Double-loop Control Structure Using Proportional Resonant and Sequence-decoupled Resonant Controllers in Static Coordinates for Dynamic Voltage Restorer

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Abstract: Among incidents on grids, the sag/swell voltage is considered as the most frequent incident. To solve this problem, custom power devices are used. In particular, the dynamic voltage restorer (DVR) is a modern and efficient customer device. DVRs are used to mitigate voltage sag/swells and harmonics on the load bus, thus protecting the sensitive loads. The DVR is a serial compensator that applies a voltage to the point of common coupling to maintain the voltage of sensitive load at the nominal value. To improve the performance of DVRs, in this study, the control strategy of the two-stage loop circuit is implemented. The external voltage control loop uses a sequence-decoupled resonant (SDR) controller, and the inner current-control loop uses the proportional resonant (PR) controller implemented in the stationary frame $\alpha\beta$.

Keywords: Dynamic voltage restorer, PR controller, SDR controller, nonlinear load

1 Introduction

The sag/swell voltage is a problem that entails several hazards for the operation of voltage-sensitive systems and devices [1-3]. Using DVRs to mitigate the sag/swell voltage and protect sensitive devices is one of the effective solutions. In the past, DVRs often used the proportional-integral (PI) feedback controller in a synchronous reference frame (SRF) [3-11]. By converting the feedback signals into SRFs, they become DC quantities. As the PI controller has a very large DC gain, the steady-state error can be effectively eliminated. However, besides converting between the reference frames, when the grid unbalanced, it is required to use double controllers and cross-decoupling, leading to increased computation and complexity in digital signal processing. In addition, PI controllers have disadvantages such as steady-state errors in the stationary frame and the need to decouple the phase dependency in three-phase systems. To improve overall performance, several solutions have been proposed, including the addition of a feedforward voltage path, multi-state feedback, and increasing the proportional gain. These changes help extend the bandwidth of the PI controller, but they also push the systems towards their stability limits, and can distort the line current caused by background harmonics introduced along the feedforward path if the grid voltage is distorted [9].

To reduce the amount of computation and still obtain the same frequency response as the PI controller in SRF, PR controllers need to be developed in the static coordinate system. The main advantage of the PR controller is an extremely high gain at the resonant frequency, which eliminates the steady-state error at this frequency. It is equivalent to an integrator, which has a very large DC gain coefficient that makes the DC static error equal to 0. The PR controllers are used to adjust the AC signal without any SRF conversion. They can achieve good grip properties and control stability. Compared with conventional PI controllers in SRF, the control complexity of PR controllers has been reduced to a certain extent.

With the unbalanced sag/swell voltage, conventional resonance controllers lose their advantages as it is not possible to separate the positive and negative sequences for individual adjustment. In Ref. [10], it is
shown that better system performance can be achieved if the gains for each sequence quantity can be adjusted individually. The SDR controller has all the advantages of conventional resonant controllers, and its control structure is easy to implement because the multi-state-variable structure uses the second-order resonant controller. With this controller, the abc quantities of the three-phase three-wire system are independently controlled for positive and negative sequence components in the stationary coordinate system αβ.

Owing to these advantages of resonant controller, researchers have used this type of controller for DVRs. Ref. [14] provides a control strategy for resonant controllers that does not cause oscillation, but due to the existence of the integral stage, it is difficult to use simple resonance control to satisfy the dynamic speed. The authors of Ref. [8] use the PR controller to eliminate the steady-state error while increasing the dynamic response speed. However, the inclusion of the proportional stage leads to poor load adaptability. Ref. [15] provides a combined strategy: resonance control to perform voltage compensation without static error and feedforward control to improve the dynamic response of the system. Additionally, a method of suppression of harmonic voltages on the capacitance is included to increase adaptability to non-linear loads.

The essence is to use the resonant control in the voltage loop structure, without using a loop according to the current. A capacitive harmonic feedback signal is sent to the DVR to generate an opposite harmonic current, indirectly removing the harmonic component in the output compensation voltage of the DVR.

To enhance the DVR's protection performance against balanced and unbalanced sag/swell events, as well as to maximize the advantages of PR and SDR controllers, the author proposes the use of a two-loop control structure in which an external voltage control loop uses an SDR controller for independent control of positive and negative sequence components, and an inner current control loop uses a PR controller. Such a structure combines the advantages of both controller types, simplifies the control structure, reduces the computation, and improves the dynamics and adaptability to nonlinear loads.

2 PR and SDR controllers

2.1 PR controller

Fig. 1 shows a structure diagram of a practical and an ideal PR controller [9].

![Fig. 1 Structure diagram of PR controllers](image-url)
In this figure, $\omega_1$ is the fundamental angular frequency; $K_{Ph}$ and $K_{Ih}$ are the proportional and integral coefficients of PR controller, respectively; $\omega_c$ is the cutoff frequency of the PR controller; and $h$ is the order of harmonic. $E(s)$ and $Y(s)$ are the Laplace operators of the feedback error signal and the output signal, respectively.

Transfer function of ideal PR controller

$$G_{PRh}(s) = K_{Ph} + K_{Ih} \frac{s}{s^2 + h^2 \alpha_1^2}$$

Transfer function of practical PR controller

$$G_{PRTh}(s) = K_{Ph} + K_{Ih} \frac{(\omega_c^2 s + h^2 \alpha_1^2)}{s^2 + 2\omega_c s + (\omega_c^2 + h^2 \alpha_1^2)}$$

$$K_{Ph} + K_{Ih} \frac{\omega_c^2 s}{s^2 + 2\omega_c s + h^2 \alpha_1^2}$$

Fig. 2 shows the positive- and negative-sequence Bode diagrams of practical and ideal PR controllers.

The resonance regulator is capable of adjusting the current error in a steady-state mode at zero, in the $h$-order harmonic frequency. Integration is performed using the $K_{Ih}$ proportional component and $R_{Ih}(s)$ resonant component, in which $R_{Ih}(s)$ is a quadratic resonance filter with resonant frequency equal to $h\alpha_1$ with zero damping coefficient and $K_{Ih}$ is used to determine the selectivity of the filter. With a practical resonance regulator, the bandwidth is expanded by adjusting $\omega_c$ appropriately to reduce sensitivity to frequency changes in the grid. In addition, system delay compensation (load delay, calculation delay and regulating delay) and harmonic compensation are discussed in detail in Ref. [9].

2.2 SDR controller

The multi-state-variable structure of ideal SDR is as follows [10]:

$$\begin{align*}
y_{a1}(s) &= \frac{1}{s} \left[ K_{e\alpha}(s) + \alpha_1 y_{\beta1}(s) \right] \\
y_{\beta1}(s) &= \frac{1}{s} \left[ K_{e\beta}(s) + \alpha_1 y_{a1}(s) \right]
\end{align*}$$

Here, $e_{a\alpha}$ and $e_{\beta\beta}$ respectively are the feedback error signals caused by coordinates $\alpha$ and $\beta$; $K_1$ is the SDR controller's integral factor; $y_{a\alpha}(s)$ and $y_{\beta\beta}(s)$ are the positive and negative sequence output operators in the synchronous frame.

Fig. 3 shows the multi-state-variable structure diagram of an ideal SDR controller [10].

The multi-state-variable structure of a practical SDR can be described as follows [10]:

$$\begin{align*}
y_{a1}(s) &= \frac{1}{s} \left[ K_{e\alpha}(s) + \alpha_1 y_{\beta1}(s) \right] \\
y_{\beta1}(s) &= \frac{1}{s} \left[ K_{e\beta}(s) + \alpha_1 y_{a1}(s) \right]
\end{align*}$$

Here, $\omega_h$ represents the cutoff frequency of the practical SDR controller.
Multi-state-variable structure diagram describes the practical SDR controller [10].

The gain factor of the ideal SDR controller can lead to serious issues related to the center frequency. To address this, the practical SDR controller described by the multi-state-variable structure (Fig. 4) [10] is regularly used.

Fig. 5 shows the positive- and negative-sequence Bode diagrams of an ideal and a practical PR controller.
Both PR and SDR resonant controllers are capable of tracking signals with the selected frequency, providing an infinite gain when working at that frequency while rejecting the disturbance signals. With the practical controller, the bandwidth of the controller around the resonant frequency is higher than that of the ideal controller; thus, it can sustain small changes in the center frequency. The SDR controller is capable of independently controlling either the positive sequence component $e_{a\beta}$ or the negative sequence component $e_{a\beta}$, while the PR controller has the ability to simultaneously control both these components.

### 3 Control model and algorithm

Fig. 6 shows a simple model of a voltage source converter (VSC) and LC filter connected to a grid \[11\]. VSC is represented as a voltage source $u_{\text{inv}}$, $i_{f}$ is the current running through the filter inductor, $u_{\text{dc}}$ is DC-Link voltage.

From the structure diagram in Fig. 6, Kirchhoff’s law is applied to the three-phase voltage and current, yielding the following equations

\[
\frac{d}{dt}i_{\alpha\beta}(t) = \frac{1}{L_{f}}u_{\text{inv}}(t) - \frac{1}{L_{f}}u_{a\beta}(t) - \frac{1}{L_{f}}R_{f}i_{\alpha\beta}(t) = 0
\]

(7)

(8)

Applying the Clarke conversion on the static frame $a\beta$ yields

\[
\frac{d}{dt}i_{\alpha\beta}(t) = \frac{1}{C_{f}}u_{a\beta}(t) - \frac{1}{C_{f}}\frac{R_{f}}{C_{f}}i_{\alpha\beta}(t) = 0
\]

(9)

(10)

Conduct interruption Eqs. (9) and (10), we get

\[
i_{\alpha\beta}(k+1) = \frac{T_{s}}{L_{f}}u_{\text{inv}}(k) - \frac{T_{s}}{L_{f}}u_{a\beta}(k) - \frac{T_{s}}{L_{f}}R_{f}i_{\alpha\beta}(k)
\]

(11)

(12)

where $T_{s}$ is the sample period.

The load voltage control algorithm is described in the form of mathematical equations and the following diagrams:

(1) Voltage regulator

From Eq. (12), we obtain the equation describing the voltage regulator using the SDR controller, as follows

\[
i_{\alpha\beta}(k+1) = i_{\alpha\beta}(k) + \frac{T_{s}}{C_{f}}u_{a\beta}(k) - \frac{T_{s}}{C_{f}}i_{\alpha\beta}(k)
\]

(13)

where $G_{\text{SDR}}^{p}$ and $G_{\text{SDR}}^{n}$ are the transfer functions of the
resonant controller corresponding to the positive sequence component and the negative sequence component, respectively.

(2) Current regulator

From Eq. (11), the equation describing the current regulator using the PR resonant controller is obtained, as follows

\[ u_{inv}^{\alpha\beta}(k+1) = u_{inv}^{\alpha\beta}(k) + R_i i_{inv}^{\alpha\beta}(k) + G_{PR} \frac{L_i}{T_S} (i_{inv}^{\alpha\beta}(k) - i_{inv}^{\alpha\beta}(k)) \]  

(14)

where \( G_{PR} \) is the transfer function of PR controller.

The current regulator and voltage regulator structures are designed using from Eqs. (13) and (14), as shown in Fig. 7.

The synthesized structure of the two regulating loops on the stationary frame \( \alpha\beta \) is shown in Fig. 8.

A schematic diagram of the DVR connected to the grid is shown in Fig. 9.

4 Simulation results

The performance of the proposed control strategy for sag/swell voltage incidents is evaluated using the simulation results; this evaluation uses a complete voltage compensation strategy and a space vector modulation method. The grid model, load model, and DVR model are set up using tools such as Simulink and SimPowerSystem of MATLAB.

Parameters used in simulation:

- Load parameters: \( R_l = 2.085 \, \Omega; \, L_l = 0.0398 \, H \).
- Source parameters: \( \omega_1 = 100\pi \, \text{rad/s}; \, U_S = 6300 \, \text{V} \).
- Filter parameters: \( L_f = 1.531 \times 10^{-4} \, H; \, R_f = 0.01 \, \Omega; \, C_f = 3 \times 10^{-6} \, \text{F} \).
- Transformer parameter: \( n = 10 \).
- Parameters of SDR controller: \( K_{up} = 53857; \, K_{ip} = 0.379; \, K_{un} = 54.35; \, K_{in} = 0.418; \, \omega_b = 30 \, \text{rad/s} \).
- Parameters of PR controller: \( K_{i\alpha} = 0.0276; \, K_{p\alpha} = 7.783; \, K_{i\beta} = 0.0315; \, K_{p\beta} = 7.852; \, \omega_c = 10 \, \text{rad/s} \).

Case 1 considers A balanced three-phase grid with noise disturbance (Fig. 10). During \( t = 0.02-0.08 \, \text{s} \), the three-phase voltage is down 0.5 pu; During \( t = 0.08-0.1 \, \text{s} \), the three-phase voltage is 1.2 pu high; During \( t = 0.06-0.1 \, \text{s} \), there is an interference; The total harmonic distortion (THD) of the source voltage is 26.76%.

![Fig. 7 Structure of regulators on stationary frame αβ](image)

![Fig. 8 Controller structure diagram of DVR on stationary frame αβ](image)
When power is supplied along with the balanced sag/swell voltage and impact noise, the load voltage, after compensating, is restored to 1 pu, and the THD is 0.03%.

For Case 2 (Fig. 11), during $t = 0.02$-0.08 s, the three-phase voltage source is unbalanced; phase A voltage...
is 0.5 pu; phase B voltage is 0.705 pu; phase C voltage is 0.865 pu; and THD of the source voltage is 14.23%.

The voltages of load, after compensation, are restored to 1 pu, and the THD is 0.14%.

For Case 3 (Fig. 12), during \( t = 0.02-0.08 \) s, the three-phase voltage source is unbalanced; phase A voltage is 0.5 pu; phase B voltage is 0.705 pu; phase C voltage is 0.865 pu; and the THD of the source voltage is 14.23%. The loading parameters at \( t = 0.02 \) s are \( R_L: 1 \text{ pu} \rightarrow 2 \text{ pu} \) and \( L_L: 1 \text{ pu} \rightarrow 2 \text{ pu} \).

The voltages of the load, after compensation, are restored to 1 pu, and the THD is 0.14%.

The simulation results show that when there are balanced or unbalanced sag/swell voltage problems on the grid, the DVR shows good protection performance: The output characteristics are not significantly affected by the harmonics, and the THD index of the load voltage is very low. With this control strategy, the adaptability to nonlinear load is adequate.

5 Conclusions

With the proposed DVR control method, it can be seen that the control structure on the static coordinate system \( \alpha \beta \) is considerably simpler. It is not necessary to use the channel interleaving as well as the transitions of \( \alpha \beta/\alpha q \), which reduces the computational burden on the control algorithms; the dynamics of the system are thus improved. Prior to balanced/ unbalanced sag/swell voltage events, even with a significant disturbance, the DVR shows very good performance: it quickly restores and stabilizes the load voltage and shows sufficient adaptability to nonlinear loads.

The design and calculation of the parameters of
the DVR controller should be noted, owing to the very large fluctuation in the current flowing through the filter inductance. The first step requires the design of the inner current loop to be considerably faster than the external voltage regulation loop. This is achieved by the current control loop using the PR controller, which has sufficiently fast dynamic characteristics. The next step is to design and regulate the SDR controller parameter for the external voltage control loop to track to the set value, so that the control quality of the new system is ensured.

Further, as the harmonic voltage regulates the resonant controllers for the frequencies outside the resonant frequency range, the output characteristics are less affected by the harmonics. However, this causes additional energy loss. To restore the voltage on the load to 1 pu when there is a sag/swell voltage event, as well as increase the adaptability to nonlinear loads, the DC power capacity requirement must be greater than that for the control strategy that uses the PI in SRF, where the requirement depends on the resonant controller parameters and the nonlinearity of the load.

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