Three-phase Four-wire Photovoltaic System with Power Quality Condition Function

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Abstract. In this paper, a novel three-phase four-wire photovoltaic system is proposed for the compensation of harmonic, reactive and three-phase unbalance in the distribution network and the demand for renewable energy generation. A novel three-level DC/DC converter is adopted for photovoltaic arrays and energy storage, and its control method, modulation strategy and neutral-point potential imbalance suppression method are given. Three-phase four-wire diode-clamped three-level converter is adopted for the bidirectional grid-connected converter. In order to realize power quality condition and active power bidirectional flow, an improved reference current calculation method is proposed, and the grid-connected current tracking control method is analyzed. Based on the theoretical analysis, the photovoltaic system is modeled and simulated by MATLAB/Simulink, which verified the feasibility and validity of the novel scheme.

Introduction

With the development of society, energy shortage and environmental degradation are becoming increasingly prominent. As a renewable clean energy, solar energy can effectively alleviate the current environmental and energy problems if it is fully utilized [1][2]. Distributed photovoltaic system has a major development advantage because it can be built in situ around the local load, without using high voltage transmission, and reduce the line loss of power in the process of long distance transmission [3]. With the development of power system, due to the grid-connection of many single-phase load grid and the distributed micro grid, there are serious harmonics, reactive power and unbalanced current in the distribution network, which consume considerable electric energy and affect the safe and stable operation of power equipment and power system [4][5].

In view of the above two hot issues, a kind of three-phase four-wire photovoltaic system that can adjust the quality of distribution network power is studied. It combines photovoltaic power generation and unbalanced compensation, effectively compensates for three-phase imbalance of the distribution network while developing clean energy, thus improving the power quality of power system.

Structure and Working Principle of the System

Figure 1 shows the three-phase four-wire photovoltaic system designed in the paper. It is mainly composed of distributed generation part, distributed energy storage part and grid-connected converter. The distributed generation part adopts MPPT control technology to maximize the generation rate of photovoltaic modules [6]. The distributed energy storage part that adopts an integrated energy management control strategy can control the working state of the grid-connected converter of the photovoltaic system and the quick charging and discharging of the energy storage part. The grid-connected converter adopts three-phase four-wire structure to realize energy exchange with the power grid and three-phase unbalanced compensation for the distribution network. Three-level DC/DC converters are used in distributed power generation and distributed energy storage for voltage conversion and neutral unbalanced suppression. Therefore, the grid-connected converter does not need to formulate corresponding strategies to balance the neutral point voltage on the DC side, which simplifies the structure and control strategy of the grid-connected converter and improves the efficiency of energy exchange with the power grid and the unbalanced compensation ability [7][8].

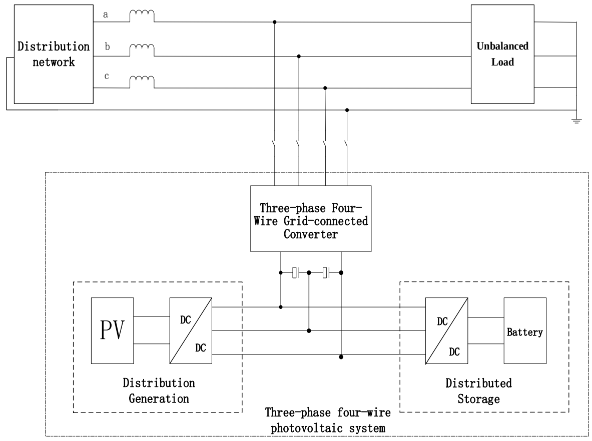

Figure 1. Three-phase four-wire photovoltaic system structure Figure

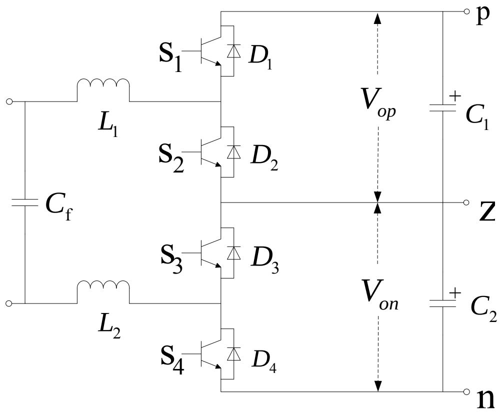

Figure 2. Main circuit topology of three-level DC/DC converter

Three-level DC/DC Converter

DC/DC converter is an important part of energy conversion and transmission. Due to a small capacity and a large switching loss, two-level DC/DC converter is not suitable for the power generation and energy storage requirements of the system [9][10]. Therefore, a new three-level DC/DC converter is adopted to meet the requirements of high-capacity and high-voltage photovoltaic system [11].

Structure and Working Principle of DC/DC Converter

The three-level DC/DC converter topology adopted by the system is shown in Figure 2.

The topology consists of a three-level cell, input filter capacitance C_f, and output capacitor C_1 and C_2. The three-level unit is composed of four switching devices, four follow current secondary diodes and filter inductor $L_1$and L_2. The kind of three-level DC/DC converter is featured by simple structure and high stability, can meet the large capacity and high voltage of distributed power generation and the requirements of quick charging and discharging of distributed energy storage [12]. Moreover, the converter is modular, which can increase the system capacity in parallel and is quite flexible [13].

Three-level DC/DC converter can achieve four working modes by changing the working state of the four switch tubes. In this paper, the working modes of the converter are named according to the on-off number of the switching tube. For example, the working mode of the converter is named as mode 23, as shown in Figure 3 when S_2 and S_3 are connected, and S_1 and S_4 are not connected

The unbalanced neutral point caused by the inherent structure of the three-level converter seriously affects the normal operation of the system [14]. The three-level DC/DC converter designed in the paper can be converted among the above four modes. Based on the simple analysis, in case of unbalanced neutral point on the DC side, the neutral point voltage can be adjusted to the equilibrium state only by switching to the 13 or 24 operating mode, and making the converter work in the mode for a period of time.

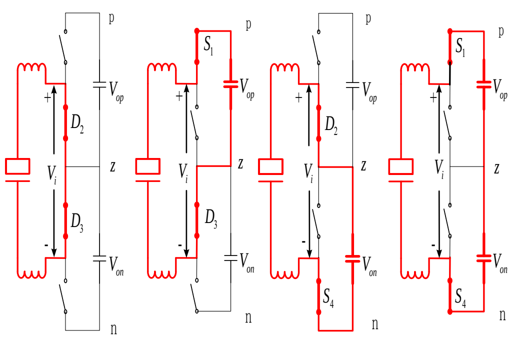

Figure 3. Four working modes

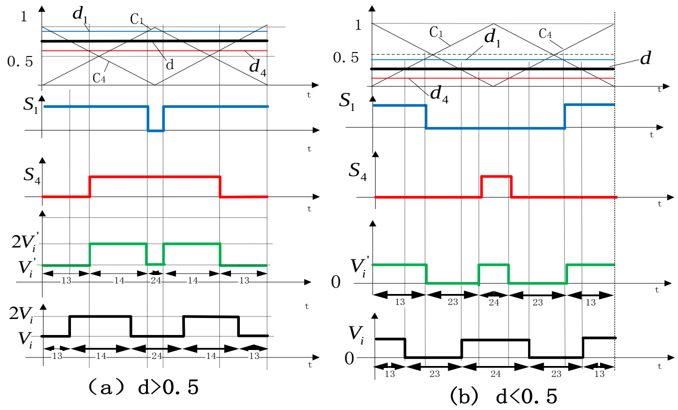

Figure 4. Switch signal waveform

Modulation Strategy of DC/DC Converter

According to the topology of the three-level DC/DC converter, and based on comparative analysis, the multi-carrier PWM strategy is adopted. To be specific, the two modulation waves are respectively intersected with the two-phase difference of 180-degree triangular carrier signals, and then the required PWM waves are obtained after comparison. The balance of two modulated waves can be achieved with this modulation method, so the neutral point voltage balance of the converter is realized [15].

In the paper, d is the main control duty ratio; d_1 and d_4 respectively represent the duty ratio conducted by switch tube S_1 and S_4 that the controller generates. the balanced main duty ratio d of the converter is obtained by modulating with the unbalanced signal d_1 and d_4 and intersecting and comparing with the directional triangular carriers respectively. In order to verify the correctness of the modulation strategy, three cases of d>0.5, d=0.5 and d<0.5 should be considered respectively in case of the unbalanced voltage at the neutral point of the converter.

When d>0.5, as shown in Figure 4 (a), the modulating signals d1 and d4 are compared with the anti-phase triangular carrier signals c1 and c4, respectively, and the switching signals s1 and s4 are obtained. And then, according to the opening of the switch signal condition, it can be judged that the three-level converter has three work modes, namely, 13, 14, 24, and the balanced output voltage waveforms V_i' and $2V_i'$ are got. Finally, based on the comparison of the voltage waveform in the unbalanced condition with the voltage waveforms $V_i$and $2V_i$ in the balanced condition, it can be concluded that the conduction time of working mode should be reduced by 13 to reach the balance in this case. When $d \leq 0.5$, the corresponding switch tube waveform can also be obtained through the same modulation method, as shown in Figure 4 (b). Under neutral unbalance, the output voltage waveform is 0 and V_i'. By comparing with the output voltage waveform of balance, it can be concluded that the neutral point balance can be modulated by reducing the conduction time of 1,3.

Control Method of DC/DC Converter

Combined with the topology structure of DC/DC converter and the modulation strategy adopted, the double closed-loop control strategy of outer voltage loop and inner current loop are adopted according to the actual situations. The outer voltage loop is used to maintain the voltage of the DC bus in a stable state, and realize no voltage difference; the inner current loop can realize real-time response and improve the response speed of the whole system. The control methods of three-level DC/DC converters in distributed energy storage and distributed generation are described below.

The double-loop control of the distributed energy storage is shown in Figure 5.

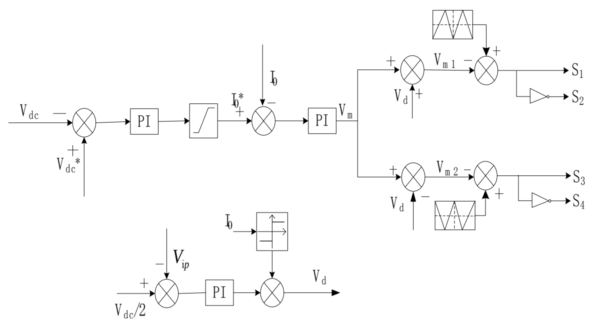

Figure 5. The control structure frame

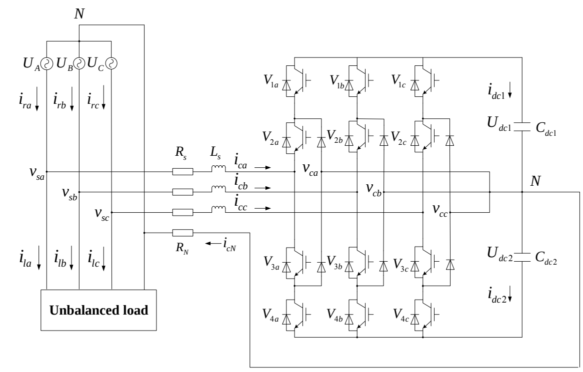

Figure 6. Topology structure of the three-phase four-wire converter

The energy storage has working states of charging and discharging, and the energy between it and the bus flows in both directions, so different control strategies are adopted by detecting the terminal current of the battery. The standard value I_0^* of the current can be obtained after the bus bar voltage Vdc current is regulated by PI. The difference value between sampling current value I_0 and current standard I_0^* is calculated. Then, the control deviation signal $V_m$can be obtained after PI regulation. Next, the voltage Vip is collected and compared with the set standard voltage $\frac{V_{dc}}{2}$ of the converter, and the he deviation signal V_d of the center point can be got after PI regulation. Finally, the difference between V_d and $V_m$is intersected with two triangular carriers whose phase difference is 180 degrees, and the PWM modulation switch signal is obtained by comparison. Thus, the converter switch tube is controlled.

The control method of the distributed power generation part is roughly the same as that of the distributed energy storage module in the state of discharge. It only needs to add MPPT control of the photovoltaic array. Thus, the specific step is not described here.

Three-phase Four-wire Grid-connected Converter

The unbalanced suppression capability of three-level DC/DC converter is previously mentioned. The three-phase four-wire grid-connected converter designed in the paper does not need to consider the problem of unbalanced DC side neutral point. Therefore, based on a single three-level unit, a diode clamped three-phase four-wire grid-connected converter is designed.

The Topology Structure and Working Principle of Grid-connected Converter

The topology structure is shown in Figure 6. It is composed by three-level bridge arm of three diode clamping, DC side capacitor $C_1$and C_2, and output connection inductance Ls. Rs is the equivalent resistance of three-phase circuit, RN denotes the equivalent resistance of the midline. Each bridge arm can be independently controlled, can independently work in three kinds of working state. The output phase voltage is $U_{dc}/2$、0 and $-U_{dc}/2$, respectively [16].

The three-phase four-wire grid-connected converter adopts the current control mode. By adjusting the frequency and phase angle of the output current and the grid voltage are the same, the active power generated by the photovoltaic system is integrated into the grid [17]. Grid-connection and unbalanced compensation can be achieved through reasonable control scheme. Specifically, firstly, the detecting the reactive power, harmonic and unbalanced current component on the load AC bus is detected. Then, it is converted to the command signal of compensation current through certain algorithm. Lastly, it is synthesized with the active current instruction signal phase that the grid inverter need injection, and the final grid current command signal is got, thus realizing the photovoltaic grid generation and unbalanced compensation with a set of grid system.

Instruction Signal Operation

As seen from the above analysis, the key to realizing photovoltaic power generation and unbalanced compensation at the same time in photovoltaic system is to obtain grid-connected current instruction integrating inverter active current and unbalanced compensation current. Traditionally, zero sequence current separation method is usually adopted to realize unbalanced compensation of three-phase load [18]. Firstly, the zero-sequence current in the three-phase four-wire system is analyzed. Three-phase current i_a, i_b and i_c in the three-phase four-wire system can be expressed as the components of zero-sequence current of a, b and c are equal, so the total zero sequence current i0 in the whole system is:

$$i_0 = \frac{(i_a+i_b+i_c)}{3} \tag{1}$$

If the zero-sequence component i_0 in each phase is removed, then:

$$\begin{cases} i'_a = i_a - i_0 \\ i'_b = i_b - i_0 \\ i'_c = i_c - i_0 \end{cases} \tag{2}$$

The three-phase current after removing the zero-sequence current component only contains positive sequence component and negative sequence component, and it can be expressed as follows:

$$\begin{cases} i'_a = \sqrt{2}\sum_{n=1}^{\infty}[I_{n+} sin(\omega t + \varphi_{n+}) + I_{n-} sin(n\omega t + \varphi_{n-})] \\ i'_b = \sqrt{2}\sum_{n=1}^{\infty}\left[I_{n+} sin\left(\omega t + \varphi_{n+} - \frac{2\pi}{3}\right) + I_{n-} sin\left(n\omega t + \varphi_{n-} + \frac{2\pi}{3}\right)\right] \\ i'_c = \sqrt{2}\sum_{n=1}^{\infty}\left[I_{n+} sin\left(\omega t + \varphi_{n+} + \frac{2\pi}{3}\right) + I_{n-} sin\left(n\omega t + \varphi_{n-} - \frac{2\pi}{3}\right)\right] \end{cases} \tag{3}$$

Moreover, it can be obtained that

$$i'_a + i'_b + i'_c = 0 \tag{4}$$

It is tested by using i_p and i_q detection methods based on the instantaneous reactive power theory, and the positive sequence components of the fundamental wave can be obtained, as shown in Equation (4.5):

$$\begin{cases} i'_{a1f} = \sqrt{2}I_{1+} sin(\omega t + \varphi_{1+}) \\ i'_{b1f} = \sqrt{2}I_{1+} sin\left(\omega t + \varphi_{1+} - \frac{2\pi}{3}\right) \\ i'_{c1f} = \sqrt{2}I_{1+} sin\left(\omega t + \varphi_{1+} + \frac{2\pi}{3}\right) \end{cases} \tag{5}$$

The compensation instruction current signal is obtained based on the difference value between load current i_a, i_b and i_c and the positive sequence fundamental current components. The compensation signal contains reactive power, harmonic, negative sequence fundamental current and zero sequence fundamental current. The compensation signal is denoted by i_{ar}, i_{br} and i_{cr}. Equation (4.6) shows their relation:

$$\begin{cases} i_{ar} = i_a - i'_{a1f} \\ i_{br} = i_b - i'_{b1f} \\ i_{cr} = i_c - i'_{c1f} \end{cases} \tag{6}$$

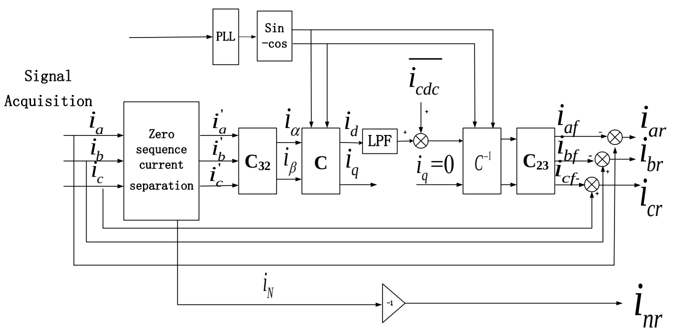

Figure 7. Operation circuit diagram of instruction signal

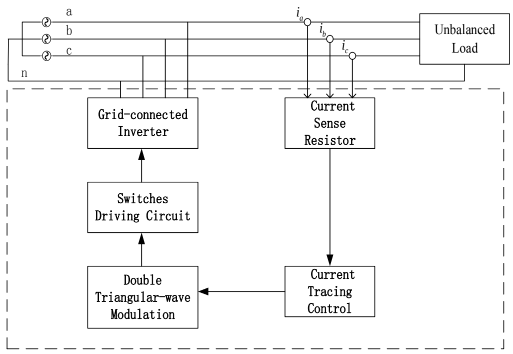

Figure 8. Grid-connected current tracking control principle

Relatively to the above command algorithm, the system also needs to consider the stability of DC side voltage of grid-connection converter so as to realize the basic function of photovoltaic grid-connection [19]. Therefore, a feedback loop is added after the active power flows through the LPF filter to stabilize the DC side voltage of the inverter. The specific instruction signal operation circuit is shown in Figure 7.

Grid-connected Current Tracking Control

The tracking control schematic diagram of the grid-connected current of the three-phase four-wire grid-connected converter is shown in Figure 8. Grid-connected converter is mainly composed of load current and voltage detection circuit module, current tracking control module, PWM modulation module, drive module and inverter main circuit. The detection circuit can detect the voltage at the grid side and the current at the load side. After the controller calculates and processes load current, the instruction signal required to compensate the current is obtained, and then the PWM pulse signal of the main circuit is controlled by the command signal. The drive circuit can amplify the pulse signal, control the on-off of the switch tube in the main circuit of the three-phase four-wire grid-connected converter, and finally send the corresponding unbalanced compensation current into the power grid.

Modulation Method of Grid-connected Converter

On the basis of comparative analysis of many modulation methods, the PWM method with same phase and dual carrier is partly selected for grid-connected converter due to the unbalanced three-phase load of the system. As shown in Figure 9, two identical triangular wave U_{c1} and U_{c2} are selected as the carriers, and then sinusoidal modulated wave Ur is compared with the two carriers respectively. According to the comparison results, the on-off state of the switch tube is determined, and the DC side level is further obtained.

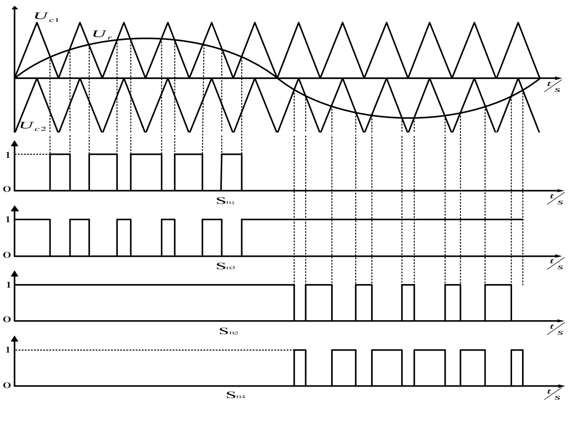

Figure 9. PWM method of same phase and dual carry

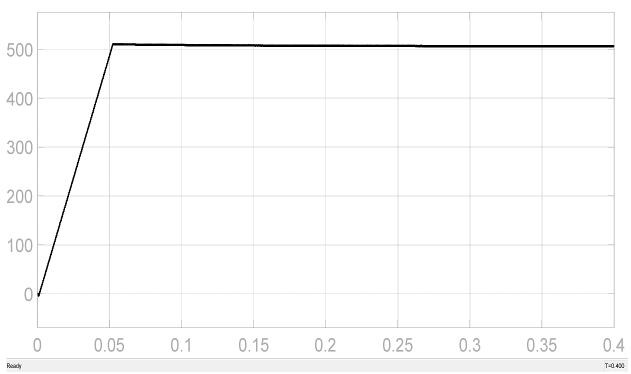

Figure 10. MPPT control of the distributed generation

Modeling and Simulation

In accordance with the above modulation strategy and control principle, the whole three-phase four-wire photovoltaic system is modeled and simulated. The DC bus voltage is 1200V; the maximum voltage of the photovoltaic module is 500V; the voltage of the battery terminal is 600V.

Figure 10 shows the output voltage of the distributed generation part after MPPT algorithm. It can be seen that the output voltage V_{ref} of the photovoltaic panel is stable at 500V after 0.05 seconds. Thus, the MPPT algorithm is correct and effective.

Figure 11 is the simulation of the bidirectional flow of energy in the distributed energy storage part of the system. As can be seen from it, P(load)=P(bus)+P(battery), and the bus power supply and energy storage part jointly provide electrical energy for the DC load, and the battery is in the discharge state within the first 0.1 seconds. P(bus)=P(load)+P(battery) after 0.1 seconds; the bus power supply supplies energy to the DC load and the energy storage part together, and the energy storage part is in the charging state. Therefore, the distributed energy storage part can realize the bidirectional flow of energy.

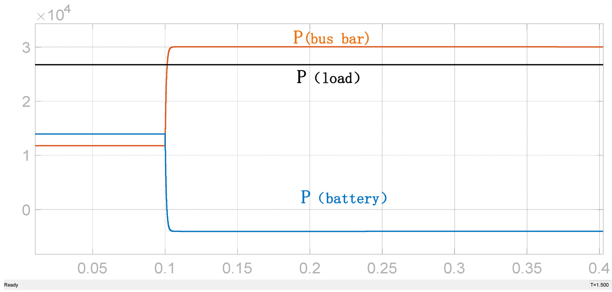

Figure 11. Battery, load and bus power

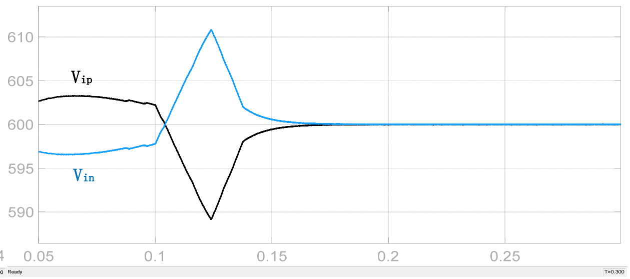

Figure 12. Neutral point voltage of three-level DC/DC converter

Figure 12 shows the simulation analysis result of the neutral point voltage of three-level DC/DC converter. As seen from it, the neutral point voltage is unbalanced in the initial state, but the neutral point voltage reaches balance in a short time, and the neutral point imbalance is effectively suppressed after adopting the double-closed-loop control method at 0.1 seconds.

Figure 13 is the simulation analysis of reactive power compensation of photovoltaic system, unbalanced compensation and harmonic compensation. As can be seen, A phase voltage and current of the distribution network have different phases in the initial stage, and there are harmonics and unbalanced current; voltage and current of the distribution network have the same phase, and three-phase current becomes standard three-phase AC after photovoltaic system is gridded at 0.1 seconds.

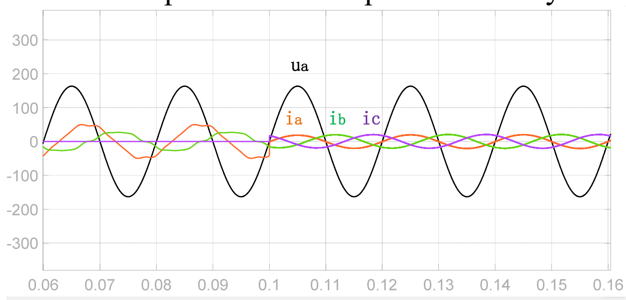

Figure 13. Voltage and current waveforms of distribution network before and after compensation

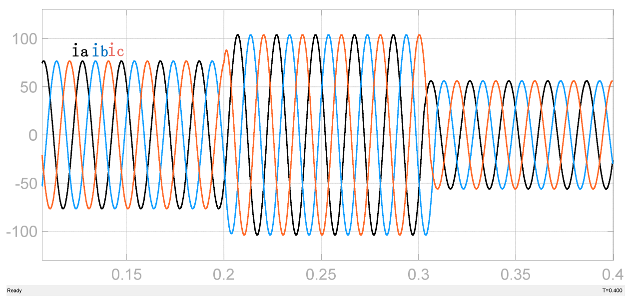

Figure 14. Three-phase current waveforms of distribution network

Figure 14 shows the simulation verification of active power exchange between micro-grid and distribution network. The micro-grid was in an independent state, and the grid current is only determined by the three-phase load value in the first 0.2 seconds. The micro-grid incorporates the excess energy into the distribution network, and the three-phase current of the distribution network increases during the time interval of 0.2~0.3 seconds; the micro-grid obtains energy from the distribution network, and the three-phase current of the distribution network decreases during the time interval of 0.3~ 0.4 seconds.

Conclusions

A new kind of three-level DC/DC converter is used in the power generation and energy storage of the three-phase four-wire photovoltaic system studied in the paper, and the modulation strategy and control method of neutral suppression are proposed. A new type of three-phase four-wire grid-connected converter is adopted in the grid-connected part, and the corresponding control method is put forward. It not only realizes the two-way active power exchange with the distribution network, but also compensates the reactive power, harmonic and unbalanced load of the distribution network, and improves the power quality of the power grid.

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