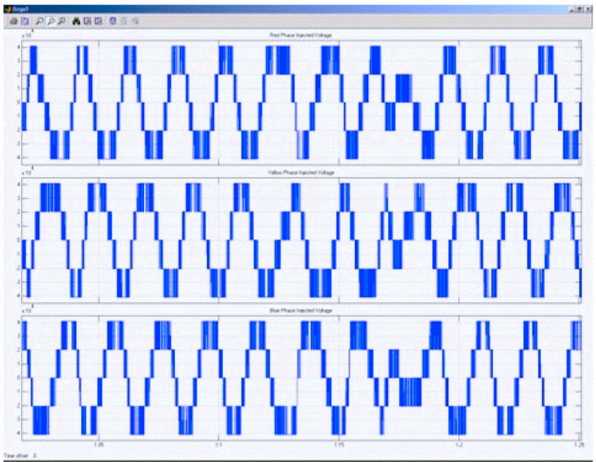

Fig. 5 Simulation results of the output three phase voltage of the 48-pulse full-wave bridge converter

In the simulation, a symmetrical 3phase phase-to-ground fault which lasts for six cycles was applied at Bus 2 as follows:

Stage 1: Normal operating state, t = 0s – 1s

Stage 2: During the three-phase fault, t = 1s – 1.12s

Stage 3: After the three-phase fault and system recovering state, t = 1.2s – 10s

The results of the simulation of the following cases (i) no SSSC, (ii) SSSC with conventional PI controller and (iii) SSSC with intelligent error driven integrator are compared and shown in Fig. 6-10.

Fig. 6 depicts the dynamic performance of the rule based SSSC control with the intelligent adaptive controller. The error driven integrator is based on on-line gain scheduling and adjustment based on the magnitude of the input error signal and its rate of change. The results in Fig. 6 show the dynamic response of the output gain of the error driven integrator following a 3-phase fault on the system. The gain changes from near zero in steady state to as high as 100.

From Fig. 7 and 8, we can see that the SSSC is very effective in damping active and reactive power flow oscillations, and the adaptive controller provides a substantial improvement in the dynamic performance of the SSSC, damping the system oscillations in less than four seconds. Furthermore, as can be seen in Fig. 9 and 10, the adaptive controller is effective in eliminating steady state errors. The SSSC with the adaptive control system is also effective in improving angle stability, as can be seen in Figure 9, where after the first swing, the maximum rotor angle difference between the two areas is reduced by more than 50% compared with the results obtained by using the SSSC with conventional PI controller.

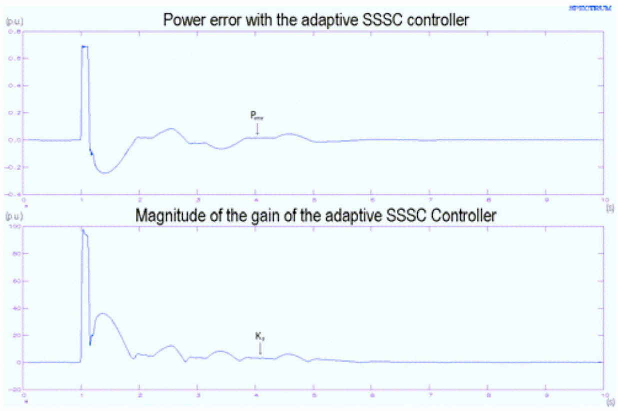

Fig. 6 Simulation results of the input active power error signal of the adaptive SSSC controller and the magnitude of the output controllable gain of the adaptive controller

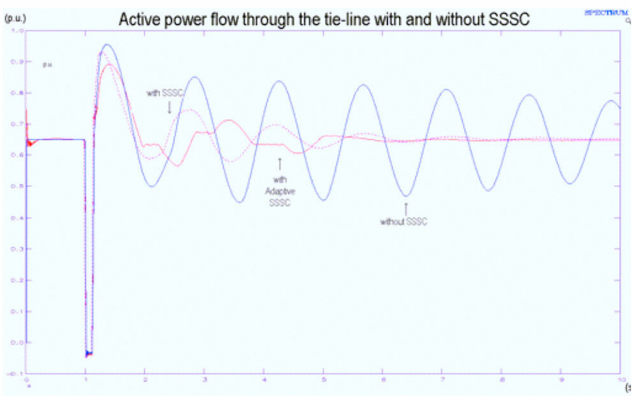

Fig. 7 Simulation results of the active power flow with and without SSSC

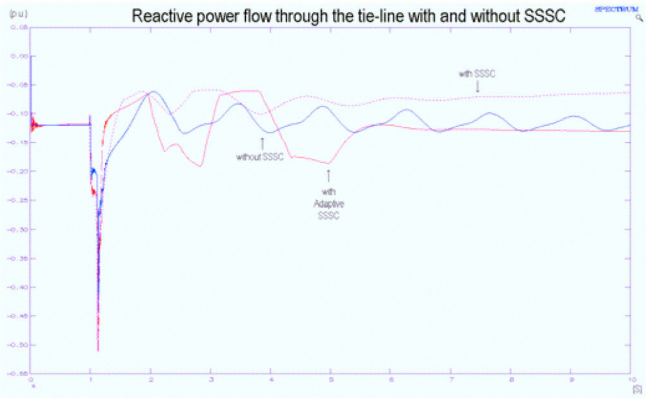

Fig. 8 Simulation results of the reactive power flow with and without SSSC

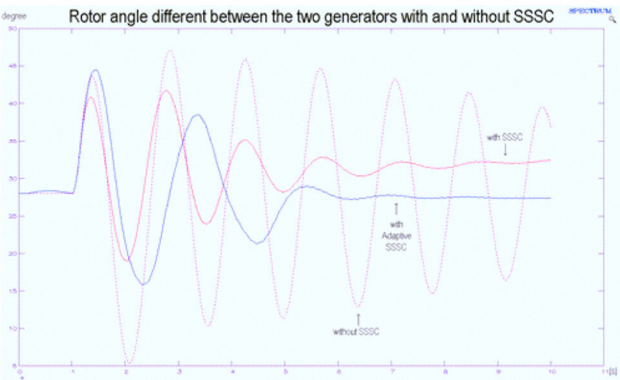

Fig. 9 Simulation results of Delta-theta of the two generators with and without SSSC

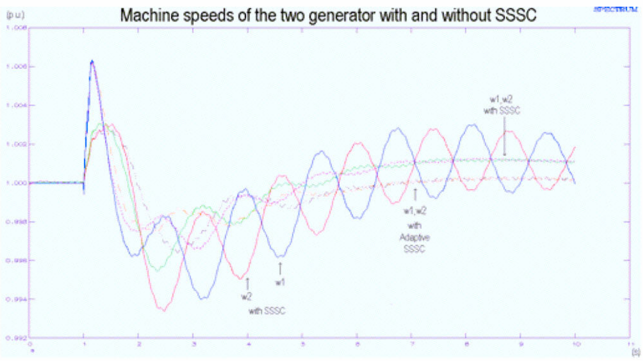

Fig. 10 Simulation results of machine speeds of the two generators with and without SSSC

VII. CONCLUSION

This paper presents the application of Static Synchronous Series Compensator, with an error driven adaptive control system to improve the dynamic performance of power systems.

Different control methods of the SSSC such as constant voltage injection control, constant impedance emulation control and constant power control modes were described in the paper. An adaptive PI controller incorporating on-line gain scheduling and adjustment based on the magnitude of the input error signal was shown to improve system damping substantially.

VIII. ACKNOWLEDGEMENT

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