Controller Design for Advanced Reactive Power Compensators Based on Input-Output linearization

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Abstract: This paper presents a reactive power compensator for electric power systems, which consists essentially of a self commutated inverter and a nonlinear controller. This compensator permits us to regulate voltage of the power systems by compensating reactive power with desired transient performance.

The design of control system is based upon the "Input-Output Linearization Technique". Such a control system enables us to stabilize globally the compensation system and thus helps to improve largely the transient performance of the global system. The system is simulated using simplified models as well as more sophisticated models for inverters in order to validate the controller performance.

1. Introduction

As sensitive electronic loads increase in industrial and commercial power systems, large amount of reactive power consumption causes extra power losses and frequency as well as voltage stability problems in power systems. Reactive power compensation has been attracting enormous attention both in academic and industrial research since a longtime [1-7].

Especially, configurations of compensators realized by self commutated inverters for power systems, called Advanced Reactive Power Compensator (also called STATCOM), have been studied [3-7] since a couple of years. However, controller design for these compensators is based upon their models linearized locally around an operating point [3-7].

Evidently, with these kinds of controllers, it is very difficult (if not impossible) to guarantee desired performances in transient states since such compensators are highly nonlinear even if linear robust and/or adaptive controllers are adopted. Even, the differential geometry technique, especially, exact "Input-State Linearization" was recently applied to power electronic components [10-11]. This method permits to establish nonlinear controllers linearizing globally nonlinear systems.

However, by this method, it is very difficult to compare the dynamic performance of the linearized system with specified performance for the original system. Moreover, the specified performance for the original system cannot be obtained directly from the linearized system.

Figure 1: Functional Diagram of the Compensator
The objective of our work is to establish a systematic controller design method based on the "Input-Output Linearization Technique". The controller designed by this method allows to stabilize globally the compensator system and achieve the desired dynamic performance for the original system directly from the linearized system.

2. Studied System

The system under study (Fig. 1) consists of a utility power system (represented by the transfer function $Z_o(s)$) and a self-commutated inverter that is capable of compensating reactive power consumed by the load ($i_L$). This inverter essentially comprises of six self-commutated thyristors, such as GTO plus six diodes, and a capacitor $C$. Figure 2 shows the simplified power circuit of the system.

![Power circuit of the studied system](image)

Figure 2: Power circuit of the studied system

The system is described by an averaged model given by (1). It can be seen that this system is nonlinear in the control portion.

\[ \begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} -R_F \\ -L_F \omega \\ -1/R_C \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} + \begin{bmatrix} 1/R_F \\ 0 \\ 1/\frac{L_F}{C} \end{bmatrix} \begin{bmatrix} \rho_d \\ \rho_q \end{bmatrix} \] (1)

where $i_d$, $i_q$, $v_d$, $v_q$, $\rho_d$ and $\rho_q$ represent transformed quantities as defined in the next paragraphs.

Using generalized Blondel-Park transformation for three phase power network [7,8], we obtain a model in d-q frame given by (2), where the carrier waveform of the fundamental component can be suppressed and harmonics are considered as disturbances of high frequency.

\[ \begin{align*}
\dot{x}_{dq} &= A_{dq}(\omega)x_{dq} + B_{dq}u_{dq} + B_{dq}^*u_{dq}^* + B_{dq}^*u_{dq}^L + B_{dq}^L u_{dq}^L, \\
y_{dq} &= C_{dq}x_{dq} + D_{dq}^*u_{dq}^* + D_{dq}^*u_{dq}^L + D_{dq}^L u_{dq}^L
\end{align*} \] (2)

where $A$, $B$, $C$ and $D$ are the parameter matrices relevant to the power network $Z_o(s)$, and eventually, the load (Fig. 2); the inputs $u_{dq}$ with the superscripts $e$, $s$ and $L$ stand for $V_{de}^e$, $V_{dq}^s$ and $I_{dq}^L$ respectively; the output $y_{dq} = \Gamma_{dq}$; the variables with the subscript $dq$ represents the different quantities in $dq$ reference.

Rewriting (1) in standard form:

\[ \begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = f(x) + g(x)u(t) + w(t) \] (3)

\[ y(t) = h(x) \]

and comparing (3) with (1), we obtain the following relationships:

\[ \begin{bmatrix} f(x) \\ u(t) \\ x(t) \end{bmatrix} = \begin{bmatrix} A \\ g(x) \\ w(t) \end{bmatrix} \begin{bmatrix} x(t) \\ u(t) \end{bmatrix} \]

3. Control Strategy

The controller design for the compensator based on “Input-Output Linearization” aims to achieve
desired dynamic performance directly for the original system directly from the linearized system.

3.1 Controller design

The main requirement imposed on the control system is to compensate reactive power as soon as possible, in both steady and transient states.

The control strategy used to meet these requirements is the high precision nonlinear tracking control that ensures exponential convergence of \(i_{dcb}\) (Fig. 2) to reference values with desired damping.

At first, the original system given by (1) is linearized to (4.1). The adopted method is the "Input-Output Linearization Technique" [12-13].

From (3), we can obtain (4.1) to (4.4).

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} =
\begin{bmatrix}
\xi_d(x, \rho_d) \\
\xi_q(x, \rho_d) \\
\eta(x, \rho_d)
\end{bmatrix}
\tag{4.1}
\]

where,

\[
\xi_d(x, \rho_d) = -\sigma_d x_1 + \omega x_2 + (V_d \rho_d x_3)/L_f
\tag{4.2}
\]

\[
\xi_q(x, \rho_d) = -\sigma_q x_2 - \omega x_1 + (V_q \rho_d x_3)/L_f
\tag{4.3}
\]

\[
\eta(x, \rho_d) = -\sigma_e x_3 + 1.5(\rho_d x_1 + \rho_q x_2)/C
\tag{4.4}
\]

\[
\sigma_f = \frac{R_f}{L_f}, \quad \sigma_e = \frac{1}{R_f C}
\]

Based on the linearized system (4.1), we apply the linear state feedback control to design the controller \([\xi_{d0}, \xi_{q0}]^T\) to get the desired damping rate for the compensator. According to (4.3) and (4.4), the control law \([\rho_d, \rho_q]^T\) can be easily established as given by (5.1) and (5.2).

\[
\rho_d = \frac{1}{x_3}[\sigma_d (x_1 - x'_1) L_f - (\sigma_f x_1 - \alpha_d) x_1 + V_d]\tag{5.1}
\]

and

\[
\rho_q = \frac{1}{x_3}[\sigma_q (x_2 - x'_2) L_f - (\sigma_f x_2 + \alpha_q) x_1 + V_q]\tag{5.2}
\]

where, \(\sigma_d\) and \(\sigma_q\) are specified damping coefficients for the compensator, \([x'_1, x'_2]^T\) is the desired output of the system.

Figure 3 shows the block diagram of the global system with the nonlinear controller.

3.2 Zero Dynamics

The zero dynamics of a system is defined to be the internal dynamics of the system when the system output is kept constantly at zero by the input. For the system given by (1), the zero dynamics is examined in the following way:

- Let \(y = 0\) and \(z = 0\), i.e.,

\[
[x_1, x_2]^T = 0 \quad \text{and} \quad [x_1, x_2] = 0,
\]

we can find the input:

\[
[\rho_d, \rho_q]^T = [V_d, V_q]^T/x_3
\]

to keep the output constantly at zero, and we get the zero dynamics shown in (6):

\[
\dot{x}_3 = -\sigma_e x_3
\tag{6}
\]

where, \(\sigma_e = \frac{1}{R_f C}\).

Obviously, the zero dynamics of the system described by (1) is exponentially stable.

4. Digital Simulations

In order to validate the methods proposed in the paper and show the performance of the controller, we performed simulations for two types of models of the compensator : Simplified model (1) and Full
model with detailed commutation behavior of the inverter (Fig. 2) modeled by the Switching Function Approach [14]. The parameters of the system is presented in Table 1.

Table 1: Parameters of the compensator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_f )</td>
<td>16 mH</td>
</tr>
<tr>
<td>( R_f )</td>
<td>0.5 ( \Omega )</td>
</tr>
<tr>
<td>( C )</td>
<td>11.5 ( \mu F )</td>
</tr>
<tr>
<td>( V_n )</td>
<td>104 volts</td>
</tr>
<tr>
<td>( I_n )</td>
<td>5 Amp</td>
</tr>
</tbody>
</table>

where, \( V_n \) and \( I_n \) are the nominal voltage and current respectively.

Figures 4 and 5 show the simulation results for the simplified model. Figs. 6 and 8 show the simulation results for the full model with detailed commutation of the inverter.

It can be seen that the response of the simplified system is very good (Figs. 4 and 5) since no switching transient is included in the system description. The system response of the complete model exhibits pronounced transients due to switching dynamics. For example, in Fig. 6, the capacitor voltage shows these pronounced high frequency (same frequency as that of PWM carrier) transients in the interval between 0.05 and 0.12 seconds.
5. Conclusions

A nonlinear controller is designed for stabilizing globally the compensator system. This nonlinear controller can improve appreciably the dynamic performance of the compensator. Especially, it enables us to achieve desired damping for the compensator directly from the linearized system.

In this paper, we present digital simulation results to show the general performances of compensating reactive power. Digital simulations are performed by two types of models one of which is shown in (1). Another type of model describes detailed dynamic behavior (including switching transients) of the inverter.

Based upon the theoretical analysis and simulation results, we conclude that:

- the modeling method adopted facilitates the control system design and performance analysis for the compensation scheme;
- the “Input-Output Linearization Technique” is suitable for designing controller for reactive power compensators;
- such a compensator can track well the references of reactive power with the specified damping;
- In comparison with linear controllers based on locally linearized system and the nonlinear controller based on the “Input-State Linearization”, the nonlinear controller established by the “Input-Output Linearization Technique” can ensure desired performances even in transient states and it is easier to be extended to a discrete form for implementation using a DSP.

Further work is in progress to implement the controller for a practical ac-dc converter system.

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6. References


