Comprehensive Compensation Strategy on the Power Quality of Micro-grid Integration Based on the Multifunctional Energy Storage Converter

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Abstract. In order to improve the utilization rate of the energy storage system as well as the power quality of micro-grid and grid under parallel operations, this paper proposed an integrated compensation strategy of power quality based on the composite controlling principle of frequency division and hysteresis loops. On the premise of not changing the operation state of the power conversion system (PCS), combined with the current generation principle of multi-objective compensation, use the residual capacity of PCS to compensate harmonic, reactive and unbalanced currents quickly, accurately and selectively, so as to realize the current control on the compensation component of the grid-connected current under the disturbance of the distorted voltage. At the same time, aiming at the dwarf-signal dynamic models of the converter, use the designed output current control loop based on $H_\infty$ resonance control theories to provide the tuning basis of the controller parameters, and thus the anti-disturbance ability of the system is improved, and the sudden change of the frequency is reduced. Finally, construct a micro-grid system with energy storage devices, and carry out experiments on the proposed control strategies. The results show that it has well governance abilities on the power quality.

1. Introduction
With the rapid development of economy, the energy crisis is becoming more and more serious, and the environment has also suffered unprecedented pollution[1]. At present, renewable energy instead of traditional fossil energy for power generation has become the main development direction. At the same time, in the utilization of distributed renewable energy, micro-grid technology plays an important role, the main characteristics of which different from traditional power generation is that the randomness and intermittence of distributed generation (such as wind and light) will affect the security and stability of the micro-grid. In recent years, increasing energy storage devices in micro-grid systems has become an important link to solve these problems[2-3]. Therefore, it is necessary to promote relevant technologies actively so as to better serve the micro-grid and distribution network as well as promote the efficient integration of the system[4].

The output power quality of the micro-grid energy storage converter is mainly affected by its current control strategies. According to the basic goal of the grid-connected current, on the premise that the output current can track the reference input accurately, the transient tracking time should be reduced as
much as possible to achieve accurate and fast-control requirements[5]. The micro-grid itself has many limitations, such as the small amount of electricity it can hold and the weak inertia. At the same time, the application of the controlling strategies such as droop control[6], load non-linearity, unbalanced sudden change, etc is added. Compared with the large power grid, the problems of power quality problems such as current harmonics, three-phase voltage imbalance, voltage sag and frequency drift fluctuation in micro-grid are more prominent[7-8]. Therefore, one of the important aspects for current domestic and foreign scholars to research is to use advanced control strategies in the case of power quality degradation, so that the converter can still maintain the grid connected output effectively and have good performance.

The multi-functional grid-connected inverter ensures the power output, and at the same time, has compensation functions on the power quality. The common advanced controlling strategies include fuzzy control[9], hierarchical control[10], frequency division control[11] and proportional resonance control[12]. Among them, the robustness of fuzzy control is strong, which is applicable to the secondary correction on charging and discharging instructions of the energy storage system, but the rules on the establishment of models are complicated; hierarchical control puts the voltage error compensation loop in the two-layer control of the micro-grid, the fault tolerance of which is strong, but has the disadvantages of slow convergence speed and large amount of calculation; the frequency division control can realize zero steady-state error of specific frequency components, however, the influence of the grid-connection frequency as well as the stability of the system is ignored; the proportional resonant controller is easy to be ex-tended to the harmonic suppression, but the process of discretization is complicated, and the controlling effects are related to discretization methods; if the traditional PI control is adopted, the structure is simple, and the feasibility is strong, but the parameters that need to be sorted out are sensitive, the defects of overshooting time and amount are existed, and it is not easy to achieve ideal controlling effects.

In summary, in order to realize the comprehensive control of harmonics, reactive power and three-phase unbalanced current of micro-grid by PCS, firstly, based on the realization of output harmonic current detection, this paper proposed a comprehensive compensation strategy on power quality for output stage based on the compound control of frequency division-hysteresis to improve the compensation response speed and realize error tracking on the zero steady state at the same time; secondly, in order to further improve the anti-disturbance abilities of the system and reduce the sudden change of frequency, the tuning basis of the controller parameters is provided based on the $H_\infty$ resonance control theories, finally, under the micro-grid grid-connected operations, the effective-ness of the proposed controlling strategies is verified to improve the power quality.

2. Generation Method for PCS Multi-Objective Compensation Current

2.1. Value detection for the multi-objective compensation current

This paper adopts the harmonic current detection method based on instantaneous power theories, using Clarke (Cabc-αβ) transformation, transform the voltage ua, ub and uc into α-β two-phase static coordinate system, then extract the basic principle by fundamental waves and filter out the harmonic wave. After d-q transformation, the fundamental DC component is

$$
\begin{align*}
\begin{bmatrix}
u_{\text{d}-\text{dc}}^f \\
u_{\text{q}-\text{dc}}^f
\end{bmatrix}
= \frac{3}{2}U_f \begin{bmatrix}
\cos(-\theta_f) \\
\sin(-\theta_f)
\end{bmatrix}
\end{align*}
$$

where $u_{\text{d}-\text{dc}}$ and $u_{\text{q}-\text{dc}}$ are the DC components of the fundamental voltage on the dq-axis, $U_f$ is the fundamental voltage amplitude.

From formula (1), we can get $u_{\text{d}-\text{dc}}/u_{\text{q}-\text{dc}} = \arctan(-\theta_f)$, then, by solving the arc-tangent, we can get $\theta_f$, after that, the fundamental voltage DC component on the α-β axis can be obtained by Park
inverse transformation of ufα-dc and ufβ-d, the DC component of the fundamental voltage on the α-β axis can be obtained:

$$
\begin{bmatrix}
u_{α-dc}^f \\
v_{β-dc}^f
\end{bmatrix} = \begin{bmatrix}
\frac{3}{\sqrt{2}}U_f \\
-\sin(ω_f t + θ_f)
\end{bmatrix}
$$

(2)

During the transformation from the α-β coordinate system to the d-q coordinate system, the sine and cosine of the synchronous rotation angle $ωot+θf$ can be directly expressed by voltages ufα-dc and ufβ-dc:

$$
\begin{bmatrix}
\sin(ω_f t + θ_f) \\
\cos(ω_f t + θ_f)
\end{bmatrix} = \frac{
u_{α-dc}^f}{\sqrt{(\nu_{α-dc}^f)^2 + (\nu_{β-dc}^f)^2}}
$$

(3)

Let t1 be the certain sampling time, t2 is the next time after t1, that is, $t_2 = t_1 + 1/fs$, fs is the sampling frequency. When the whole detection circuit is in steady-state operations, ignore the inherent delay of the low-pass filter (LPF), then we have

$$
\cos(ω_f / f_s) = \cos(ω_f (t_2 - t_1)) = \cos(ω_f t_2 + θ_f)\cos(ω_f t_1 + θ_f) + \sin(ω_f t_2 + θ_f)\sin(ω_f t_1 + θ_f)
$$

(4)

The whole detection principle of the harmonic current is shown in Figure 1. After the voltage signal is transformed, the fundamental components of the voltage signal are converted into two parts: DC and harmonic AC. The accurate initial phase $θ_0$ and system frequency $ω_0$ can be obtained. At the same time, $i_α$ and $i_β$ are the active current id and reactive current iq which are changed from Park to the DC form, and the unbalanced current and harmonic contained in it are also reflected in id and iq. Then, use LPF to filter out the harmonic waves, the active current id-dc and reactive current iq-dc. The fundamental active current $i_αh$ and $i_βh$ are obtained by the Park inverse transformation, and then subtract $i_αh$ and $i_βh$ from $i_α$ and $i_β$. The compensation current $Δi_{αβ}$ is composed of reactive power, harmonic waves and unbalanced fundamental waves.

2.2. Composite control method of PCS

The schematic diagram of PCS composite controlling method proposed in this paper is shown in Figure 2, which includes frequency division control and hysteresis control. At the same time, set a switch selection function to realize the switching between them: the harmonic current error of PCS is small when the micro-grid is running in the grid-connected state, in order to further eliminate the error, use the advantage of small steady-state errors for the frequency division control to realize the zero error.
control of the current. On the contrary, when the tracking error is large, use the hysteresis control to improve the tracking speed.

\[ I_{err_{abc}} = I_{*_{abc}} - I_{Labc} \]  

(5)

Set the ring width as constant H, then the principle of the compound control strategy is as follows: when \(|I_{err}| > H\), use the hysteresis control, pass the error signal \(I_{err}\) through the hysteresis comparator with the fixed ring width \(H\) to obtain the PWM signal. Drive the switch tube to control the output current within the limited positive and negative ring width (±H), as shown in Figure 3. \(I_{err}^+\) and \(I_{err}^-\) represent the increase and decrease of the tracking error, respectively.

When \(|I_{err}| < H\), use the frequency division control. After the current tracking error signal \(I_{err}\) passes through the frequency division controller, generate the PWM signal by the PWM technology to control PCS. Adopt the CPI control mode for the frequency division control, that is to say, transform the vector proportional integral (VPI) control equivalently by the formula \(f_{abc} = f_{dqe-jot}\).

In the above formulas, \(\tau_p\) and \(\tau_i\) are proportional and integral coefficient respectively. By comparing VPI with CPI, it can be seen that there are coupling relationships between VPI control proportion \(\tau_p\) and \(j\omega\tau_p/s\) in (7), resulting in the difficulties to realize the single response control of the system. In order to improve the response ability, parallel the proportional control items \(\tau_{po}\) on the basis of the CPI control. After the parallel connection, the expression is as follows:

\[ G_{PCPI}(s) = \frac{\tau_p s^2 + \tau_i s}{s^2 + \omega_p^2} \]  

(6)

\[ G_{VPI}(s) = \frac{\tau_p s^2 + \tau_i s}{s^2 + \omega_p^2} \]  

(7)

\[ G_{CPI}(s) = \frac{\tau_p s + \tau_i s}{s} \]  

(7)

In the above formulas, \(\tau_p\) and \(\tau_i\) are proportional and integral coefficient respectively. By comparing VPI with CPI, it can be seen that there are coupling relationships between VPI control proportion \(\tau_p\) and \(j\omega\tau_p/s\) in (7), resulting in the difficulties to realize the single response control of the system. In order to improve the response ability, parallel the proportional control items \(\tau_{po}\) on the basis of the CPI control. After the parallel connection, the expression is as follows:

\[ G_{PCPI}(s) = \tau_{po} + \frac{\tau_p s + \tau_i s + j\omega\tau_p}{s} \]  

(8)

Transform the expression (8) in the rotating d-q coordinate system into the two-phase stationary \(\alpha-\beta\) coordinate system, and obtain expression (9):

\[ G_{PVPI}(s) = G_{PCPI}(s + j\omega_o) = \tau_{po} + \frac{\tau_p s + \tau_i}{s - j\omega_o} \]  

(9)

Formula (9) is one of the proportional resonant controllers. PVPI is composed of the proportional control \(P\) and the VPI control in parallel. In the controlling process, the dynamic performance can be adjusted independently by changing the proportional term \(\tau_{po}\), which improves the response.
performance of the VPI control for the PCS. Therefore, the algorithm of the frequency division control is as follows:

\[ U_{PVPI}(s) = I_{err}(s) \sum_{i=1}^{N} G_{PVPI}(s) = I_{err}(s) \left[ \sum_{i=1}^{N} \left( \tau_{ip} + \frac{\tau_{iu}}{s - j\omega_0} \right) \right] \]  

(10)

The trigger pulse of switching devices UPVPI(s) can be generated by modulating the output of the frequency division control and triangular waves. The comprehensive compensation current of the distribution network response can be injected through the composite control method of PCS, so as to improve the power quality accurately and rapidly.

2.3. Parameter design of adaptive PVPI based on the \( H_{\infty} \) theories

Due to the existence of non-linear, unbalanced sensitive load and other random disturbance factors, the composite control also requires PCS to output the grid-connected frequency modulation \( fr \) and maintain the stability of the DC bus voltage \( u_{dc} \). Therefore, introduce the PVPI adaptive controller based on \( H_{\infty} \) theories, and give the tuning basis of the relevant parameters. The specific designing method is as follows:

Derive the small signal modeling method of voltage loop, current loop, droop controller and filter circuit according to reference. In addition, \( \Delta \) represents the small signal under the stable operation of PCS, and the subscript \( N \) represents the rated value, \( u_{err\_dc} = u_{dc\_N} - u_{dc} \). The small signal model of PCS is deduced as follows:

\[ \Delta u_{dc} = \frac{k_p f_{rN}}{C_{u_{dc}}} + k_u u_{dc} \Delta f_r - k_u \Delta u_{dcN} \]  

(11)

\[ \Delta f_r = -\frac{3k_p f_{rN}}{f_r} + k_u u_{dc\_N} \Delta f_r - k_u \Delta u_{dcN} \]  

(12)

In the above formulas, \( k_p \) and \( k_u \) are frequency and voltage sag coefficient respectively, \( dL \) and \( P_{loss} \) are load disturbance and grid connected power shortage respectively. C is the PCS capacitance and P is the integral operator. Based on formulas (11) and (12), select the state variables \( x = [\Delta u_{dc\_N} u_{err\_dc} \Delta f] \), disturbance variable \( \lambda = [\Delta dL \ \Delta Perr] \), input variable \( \mu = \Delta u_{dc\_N} \), then the state equation of the PCS converter is as follows:

\[ \Delta x = A_1 x + B_{11} \lambda + B_{12} \mu \]  

(13)

In the formula,

\[ A_1 = \begin{bmatrix} k_p f_{rN}^2 + k_u u_{dc} & 0 & 0 \\ 0 & 0 & -1 \\ 3k_p f_{rN}^2 + k_u u_{dc} & \tau_i \end{bmatrix} C_{u_{dc}} \]

\[ B_{11} = \begin{bmatrix} 0 \\ 1/f_r \\ 1/f_r \end{bmatrix} \]

\[ B_{12} = \begin{bmatrix} 0 \\ 0 \\ -k_u \end{bmatrix} \]

The output variable \( y = \Delta Perr \), \( Perr = Pb - P_{loss} \) is the deviation of the grid-connected power, \( Pb \) is the energy storage output power, then the PCS output equation is

\[ y = C_{11} x + D_{11} \lambda + D_{12} \mu \]  

(14)

where \( C_{11} = [0 \ \tau_i \ \tau_i] \); \( D_{11} = [0 \ -1] \); \( D_{12} = \tau_i \).

Therefore, the transfer function on the input and output of the system is

\[ \begin{bmatrix} \Delta x \\ y \end{bmatrix} = \begin{bmatrix} A_1 & B_{11} & B_{12} \\ 0 & C_{11} & D_{11} \end{bmatrix} \begin{bmatrix} x \\ \lambda \\ \mu \end{bmatrix} \]  

(15)
As shown in Figure 4, ΔPerr obtains the system frequency deviation Δferr through the transfer function Bg(s), and obtains the DC bus voltage estimation value ΔBds through W(s). According to the definition of norm $\|H(s)\|_\infty$, we have

$$\|G(s)S(s)\|_\infty = \|G(s)[1-W(s)B_g(s)]\|_\infty = \sup_{\text{Res}>0} |G(s)[1-W(s)B_g(s)]|$$

(16)

According to the maximum modulus theorem, the following formula holds for all W(s):

$$\|G(s)[1-W(s)B_g(s)]\|_\infty \geq 0$$

(17)

At the same time, in order to ensure the internal stability and realizability of the system, the constraints that W(s) should satisfy are:

1. W(s) is stable and regular;
2. $\lim_{s \to 0} S(s) = \lim_{s \to 0} [1-W(s)B_g(s)] = 0$

Because W(s) is often irregular, in order to obtain more accurate Δudc, it is necessary to add a low-pass filter J(s) to attenuate the high frequency:

$$J(s) = \beta_0 \frac{(1+s)}{s^2}$$

(18)

In the above formula, $\beta_0$ is a constant, and 1 represents the performance of the closed-loop system. To satisfy the system asymptotic tracking constraint,

$$\lim_{s \to 0} [1-W(s)B_g(s)J(s)] = 0$$

(19)

Carry out the tests by the MATLAB HINFSYN function toolbox, select $\beta_0=0.6, 1=0.02$, generate the optimal $W_{\text{opt}}(s)$:

$$W_{\text{opt}}(s) = \frac{256.4\omega_g s}{s^2 + 17.4\omega_g \omega_0 s + 6.64\omega_g^2}$$

(20)

In the above formula, $\omega_0$ is the natural resonance frequency, and $\xi_0$ is the damping ratio. The larger $\xi_0$ is, the smaller the frequency overshoot of the system is, and the better the stability is. On the contrary, the system gain near $\xi_0$ is larger. Then, according to formulas (9) and (16), select the appropriate PT parameters $\tau_p$ and $\tau_i$ to minimize

$$\|G(s)S(s)\|_\infty = \|G(s)[1-W_{\text{opt}}(s)B_g(s)]\|_\infty = 0$$

(21)

3. Experimental Verification

Use MATLAB/Simulink to establish the micro-grid structure diagram which is composed of micro power supplies, energy storage and load, as shown in Figure 5. On this basis, the experimental platform as is shown in Figure 6 is built to verify the control strategy of the energy storage converter proposed in this paper. The micro-grid is connected with the distribution network, and PQ control is adopted for wind and photo-voltaic interface converters.
3.1. Experimental analysis of harmonic and reactive power compensations

As shown in Figure 7, according to the upper scheduling instructions, the output current waveform of the battery energy storage system before and after the PCS participates in the power quality compensation. The frequency division controller can perform frequency division control compensations for the specific number of the harmonic waves, and the harmonic currents of 5 times, 7 times and other specific times detected based on the instantaneous power theories are controlled by the corresponding times of the resonance adjustment in the controller. The suppression effects of the wave current is shown in Figure 8. It can be clearly found that PCS can compensate the harmonic current of different times selectively, and the effects are obvious.

Figure 8 shows the voltage and current phase waveforms before and after the reactive power compensations. The energy storage device participates in the compensation after 2.515s. It can be seen that the phase difference between the voltage and current after compensation is significantly improved compared with that before, and the power factor is close to 1, which effectively realizes the reactive power compensations. Figure 9 shows the wave-forms before and after the compensations of the three-phase unbalanced current. It can be seen that the unbalanced current output from the micro-grid to the distribution network is eliminated by using the controller proposed in this paper. At the same time, it can be seen from Figure 8 and Figure 9 that after PCS is put into operations, the overshoot is small, and the regulation performance of the compensation system is fast.
3.2. Experimental analysis on the stability of the system
In addition, when the micro-grid is in the grid-connected state, the voltage and frequency are supported of the system by the grid. However, due to the changes of the wind speed, wind direction, illumination intensity and illumination angle, the prediction of the output power for the distributed generation system will produce certain deviations. At the same time, considering the sudden changes of the grid-side loads, the frequency of grid-connection will fluctuate slightly, as shown in Figure 10.

![Figure 10. Frequency diagram of micro-grid in grid-connected operations.](image)

4. Concluding Remarks
In this paper, the new control strategies of PCS in the micro-grid is studied in details, which provides a new research idea for improving the power quality of the micro-grid under grid-connected operations. The conclusions are as follows:

1) Aiming at the disturbance characteristics of non-linear and unbalanced sensitive loads in the micro-grid, the detection and generation principle of the compensated currents are given, and comprehensive compensation strategies for PCS based on the controlling of frequency division-hysteresis is proposed. The multi-controlling objectives on the reactive power compensation of output stage, the current balance and sine curves are realized, and the tracking accuracy is high;

2) On this basis, the resonant controller based on $H\infty$ theories is further designed, the parameters of PVPI are adjusted, the input and output power of the PCS are optimized, the anti-interference performances are improved, and the dynamic compensation control of the operating frequency is realized.

3) The next step is to expand on the basis of the existing experimental conditions, and carry out qualitative analysis and capacity evaluation re-search on improving the efficiency of the micro-grid by functional reuses of energy storage devices.

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