Inverter Control Using Output Feedback for Power Compensating Devices

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Abstract—This paper presents an inverter control strategy using output feedback control. The controller is designed in discrete-time using pole shifting law in the polynomial domain that radially shifts the open-loop system poles towards the origin. This type of inverter control is very useful for custom power applications in which the inverters have to inject unbalanced and/or harmonic voltage or current or both for neutralizing voltage or current unbalance or harmonics. The proposed controller design is tested on three different compensating type custom power devices: the Distribution STATIC COMPensator (DSTATCOM), the Dynamic Voltage Restorer (DVR) and the Unified Power Quality Conditioner (UPQC). The simulations have been carried out using PSCAD/EMTDC.

Index Terms—Custom power, DSTATCOM, DVR, UPQC, output feedback, pole shift control, PSCAD/EMTDC and distribution system.

1. INTRODUCTION

The concept of employing power electronic (static) controllers in distribution systems for supplying a compatible level of power quality is called custom power. This is necessary for the adequate performance of selected facilities and processes. These power electronic devices are either connected in shunt, in series or a combination of both with the distribution system. Various control switching strategies are available in the literature [1-4]. These are hysteresis control, sliding mode control, fuzzy logic control, linear quadratic regulator, deadbeat controller etc. Among these, hysteresis control is the most popular. But this controller may result in very high switching frequency that may be undesirable for some applications.

This paper discusses the operation of various custom power devices i.e., DSTATCOM, DVR and UPQC using output feedback control. These devices employ voltage source converters (VSCs) which are supplied by a constant dc source. The main aim of the DSTATCOM [5] is to protect the utility system from all kinds of disturbances occurring due to consumer loads while the DVR [8,9] regulates the voltage at the load terminals against, sag/swell, distortion or unbalance occurring in the supply voltage. The UPQC [10,11] can be operated in such a way that it can correct for the unbalance and distortion in the source voltage and load current simultaneously. A pole shifting algorithm [6,7] is designed for each of the devices. In this algorithm, the error between the reference value of the voltage/current and the actual value is minimized to obtain the control action. The extensive simulation studies have been carried out using PSCAD/EMTDC (Version 3.0) software package.

2. OUTPUT FEEDBACK CONTROL OF INVERTER

The purpose of the inverter controller is to determine the switching actions such that the reference voltage/current is tracked accurately. This is a discrete-time control technique in which the closed-loop poles are chosen by radially shifting the open-loop poles towards the origin i.e., more stable locations [6,7]. This controller is also known as pole shift controller. Let the discrete-time model of the system be given in an input-output form as

\[ A(z^{-1})y(k) = B(z^{-1})u_c(k) \] (1)

where \( y(k) \) is the sampled value of the system output such as voltage/current and \( u_c \) is the control input. The polynomials \( A \) and \( B \) are given by

\[ A(z^{-1}) = 1 + a_1 z^{-1} + \ldots + a_m z^{-m} \]
\[ B(z^{-1}) = b_1 z^{-1} + \ldots + b_m z^{-m} \] (2)

In the above equation \( z^{-1} \) is the delay operator.

Let the control law be given by

\[ u_c(k) = \frac{S(z^{-1})}{R(z^{-1})} [y_{ref}(k) - y(k)] \] (3)

In (3), \( y_{ref} \) is the reference value and the polynomials \( S \) and \( R \) are given by

\[ S(z^{-1}) = s_0 + s_1 z^{-1} + \ldots + s_{m-1} z^{-(m-1)} \]
\[ R(z^{-1}) = 1 + r_1 z^{-1} + \ldots + r_m z^{-(m-1)} \] (4)

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Substituting (3) in (1) and rearranging we get the closed-loop system as

$$\phi(k) = \frac{B_z(s^{-1})S_z(s^{-1})}{A_z(s^{-1})R_z(s^{-1})}y_{ref}(k)$$

(5)

The controller parameters are then obtained by the solution of the following Diophantine equation or Aryabhata/Bezout identity

$$A_z(s^{-1})R_z(s^{-1}) + B_z(s^{-1})S_z(s^{-1}) = \tau(s^{-1})$$

(6)

In the above equation, \(\tau(s^{-1})\) is the closed-loop system characteristic equation obtained after shifting the open-loop poles and is given by

$$\tau(s^{-1}) = A_z(z^{-1}) = 1 + a_1z^{-1} + \cdots + a_nz^{-n}$$

(7)

where \(0 < \lambda < 1\) is called the pole shift factor that determines the penalty on control. The closer \(\lambda\) is to one, the smaller will be the control action. The solution of (6,7) yields the coefficients of \(S\) and \(R\) i.e., the controller parameters. In the following sections the operation of various compensating type custom power devices i.e., the DSTATCOM, the DVR and the UPQC using pole shift control technique will be discussed.

3. POLE SHIFT CONTROL OF DSTATCOM

The schematic diagram of a single-phase distribution system compensated by a DSTATCOM is shown in Fig. 1. A DSTATCOM is a power electronic-converter-based device connected in shunt with the distribution system.

![Fig. 1 Equivalent circuit of a shunt compensated distribution system.](image)

In Fig. 1, the load is supplied by the source \(v_s\) through a feeder (represented by \(R_L\) and \(L_L\)). The load and the DSTATCOM are connected at the point of common coupling (PCC). The PCC voltage is denoted by \(v_p\). The DSTATCOM is realized by an H-bridge inverter that is connected to the load through a transformer having a leakage inductance of \(L_T\). The DSTATCOM injects a current \(i_i\) into the distribution system to cancel out the harmonic components of the load current \(i_l\). As a consequence the source current \(i_s\) becomes free of harmonics.

The basic aim of the DSTATCOM is to track a reference current \(i_s^*\) through the switching action of the inverter. The reference current is generated such that the compensated load behaves in a desired manner [5]. Theoretically, we can choose \(i_s^*\) to have any arbitrary magnitude and angle. The purpose of the pole shift controller is to determine the switching actions such that the reference current is tracked accurately.

The inverter output voltage can be written as \(u_sV_{dc}\) where \(u_s = \pm 1\) is the switching function. Defining a state vector as \(x^T = [i_l\ i_s/m\ n\ V_{dc}]\), the state space model for the system of Fig. 1 can be given as

$$x = Ax + Bu$$

$$y = Cx$$

(8)

where

$$A = \begin{bmatrix} 0 & 0 & 1/n & 0 \\ 0 & \frac{R_f}{L_f} & -\frac{1}{n^2L_f} & 0 \\ \frac{n^2}{C_f} & \frac{n^2}{C_f} & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} V_{dc} \\ 0 \\ \frac{V_{dc}}{nl_f} \\ 0 \end{bmatrix}$$

(9)

$$C = [1 \ 0 \ 0]$$ and \(z^T = [u_s\ v_s]\)

Here \(u_s\) is the continuous control action on the secondary side (line side). The injected current \(i_i\) is the system output. The discretization of (9) results in the following equation

$$x(k+1) = Fz(k) + Gz(k)$$

(10)

The transfer function of equation (10) can be obtained and written in an input-output form as given in (1). In this case, the polynomials \(A\) and \(B\) are of order 3 and hence from (4), the order of polynomials \(S\) and \(R\) will be 2. For a particular pole shift factor \(\lambda\), the controller parameters i.e., \(s_0\ s_1\ s_2\ r_1\ r_2\) are obtained by the solution of (6,7). These are then substituted in (3) to get the control input \(u_s(k)\). Once \(u_s(k)\) is obtained, the switching action is obtained using the following logic

If \(u_s(k) > h\)
then close switches \(S_1\) and \(S_2\) i.e. \(u = +1\)

else if \(u_s(k) < -h\)
then close switches \(S_3\) and \(S_4\) i.e. \(u = -1\)
where \( h \) is a very small scalar constant. The switching law of (11) produces a variable switching frequency control action.

The system shown in Fig. 1 is simulated using PSCAD/EMTDC. The system parameters and the transformer data chosen for the simulation studies are given in Table 1.

<table>
<thead>
<tr>
<th>System quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Voltage (( v_i ))</td>
<td>6.35 kV rms</td>
</tr>
<tr>
<td>System Fundamental Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Feeder impedance ( R_f + j \omega L_f )</td>
<td>6.05 + j 36.28 ( \Omega )</td>
</tr>
<tr>
<td>Load impedance ( R_L )</td>
<td>242 + j 181.5 ( \Omega )</td>
</tr>
<tr>
<td>Filter parameters (Primary side) ( L_f )</td>
<td>61.62 ( \mu )H</td>
</tr>
<tr>
<td>( C_f )</td>
<td>2348 ( \mu )F</td>
</tr>
<tr>
<td>( R_f ) (Primary Side)</td>
<td>0.0194 ( \Omega )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transformer Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVA Rating</td>
</tr>
<tr>
<td>Turns Ratio, ( L : n )</td>
</tr>
<tr>
<td>Leakage Reactance (ad)</td>
</tr>
</tbody>
</table>

The DSTATCOM is supplied by a dc source \( (V_{dc}) \) with a magnitude of 0.55 kV. It is desired that the DSTATCOM injects a sinusoidal current with a peak of 300 A with a leading phase angle of 30° with respect to \( v_i \) at the system fundamental frequency of 50 Hz. The switching control \( \omega_c \) is obtained as given in (3) with the reference \( y_{ad} \) as above. The value of the pole shift factor \( \lambda \) is chosen to be 0.9. The controller parameters are calculated using MATLAB.

The simulation results are shown in Fig. 2. In this figure the injected current \( (i_d) \), the source current \( (i_s) \) and the load current \( (i_f) \) are shown. It can be seen that the controller settles within 2 cycles (40 ms). The injected current \( (i_d) \) tracks perfectly its reference value with a peak of 300 A. As a consequence the source current and the load current are perfectly sinusoidal.

![Fig. 2 DSTATCOM current control using pole shift technique.](image)

### 4. POLE SHIFT CONTROL OF DVR

A dynamic voltage regulator (DVR) is a power electronic-converter-based device that is connected in series with the distribution feeder. This injects a voltage in series to correct for sag/swell and also to regulate the load bus voltage to a reference value [8]. The schematic diagram of a DVR connected to a single-phase distribution system is shown in Fig. 3.

![Fig. 3 Equivalent circuit of a series compensated distribution system.](image)

Like DSTATCOM, a structure is used in which a switch frequency LC filter \( (L_C - C_d) \) is placed in the transformer primary [9]. The secondary of the transformer is directly connected to the feeder. This will constrain the switch frequency harmonics to mainly in the primary side of the transformer. \( R_d \) represents the switching losses of the inverter and \( L_f \) represents the leakage inductance of the transformer. The voltage \( v_o \) is the injected voltage that corrects for any disturbance in the load voltage \( (v_i) \). It is required that the load voltage \( v_i \) follows a reference voltage \( v_i^* \). Theoretically, we can choose \( v_i^* \) to have any arbitrary magnitude and angle. From Fig. 3, the DVR reference voltage is obtained by

\[
v_i^* = v_i^* - v_i + L_f \frac{di_d}{dt}
\]

Like in the DSTATCOM case, the inverter output voltage can be written as \( u V_{dc} \). Defining a state variable as \( x^T = [v_d \ v_d \ i_d/n] \), the state space model for the system of Fig. 3 can be written as

\[
x = Ax + Bz
\]

\[
y = Cx
\]

where

\[
A = \begin{bmatrix} 0 & n^2 \\ -1/n^2 L_d & -R_d/nL_d \\ 1/n^2 L_d \\ 0 \\ -1/n^2 L_d & -R_d/nL_d \\ 1/n^2 L_d & -R_d/nL_d \end{bmatrix}, B = \begin{bmatrix} 0 & -n^2 \\ 0 & C_d \\ -n^2 L_d & 0 \end{bmatrix}
\]

\[
C = [1 \\ 0 \\ 1/n] \text{ and } z^T = [v_C \ i_s]
\]
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In (14), the source current, is the forcing function along with u. The injected DVR voltage v, is the output. Here u is the continuous switching variable obtained from the pole shift controller as discussed in Section 2. Note that, in this case, the polynomials A and B are of order 2 and hence from (4), the order of polynomials S and R will be 1. The controller parameters i.e., s, s, and r, are obtained by the solution of (6, 7) as discussed earlier. The switching action is obtained using the control input u, as per (11). The pole shift controller then tracks the reference voltage v* in the same manner as discussed before.

The system of Fig. 3 is simulated using the PSCAD/EMTDC software package. The system parameters and the transformer data chosen for the simulation studies are same as given in Table 1. The value of the dc source (Vdc) is also same i.e., 0.5 kV. It is desired that the DVR inject a voltage such that the voltage at the load terminals has a peak of 8 kV with a phase angle of 30° lagging with respect to v1 at the fundamental frequency. The error between the reference DVR voltage v* given in (12) and the actual injected voltage (vi) is minimized using pole shift controller to get the switching control u. The controller parameters are calculated using MATLAB. The value of the pole shift factor (A) is chosen to be 0.9.

The simulation results are shown in Fig. 4. In this figure, the injected DVR voltage (vi), the load voltage (vL) and the PCC voltage i.e. terminal voltage (vT) are shown. The DVR injects the required voltage such that the load voltage tracks its reference value. From Fig. 4, it can be seen that the load voltage vL is perfectly sinusoidal with the desired peak. Also the tracking operation is perfect.

![Fig. 4 DVR voltage control using pole shift technique.](image)

5. POLE SHIFT CONTROL OF UPQC

A unified power quality conditioner (UPQC) contains both a series compensator and a shunt compensator connected through a common dc energy storage. The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative-sequence current and harmonics [10-11]. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The series component of a UPQC injects a voltage in series to maintain the load voltage balanced while the shunt component injects a current in the ac system so that the source current is balanced sinusoidal. Hence the UPQC combines the operations of a DSTATCOM and a DVR.

The schematic PSCAD/EMTDC simulation diagram of a UPQC compensated single-phase distribution system is shown in Fig. 5. It can be seen that this figure is a combination of the circuits in Figs. 1 and 3. The UPQC consists of two single-phase voltage source converters (VSCs) that are connected to a common dc storage. The UPQC connection in Fig. 5 is called the left-shunt structure [12] as the shunt compensator is connected on the left-hand side of the series compensator. In Fig. 5, the injected shunt current is measured by an ammeter denoted by i, while the injected series voltage is measured by a voltmeter denoted by v. In this case, the value of the dc source (Vdc) is chosen as 1.0 kV. All other parameters of the DSTATCOM and the DVR including the LC filter parameters are same as chosen in the previous sections.

Two decoupled pole shift controllers, one each for shunt and series converters are designed using the technique discussed before. The value of the pole shift factor (A) is again chosen to be 0.9. The state space models for the two converters are same as given in (8, 13). The system is simulated in which it is desired that the shunt converter injects a sinusoidal current with a peak of 100 A with a phase angle of 30° leading and the series converter injects a voltage such that the load voltage has a peak of 9 kV with a phase angle of 90° lagging with respect to the source voltage.

The simulation results are shown in Fig. 6. In this figure the injected DSTATCOM current (i,), the load voltage (vL) and the PCC voltage i.e. the terminal voltage (vT) are shown. It can be seen that the injected current and the load voltage are perfectly sinusoidal with the desired peak. Also the tracking performance is very satisfactory.

6. CONCLUSIONS

An inverter control technique using output feedback control for custom power applications has been discussed. In this technique, the open-loop system poles are radially shifted towards the origin. This pole shift control produces a variable switching frequency control action. The efficacy of the controller is tested for three compensating type custom power devices. These power electronic devices are supplied through a constant dc voltage source. It has been demonstrated that using the proposed controller design, the desired reference voltage/current is tracked accurately. This type of control can only be used in the cases where the system state space model is well known. For simplicity, a single-phase distribution system is considered for all the system studies. This control philosophy can easily be extended to a three-phase distribution system.
REFERENCES


