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Autores:
MANOLOIU, ALISA ; PEREIRA, HEVERTON A. ; TEODORESCU, REMUS ; BONGIORNO, MASSIMO ; EREMIA, MIRCEA ; SILVA, SELENIO R.

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Comparison of PI and PR Current Controllers applied on Two-Level VSC-HVDC Transmission System

Alisa Manoloiu1, Heverton A. Pereira2,3, Remus Teodorescu3, Massimo Bongiorno4, Mircea Eremia1, Selênio R. Silva5

1 University “Politehnica” of Bucharest, Romania, alisa.manoloiu@gmail.com
2 Federal University of Viçosa, Brazil, heverton.pereira@ufv.br
3 Aalborg University, Denmark, ret@et.aau.dk
4 Chalmers University of Technology, Sweden, massimo.bongiorno@chalmers.se
5 Federal University of Minas Gerais, Brazil, selenios@dee.ufmg.br

Abstract—This paper analyzes differences between $a\beta$ and $dq$ reference frames regarding the control of two-level VSC-HVDC current loop and dc-link voltage outer loop. In the first part, voltage feedforward effect is considered with PI and PR controllers. In the second part, the feedforward effect is removed and the PR gains are tuned to keep the dynamic performance. Also, the power feedforward is removed and the outer loop PI controller is tuned in order to maintain the system dynamic performance. The paper is completed with simulation results, which highlight the advantages of using PR controller.

Index Terms—Current control, PI Control, PR control, VSC-HVDC.

INTRODUCTION

Voltage source converters (VSCs) have been widely used in power systems, for distributed generation, high voltage direct current transmission (HVDC) and back-to-back inverter drives. This technology can provide auxiliary functions as voltage regulation and harmonic compensation that have been also required for many grid codes.

Depending on the penetration levels of decentralized generation and grid parameters, it is noticed that stability problems can appear due to large droop gains and demanded power changes [1], [2]. Thus, HVDC-VSCs should have a good current control design in order to be robust against grid disturbances, besides helping the AC grid to mitigate disturbances.

Most controllers with sinusoidal reference tracking have complex computational requirements or have high parametric sensitivity. On the other hand, simple linear proportional integral (PI) controllers have drawbacks as error in steady-state and the need to decouple phase dependency in three phase systems [3]. In this manner, resonant controllers have become a widely employed option in several different applications [4].

The design of PR controllers is usually performed by Bode diagrams and phase-margin criterion, or using Nyquist diagram [5]. Many works compare PI and PR controllers [3], [5], [6] based on performance. PI controllers performance can be improved with addition of a grid voltage feedforward path that can expand the PI controller bandwidth but, unfortunately, push the systems towards their stability limits [3].

![Electric diagram of VSC-HVDC](image)

Figure 1. Electric diagram of VSC-HVDC (a) and control diagram with inner and outer loop (b).

This work proposes the use of PR controllers tuned without voltage feedforward path with similar performance to a PR controller with feedforward path. This control strategy without voltage feedforward is an alternative for connecting to weak ac grids, since the feedforward affects system stability performance [7], [8].

The VSC-HVDC transmission system studied in this work is presented in Fig. 1 (a), and the control diagram with inner and outer loops is represented in Fig. 1 (b). Feedforward effect is analyzed in two frames: synchronous $dq$, Fig. 2(a), and stationary $a\beta$, Fig. 2(b), for inner and outer loop, respectively.

METHODOLOGY

The aims of this paper is to compare the inner loop control characteristics in both synchronous $dq$ frame and stationary $a\beta$ frame regarding the impact of the voltage feedforward path. The inner loop structures in $dq$ and $a\beta$ reference frames are shown in Fig. 2 (a) and (b), respectively. In Fig. 2(a) it is necessary to add a phase-locked loop (PLL) for grid voltage...
phase tracking. The current loop performance is analyzed using the transfer functions given by (1)-(4), for $dq$ and $q\beta$ reference frame, respectively.

$$\frac{I_d}{I_d} = \frac{-G_{pl}}{sL+R-G_{pl}}$$ (1)

$$\frac{I_\alpha}{I_\alpha} = \frac{-G_{pr}}{sL+R-G_{pr}}$$ (2)

$$G_{pl} = k_p^d + \frac{k_d^d}{s}$$ (3)

$$G_{pr} = k_p^\alpha \frac{s\cos \omega - \omega \sin \phi}{s^2 + \omega^2}$$ (4)

Where $\phi$ is an additional degree of freedom that allows to add a phase lead at the considered frequency $\omega$.

Figure 2. VSC control – inner and outer loop: (a) $dq$ reference frame; (b) $q\beta$ reference frame.

In Fig. 2 (b), the blocks $F_1$ and $F_2$ stand for the relations between current in $q\beta$ frame and active/reactive powers. They result from the Laplace transformation in $q\beta$ voltages:

$$F_1 = \frac{\sqrt{6}}{3V} \frac{s}{s^2 + \omega^2}$$ and $$F_2 = \frac{\sqrt{6}}{3V} \frac{s}{s^2 + \omega^2}$$

The PI controller is tuned using the methodology proposed in [9], and the PR controller is tuned to have a similar performance, using [4]. Fig. 3 shows the open loop Bode diagram for $dq$ and $q\beta$ reference frame. It can be observed that the systems have the same phase margin for both PI and PR controllers.

The effect of perturbation arising from the grid is modelled using Fig. 2, and through the transfer functions given by (5) and (6). (7), (8) and (9) are the transfer functions that show the perturbation effect in the dc voltage outer loop, with a generic inner loop in $dq$ frame.

$$\frac{I_d}{V_g} = \frac{-1-H_{FF}^v}{sL+R-P_R}$$ (5)

Where $H_{FF}^v$ and $H_{FF}^\alpha$ are feedforward paths that represent low pass filter measurements and $\text{den}_1$, $\text{den}_2$ and $\text{den}_3$ are given by:

$$\text{den}_1 = 1 + \frac{2P_1P_2}{sC(sL+R)} + \frac{P_1}{sL+R}$$ (10)

$$\text{den}_2 = 1 + \frac{3V_d}{sC(sL+R)} \left( H_{FF}^v - 1 \right) + \frac{P_1}{sL+R}$$ (11)

$$\text{den}_3 = 1 - \frac{2}{sC} + \frac{2P_1}{sC(sL+R)} \left( H_{FF}^\alpha - 1 \right) + \frac{P_1}{sL+R}$$ (12)

RESULTS – PART I: INNER LOOP PERFORMANCE

Grid System parameters used in the inner loop simulations are shown in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor inductance</td>
<td>24.53 mH</td>
</tr>
<tr>
<td>Reactor resistance</td>
<td>0.06 $\Omega$</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>170 kV</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DC Capacitor</td>
<td>17.78 $\mu F$</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>+/- 150 kV</td>
</tr>
</tbody>
</table>

The cut frequencies for voltage in $dq$ and $q\beta$ reference frame and for power are presented in Table II.

<table>
<thead>
<tr>
<th>Cut frequency [Hz]</th>
<th>Voltage feedforward in $dq$</th>
<th>Voltage feedforward in $q\beta$</th>
<th>Power feedforward</th>
</tr>
</thead>
</table>
A. PI and PR controller performances

In this section, the impact of voltage feedforward is analyzed in PI and PR controllers for a step change in grid voltage, as illustrated in Fig. 4. The analysis shows similar performance characteristics when the system is modeled in \( a\beta \) or \( dq \) with feedforward and a better performance in \( a\beta \) when the system works without feedforward.

![Figure 4. Feedforward effect during disturbance in the grid voltage.](image)

Fig. 5(a) shows the response of the close loop system when a step variation is made in the current reference for PI and PR controllers. Both controllers have similar performance regarding time to track the references, as observed in Fig. 5(b).

![Figure 5. Control in \( a\beta \) and \( dq \) frames (a) step response; (b) settling time error.](image)

PI and PR current loop controllers have the gains presented in Table III. The PR controller that substitutes the voltage feedforward effect is tuned differently, with higher proportional and integral gains.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Gain</th>
<th>kp</th>
<th>ki</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td></td>
<td>38.5</td>
<td>94.2</td>
</tr>
<tr>
<td>PR</td>
<td></td>
<td>45.4</td>
<td>10000</td>
</tr>
<tr>
<td>PR without voltage FF</td>
<td></td>
<td>227.4</td>
<td>50000</td>
</tr>
</tbody>
</table>

B. PR controller without voltage feedforward

In order to design a controller for the case without voltage feedforward, the proportional gain was chosen to maintain the stability and to get a good steady state phase and amplitude error.

PR controller without feedforward was tuned to provide similar overshooting than a PR with feedforward during grid disturbances, as shown in Fig. 6. The PR proportional gain, \( k_p \), was selected as a function of the reactor parameters – reactance and resistance, and the sampling time [4].

![Figure 6. Comparison between PR structures during voltage disturbance.](image)

Gain modifications do not affect the overshoot dynamic in terms of current step response, as seen in Fig. 7. Voltage feedforward should be avoided in weak grids since instability problems are possible to occur [10]. In this case, a system without feedforward has superior damping and tracking performance than a system with feedforward.

![Figure 7. Comparison between step response of PR structures.](image)
Fig. 8 shows the open loop Bode diagrams for $I_a/I_d$ for PR with feedforward and improved PR without feedforward. In both cases, the system has similar phase margin and cut-off frequency. Thus, removing feedforward path with a new PR tuning can keep the system dynamic and eliminate the grid voltage measurement.

![Figure 8. Bode plot comparison between PR with feedforward and tuned PR without feedforward.](image)

**RESULTS – PART II: OUTER LOOP PERFORMANCE**

The controller dynamics considering outer loop is analyzed in this section. The outer loop controls the square dc-link voltage, as shown in Fig. 2. There is a PI controller in the outer loop, and two topologies for inner loop controllers, such as presented in the previous case. The control gains in all study cases with outer loop control are shown in Table IV.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Gain</th>
<th>Case I - $V_{dc}^2$ step response</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>kp</td>
<td>-38.5</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>-74.2</td>
</tr>
<tr>
<td>PI</td>
<td>kp</td>
<td>$8.4 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>0.01</td>
</tr>
<tr>
<td>PR</td>
<td>kp</td>
<td>45.4</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>10000</td>
</tr>
<tr>
<td>PR without voltage FF</td>
<td>kp</td>
<td>227.4</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>50000</td>
</tr>
<tr>
<td>Case II - without voltage feedforward</td>
<td>kp</td>
<td>818</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>100</td>
</tr>
<tr>
<td>PR</td>
<td>kp</td>
<td>13.6 $10^3$</td>
</tr>
<tr>
<td>PR without voltage FF</td>
<td>kp</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>100</td>
</tr>
<tr>
<td>Case III - without power feedforward</td>
<td>kp</td>
<td>45.4</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>10000</td>
</tr>
<tr>
<td>PR</td>
<td>kp</td>
<td>0.013</td>
</tr>
<tr>
<td>PR without power FF</td>
<td>kp</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>ki</td>
<td>100</td>
</tr>
</tbody>
</table>

First, a step response in $V_{dc}^2$ is analyzed. Fig. 9 shows that a PR controller tuned to work without feedforward has similar performance to PI controller. The better performance of PR without feedforward is explained because voltage feedforward does not affect the $V_{dc}^2$ step response.

A. **PR controller without voltage feedforward**

The perturbation rejection performance is studied by a step response in the grid voltage. The PR controller was tuned to improve the performance, as shown in Table IV. Fig. 10 shows the dynamic behavior of $V_{dc}^2$ due to a perturbation in the grid voltage. Both controllers have similar dynamic performance.

![Figure 9. Outer loop response due to a step in $V_{dc}^2$.](image)

![Figure 10. Dynamic behavior of $V_{dc}^2$ due to step in the grid voltage](image)

Figure 11 shows the open loop Bode diagrams for $V_{dc}^2/I_d$ for PR with feedforward and improved PR without feedforward. In both cases, the system has similar phase margin and cut-off frequency. Thus, removing feedforward path with a new PR tuning can keep the system dynamic and eliminate the grid voltage measurement.

![Figure 11. Outer loop response due to a step in $V_{dc}^2$.](image)

**TABLE IV Outer loop control parameters**

An important characteristic is the improvement in the outer loop response due to the new controllers tuning. Fig. 11 shows a step in $V_{dc}^2$, and now the PR controller has similar dynamic behavior to the PI controller due to a step change in $V_{dc}^2$, as seen in Fig. 11.

The controllers were tuned to improve the dynamic system performance, both during disturbances and reference variation.
Thus, it is possible to eliminate the voltage feedforward measurements and keeping the system characteristics.

B. PI2 controller without power feedforward

Other feedforward term that influences the system dynamic is the dc-link power injection, as shown in Fig. 2. In this case, the PR controller tuning has a small influence in the control capacity of rejecting a disturbance.

The solution adopted in this work was to tune the PI controller in the outer loop, improving the dynamic response and consequently improving the system dynamic. Table IV shows the new gains for PI2.

Fig. 12 shows the dynamic behavior of $V_{dc}^2$ due to a perturbation in the power injected in the dc bus. In this study case, a step of 100 MW was performed. The tuning in the PI2 control gains affect $V_{dc}^2$ step response as shown in Fig. 13.

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REFERENCES


