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Abstract ***– Controllable series line compensation by series flexible ac transmission system (FACTS) devices can provide significant transient stability improvement and effective power oscillation damping. The work presented in this paper gives an overview of control issues of series FACTS devices contributing to stable power system operation when applying suitable controllers with appropriately selected system measurements. Firstly, this paper describes two internal control schemes, which are based on the automatic power flow control mode and line impedance compensation mode, for a switching converter type based series FACTS device. Secondly, it shows that the external (secondary) control can give a solution for overall system optimization by providing well-established supplementary controls and adaptive reference changes to the internal controller. Case studies are presented with simulation results by applying the proposed controllers to the series FACTS device on a power system.***

I. INTRODUCTION

Power systems sometimes have flexible alternating current transmission system (FACTS) devices to enhance the capability of the electric power network. Various members of the FACTS family can be used to re-route active power from one part of a network to another, thus eliminating congestion, increasing utilization of lowest cost generation, improving the damping of power system oscillations, and providing voltage stability. Both theoretical and practical studies for gate turn-off thyristors (GTOs) based FACTS devices have been proposed in the literature [1]-[25]. This paper focuses on a representative switching converter type based series FACTS device, which is the static synchronous series compensator (SSSC).

There are two important control issues to be considered for the SSSC, namely the internal and external controls. The *internal control* defines the operation of the inverter in order to produce the commanded series injected voltage by providing gating signals to the converter valves such that the converter output voltages correctly respond to the internal reference variables. The objectives of the *external control* are to improve dynamic damping performance by applying suitable supplementary controls and to adapt the internal reference variables to changed operating conditions.

This paper presents an overview of overall control schemes for switching converter type based series FACTS device. Case studies are given to show the effectiveness of various controllers for the SSSC on improving system dynamic performances.

II. INTERNAL CONTROL OF SERIES FACTS DEVICE

The main internal control objectives of the SSSC shown in Fig. 1 are to ensure that the injected voltage at the ac terminal of the inverter is in quadrature with the transmission line current and to keep the dc capacitor voltage V_{dc} constant during steady state operation. There are two representative internal control schemes, which are based on the automatic power flow control mode and the line impedance compensation mode.

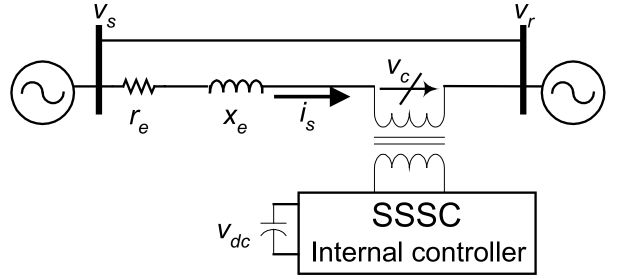

Fig. 1. The simplified schematic of the SSSC in a power system.

A. Automatic power flow control mode

The SSSC converter can control the reactive and/or active power on an ac system by rapidly changing both the phase angle and the magnitude of the converter's output voltage. Especially, the exchange of active power, which is the particular characteristic of the SSSC, is accomplished by controlling the dc voltage inside the SSSC. The *P-Q* (real and reactive power) automatic power flow control [1] diagram is shown in Fig. 2.

In Fig.2, P^* and Q^* are the desired reference values of transmitted real power and reactive power at the ac terminals of the inverter, respectively. An instantaneous three-phase set of injected line voltages, v_{ca}, v_{cb}, and v_{cc} is used for the inputs of the vector phase-locked loop (PLL). Also, the transmission *line currents* i_{sa}, i_{sb}, and i_{sc} are transformed to d-q current components, which are used in the feedforward control path (this is therefore called the *current-control* mode), using the synchronously rotating reference frame.

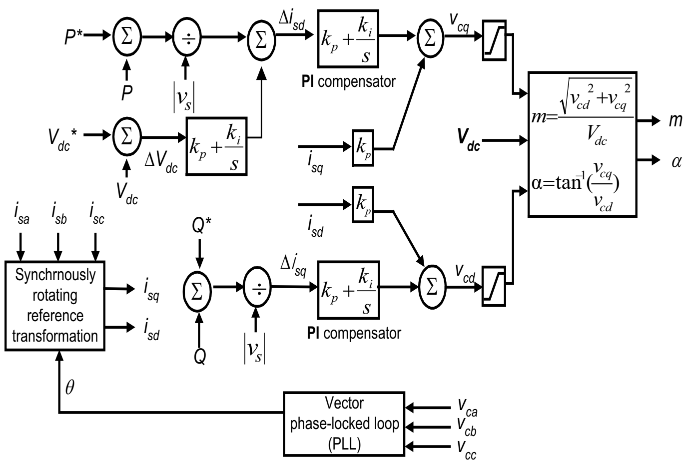

Fig. 2. Automatic power flow control diagram for SSSC.

For modeling of automatic power flow control, the associated equations can be represented in terms of ω_s, (synchronous speed of system) i_s, v_s (the sending-end voltage), v_r (the receiving-end voltage), r_e (the transmission line resistance), and x_e (transmission line reactance plus leakage reactance of connected transformer) in per unit as follows (see Fig. 1).

$$\frac{d}{dt}\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} -\frac{r_e\omega_s}{x_e} & 0 & 0 \\ 0 & -\frac{r_e\omega_s}{x_e} & 0 \\ 0 & 0 & -\frac{r_e\omega_s}{x_e} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \begin{bmatrix} \frac{\omega_s}{x_e}(v_{sa}+v_{ca}-v_{ra}) \\ \frac{\omega_s}{x_e}(v_{sb}+v_{cb}-v_{rb}) \\ \frac{\omega_s}{x_e}(v_{sc}+v_{cc}-v_{rc}) \end{bmatrix} \tag{1}$$

The inverter is assumed to have no conduction losses in (1). By the same synchronously rotating reference frame based transformation, the following d-q vector representation can be obtained from (1) for modeling of the internal controller.

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{r_e\omega_s}{x_e} & \omega \\ -\omega & -\frac{r_e\omega_s}{x_e} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \frac{\omega_s}{x_e}(|v_s| + v_{cd} - v_{rd}) \\ \frac{\omega_s}{x_e}(v_{cq} - v_{rq}) \end{bmatrix} \tag{2}$$

Assuming the practical situation that $x_e >> r_e$, equation (2) gives the steady state line current components as

$$\begin{aligned} i_{sd} &= \frac{\omega_s}{\omega x_e}(v_{cq} - v_{rq}) \\ i_{sq} &= -\frac{\omega_s}{\omega x_e}(|v_s| + v_{cd} - v_{rd}). \end{aligned} \tag{3}$$

The real and reactive powers in per unit can be expressed as follows using (3)

$$\begin{aligned} P &= v_s i_{sd} = v_s\left[\frac{\omega_s}{\omega x_e}(v_{cq} - v_{rq})\right] \\ Q &= -v_s i_{sq} = v_s\left[\frac{\omega_s}{\omega x_e}(|v_s| + v_{cd} - v_{rd})\right]. \end{aligned} \tag{4}$$

Equation (4) shows that the real power P and reactive power Q depend on v_{cq} (the quadratic component of injection phase voltage v_c) and v_{cd} (the in-phase component of injection phase voltage v_c), respectively. It is now possible to define feedback loops and proportional-integral (PI) compensation from (3) and (4) for the SSSC based on the automatic power flow control mode as follows [19]

$$\begin{aligned} v_{cq} &= (a + \frac{b}{s})(i^*_{sd} - i_{sd}) + ci_{sq} \\ &= (a + \frac{b}{s})\left(\frac{(P^* - P)}{|v_s|} + (d + \frac{e}{s})(V^*_{dc} - V_{dc})\right) + ci_{sq} \\ v_{cd} &= (f + \frac{g}{s})(i^*_{sq} - i_{sq}) + hi_{sd} = (f + \frac{g}{s})\frac{(Q^* - Q)}{|v_s|} + hi_{sd}. \end{aligned} \tag{5}$$

B. Line impedance compensation mode

The internal control scheme based on the line impedance compensation mode is shown in Fig. 3. For the operation of the line impedance compensation mode, the transmission line currents i_{sa}, i_{sb}, and i_{sc} are first transformed by Park's transformation [1] into d-q axes components i_d and i_q in a synchronously rotating reference frame. Then, the peak value of the current vector $\sqrt{i_d^{\,2} + i_q^{\,2}}$ is calculated. The desired magnitude $\left|v_{c,pk}\right|$ of the compensating voltage vector is now determined by multiplying the magnitude of the current vector $\sqrt{i_d^{\,2} + i_q^{\,2}}$ by the factor $2\sqrt{2}/V_{dc}$ and the total commanded value of capacitive reactance X_C, and the result is the modulation index m_i for the sinusoidal PWM inverter [8].

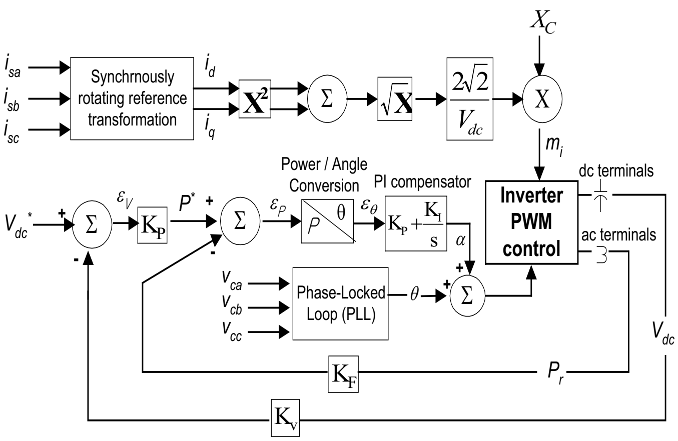

Fig. 3. Internal control based on line impedance compensation mode.

Also, there are an inner power control loop and an outer voltage control loop. The dc capacitor voltage V_{dc} is fed back and subtracted from the reference value V_{dc}^* to form the voltage error ε_V in the outer loop, which is used to produce the commanded power P^*. The action of the SSSC in maintaining a constant voltage V_{dc} at steady state ensures that no real power is exchanged between the inverter and the transmission line, thereby ensuring that the line current leads the injected voltage by 90°. Meanwhile, the instantaneous real power P_r at the ac terminal of the inverter is fed back and subtracted from the commanded power P^* to form the error ε_P for the inner loop, which is thereafter converted to the commanded phase angle α for the PWM inverter after passing through the power/angle conversion block and PI compensator. For the detailed dynamics of the feedback regulator in Fig. 3, the associated differential equations are given in [8] and [16].

C. Case study

 Example-1

To evaluate the dynamic performance of the SSSC with internal control (by automatic power flow control mode), a three phase short circuit of 100 ms is applied to the receiving-end in Fig. 1 at t=1 s. The generator at the sending-end operates with a pre-fault rotor angle of 53.6° in a steady-state operating point of (P_t=1.0 pu, Q_t=0.59 pu). The result in Fig. 4 shows that the SSSC internal control improves the damping performance of the system effectively.

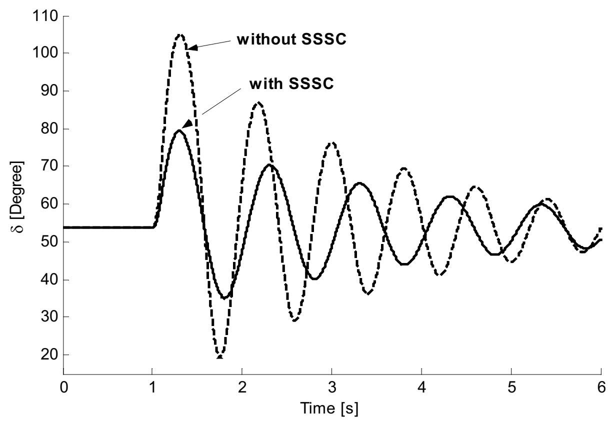

Fig. 4. A 100 ms three phase short circuit test: δ [°].

III. EXTERNAL CONTROL OF SERIES FACTS DEVICE

The objective of the external controller is to give a solution for the overall system optimization by providing well-established supplementary controls and adaptive reference changes to the internal controller. Focusing on the SSSC based on the line impedance compensation mode, design issues for the external controller are discussed in this section.

A. Selection of input signals

Damping is improved by adding an external control loop to the compensator, but a remaining open question is the selection of the input signals for the external loop [21]. It is suggested in [20] that the speed deviation signal $\Delta\omega$ from a nearby generator somewhere in a power system could be used to generate the supplementary control signal ΔX_C. The SSSC can be placed at some distant location forming the remote feedback loop, and in addition to $\Delta\omega$, the active power deviation signal ΔP_S is also considered as an input to the external controller as shown in Fig. 5. This is therefore a *dual input*-based controller design.

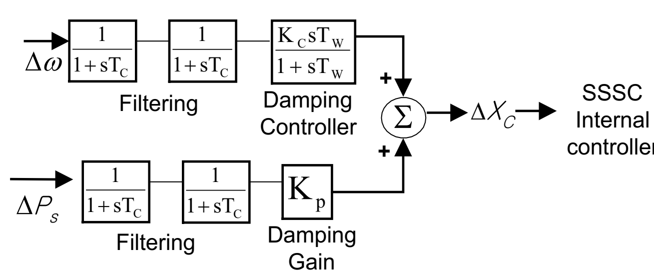

Fig. 5. External controller with two inputs.

The active power deviation signal ΔP_S exhibits the derivative behavior of the speed deviation signal $\Delta\omega$ from the dynamic swing equations [26] as shown in (6)~(8).

$$\dot{\delta}_i = \omega_i - \omega_s = \Delta\omega_i \tag{6}$$

$$M_i \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - P_{ei} = \Delta P_{si} \tag{7}$$

$$\Delta\dot{\omega}_i = \frac{1}{M_i}(\Delta P_{si} - D_i \Delta\omega_i)\ ,(i = 1,\cdots m) \tag{8}$$

where M is the machine inertia coefficient, P is the mechanical power, P_e is the electrical power, D is the machine-damping coefficient, and subscript i is the generator number at each local system.

From the *Barbalat* lemma [27] (which states that if a function f: $[0, \infty) \rightarrow \mathfrak{R}$ is uniformly continuous and bounded, then it follows that $\partial f/\partial t \rightarrow 0$ as $t \rightarrow \infty$), the convergence of ΔP_S in dynamics is guaranteed as long as $\Delta\omega$ is bounded within some stability limits. Its usefulness is therefore theoretically feasible, and the result given in section III-*C* shows that the dual inputs (ΔP_S and $\Delta\omega$) can provide more effective damping compared to the case when the external controller uses only $\Delta\omega$ as one input.

B. Selection of control methodologies

The linear PI compensator in Fig. 5 operates well at one particular operating point where the external controller has been tuned. In other words, its transient and dynamic performances might be degraded at any other operating point, or its parameters have to be re-tuned. Instead of a linear controller tuned by an *ad-hoc* approach, the following various advanced control techniques can be applied to the controller design.

- Nonlinear control
- Optimal control
- Robust control
- Model reference adaptive control
- Hybrid control
- Intelligent control, etc.

As a nonlinear optimal-intelligent control method, the adaptive critic designs (ACD) algorithm [28]-[36] has been successfully applied for the design of the external controller [20]. The study carried out in [20] proved that the functional operations by the external controller for a FACTS device can contribute towards eventual hierarchical control and possible global dynamic optimization in large-scale power networks.

C. Case study

 Example-2

The dynamic performance of the external controller is evaluated by a 100 ms three-phase short circuit applied to receiving-end as shown in Fig. 1 at t=1 s. However, there are two transmission lines flowing the same amount power between the sending and receiving-ends. The generator at the sending-end operates with a rotor angle of 16.9° (P_t=0.25 pu, Q_t=0.16 pu) at the pre-fault steady-state operating point. The results are shown in Fig. 6 for the PI based linear controller and Fig. 7 for the ACD based nonlinear intelligent controller.

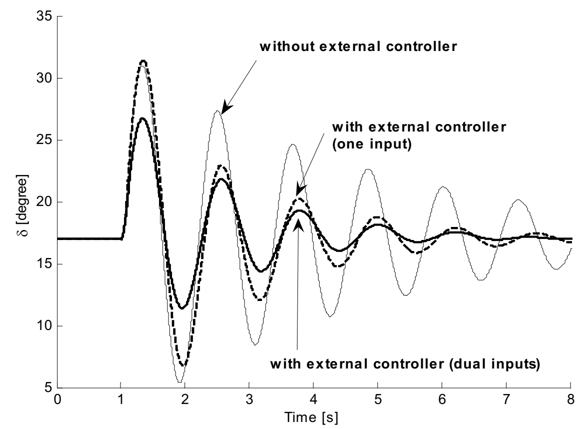

Fig. 6. Dynamic performance: comparison of external controller (linear PI compensator) with dual input and one input.

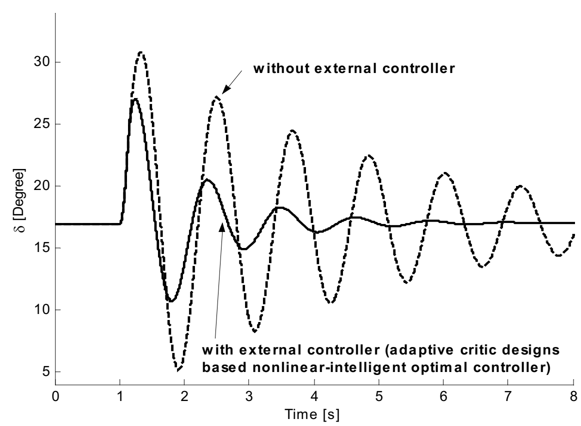

Fig. 7. Dynamic performance of the ACD based nonlinear-intelligent optimal controller.

As mentioned in section III-*A*, the result in Fig. 6 proves that the external controller with dual inputs (ΔP_S and $\Delta\omega$) has a better damping performance than with only one input ($\Delta\omega$). Fig. 7 shows that the well-designed optimal-intelligent controller (by the ACD algorithm reported in [20]) improves the system dynamic damping performance very effectively.

□ *Example-3*

For the case of a transmission line change in practice, the transient performance of the optimal-intelligent controller is tested by applying step changes in the value of X_C (reference input of the internal controller in Fig. 3) as shown in Fig. 8. The first reference value X_C of 0.089 pu is decreased to 0.05 pu at t=1 s and restored to the original value of 0.089 pu at t=10 s. The result in Fig. 9 shows that the ACD based optimal-intelligent controller still works for effective dynamic transient response. In case that the operating condition is changed, the new correct value of X_C can be calculated by formulating the corresponding sending and receiving-end active powers (P_s and P_r) as given in (9) or by forming look-up tables.

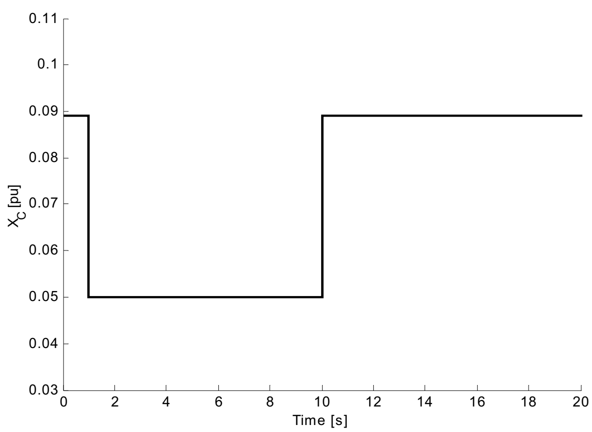

Fig. 8. Step changes in the value of X_C.

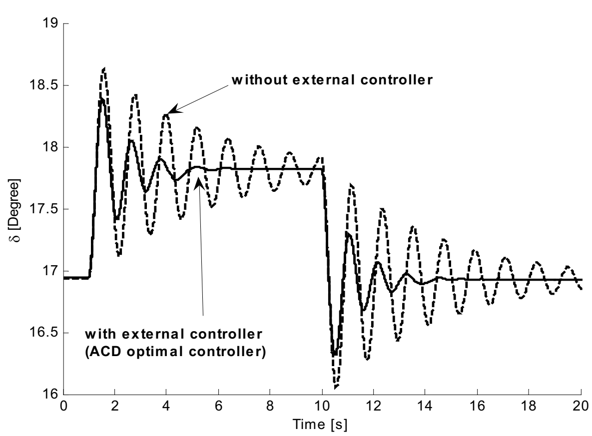

Fig. 9. Dynamic performance for step changes.

$$X_C = f(P_s, P_r) \tag{9}$$

IV. CONCLUSIONS

This paper presented an overview of internal and external control schemes for the switching converter type based series flexible ac transmission system (FACTS) device, which is the static synchronous series compensator (SSSC). The internal control was implemented based on the automatic power flow control mode and line impedance compensation modes. Also, it was shown that external control could give a solution for overall optimization for a dynamic power system by providing supplementary controls. With appropriately selected input variables, various advanced control techniques can be applied for the design of external controllers.

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