Research on Design and Simulation of Compound Voltage Quality Regulator

Guomin Zhang¹, Xiaoya Zhen¹ and Hongwei Man²

¹Pingdingshan Power Supply Company, at the intersection of Zhannan Road and Xinhua Road, Zhanhe District, Pingdingshan City
²Pingdingshan Electric Power Design Institute Co. Ltd, at east of intersection of Hexie Road and Xiangyun Road, Xinhua District, Pingdingshan City
529930823@qq.com

Abstract. A voltage regulator based on cascaded multi-level structure is proposed. Based on the analysis of its working principle, the voltage quality problems (voltage sag, swell, voltage harmonics, fluctuation, flicker) in the power quality appearing in the distribution network, the main circuit topology, control methods and compensation strategies are proposed. The regulator can compensate for various voltage quality problems. To ensure that the voltage quality is within the rated range, a simulation model of a cascaded multi-level composite voltage regulator is established in the simulation software, and it is verified that the design scheme proposed in this paper can solve various voltage quality problems in the distribution network.

1. Introduction

Voltage quality is an important aspect of power quality. With the increase of sensitive loads such as computer information systems, the requirements for voltage quality are becoming stricter. A 0.1 second voltage dip cannot accurately control the robot arm and cause the entire batch of industrial products to be scrapped. Typical problems caused by voltage quality include: increased motor loss, malfunction of relay device, resonance, aging of insulation equipment, abnormal communication information system, overheat damage of reactive compensation equipment, overheat of neutral line, inaccurate of detection instrument, increased transformer loss.

With the increase of users' sensitive loads in distribution networks and the requirements of sensitive loads for voltage quality, the suppression of voltage fluctuations has gradually become the focus of power quality management. Dynamic voltage restorers can effectively ensure that sensitive loads maintain voltage when the system voltage fluctuates is stable, the principle is to inject the compensation voltage through the series compensation device to ensure that the sensitive load is not affected. At present, a lot of work and experimental research have been carried out on the performance and structure of the voltage regulation device. The voltage regulation device is generally supported by a voltage source, which is provided by an energy storage device or rectified from the grid side. Energy storage equipment mainly has the form of storage battery, mechanical energy storage, etc. The way to obtain energy on the grid side is that the PWM rectifier device obtains a stable DC voltage from the grid side.
Energy storage equipment is expensive, bulky, and uneconomical. The rectification type is directly obtained from the grid side rectification, generally obtained by PWM rectification, which has the advantages of small size and long continuous compensation time. It has been widely used in UPS power supply. DVR (Dynamic Voltage Restorer) has achieved good applications in terms of voltage sag [8]. But most of them are suppression of single problems, and there is no unified solution to the composite compensation of voltage swell, harmonics, flicker and so on [9-13].

This designed multi-level voltage quality regulators is based on various voltage quality problems in the distribution network. Based on the main circuit topology and control strategy, it has simulated various voltage problems (voltage symmetric and asymmetric sag, Swell, harmonic), the simulation results verify that the proposed control strategy and main circuit topology can effectively solve various voltage quality problems in the distribution network.

2. Main circuit topology and working principle

![Figure 1. Circuit topology of the voltage regulator](image)

The circuit of the voltage quality adjustment device includes a PWM rectifier, an energy storage capacitor, a PWM inverter, a low-pass filter, and a protection control system. When the power supply voltage fluctuates, the voltage adjustment device monitors and outputs the command voltage according to the fluctuation category, and compensates on the load side, keep the load voltage constant.

The voltage source PWM inverter is the core part of the device. The PWM inverter is connected in series between the DC voltage stabilizing capacitor and the load, and the output voltage obtained by rectifying the DC voltage is inverted to compensate on the load side, so that the load side is maintained within the rated voltage range.

The voltage regulating device is connected in series between the power supply and the load, and compensates the voltage to the load side according to the voltage fluctuation and the compensation strategy of the device, so that the load side voltage is guaranteed to be within the rated range regardless of whether the system voltage is normal or fluctuating.

Working principle: The monitoring circuit of the voltage regulating device samples the power supply voltage, and when the power supply voltage fluctuates, it outputs a compensation voltage command by controlling the drive circuit; The driving signal is formed through the analog circuit; the driving signal is used to control the opening and closing of the insulated gate bipolar transistor of the PWM inverter. The voltage of the inverter output is eliminated by the low-pass filter and superimposed on the load side voltage, thereby the voltage on the load side is stably controlled within the rated range to achieve the goal of dealing with various voltage quality problems.

3. Control strategy and key parameter design

The circuit of voltage quality adjustment device adopts bridge cascade multilevel structure
3.1. H bridge cascade number and parameter design

Set the voltage sag index: the lowest drop to 10% of the rated voltage, the maximum compensation voltage output by the voltage regulator is 90% of the rated voltage. That is: U_o = 90% U_e.

Choose low voltage 380V, single phase voltage 220V.

The DC bus voltage of a cascade bridge is 250 volts, and the utilization efficiency is 0.8. The number of cascaded H bridges available is

\[ N = \left[ \frac{\sqrt{2} U_{\text{omax}}}{U_{dc} \times k_{dc}} \right] + 1 = 2.7 \]

In order to make the function of the voltage quality adjustment device closer to the high-voltage system, the regulator is designed with four bridges in cascade.

Current selection of H-bridge module:

The rated capacity of the regulator is 100kva, which meets 1.3 times overload for 1 hour, and the rated current can be calculated.

\[ I_N = \frac{\alpha \times P_N}{\sqrt{3} U_N} = 188A \]

Considering a certain margin, choose a current of 300A.

3.2. Parameter design of PWM rectifier

In order to ensure accurate tracking performance of the current input from the grid side of the rectifier, the inductance L needs to meet the following conditions.

\[ L \leq \frac{2U_{dc}}{3 \times I_{m} \omega} = 5.5 \times 10^{-3} \text{H} \]

In addition, the input current distortion of the PWM rectifier must be sufficiently small:

\[ L \geq \frac{(2U_{dc} - E_{m})}{(2U_{dc} \Delta U_{max})} E_{m} T_s = 1.3 \times 10^{-3} \text{H} \]

The value of inductance L should be between 1.3mH and 5.5mH. Considering that the PWM rectification adopts carrier phase shift control, it can increase the equivalent switching frequency of the switch and reduce the switching ripple. Under the same ripple, the reactor takes a quarter of the number of cascade bridges, and considers L to be 0.4mH.

The DC stabilizing capacitor meets:

\[ C_{dc} = \frac{P_h}{\omega U_{dc} \Delta U_{dc}} \]

Among them, Ph is the maximum harmonic power transmitted in a half power frequency period, taking 5% of the total transmission capacity, which is: Ph=0.05P, \( \Delta V_d \),which is the peak ripple voltage, and the voltage fluctuation is 1% of the rated voltage, and the capacitance value can be obtained

\[ C_{dc} = \frac{0.05*100*1000}{2\pi f * 250*250*1%} = 25464\mu F \]

Select a certain output capacitance margin, and based on simulation and actual engineering experience, the final value of the selected capacitor is 26000μF.

3.3. Parameter design of PWM inverter

The PWM inverter cascade bridge unit adopts carrier modulation wave split-phase control.

The carrier frequency of the fundamental modulation is preliminarily determined as the four cascade bridges used in the design of this voltage regulation device, and the switching frequency is equivalent to

\[ f_{\text{equ}} = 12000\text{Hz} \]

The filter cut-off frequency of the PWM inverter is
\[ f_{LC} = \left( \frac{1}{5} ~ \frac{1}{10} \right) f_{equ} = (1200 ~ 2400) \text{Hz} \]

\[ f_{LC} = 1500 \text{Hz} \]

The transfer function of the pair is:

\[ \frac{u_{out}}{u_{in}} = \frac{s L_s + R_s}{s^3 L_C L + s^2 C L R_s + s (L + L_s) + R_s} \]

\[ L_s, R_s \] are the system equivalent inductance value and resistance value.

According to the transmission function, the harmonic output of the low-pass filter is less than or equal to 3%.

\[ \frac{j \omega L_s + R_s}{(j \omega)^3 L_s C L + (j \omega)^2 C L R_s + j \omega (L + L_s) + R_s} \leq 3\% \]

Since the high-frequency characteristics of the low-pass filter of the inverter are not affected by the load characteristics, the load parameters can be simplified and the inequality is obtained as

\[ \left| \frac{1}{(j \omega)^2 C L + 1} \right| \leq 3\% \]

It can be obtained that \( L = 0.4 \text{ mH} \).

Considering that the increase of \( C \) value requires greater capacity of the filter inductor \( L \) of the inverter, it increases the cost of the inverter and reduces the efficiency; at the same time, the value of the capacitor \( C \) is too small, the output impedance is too large, and the comprehensive weight balance is considered, Select 15% of the output capacity of the inverter module to determine the value of the capacitor.

\[ C \leq 15\% \times \frac{P}{3 \times 2 \pi f_r \times u_c^2} = 390 \mu F \]

\( f_r \) is the harmonic frequency with the largest instantaneous value, \( u_c \) is the rated voltage of the capacitor, \( P \) is the rated output capacity of the PWM inverter, Use circuit resonance conditions

\[ \omega L - \frac{1}{\omega C} = 0 \]

Get the capacitance value at the fundamental resonance \( C = 0.05 \mu F \)

3.4. Compensation control strategy

To monitor the fluctuation of the power supply voltage, the instantaneous reactive power theory is used, and the instantaneous value of the load side voltage is \( u_a, u_b, u_c \).

The ripple voltage command is \( u_a, u_b, u_c \)

When the power supply voltage waveform is distorted, the line voltage is converted from the three-phase static coordinates of the transformation matrix to the two-phase stationary \( \alpha \beta \) coordinates, and
then transformed into the two-phase rotating coordinates by the matrix $C$, and the resulting DC voltage is the fundamental component of the three-phase AC voltage. Is the harmonic component of the original three-phase AC voltage, By filtering the harmonic components through the filter, you can get $u_p, u_q$. In this way, the $u_a, u_b, u_c$ fundamental component $u_{aL}, u_{bL}, u_{cL}$ can be obtained.

$$
\begin{pmatrix}
u_a \\
u_b \\
u_c
\end{pmatrix} = C_{32}
\begin{pmatrix}
u_a \\
u_b \\
u_c
\end{pmatrix}
C_{32} = \sqrt{2/3}
\begin{pmatrix}
1 & -\sqrt{3}/2 & -\sqrt{3}/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 
\end{pmatrix}
$$

In the formula $u_p, u_q$.

According to the instantaneous reactive power theory, we can draw:

$$
\begin{pmatrix}
u_a \\
u_b \\
u_c
\end{pmatrix} = C
\begin{pmatrix}
u_a \\
u_b \\
u_c
\end{pmatrix}
$$

The harmonic component of the load voltage is:

$$
\begin{cases}
u_a = u_a - u_{aL} \\
u_b = u_b - u_{bL} \\
u_c = u_c - u_{cL}
\end{cases}
$$

The resulting disturbance voltage command is:

$$
\begin{cases}
u_a^1 = -u_{aL} \\
u_b^1 = -u_{bL} \\
u_c^1 = -u_{cL}
\end{cases}
$$

The following figure is the logic block diagram of the control strategy when the power supply voltage is distorted.

**Figure 3. Fluctuation instruction formation diagram**

The control goal of the device is to ensure that the load voltage is equal to the rated power supply voltage:

$$
E_{load} = E_s
$$

$$
E_{sag} = \dot{I}_s (R_s + jX_s) + \dot{E}_{dvr} + \dot{E}_L + \dot{E}_{load}
$$

Ignore the line impedance, get $\dot{E}_{dvr} = E_{sag} - \dot{E}_L - \dot{E}_{load}$. Consider the limit case, the system voltage is interrupted, then $\dot{E}_{sag} = 0$

$$
E_{dvr} = -\dot{E}_L - \dot{E}_{load}
$$

And when $\dot{E}_L$ and $\dot{E}_{load}$ is in the same phase, the DVR outputs the maximum voltage.
When the regulator is running. The series voltage drop is

\[ E_{dvr} = E_L + E_s = \left(1 + \frac{X_L}{\sqrt{R_{load}^2 + X_{load}^2}}\right)E_s \]

\[ E_{dvr} = (1 + \frac{X_L}{\sqrt{R_{load}^2 + X_{load}^2}})E_s \]

\[ V_{sys} \rightarrow V_{DVR} \rightarrow V_{load} \]

\[ V_{load} \rightarrow V_{DVR} \rightarrow V_{sys} \]

Figure 4. Compensation principle diagram

The regulator adopts independent control of each phase voltage, and can obtain good compensation when asymmetric harmonics, swells, sags, single-phase or multi-phase voltage distortion occur, according to the control principle diagram,

\[ U_{sys} = U_{sag} + U_{DVR} + E_L + U_{load} \]

During normal operation, the load measurement voltage is a sinusoidal fundamental component without any distortion. When the monitoring circuit detects voltage fluctuations, the voltage reference value of the regulator's access point is compared with the feedback value and then obtained through the PI controller. Modulated wave of IGBT opening and closing commands

\[ V_{sys} \rightarrow V_{DVR} \rightarrow V_{load} \]

\[ V_{load} \rightarrow V_{DVR} \rightarrow V_{sys} \]

Figure 5. Control principle diagram

4. Simulation analysis

Based on the power system transient simulation software, the circuit model of the compound voltage regulator is built. The main circuit is composed of the system power supply, the compound voltage regulator and the load.

When the power supply voltage changes more than plus or minus 5% of the effective value, or the harmonic distortion rate exceeds 4%, it is regarded as a voltage fluctuation, which needs to be compensated within the specified voltage range during the continuous fluctuation time.

During normal operation, the regulating device only needs to compensate the pressure drop of the reactor, and the compensation amount of fluctuation can be regarded as zero compensation. which is

\[ U_{sys} = E_{sag} + U_{DVR} + E_L + U_{load} \]

During normal operation, the voltage drop of the device compensation reactor can meet the load within the rated voltage range. When the system voltage is distorted, the device needs to compensate the voltage drop of the reactor and the compensation component of the power supply voltage distortion, that is, the size of the compensation reactor is equal Compensation for suppression of voltage and dip, swell and harmonics in opposite directions.
4.1. Symmetrical analysis

A 50% voltage drop occurs during the three-phase fault of the power supply voltage.

Figure 6. Three-phase voltage waveform with sag.

Figure 7. Three-phase voltage waveform after compensation.

Figure 8. Effective value of phase A before compensation.

Figure 9. Effective value of phase A voltage after compensation.

The power supply voltage three phases have a 50% voltage rise during the fault time.

Figure 10. Three-phase voltage waveform with swell.

Figure 11. Three-phase voltage waveform after compensation.

Figure 12. Effective voltage of phase A before compensation.

Figure 13. Effective value of phase A voltage after compensation.

The system voltage three-phase injects 10% of the 3rd harmonic in 0.2-0.3s.
8.2. Asymmetry analysis
The power supply voltage phase A has a 50% voltage rise during the fault time, phase B has a 50% voltage drop during the fault time, and phase C has no voltage change.
Three-phase voltage phase C injects 10% of the 7th harmonic during the fault time, phase B injects 10% of the fifth harmonic during the fault time, and phase A injects 10% of the 3rd harmonic during the fault time. The uniform setting is 0.2s-0.3s.

![Waveforms of the 3rd, 5th, 7th harmonics of the three-phase supply voltage.](image1)

![Voltage waveform after harmonic suppression.](image2)

![Phase A voltage distortion rate after harmonic injection.](image3)

![Phase A voltage distortion rate after compensation.](image4)

The load fluctuation voltage is compensated to the rated voltage within the set fault time. The energy storage device is obtained by PWM rectification from the grid side, which can meet the continuous stability compensation during voltage fluctuation. According to simulation verification, the effective value of the load side voltage is positive or negative after compensation. Within 5%, the harmonic distortion rate is within 3%. It can be seen that, whether it is symmetrical three-phase swell, sag or asymmetric three-phase voltage swell, sag, harmonic disturbance, the composite voltage quality regulator has achieved good compensation effect.

5. Conclusion
This paper analyzes various typical problems and treatment methods of current voltage quality, and proposes a voltage regulator with a cascade multi-level structure.

The instantaneous reactive power theory is used to monitor the fluctuation and distortion of the power supply voltage, and the load voltage is continuously tracked and compensated. The voltage fluctuations such as symmetrical voltage rise and fall, harmonic and three-phase asymmetric voltage rise and fall, third, fifth and seventh harmonic injection are simulated and verified. It was verified that the load voltage was compensated to the rated voltage within the predetermined fault duration and the harmonic distortion rate was less than 4%. The goal of compensation has been achieved, and the correctness and effectiveness of the theoretical analysis have been verified, which provides reference for the practical development and popularization of the composite voltage quality adjustment device.

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