The Study of Fuzzy-Logic Controller for SSSC
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Abstract— Power transfer capability of long transmission lines is limited by stability considerations. Reducing the effective reactance of lines by series compensation is a direct approach to increase transmission capability; often, it is the most economical solution. The Static Synchronous Series Compensator (SSSC) is a series connected FACTS controller, which is capable of providing reactive power compensation to a power system. The reactive power flow/transmission line side voltage is controlled by adjusting the phase angle of the series injected voltage. In this paper, an improved fuzzy logic-based controller for SSSC is developed for the stability of the power system. These models are first validated by means of MATLAB simulations on a test system.

Keywords— SSSC, Modeling, Controls Methods, Fuzzy-Logic controller.

I. INTRODUCTION

The SSSC is a series voltage source based Flexible AC Transmission System of the most recent FACTS. The SSSC is usually combined with a Static Synchronous Compensator (STATCOM) and they are operated as a Unified Power Flow Controller (UPFC). It can be considered as a synchronous voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. The injected voltage is almost in quadrature with the line current. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. This variable reactance influences the electric power flow in the transmission line.

A SSSC consists of a VSC connected in series with the transmission line through a coupling transformer. The transformer is used to inject an independently controlled voltage in quadrature with the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted power. The VSC generates a set of 3-phase voltages with controllable magnitude and phase angle at the desired frequency; thus, a SSSC is analogous to a synchronous sinusoidal voltage source.

Where Vs and Vr are voltages at the sending-end and receiving-end of the transmission line, and R1,R2 and X1,X2 are transmission line resistance and reactance respectively. The phase angle between Vs and Vr is \(\phi\). Since the SSSC has a VSC topology, the dc capacitor is used to maintain the DC voltage, giving the SSSC the ability to increase or decrease the transmitted power across the line by a fixed fraction of the maximum power, independent of the phase angle. As a result of the SSSC’s ability for reactive power generation or absorption, it makes the surrounding power System impervious to classical sub synchronous resonance.

\[ V_d = k V_{DC} \cos \phi \]
\[ V_q = k V_{DC} \sin \phi \]

Where \(k\) is the gain of the converter that relates the DC-side voltage to the peak value of output phase voltage at the converter AC-side and \(\phi\) is the phase angle between injected voltage and transmission line current.

A. Decoupled Control Method

The implemented feedback loop makes use of Park transformation on the measured three-phase output currents. This conversion is also referred to as abc-to-dq transformation and used to convert the measured currents to rotating synchronous coordinates d-q. Thanks to the coordinate transformations id and iq are dc components thus it is more convenient to perform calculations.

\[ V_d = \frac{2}{3} [V_a \sin (\alpha t) + V_b \sin (\alpha t - \frac{2\pi}{3}) + V_c \sin (\alpha t + \frac{2\pi}{3})] \]
\[ V_q = \frac{2}{3} [V_a \cos (\alpha t) + V_b \cos (\alpha t - \frac{2\pi}{3}) + V_c \cos (\alpha t + \frac{2\pi}{3})] \]
\[ V_0 = \frac{1}{3} [V_a + V_b + V_c] \]

The new decoupled control system is based on a full dq decoupled current control strategy using both direct and quadrature current components of the SSSC AC current.

It can be shown that with line resistance included, the mathematical model for the response of a Voltage Sourced
Converter to an. applied voltage \( V = V_d \) into a synchronously rotating orthogonal system can be given as:

\[
\begin{align*}
\frac{dI_{se\_d}}{dt} &= \frac{R_{se}}{L_{se}} I_{se\_d} + \frac{1}{L_{se}} (V_{2\_d} - V_{se\_d}) \\
\frac{dI_{se\_q}}{dt} &= \frac{R_{se}}{L_{se}} I_{se\_q} + \frac{1}{L_{se}} (V_{se\_q} - V_{2\_q})
\end{align*}
\]  

(2)

For the purposes of further derivation of the new control system, the classical decoupled watt-var algorithm was studied. By interdicting two new variables \( X_1 \) and \( X_2 \)

\[
\begin{align*}
U_1 &= a I_{sh\_q} + \frac{1}{L_{se}} (V_{2\_d} - V_{se\_d}) \\
U_2 &= -a I_{se\_q} + \frac{1}{L_{se}} (V_{se\_q})
\end{align*}
\]

(3)

\[
\begin{align*}
\frac{dI_{se\_d}}{dt} &= \frac{R_{se}}{L_{se}} I_{se\_d} + U_1 \\
\frac{dI_{se\_q}}{dt} &= \frac{R_{se}}{L_{se}} I_{se\_q} + U_2
\end{align*}
\]

(4)

Thus we see that if we have \( U_1 \) and \( U_2 \) as control variables.

Thus it is seen from equation (04) that by controlling \( U_1 \) and \( U_2 \) one can independently regulate \( I_{se\_d} \) and \( I_{se\_q} \) thereby controlling the real (\( P_a \)) and the reactive power flow (\( Q_{wa} \)).

\[
\begin{align*}
e_1 &= I_{ref\_d} - I_{se\_d} \\
e_2 &= I_{ref\_q} - I_{se\_q}
\end{align*}
\]

(5)

\[
\begin{align*}
U_1(t) &= K_{pi} e_1(t) + K_{ti} \int e_1(\tau)d\tau \\
U_2(t) &= K_{pi} e_2(t) + K_{ti} \int e_2(\tau)d\tau
\end{align*}
\]

Note that the controller inputs are \( I_{se\_d} \) and \( I_{se\_q} \) instead of \( p \) and \( q \).

\[
\begin{align*}
\frac{p_{ref\_d}}{p_{ref\_q}} &= \frac{1}{V_{2\_d}^2 + V_{2\_q}^2} \left[ V_{2\_d} - V_{se\_d} \right] \\
\frac{q_{ref\_d}}{q_{ref\_q}} &= \frac{1}{V_{2\_d}^2 + V_{2\_q}^2} \left[ V_{2\_q} - V_{se\_d} \right]
\end{align*}
\]

(6)

The desired current references namely \( I_dref \) and \( I_qref \) are compared with actual current components \( I_d \) and \( I_q \) respectively and the error signals are processed in the PI controller. Based on these controller parameters set, the required small displacement angle \( \beta \) to control the angle of the injected voltage with respect to the line current has been derived. A Phase Locked Loop (PLL) is used to determine the instantaneous angle \( \theta \) of the three-phase line voltage \( V_{abc} \).

The current components \( I_d \) and \( I_q \) of the three phase line currents are used to determine the angle \( \theta \) relative to the voltage \( V_{abc} \). Depending upon the instantaneous reactive power with respect to the desired value either \( \pi/2 \) is added (inductive) or subtracted (capacitive) with \( \beta \). Thus, the required phase angle is derived as in the equation 07.[2]

\[
\theta_{ref} = \theta + \frac{\pi}{2} \pm \pi(\beta/\pi)
\]

(7)

**B. Fuzzy logic controller (FLC) design methodology**

This closed loop current control enables the system to respond expected and/or unexpected load variations by modifying the modulation index and sine waves used for the generation of PWM signals to keep the output current at a predetermined value.

The disadvantage of PI controller is its inability to react to abrupt changes in the error signal, \( e \), because it is only capable of determining the instantaneous value of the error signal without considering the change of the rise and fall of the error, which in mathematical terms is the derivative of the error signal, denoted as \( \Delta e \). To solve this problem, Fuzzy logic control as it is shown in Figure 3, is proposed.

![Fig. 3 Sample fuzzy logic controller](image)

Each of the two linguistic variables is defined over a universe of discourse namely \( U_e \) and \( U_{\Delta e} \) respectively. Let the universe of discourse for each of the input linguistic variable be divided into 5 fuzzy sets namely, Positive Big (PB), Positive Medium (PM), Zero (ZE), Negative Medium (NM), and Negative Big (NB). Each of the fuzzy set has a definite support. Each fuzzy set can be triangular, or trapezoidal or sigmoid. In this case, triangular fuzzy sets are...
used. Let the universe of discourse for the error be {-0.02 0.02}. Let the universe of discourse for the rate of change of error be {-0.006 0.006}.

Fig. 4 Five fuzzy sets of the inputs.

Fig. 5. Five fuzzy sets of the output.

The expert knowledge is generally given in the following format.

"IF (e set of conditions) THEN (u set of consequent can be inferred)".

These statements contain a set of conditions and a set of decisions to be inferred. The set of decisions could be fuzzy sets.

| A F U Z Z Y  K N O W L E D G E  B A S E. |
|-------------------------|------------|------------|-------------|---|---|
| e \( \Delta e \) | NB | NM | ZE | PM | PB |
| NB | NB | NM | NM | ZE | PM | PM |
| NM | NM | NM | ZE | PM | PM |
| ZE | ZE | PM | PM | PB | PB |
| PM | PB | PB |

III. D I G I T A L S I M U L A T I O N R E S U L T S

The proposed system configuration of Figure 1 has been simulated by Simulink of Matlab as it is shown in Fig. 6. The power grid consists of two power generation substations and one major load center at bus B4.

Fig. 6 MATLAB/SIMULINK model for the studied system configuration

Fig. 7 SSSC injected voltage \( V_a \)

Fig. 8 SSSC injected voltage \( V_{mag} \)
The SSSC located at the left end of the 300-km line L2, between the 500 kV buses B2 and B3, is used to control the active and reactive powers flowing through bus B3. The SSSC is connected to the power system at t=0 Sec, initially, Pref=530 MW and Qref=140 Mvar.

**Step 1** - at t=0.1 sec, Pref is changed to 630 MW. The SSSC reacts by generating real power P=5 MW and absorbs about -0.35 p.u. of reactive power into the AC system at bus 3. The 100% settling time is approximately 55 ms.

**Step 2** - at t=0.2 sec, Pref is changed from 6.3 pu to 4.3 pu. The dynamic behavior is stable and takes about 30 ms for the settling time. The SSSC absorbs 16 MW and injected 26 Mvar.

**Step 3** - at t=0.3 sec, Pref is changed to 530 MW. The real power is set back to its nominal value and the SSSC operating point comes back to zero.

**Step 4** - at t=0.4 sec, Qref is changed from -1.4 pu to -2.4 pu. The SSSC operates inductive absorbs Q=49.5 Mvar and 38.9 MW.

**Step 5** - at t=0.5 sec, Qref is changed to -0.4 pu. The SSSC injects about 0.26 p.u. of reactive power into the ac network at bus B3.

**Step 6** - at t=0.6 sec, Qref is changed to -1.4 pu. The SSSC operating point comes back to zero.

It is clear from Figures 10 and 11 the successful impact of tension injected on P and Q flowing in the 3 transmission lines. The magnitude of the injected voltage is controlled by varying the dc voltage which is proportional to Vinj.

SSSC can be considered as a synchronous voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. The injected voltage is almost in quadrature with the line current. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. This variable reactance influences the electric power flow in the transmission line.

## IV. 4. CONCLUSION

In this paper a Static Synchronous Series Compensator (SSSC) is constructed from a conventional 48-pulse inverter. A detailed closed loop control is designed to control the...
power flows over the power line. The operation of the
designed device is verified by a series of simulations in
MATLAB environment and the obtained results proved to be
satisfactory. In general, the SSSC has showed a quick
transient response. It has also been observed the SSSC ability
in increasing and modifying the transmittable power of a line,
where it has been implemented.

The compensation of the reactive power flow over the
power line due to the power line inductance is compensated
with the help of series injected voltage. The balance or the
stability of the system is not affected. The performance of the
developed method in this paper thus demonstrates the
damping of the power system oscillations using the
effectiveness of fuzzy logic controller for different system
load power.

It is shown that the SSSC with fuzzy logic controller
provides better performance in the enhancement of dynamic
and transient stability.

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