Research on Regulation Technology of Voltage Quality in the Distribution Network Connected with Distributed PV System

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Abstract—The point of common coupling (PCC) voltage fluctuation and waveform distortion will arise due to high penetration of distributed PV system connected to the distribution network. This paper analyzes the principle of voltage fluctuation and distortion in the PCC, points out shortcomings of the existing regulation methods, and proposes the voltage quality regulation technology that is based on the dual second-order generalized integration phase-locked loop with a pre-filter (DSOGI-WPF-PLL), realizes the voltage phase locked and the fundamental frequency positive sequence voltage component detected very accurately, meanwhile extracts the harmonic voltage components. In order to suppress PCC voltage fluctuation and distortion, the comprehensive controller with proportional integral control and repetitive control is used to achieve good tracking of the reference current. The MATLAB/Simulink simulation results demonstrate the effectiveness of the proposed control technique.

Keywords—distributed PV; point of common coupling; distributed network; voltage regulation; voltage quality

I. INTRODUCTION

With the development of economy, the conventional energy is drying up, distributed photovoltaic system, as a kind of power generation technology with energy conservation and environment protection, is attracting more and more people's attention. More and more photovoltaic systems are connected to distribution network, which may cause many new problems, such as the voltage rise at point of common coupling (PCC)^[1]. Besides, the power generation condition of photovoltaic system determines the harmonics of inverter output current. In weak solar radiation, such as sunrise and sunset, the total harmonic distortion (THD) of photovoltaic system's output current increases^[2]. Under 10% rated power, the harmonics of current may reach even more than 20%. Due the presence of the line impedance of distribution network, the harmonics will cause voltage distortion of PCC. Obviously, distribution network connected with distributed photovoltaic systems, there is a serious voltage fluctuation and distortion at PCC.

In order to suppress voltage fluctuation in distribution network, the reactive power adjusting method is usually used, that is, connecting reactive adjusting devices with network, such as thyristor controlled reactor (TCR)[3-4], thyristor switched capacitor (TSC)[5-6], static var generator (SVG)[7-9] and so on. Compared with SVG, TCR and TSC are easier to be

controlled, but have a slower response, moreover, TCR has higher harmonic and consumption while TSC takes discontinuous regulation. To suppress voltage distortion, harmonic control devices needed to be connected to distribution network. Currently used harmonic control devices are passive harmonic filters (LC), active power filter (APF) [10-12] and so on. But the above devices have a limited function, which can only compensate reactive power or harmonics for distribution network. In some distribution networks, there may be used a combination of two types of devices above, which inevitably increases the cost and complexity of system. To improve the voltage quality at PCC, this paper focuses on the research of voltage quality regulation technology, and puts forward the method of connecting voltage quality adjusting devices, which may inject or absorb reactive current and harmonic current.

II. ANALYSIS OF VOLTAGE FLUCTUATION AND DISTORTION

A. Analysis of Voltage Fluctuation

Figure 1 shows distribution network connected with photovoltaic inverter. Where, $\vec{V}_s$ is the voltage vector of distribution network bus, generally distribution system can be considered infinite power system, so the voltage amplitude is substantially constant, i.e., $\vec{V}_s$ is constant. $Z = R + jX$ is the line impedance of distribution network, where R and X are the resistive component and the reactance component respectively. P and Q are the active power and reactive power transmitting towards the distribution network bus respectively. P_L and Q_L are the active power and reactive power of local loads at PCC respectively. P_{inv} and Q_{inv} are the active power and reactive power of photovoltaic inverters respectively. $\vec{V}_{PCC}$ is the voltage vector of PCC

FIGURE I. THE DISTRIBUTION NETWORK WITH DISTRIBUTED PV SYSTEM

According to [13], the voltage drop caused by line impedance of distribution network is as follows.

$$\dot{V}_{PCC} - \dot{V}_s = \frac{PR + QX}{V_{PCC}} + j \frac{PX - QR}{V_{PCC}} \quad (1)$$

Compared with the vertical component of the voltage drop, the horizontal component is relatively small, and can usually be ignored. So Eq. (1) can be simplified to Eq. (2).

$$V_{PCC} - V_s \approx \frac{PR + QX}{V_{PCC}} \quad (2)$$

The PCC voltage V_{PCC} , can be obtained from Eq. (2), as shown in Eq. (3).

$$V_{PCC} = \frac{V_s + \sqrt{V_s^2 + 4(PR + QX)}}{2} \quad (3)$$

Where, $P = P_{inv} - P_L$, $Q = Q_{inv} - Q_L$. According to Eq. (3), the voltage at PCC fluctuates with the fluctuation of photovoltaic system's output power and local load.

B. Analysis of Voltage Distortion

Figure 2 is single-phase harmonic equivalent circuit of distribution network with distributed generation.

FIGURE II. SINGLE-PHASE HARMONIC EQUIVALENT CIRCUIT OF DISTRIBUTION NETWORK WITH DISTRIBUTED GENERATION

In Figure 2, V_{Sh} is the harmonic voltage of distribution network bus; I_h is the equivalent harmonic current of photovoltaic grid-connected inverter and local load; Z_{eq} is the

equivalent impedance of photovoltaic grid-connected inverter and local load; V_{PCCh} is the harmonic voltage at PCC, its value as shown in Eq. (4).

$$V_{PCCh} = \frac{Z \cdot Z_{eq}}{Z + Z_{eq}} \cdot I_h + \frac{Z_{eq}}{Z + Z_{eq}} \cdot V_{Sh} \quad (4)$$

According to Eq. (4), voltage at PCC will be distorted due to the effect of both harmonic voltage source and the harmonic current source.

III. PCC VOLTAGE QUALITY REGULATION TECHNOLOGY

The PCC voltage quality regulation technology includes voltage fluctuation regulation and distortion suppression. The schematic of the proposed regulation technology is shown in Figure 3.

FIGURE III. CONTROL PRINCIPLE DIAGRAM OF VOLTAGE QUALITY REGULATOR

There are n sets of inverters connected to distribution network in Figure 3. For improving voltage quality of PCC, the voltage quality regulating device, shown in red border, is used. There are two main ideas. One is to monitor PCC voltage fluctuation by detecting its fundamental positive sequence component V_{dfp} in the synchronization reference frame. If this value exceeds the standard [14], then reactive current reference I_q^* of the voltage quality regulating device can be obtained by Eq. (5).

$$I_q^* = -PI(s) \cdot (V_{dfp}^* - V_{dfp}) \quad (5)$$

Where, $PI(s)$ is the transfer function of PI controller; V_{dfp}^* is the desired d-axis fundamental positive sequence component of PCC voltage. The voltage quality regulating device makes PCC voltage stable by injecting or absorbing reactive power. The other is that the voltage quality adjusting

device extracts harmonic voltage V_{PCCh} , and injects reactive current $-G \cdot V_{PCCh}$ (G is a positive constant), as shown in dotted lines of Figure 2. At this time, the harmonic voltage V_{PCCh} can be calculated as Eq. (6).

$$V_{PCCh} = \frac{1}{1 + G \cdot \frac{Z \cdot Z_{eq}}{Z + Z_{eq}}} \cdot \left(\frac{Z \cdot Z_{eq}}{Z + Z_{eq}} \cdot I_h + \frac{Z_{eq}}{Z + Z_{eq}} \cdot V_{Sh} \right) \quad (6)$$

Comparing Eq. (4) with (6), it can be seen that

$$\left| \frac{1}{1 + G \cdot \frac{Z \cdot Z_{eq}}{Z + Z_{eq}}} \right| < 1$$

, so injecting harmonic current $-G \cdot V_{PCCh}$ reduces the harmonic voltage at PCC, which meets the standard requirements[15]. Two key technologies are needed to realize the above ideas. One is how to lock phase angle and detect the fundamental component of voltage accurately, and extract the harmonic voltage component effectively under the condition of severe voltage distortion. The other is how to track the current reference well.

A. Extraction of Fundamental and Harmonic Voltage Component and PLL Technology

Based on the second order generalized integrator phase locked loop with pre-filter (SOGI-WPF-PLL)[16], this paper uses the dual second order generalized integrator phase locked loop with pre-filter (DSOGI-WPF-PLL), as shown in Figure 4.

FIGURE IV. PHASE LOCKED-LOOP OF DUAL SECOND-ORDER GENERALIZED INTEGRATOR WITH PREFILTER

In Figure 4, the transfer functions from v_α to v_α' , and from v_β to v_β' , are same, as shown in Eq. (7).

$$D(s) = \left(\frac{2\xi\omega_0 \cdot s}{s^2 + 2\xi\omega_0 \cdot s + \omega_0^2} \right)^2 \quad (7)$$

Where, ξ is damping coefficient; ω_0 is fundamental frequency. For $h\omega_0$ frequency harmonic, its gain is shown in Eq. (8).

$$|D(jh\omega_0)| \approx \left(\frac{2\xi}{h} \right)^2 \quad (8)$$

It can be seen that SOGI-WPF can effectively filter out the frequency components except the fundamental frequency.

When v_α and v_β pass through SOGI-WPF respectively, v_α' and the quadrature component qv_α' , v_β' and the quadrature component qv_β' can be got. According to [17], the instantaneous value of the fundamental positive sequence voltage and negative sequence voltage in the two-phase stationary frame is shown in Eq. (9) and (10) respectively.

Where $q = e^{-j\frac{\pi}{2}}$

$$\begin{bmatrix} v_{\alpha fp} \\ v_{\beta fp} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix} \begin{bmatrix} v_{\alpha f} \\ v_{\beta f} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} v_{\alpha fN} \\ v_{\beta fN} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix} \begin{bmatrix} v_{\alpha f} \\ v_{\beta f} \end{bmatrix} \quad (10)$$

Fundamental positive sequence voltage components v_{dfp} and v_{qfp} in the synchronization reference frame can be got from Eq. (11). Then v_{qfp} is used to lock the voltage phase angle, as shown in Figure 4.

$$\begin{bmatrix} v_{dfp} \\ v_{qfp} \end{bmatrix} = T_{dq} \begin{bmatrix} v_{\alpha fp} \\ v_{\beta fp} \end{bmatrix} \quad (11)$$

$$T_{dq} = \begin{bmatrix} \cos \theta_{PLL} & \sin \theta_{PLL} \\ -\sin \theta_{PLL} & \cos \theta_{PLL} \end{bmatrix}, \quad \theta_{PLL} \text{ is the phase angle of voltage.}$$

The extraction of harmonic voltage components are as follows.

$$v_{\alpha h} = v_{\alpha} - v_{\alpha fp} - v_{\alpha fN} \quad (12)$$

$$v_{\beta h} = v_{\beta} - v_{\beta fp} - v_{\beta fN} \quad (13)$$

In order to verify the effectiveness of the proposed technique, the simulation analysis is performed, which include getting the amplitude and phase of fundamental positive sequence voltage, and extracting harmonic. The fundamental frequency of grid is 50Hz. Sampling frequency is 10 kHz. The RMS of fundamental phase voltage is 220V. There are 6% 5th negative sequence, 5% 7th positive sequence, and 5% 11th negative sequence harmonic voltage components in the grid voltage. Simulation results are shown in Figure 5, Figure 6, and Figure 7.

FIGURE 5. VOLTAGE WAVEFORM, ITS PHASE ANGLE AND FUNDAMENTAL FREQUENCY POSITIVE-SEQUENCE COMPONENT

From Figure 5, it can be seen that, even under serious distortion of the voltage at PCC, the DSOGI-WPF-PLL can track the phase angel of the voltage and detect the amplitude of fundamental positive sequence voltage quickly and accurately. There are three traces in both Figure 6 and Figure 7. The top is the α -axis/ β -axis harmonic component, the medium is the actual α -axis/ β -axis harmonic component, and the bottom is extraction error. It can be seen from the two figures that the maximum error of harmonic extraction does not exceed 5V in steady state.

FIGURE VI. HARMONIC VOLTAGE WAVEFORM OF THE EXTRACTION OF $v_{\alpha h}$ COMPONENT, THE REAL COMPONENT AND THE ERROR

FIGURE VII. HARMONIC VOLTAGE WAVEFORM OF THE EXTRACTION OF $v_{\beta h}$ COMPONENT, THE REAL COMPONENT AND THE ERROR

B. Current Control Technique

The current control technique can compensate reactive current and harmonic current at the same time. After getting harmonic voltage at PCC, the harmonic current factor $I_{\alpha\beta h}^*$ can be obtained from Eq. (14).

$$I_{\alpha\beta h}^* = -G \cdot V_{\alpha\beta h} \quad (14)$$

The reactive current reference I_q^* and the d-axis current reference I_d^* generated from the DC-link voltage control, are transformed to the fundamental current control reference $I_{\alpha\beta f}^*$. Then total current reference $I_{\alpha\beta}^*$ is the sum of $I_{\alpha\beta f}^*$ and $I_{\alpha\beta h}^*$.

In order to better track the current reference, this paper adopts a comprehensive controller, i.e., PI controller parallel with repetitive controller, as shown in Figure 8. Where, Q is a constant slightly less than 1; k_r is the gain of repetitive controller; T_s is the sampling period; $T = NT_s$ is the period of fundamental current; $T_k = kT_s$ is the time constant of phase

compensation; $\frac{1 - e^{-sT_s}}{s}$ is zero-order hold model; $S(s) = \frac{\omega_c^2}{s^2 + \sqrt{2}\omega_c s + \omega_c^2}$ is the second-order low pass filter with cutoff frequency ω_c .

FIGURE VIII. THE COMPREHENSIVE CONTROLLER OF PROPORTIONAL INTEGRAL CONTROLLER AND REPETITIVE CONTROLLER

IV. MATLAB SIMULATION RESULTS

In order to verify the feasibility of the proposed voltage quality regulation technology, simulation model is built in MATLAB/Simulink. The parameters of voltage quality regulating device are as follows. Both switching frequency and sampling frequency are 10 kHz. The DC-link voltage reference is 700V, and its proportional and integral gain of PI controller

are 5 and 10 respectively. V_{dfp}^* is set 392V, and its proportional and integral gain of PI controller of 10 and 30 respectively. G is 3. The proportional and integral gain of inner current loop controller is 40 and 100 respectively. Parameters of repetitive controller are: $Q = 0.95$, $k_r = 0.15$. Parameters of distribution network are as follows. The three-phase AC voltage frequency is 50Hz. The RMS of single phase voltage is 220V. Line resistance of the distribution network is 0.3Ω , and the inductance is $0.4mH$

FIGURE IX. VOLTAGE WAVEFORM AT PCC AND ITS FUNDAMENTAL FREQUENCY POSITIVE-SEQUENCE COMPONENT

When 4 sets 10kW inverters are connected to the network, and operated at unity power factor and power rating, the voltage quality regulating device works during the 0-0.2s period and stops after 0.2s, the PCC voltage and its fundamental positive sequence component is shown in Figure 9. It can be seen that, when voltage quality regulating device stops working, the voltage at PCC increases and its fundamental component changes from 390V to 421V, which demonstrates the effectiveness of the proposed voltage regulation technology.

FIGURE X. VOLTAGE WAVEFORM OF PCC

FIGURE XI. HARMONIC ANALYSIS OF PCC VOLTAGE

When 4 sets 10kW inverters are operated at the power of 25%, then a lot of harmonic current injects into distribution network, which leads to the PCC voltage distortion, as shown in Figure 10. The voltage quality regulating device works during the 0-0.2s period and stops after 0.2s. Figure 11(a) shows the FFT analysis of A-phase PCC voltage in two periods from 0.16s when the voltage quality regulating device works, THD of PCC voltage is 3.08%, satisfying with the relevant standards. When the proposed device is invalid, THD of PCC voltage increased to 7.09%. This indicates that the proposed technology can effectively suppress PCC harmonic voltage.

V. CONCLUSION

This paper analyses the causes of PCC voltage fluctuation and distortion of distribution network with distributed photovoltaic systems, and utilizing voltage quality regulating device to make PCC voltage normal. Injecting or absorbing reactive current of the device is determined by detecting the

fundamental positive sequence voltage, which can realize regulating the PCC voltage amplitude. The device also absorbs harmonic current by extracting harmonic voltage component, which can realize the suppression of PCC voltage harmonics. Simulation results show the effectiveness of the proposed the voltage quality regulation technology.

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