An Active Power-Decoupling Method for Single-phase FACTS Device

Junmin Zhang1*, Min Zhao2, Zhi Zheng1
1 Collage of Computer Science, South-Central University For Nationalities, Wuhan, Hubei, 430074, China
2 Engineering Research Centre for Metallurgical Automation and Detecting Technology of Ministry of Education, Wuhan University of Science and Technology, Wuhan, Hubei, 430074, China
*Corresponding author’s e-mail: 173902815@qq.com

Abstract. Single-phase FACTS device can be implemented by an H-bridge inverter which has a large electrolytic capacitor to absorb the 2-ω ripple pulsating. This paper introduced a topological structure by adding a film capacitor and a filtering inductor in AC side and calculated the minimum capacitance of the film. Through the control method, the power of 2-ω ripple can be absorbed completely in theory, and the total size of the capacitor can be reduced by 10 times. The control strategy consisted of three parts: DC voltage control, grid current control, and film capacitor current voltage control. The first part ensured FACTS’s work normally, the second and third parts can be named double-loop control to transform 2-ω ripple power from the electrolytic capacitor in DC side to the film capacitor in AC side. The structure in this paper was the simplest, and control strategy can be verified by simulation.

1. Introduction
The flexible ac transmission systems (FACTS), especially single-phase FACTS have been widely used in power grid to enhance the stability, improve the controllability, and increase system transmission capability [1-8]. However, there is 2-ω ripple pulsating power when the input voltage and current are sinusoidal. So the electrolytic capacitor must be in DC side, resulting in short life-time, higher volume, low power density and cost for the FACTS [9-20].

Several topologies and active power-decoupling methods have been studied to solve 2-ω ripple power problem [7-23]. The basic idea of topologies is adding extra-decoupling circuit and energy storage components, which divert the 2-ripple energy from DC-link to energy storage component. And the only task of capacitor in DC-link is to filter switching ripples, thus the capacitance is been reduced. Therefore film capacitor can be chosen to substitute the electronic ones in DC side and storage component, that will reduce the FACTS’s volume, prolong its life-time and increase its power density.

And the active power-decoupling methods contain two parts [7-23]: grid current control method and power-decoupling method. The PI controller is used for DC voltage to maintain a constant. And the quasi-PR controllers are used to control grid current and insure 2-ω ripple energy transform.

In this paper, a topological structure by adding a film capacitor and a filtering inductor in AC side has been introduced, and the active power-decoupling method can be theoretically transformed 2-ω ripple power from AC side to DC side so that the total capacitor size can be reduced by 10 times. By control method, the control method was made of three parts: DC voltage control, grid current control,
and film capacitor current voltage control. The first part ensured FACTS’s work normally, the second and third parts can be named double-loop control to transform 2-ω ripple power from the electrolytic capacitor in DC side to the film capacitor in AC side.

2. **Theoretical analysis**

The novel topology is shown in figure 1.

![Figure 1. A novel topology](image)

In figure 1, there is a single-phase FACTS, and a film capacitor has been set in AC side to absorb the second-order ripple power. Three inductors are used to filter switching harmonics. The capacitance in DC side is calculated by (1) [2].

\[
C_{dc} = \frac{U_s I_s}{\omega \Delta U_{dc}}. \tag{1}
\]

Here \( U_s \) and \( I_s \) are grid rated voltage and current respectively. \( U_{dc} \) and \( \Delta U_{dc} \) are average and peak-to-peak voltage in DC side respectively. And \( \omega \) is grid angular frequency.

Considering the two voltages \((u_a, u_b)\) in figure 1 as controlled sources, the equivalent circuit is shown in figure 2.

![Figure 2. Equivalent circuit of the novel topology](image)

Assuming filtering inductor: \( L_1 = L_2 = L_3 = L \). The grid voltage and current is

\[
\begin{align*}
    u_s &= 2 \frac{1}{2} U_s \sin(\omega t) \\
    i_s &= 2 \frac{1}{2} I_s \sin(\omega t + \phi).
\end{align*} \tag{2}
\]

And the voltage and current of the ac capacitor is

\[
\begin{align*}
    u_w &= U_w \sin(\omega t + \theta) \\
    i_w &= I_w \cos(\omega t + \theta) \\
    C_{ac} &= I_w (\omega U_w)^{-1}.
\end{align*} \tag{3}
\]

The instantaneous power between \( a \) and \( b \) is

\[
\begin{align*}
    p_{ab} &= u_i - 2L \frac{di}{dt} = \frac{1}{2} U_i \cos \varphi \\
    &+ \frac{1}{2} U_i I_s \sin(2 \omega t + \theta - \frac{\pi}{2}) - \omega L_i^2 \sin(2 \omega t + 2 \varphi) \\
    &= p_{ab, 0} + \frac{1}{2} p_{ab, 2\omega} \sin(2 \omega t + \varphi_a). \tag{4}
\end{align*}
\]
Where $p_{ab\_0} = \frac{1}{2}U_a I_a \cos \phi$, $p_{ab\_ac} = \frac{1}{2}((U_a I_a)^2 + 2L_0 I_a^2 + 4oL I_a^2 \sin \phi)^2$, $\tan \theta_{ac} = \frac{U_a I_a \cos \phi - 2LoI_a^2 \sin(2\phi)}{U_a I_a \sin \phi - 2LoI_a^2 \cos(2\phi)}$.

Then the instantaneous power in $C_{ac}$ is

$$p_{ac} = \frac{1}{2} oC_{ac} U_a^2 (1 - 2o^2 LC_{ac}) \sin(2ot + \theta)$$

$$= \frac{1}{2} oC_{ac} L_0^2 (\frac{1}{oC_{ac}} - 2oL) \sin(2ot + \theta)$$

$$= \frac{1}{2} oC_{ac} Z \sin(2ot + \theta).$$

Where $Z = o^2 C_{ac} (\frac{1}{oC_{ac}} - 2oL)$.

The second-order ripper energy in AC side should be transformed to the $C_{ac}$

$$p_{ab\_ac} = p_{ac}.$$ (6)

Therefore, the magnitude and phase of ac capacitor are

$$U_{ac} = \left(\frac{p_{ab\_ac}}{Z}\right)^{\frac{1}{2}}$$

$$I_{ac} = \frac{U_{ac}}{oC_{ac} - o(L_a + L_s)}$$

$$\theta = 2^- \phi.$$ (7)

According:

$$C_{ac} = \frac{I_{ac}^2}{oU_a I_a}.$$ (8)

$$C_{dc} = \frac{I_{dc}^2}{o\Delta U_d U_{dc}}.$$ (9)

$$\frac{C_{ac}}{C_{dc}} = \frac{\Delta U_d U_{dc}}{U_d^2} \frac{I_{ac}^2}{I_{dc}^2} = \frac{\Delta U_d U_{dc}}{U_d^2}.$$ (9)

Usually $U_{dc}$ and $U_s$ are the same order of magnitudes, and $\Delta U_{dc}$ is 5% of $U_{dc}$. From (9), the total capacitance can be reduced by almost 10 times.

3. Control Strategy

Figure 3 shows the power-decoupling method for single-phase FACTS device, which consists of DC voltage control I by a conventional PI controller, grid current control II by controlling the magnitude of grid current and the phase angle $\phi$ between grid voltage and current, ac voltage and current control III by double close-loop.
3.1. DC voltage control I

In part I, the PI controller is used to maintain the DC side voltage. The transfer function of PI is

\[ G_{pr}(s) = K_p + \frac{K_i}{s}. \]  

(10)

The amplitude frequency characteristic diagram is in figure 4.

Some text.

![Figure 4. the Amplitude-frequency characteristic diagram of PI](image)

The conventional PI controller can keep the voltage in the DC side.

3.2. Grid current control II

In part II and III, the quasi-PR controllers are is used. The transfer function of the controller is

\[ G_{pr}(s) = K_p + \frac{2K_r \omega_r s}{s^2 + 2\omega_c s + \omega_0^2}. \]  

(11)

Where \( K_p \) and \( K_r \) are the coefficients of the controller, \( \omega_0 \) and \( \omega_c \) are resonance and cut-off angular frequencies respectively. The amplitude frequency characteristic diagram is in figure 5.

![Figure 5. the Amplitude-frequency characteristic diagram of quasi-PR](image)

The quasi-PR controller can track the fundamental frequency signal.

4. Matlab Experiment Results

To verify the effectiveness of the active power-decoupling method in this paper, we use matlab/Simulink to build a model of single-phase FACTS Device. And the simulation parameters are listed in Table 1.

| Table 1. Simulation parameters |
|--------------------------------|
| Grid voltage \( U_s \)        | 220V(50Hz) |
| Grid current \( I_s \)         | 20A        |
| DC voltage \( U_{dc} \)        | 400V       |
| DC capacitance \( C_{dc} \)    | 50μF       |
| AC capacitance \( C_{ac} \)    | 300μF      |
Filter \( L_1 = L_2 = L_3 = L \) = 0.4mH

Switching frequency = 6KHz

If the \( \Delta U_{dc} \) is 5\% of \( U_{dc} \), the DC capacitance is 1.7mF by (1) in conventional single-phase H-bridge. In order to transform the 2-\( \omega \) ripple energy from DC side to AC side completely, the capacitance of \( C_{ac} \) is 289\( \mu \)F by (9). We designed \( C_{ac} \) to be 300\( \mu \)F in simulation. And the capacitor in DC side can be only used to filter the switching harmonic, then the capacitance of \( C_{dc} \) is 50\( \mu \)F [22]. In this paper, the total capacitance is 350\( \mu \)F, is 1/7 in conventional single-phase H-bridge. If the allowed DC voltage ripple is less, the capacitance ratio between the method in this paper and conventional single-phase H-bridge will be less.

Three filter inductance \( L_1 \), \( L_2 \) and \( L_3 \), if allowed the currents (including \( i_s \) and \( i_{Cac} \)) ripple is 20\%, is set to be 0.4mH.

Figure 6 and figure 7 show the results of grid current and AC capacitor when the controlling angle \( j = 90^\circ \), like the variable capacitor. figure 8 and figure 9 show the results of grid current and AC capacitor when the controlling angle \( j = 0^\circ \), like the variable resistor. figure 10 and figure 11 show the results of grid current and AC capacitor when the controlling angle \( j = -90^\circ \), like the variable inductor. And figure 11 shows the results of voltage in DC side.

The dynamics time of grid current is about 0.002s in figure 6, figure 8 and figure 10. The dynamics time of AC voltage and current are about 0.1s in figure 7, figure 9, and figure 11. And the dynamics time of DC voltage is about 0.02s in figure 12.
5. Conclusion
An active power-decoupling method for single-phase FACTS device is studied. The topology in this paper is simplest in references. AC capacitor can be used to absorb the 2-ω ripple energy, and DC ones can be used to absorb the switching frequency. Then the capacitors will sharp fall, so the electronic capacitor in conventional H-bridge can be replaced by the film ones. Therefor the volume of FACS’s device is reduced in this paper. The simulation results have verified the feasibility of the topology and control method.

Acknowledgments
This paper is sponsored by Engineering Research Centre for Metallurgical Automation and Detecting Technology of Ministry of Education, Wuhan University of Science and Technology.

References
[1] Cao, D., Jiang, S., Peng, F. Z., and Li, Y. (2012) Low cost transformer isolated boost half-bridge micro-inverter for single-phase grid-connected photovoltaic system. In: Proc. IEEE 27th Annu. Appl. Power Electron. Conf. Expo. Orlando, FL. pp. 71–78.
[2] Chen, R. R., Liu, Y. T., and Peng, F. Z. (2017) A solid State Variable Capacitor With Minimum Capacitor. J. IEEE Trans. Power Electronics. 32: 5035–5044.
[3] Liu, Y. T., and Peng, F. Z. (2017) Real DC Capacitor-less Active Capacitors. In: Proc. IEEE 28th Annu. Appl. Power Electron. Conf. Expo. Tampa, FL. pp. 44-51.
[4] Akagi, H., Inoue S., and Yoshii T. (2007) Control and performance of a transformerless Cascade PWM STATCOM with star configuration, J. IEEE Trans. Ind. Appl. 43: 1041–1049.
[5] Yiqiao, L. and Nwankpa, C. O. (1999) A new type of STATCOM based on cascading voltage-source inverters with phase-shifted unipolar SPWM, J. IEEE Trans. Ind. Appl. 35: 1118–1123.
[6] Krein, P. T., Balog, R. S., and Mirjafari, M. (2012) Minimum energy and capacitance
requirements for single-phase inverters and rectifiers using a ripple port, J. IEEE Trans. Power Electron. 27: pp. 4690–4698.

[7] Shimizu, T., Jin, Y., and Kimura, G. (2000) DC ripple current reduction on a single-phase PWM voltage-source rectifier, J. IEEE Trans. Ind. Appl. 36: 1419–1429.

[8] Tsuno, K., Shimizu, T., Wada, K., and Ishii, K. (2004) Optimization of the DC ripple energy compensating circuit on a single-phase voltage source PWM rectifier. In: Proc. Power Electron. Spec. Conf. Aachen. pp. 316–321.

[9] Wang, R., Wang, F., Boroyevich, D., Ning, P., and Lai, R. (2011) A high power density single-phase PWM rectifier with active ripple energy storage, J. IEEE Trans. Power Electron. 26: 1430–1443.

[10] Wang, R., Wang, F., Lai, R., Ning, P., and Burgos, R. (2009) Study of energy storage capacitor reduction for single phase PWM rectifier. In: Proc. 24th Annu. Power Electron. Conf. Washington, DC. pp. 1177–1183.

[11] Chao, K. H., Cheng, P. T., and Shimizu, T. (2009) New control methods for single phase PWM regenerative rectifier with power decoupling function. In: Proc. Int. Conf. Power Electron. Drive Syst. Taipei. pp. 1091–1096.

[12] Harb, S., and Balog, R. S. (2013) Single-phase PWM rectifier with power decoupling ripple-port for double-line-frequency ripple cancellation. In: Proc. IEEE 28th Annu. Appl. Power Electron. Conf. Expo. Long Beach, CA. pp. 1025–1029.

[13] Li, H., Zhang, K., Zhao, H., Fan, S., and Xiong, J. (2014) Active power decoupling for high-power single-phase PWM rectifiers, J. IEEE Trans. Power Electron. 28: 1308–1319.

[14] Liang, S., Lu, X., Chen, R., Liu, Y., Zhang S., and Peng, F. Z. (2014) A solid state Variable Capacitor with minimum DC capacitance. In: Proc. IEEE 29th Annu. Appl. Power Electron. Conf. Expo. Fort Worth, TX. pp. 3496–3501.

[15] Fan, S., Xue, Y., and Zhang K. (2012) A novel active power decoupling method for single-phase photovoltaic or energy storage applications. In: Proc. IEEE Energy Convers. Congr. Expo. Raleigh, NC. pp 54–59.

[16] Bush C. R., and Wang, B. (2009) A single-phase current source solar inverter with reduced-size DC link. In: Proc. IEEE Energy Convers. Congr. Expo. San Jose, CA. pp 2439–2446.

[17] Hu, H., Harb, S., Kutkut, N., Batarseh, I., Shen, Z. J. (2010) Power decoupling techniques for micro-inverters in PV systems—A review. In: Proc. IEEE Energy Convers. Congr. Expo. Atlanta, GA. pp. 3235–3240.

[18] Kyrritis, A. C., Papanikolau N. P., and Tatakis, E. C. (2007) A novel parallel active filter for current pulsation smoothing on single stage grid-connected AC-PV modules. In: Proc. Eur. Conf. Power Electron. Appl. Aalborg, Denmark. pp. 1–10, Jan.

[19] Liu, X., Wang, P., Loh, P. C. (2011) Six switches solution for single-phase AC/DC/AC converter with capability of second-order power mitigation in DC-link capacitor. In: Proc. IEEE Energy Convers. Congr. Expo. pp. 1368–1375.

[20] Blaabjerg, F., Neacsu, D. O., and Pedersen, J. K. (1999) Adaptive SVM to compensate DC-link voltage ripple for four-switch three-phase voltage-source inverters, J. IEEE Trans. Power Electron. 14: 743–752.

[21] Kiefersdorf, F. D., Forster, M., and Lipo, T. A. (2004) Reduction of DC-bus capacitor ripple current with PAM/PWM converter. J. IEEE Trans. Ind. Appl. 40: 607–614.

[22] Lu, X. and Peng, F. Z. (2012) Theoretical analysis of DC link capacitor current ripple reduction in the HEV DC-DC converter and inverter system using a carrier modulation method. In: Proc. IEEE Energy Convers. Congr. Expo. Raleigh, NC. pp. 2833–2839.