Adaptive Command Current Observation Algorithm of UPQC on Experimental Microgrid

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Abstract: The experimental microgrid is developed to test the feasibility of different source-network-load matching microgrid structures. The different combinations of distributed energy and loads put forward higher requirements for the accuracy and adaptive ability of power quality management. In this paper, the unified power quality regulator (UPQC) was used to control the power quality and a control strategy with adaptive ability to disturbance of the microgrid models was proposed. On the one hand, the adaptive observer was designed to detect the compensation current signal, which reduced the influence of voltage harmonic components on the compensation current detection accuracy while reducing the amount of observation calculation. On the other hand, aimed at the slow response of traditional PID to DC voltage fluctuation of inverters and thus affecting the accuracy of current observation, the nonlinear variable domain fuzzy controller, which can modify the fuzzy expansion factor online, was adopted to improve the real-time performance of the control. The algorithm was simulated in MATLAB platform, and the results verified the effectiveness of the control strategy.

1. Introduction
The experimental microgrid presents different power quality problems in different matching modes [1-2], and UPQC is a device that can comprehensively compensate for power quality problems such as grid voltage, current harmonics, and flicker. The UPQC device in reference [3] was located at the parallel point of the microgrid. The structure adopted the voltage series compensation module and the current parallel compensation module. The PCC terminal voltage distortion and load current harmonics at the parallel point were well compensated. The innovation of reference [4] lay in its topological structure. It adopted three-phase four-arm structure, which can compensate voltage and current comprehensively. The scheme used super-capacitor as energy storage device on DC side. This scheme effectively solved the power pulsation problem of microgrid relatively. Aimed at the change of operation conditions of microgrid, the influence of different UPQC access capacity on harmonic control effect was studied by Han B M [5]. Advanced predictive control theory was introduced into UPQC in reference [6], which combined traditional command current detection algorithm with adaptive prediction algorithm to improve the real-time performance of UPQC system compensation current detection.

Aimed at the low accuracy of current compensation in UPQC system of AC/DC hybrid microgrid, this paper focuses on the detection of instruction current signal and the control strategy of DC side voltage. A method of instruction current detection was proposed, which combined instantaneous reactive power theory with adaptive observation algorithm. To solve the problem of DC voltage fluctuation
affecting current observation accuracy, a variable universe fuzzy control structure was proposed, which can effectively reduce DC terminal voltage fluctuation caused by the moving of working point of distributed power generation.

2. UPQC Model of AC / DC Hybrid Microgrid

2.1 UPQC System Structure of AC / DC Hybrid Microgrid

The power quality of AC/DC hybrid microgrid is affected by voltage fluctuation of distribution network, AC and DC microgrid, as well as various non-linear and unbalanced loads. The structure block diagram of AC/DC hybrid microgrid with UPQC compensation structure is shown in Figure 1.

![Figure 1. Structure block diagram of AC / DC hybrid microgrid with UPQC compensation structure](image)

In the simulation, the traditional instantaneous reactive power detection method was used to detect the instruction voltage of the series compensation unit. The triangular wave comparison method was used to generate the PWM signal for the series compensation unit, and the hysteresis comparative control method was used to generate the PWM pulse for the parallel compensation unit.

2.2 UPQC Mathematical Modeling

The UPQC series and parallel converters are all three-phase full-bridge inverters. The mathematical model of UPQC series side is [1]:

\[
\begin{align*}
C_1 \frac{du_{a2}}{dt} & = i_{a1} - i_{a3} = m_{a1} - i_{a3} \\
C_1 \frac{du_{b2}}{dt} & = i_{b1} - i_{b3} = m_{b1} - i_{b3} \\
C_1 \frac{du_{c2}}{dt} & = i_{c1} - i_{c3} = m_{c1} - i_{c3} \\
L_1 \frac{di_{a1}}{dt} & + i_{a1} R_1 + \frac{1}{3} U_a (S_{a1} + S_{b1} + S_{c1}) - u_{a2} = 0 \\
L_1 \frac{di_{b1}}{dt} & + i_{b1} R_1 + \frac{1}{3} U_a (S_{a1} - 2S_{b1} + S_{c1}) - u_{b2} = 0 \\
L_1 \frac{di_{c1}}{dt} & + i_{c1} R_1 + \frac{1}{3} U_a (S_{a1} + S_{b1} - 2S_{c1}) - u_{c2} = 0
\end{align*}
\]

Among them: \(u_{a2}\) and \(i_{a2}\) are the three-phase voltage of the secondary side of the transformer connected in series with the grid and the secondary current of the transformer. \(i_{a1}\), \(i_{a3}\) and \(i_{c1}\) are the inflow current of the series side, the three-phase current of the grid terminal and the inflow current of the inverter on the series side. \(U_a\), \(R_1\), \(L_1\) and \(C_1\) are DC terminal voltage, series side line resistance, filter inductor and capacitor. The mathematical model of the parallel side of the UPQC is:
\[ \begin{align*}
L_e \frac{di_{ac}}{dt} + i_{ac} R_e + \frac{1}{3} U_e (-2S_{a1} + S_{b1} + S_{c1}) + u_{ac} &= 0 \\
L_e \frac{di_{bc}}{dt} + i_{bc} R_e + \frac{1}{3} U_e (S_{a1} - 2S_{b1} + S_{c1}) + u_{bc} &= 0 \\
L_e \frac{di_{ca}}{dt} + i_{ca} R_e + \frac{1}{3} U_e (S_{a1} + S_{b1} - 2S_{c1}) + u_{ca} &= 0 
\end{align*} \] (3)

\[ \begin{align*}
C_e \frac{di_{ac}}{dt} &= i_{ac} + i_{ac2} - i_{a1} \\
C_e \frac{di_{bc}}{dt} &= i_{bc} + i_{bc2} - i_{b1} \\
C_e \frac{di_{ca}}{dt} &= i_{ca} + i_{ca2} - i_{c1} 
\end{align*} \] (4)

\[ \begin{align*}
i_{dc} &= C_{dc} \frac{dU_{dc}}{dt} = i_{dc1} - i_{dc2} 
\end{align*} \] (5)

Among them: \( u_{ac}, i_{ac} \), are load terminal three-phase voltage, load current and the parallel side inverter inflow current. \( R_e, L_e \) and \( C_e \) are the parallel side line resistance, filter inductor and capacitor, and \( C_{dc} \) is the DC terminal capacitor. \( i_{ac}, i_{bc} \) and \( i_{ca} \) respectively are total current flowing into the storage capacitor, branch current of the series and parallel units flowing into the DC storage capacitor. The relationship between the \( i_{ac}, i_{bc} \) and the three-phase compensation current is expressed as follows:

\[ \begin{align*}
\left\{ \begin{array}{l}
i_{ac1} = i_{ac1} S_{a1} + i_{bc1} S_{b1} + i_{ca1} S_{c1} \\
i_{ac2} = i_{ac2} S_{a2} + i_{bc2} S_{b2} + i_{ca2} S_{c2}
\end{array} \right. 
\] (6)

The resulting mathematical model of the current of the DC energy storage unit is:

\[ i_{dc} = C_{dc} \frac{dU_{dc}}{dt} = (i_{ac1} S_{a1} + i_{bc1} S_{b1} + i_{ca1} S_{c1}) - (i_{ac2} S_{a2} + i_{bc2} S_{b2} + i_{ca2} S_{c2}) \] (7)

3. Command current detection based on adaptive observation algorithm

The existence of voltage transient signal in current detection algorithm makes the current detection accuracy affected by distorted voltage. The adaptive observation algorithm changes the instantaneous value of the voltage to the voltage integral value, thereby reducing the influence of abrupt voltage signal on the current detection accuracy.

The difference between the load current and the fundamental active current is the sum of the fundamental reactive current and the harmonic current, The product of the fundamental voltage of the grid and the sum of the reactive current and the harmonic current has an integral of zero over a period\(^{14}\). Take the phase a as an example:

\[ i_{aL} - i_{aP} = i_{aL0} + i_{ah} \] (8)

\[ \int_{0}^{T} u_{ma} (i_{ma} + i_{mah}) \, dt = 0 \Rightarrow \int_{0}^{T} u_{ma} (i_{ma} + i_{mah}) \, dt = \int_{0}^{T} u_{ma} (i_{ma} - i_{aP}) \, dt = 0 \] (9)

Since the \( i_{aP} \) and \( u_{ma} \) have the same phase and frequency, \( i_{aP} \) can be expressed as \( i_{aP} = k \cdot u_{ma} \):

\[ \int_{0}^{T} u_{ma} (i_{ma} + i_{mah}) \, dt = \int_{0}^{T} u_{ma} i_{ma} \, dt - k \int_{0}^{T} u_{ma}^2 \, dt \]

\[ k = k + \alpha u_{a} \] (12)

\( \alpha \) is the correction rate coefficient and \( u_{a} \) is the output of the adaptive link. The adaptive observer takes the integral value of equation (9) as input, and the output of the adaptive link determines the dynamic correction value of the proportional coefficient k. If the integral value is less than 0, decrease k. If the integral value is greater than 0, increase k until the system is stable at the integral value of 0 to obtain a stable command current signal.
4. Design of Variable Universe Fuzzy Controller for Energy Storage Side Voltage

In order to solve the problem that the DC terminal voltage PID controller is slow in response and is easily affected by system parameter changes, a variable universe fuzzy controller was introduced into the UPQC DC energy storage voltage stabilizing circuit to replace the traditional PI controller. The structure is shown in Figure 3:

When the DC terminal voltage error e and error change rate ec signals are large, the system enters the coarse adjustment process. At this time, the input universe should be expanded and the output universe unchanged. When e and ec are small, the system enters a fine tuning process, and the input universe and the output universe are both compressed. The variable universe control law was debugged through a large number of simulations, and the input-output scaling factor fuzzy rule table was established. The scaling factors $\alpha_1$ and $\alpha_2$ are quantized into 4 levels according to B, M, S and E, and the corresponding peaks are 1, 0.75, 0.5 and 0.25, respectively. The scaling factor $\beta$ of the control quantity is quantized into 4 grades according to PB, PM, PS and PE, and the corresponding peaks are 0.5, 0.67, 0.83 and 1.

Table 1. The fuzzy rule table of the input variable expansion factor $\alpha_1$

| ec   | NB | NM | NS | Z  | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| NB   | B  | B  | M  | S  | M  | B  | B  |
| NM   | B  | M  | S  | S  | S  | M  | B  |
| NS   | M  | M  | S  | E  | E  | M  | M  |
| Z    | M  | S  | E  | E  | E  | S  | M  |
| PS   | M  | S  | E  | S  | S  | M  | B  |
| PM   | B  | B  | S  | S  | S  | B  | B  |
| PB   | B  | B  | B  | B  | B  | B  | B  |

Table 2. The fuzzy rule table of the input variable expansion factor $\alpha_2$

| ec   | NB | NM | NS | Z  | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| NB   | B  | B  | M  | M  | M  | B  | B  |
| NM   | B  | B  | S  | S  | S  | B  | B  |
| NS   | M  | M  | S  | E  | E  | M  | M  |
| Z    | M  | S  | E  | E  | E  | S  | M  |
| PS   | M  | S  | E  | S  | S  | M  | B  |
| PM   | B  | B  | S  | S  | S  | B  | B  |
| PB   | B  | B  | M  | M  | M  | B  | B  |

Table 3. The fuzzy rule table of the output variable expansion factor $\beta$

| ec   | NB | NM | NS | Z  | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| NB   | PB | PM | PS | PE | PS | PM | PB |
| NM   | PB | PB | PM | PM | PM | PB | PB |
| NS   | PM | PM | PS | PS | PS | PM | PB |
| Z    | PM | PM | PS | PE | PE | PM | PM |
| PS   | PM | PS | PE | PE | PE | PS | PM |
| PM   | PM | PM | PS | PS | PS | PM | PM |

According to the three fuzzy rule tables, a expansion factor fuzzy reasoning device with two inputs
and three outputs was established to realize the online adjustment of the input and output universe of the DC energy storage control system.

5. Simulation results

5.1 Simulation of Adaptive Command Current Observation

The structure of microgrid and compensation network is shown in figure 1. A simulation platform was set up in MATLAB to verify the method studied. The effective value of grid phase voltage is 220V. The values of series side filter circuits $C_1$ and $L_1$ are 1μF and 1mH, while the values of parallel side filter circuits $C_2$ and $L_2$ are 1μF and 2mH. The capacitance capacity of DC side is 0.03F, and its voltage $U_{dc}$ is 700V. The initial value of proportional coefficient $k$ is 0.14, and the correction rate coefficient $\alpha$ is 0.01. After the simulation waveform data was processed and analyzed by FFT Analysis.

![Figure 4. Simulation curve and FFT analysis before and after compensation based on adaptive command current observation](image1)

After using the improved adaptive observation method to detect the command current, the harmonic content of the grid current in the 0.06s-0.10s decreased from 26.15 % to 3.03 %

5.2 Simulation of Voltage Variable Universe Fuzzy Control for Energy Storage Unit

Figure 5 is the DC voltage measurement simulation curve using PID and variable universe fuzzy control. The introduction of nonlinear load simulation results at 0.5s shows that the variable universe fuzzy controller can stabilize the energy storage side voltage to a given value at 0.02s, and the PID controller needs 0.15s under the condition of optimal parameter setting. When the 0.5s nonlinear load was introduced, the DC energy storage terminal voltage of variable universe fuzzy control decreased by 2.8 %, returned to the given value after 0.06s, while the energy storage terminal voltage of PID control decreased by 7.1 %, and it took 0.15s to return to the given value of 700V. Simulation results showed that the variable universe fuzzy controller of DC energy storage side voltage has faster response speed and stronger anti-interference ability than PID control.

![Figure 5. Simulation curve of DC energy storage voltage under two control algorithm](image2)

6. Conclusion

From the simulation results, it can be seen that the adaptive observation algorithm reduced the grid
current THD effectively. The response speed of DC terminal voltage was increased by more than 2 times after adopting the variable universe fuzzy control strategy. The effectiveness of the proposed detection method was verified, and it can be used for power quality control of experimental microgrid.

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