DESIGN OF A NOVEL CONTROL STRATEGY FOR DISTRIBUTED GENERATION TO IMPROVEMENT POWER QUALITY IN DISTRIBUTION NETWORK

PEI Wei
Institute of Electrical Engineering,
Chinese Academy of Science (CAS),
and Graduate School of CAS
BeiJing, P. R. China
peiwei@mail.iee.ac.cn

KONG Li
Institute of Electrical Engineering,
Chinese Academy of Science (CAS),
BeiJing, P. R. China
kongli@mail.iee.ac.cn

SHENG Kun
Institute of Electrical Engineering,
Chinese Academy of Science (CAS),
and Graduate School of CAS
BeiJing, P. R. China
shengkun@mail.iee.ac.cn

ABSTRACT

DGs have two operation environments: a standalone ac system and a grid-interconnection to the utility mains. This paper presents the converters of DGs in distribution network, especially in microgrid, employing an integrated control algorithm, which is composed of interconnect control module and island control module, to ensure the converters of DGs operate stably and maintain the network power quality. In a grid-interconnection operation modl, to fundamental components, the proposed control scheme adopted PI feedback and source voltage feed-forward to track fundamental command accurately. And to harmonic components, the proposed control scheme adopted deadbeat controller to compensate the harmonic current rapidly. In a standalone operation modl, the real power- phase angle (P-ω) droop, the reactive power-voltage (Q-v) droop, and harmonic power-equivalent impedance (H-X) droop technique has been used as load-sharing scheme. Experimental results from a prototype system consisting of two 2-kVA inverter modules verified the efficiency.

Ⅰ INTRODUCTION

Distributed generation (DG) interfaced with utility grid are being focused and applied increasingly due to the fact that traditional electric power systems are being more and more stressed by expanding power demand, limit of delivery capability, the difficulties of building new transmission lines, and so on. In recent years, Consortium for Electric Reliability Technology Solutions (CERTS) proposed an entirely new approach to integrating DG – micorgrid [1], which assumes an aggregation of loads and microsources operating as a single system. A necessary feature of microgrid is that it can act as an autonomous system. When the utility grid is break down or unavailable, the microgrid can still operate independently. So in microgrid, DGs have two operation environments: a standalone ac system in independent microgrid and a grid-interconnection to the utility mains. The converter systems must be capable to operate in typical voltage and frequencies, grid connected or standalone.

When microgrid is connected to the bulk power system, the converters of DGs in microgrid are as current controlled voltage source converter (VSI). When in microgrid islanding mode, DGs must participate in voltage and frequency control to balance power production and consumption, like the parallel operation of the uninterruptible power supply (UPS).

However, the harmonic current brought by nonlinear load and power electronic equipments may cause the harmonic interaction, resonance and circulates between DGs both in microgrid islanding mode and in grid-interconnection mode. Some compensating and sharing methods have been presented to solved those problems [2-4], but these techniques have some limitations: the controller uses an algorithm which is too complicated to calculate the harmonic current, the delay from complicated harmonic compensate filter, and et al. And DGs in the microgrid are more intractable in these limitations because they must operate stably both in standalone ac system and in grid-interconnection to the utility mains. So the purpose of this paper is to present an integrated control algorithm, which is composed of interconnect control module and island control module, to ensure the converters of DGs operate stably and maintain the network power quality.

The paper is outlined as follows. Chapter Ⅱ illustrate the basic architecture of the proposed control algorithm, and explain detailed the design of the island controller and the grid-interconnection controller. The results of proposed control algorithm is shown in Cheaper Ⅲ and followed by conclusions in Cheaper Ⅳ.

Ⅱ CONTROL ALGORITHM

During interconnected mode, the Microgrid Control Center (MCC) collects information from the DGs and loads in order to automatically perform operations on the microgrid as economic scheduling, security assessment and demand side management. The controllers of DGs receive the power and command to achieve uniform goal and to reduce harmonic. When microgrid is island mode, the controllers of DGs participate in voltage and frequency control to balance power production and consumption, and insure that each DG rapidly picks up its share of fundamental and harmonic power to maintain voltage quality.

Fig.1 demonstrates the basic control algorithm of the distributed generation system.

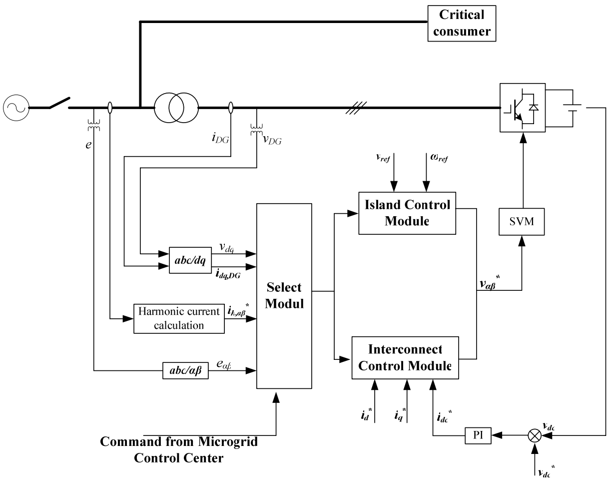

Fig.1 The basic control algorithm

The basic control algorithm of the distributed generation system is composed of island control module and interconnect control module. The switch between the interconnect module and the island module usually is controlled by the command from MCC according to the state of microgrid separation device [5]. To realize this reference voltage vector in the circuit, the well known SVM scheme is employed.

A. Current and Voltage Transform

The harmonic components of the load current are obtained by using instantaneous reactive power theory as (1).

$$\begin{pmatrix} i_p \\ i_q \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \sin\theta & -\cos\theta \\ -\cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix} \begin{pmatrix} i_{a,net} \\ i_{b,net} \\ i_{c,net} \end{pmatrix} \quad (1)$$

θ is the instantaneous angle of the net voltage vector. It can be obtained from phase locked loop (PLL).

Utilizing park transformation, the DG current and voltage are converted from the three phase coordinates to synchronously rotating frame, and the fundamental components can be obtained through Low Pass Filter (LPF).

B. Interconnect Control Module

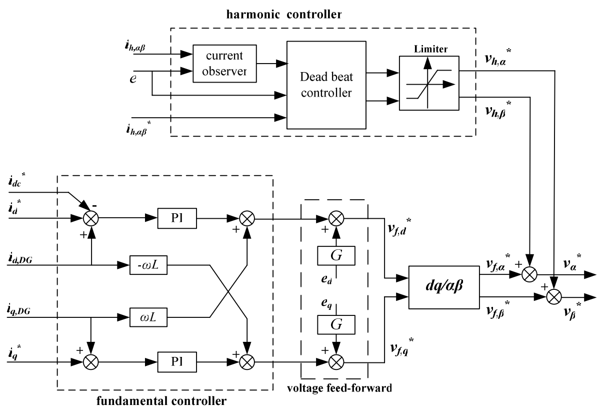

Fig.2 Interconnect Control Module

Interconnect Control Module is divided into fundamental controller and harmonic controller as be shown in Fig.2.

The reference voltage v_α^* and v_β^*, which are made by $v_{f,\alpha\beta}^*$ and $v_{h,\alpha\beta}^*$, in stationary α-β frame represent the average voltage vector of converter. $v_{f,\alpha\beta}^*$ is the reference value of fundamental component and $v_{h,\alpha\beta}^*$ is the reference value of harmonic component.

To fundamental components, converter model in synchronously rotating frame can be written as (2):

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{L}\begin{bmatrix} i_d \\ i_q \end{bmatrix} V_{dc} - \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{1}{L}\begin{bmatrix} e_d \\ e_q \end{bmatrix} - \frac{R}{L}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2)$$

In equation (2), L the leakage inductance of transformer reflected to secondary.

Cross-coupling terms of this model between d-axis components and q-axis components need to be decoupled through fundamental controller part in fig.3. And then d-axis components and q-axis components can be controlled independently each other.

The impact of network voltage disturbance to output current can be expressed as (3).

$$-\hat{i}_d = \frac{1 - GV_{dc}}{(Ls + R) + H(s)G_1 V_{dc}} \hat{e}_d \quad (3)$$

If $G=1/V_{dc}$, the impact of network voltage disturbance to output current will be reduce to zero in theory. So proposed algorithm adopt a network voltage feed-forward method to reduce the impact of network voltage disturbance as voltage feed-forward part in fig.3.

The reference current d-axis component is made by i_{dc}, i_d, and i_d^*. i_{dc} is used to maintain the DC voltage invariableness; And the reference current q-axis component i_q^* is selected in view of reactive power control. i_d^* and i_q^* are the expectation value for d-axis current component and q-axis current component, which are specified by MCC or local microsource controller.

The VAr associated with the harmonic compensating would only occupy small portion of the total VA capacity because the most capacity of converter must be used to guarantee the fundamental power output. Then it is difficult that DGs' controller eliminate harmonic completely using certain compensate method at the same time control fundamental power flow. Then to harmonic components, it is more feasible to reduce harmonic to a degree rapidly than to try to eliminate harmonic completely. In this control algorithm, deadbeat control is employed to control the output compensating harmonic current. To compensate the computation delay, the simple predictive current control is achieved by the current observer with deadbeat response.

The harmonic component in p-q instantaneous reactive power frame is transformed into stationary α-β frame first and the equivalent circuit for α-axis is shown in Fig.3.

The β-axis equivalent circuit is identical.

The dynamic equation for α-axis describing the system in fig.2 is:

$$\frac{d}{dt} i_{h,\alpha} \cdot L = v_{h,\alpha} - e_{\alpha} \tag{4}$$

$V_{c,\alpha}$ is instantaneous compensating voltage of the converter. The β-axis equation is identical. L the leakage inductance of transformer reflected to secondary.

Based on the assumption that the switching period T_s is set to enough small value, (4) can be written approximately as:

$$i_{h,\alpha}(k+1) = i_{h,\alpha}(k) + \frac{T_s}{L} v_{h,\alpha}(k) - \frac{T_s}{L} e_{\alpha}(k) \tag{5}$$

If the output compensating current i_α and i_β should be the reference compensating current at the $(k+1)^{th}$ sampling instant, the required output voltage of converter can be computed as follow.

$$v_{h,\alpha}(k) = \frac{L}{T_s} i^*_{h,\alpha}(k+1) - \frac{L}{T_s} i_{h,\alpha}(k) + e_{\alpha}(k) \tag{6}$$

The computed reference values need to be predicted to compensate for the computation and control delay, so a current observer with corrective prediction error feedback can be designed as follow.

$$\hat{i}_{h,\alpha}(k+1) = \hat{i}_{h,\alpha}(k) + \frac{T_s}{L}(v_{h,\alpha}(k) - e_{\alpha}(k)) + G(i_{h,\alpha}(k) - \hat{i}_{h,\alpha}(k)) \tag{7}$$

Then the deadbeat observer is realized when G=1, and the deadbeat control law in (6) can be transformed into (8).

$$v_{h,\alpha}(k) = \frac{L}{T_s} i^*_{h,\alpha}(k+1) - \frac{L}{T_s} \hat{i}_{h,\alpha}(k) + e_{\alpha}(k) \tag{8}$$

C. Island Control Module

In order to ensure exact load sharing of active power, reactive power and harmonic between DGs, a combined droop method is proposed for load sharing of paralleled converters. Fig. 3 shows the diagram of the proposed combined droop method.

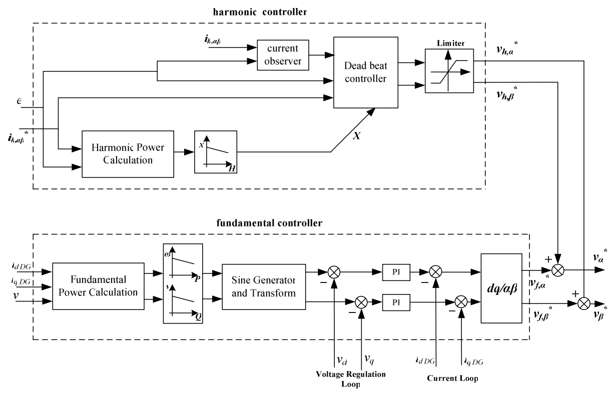

Fig.3 Island Control Module

To fundamental components, the droop controller used P-ω droop and Q-v droop to insure that each DG rapidly picks up its share of fundamental active and reactive power. The P-ω droop and Q-v droop are to calculate the power output of each DGs, and then to determine the fundamental voltage command and phase angle command. The phase angle ω is used as the P droop control variable instead of frequency in the proposed method, and then frequency can be maintain at nominal value since constant active power in stead state. The P-ω and Q-v droop characteristics as follow.

$$\begin{aligned} \omega_i^* &= \omega_{i,rated} - k_{\omega i}(P_{i,rated} - P_i) \\ V_i^* &= V_{i,rated} - k_{vi}(V_{i,rated} - V_i) \end{aligned} \tag{9}$$

And the droop coefficient of P-ω and Q-v droop are defined as (9) to guarantee active power can be shared in proportion to the rated capacity of each DG' converter.

$$\begin{aligned} k_{\omega 1} P_{1,rated} &= k_{\omega 2} P_{2,rated} = \cdots = k_{\omega n} P_{n,rated} \\ k_{v1} V_{1,rated} &= k_{v2} V_{2,rated} = \cdots = k_{vn} V_{n,rated} \end{aligned} \tag{10}$$

The above combined droop method does not guarantee the harmonic components of the load current to be shared. To harmonic components, the proposed scheme adopted the droop of harmonic power (H) to equivalent impedance (X).The H-X droop characteristics as follow.

$$\begin{aligned} X_i^* &= X_{i,rated} - k_{Xi}(H_{i,rated} - H_i) \\ k_{X1} H_{1,rated} &= k_{X2} H_{2,rated} = \cdots = k_{Xn} H_{n,rated} \end{aligned} \tag{11}$$

Then L of the deadbeat control law in (6) would be regulated according to equivalent impedance to guarantee the harmonic components of the load current to be shared as shown in Fig.3.

Then the converters of DGs with P-ω, Q-v and H-X droop can operation both in microgrid islanding mode and in grid-interconnection mode, and share the real power, the reactive power and the harmonic power without any communication.

Ⅲ EXPERIMENTAL RESULTS

Two 2-kVA three-phase inverter units were built as Fig.4, confirming experimentally the validity of the proposed strategy. Each inverter consisted of a three-phase IGBT full bridge and an LC output filter, with the following parameters: L = 2.2mH, C=420μF. The impedances of the lines between the inverters and the load are Z_{l1} = 0.06 + j0.012 Ω, and Z_{l2} =0.1 + j0.02Ω. The controllers of DGs were implemented by using two TMS320LF2407A.

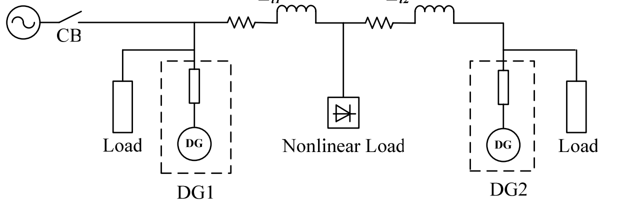

Fig.4 Experimental circuit of two DGs supplying load

Fig.5 shows the voltage and current waveform of converter in interconnect mode. Fig.6 shows the voltage and current waveform of source. The DGs not only supply local load but also inject power to the main grid. The measured source current THD was 3.8%. Results show that the control scheme succeeded not only in tracking fundamental command accurately but in compensating the harmonic current rapidly.

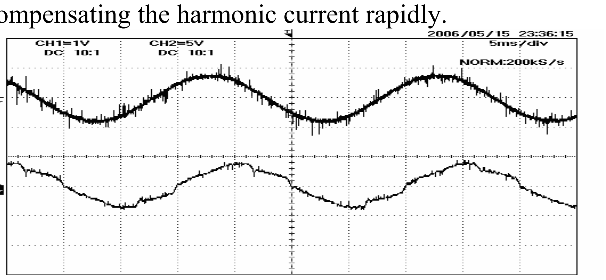

Fig.5 The voltage and current waveform of converter in interconnect mode（1）Voltage of phase A (v_a 200*V/div*)（2）Current of phase A ($i_{a,DG}$ 10*A/div*)

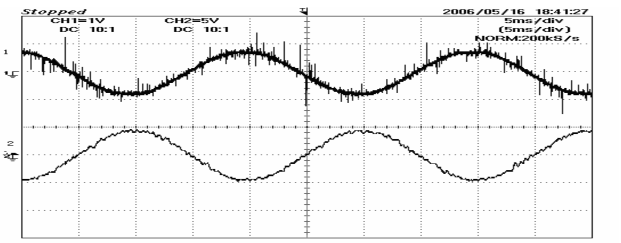

Fig.6 The voltage and current waveform of source in interconnect mode（1）Voltage of phase A (v_a 200*V/div*)（2）Current of phase A ($i_{a,DG}$ 10*A/div*)

The second experimental test consists in supplying generation load and nonlinear load only by means of the two parallel inverter systems to simulate the island state of microgrid. Fig.7 shows the voltage waveform of source and the current waveform of two converters.

As it can be seen, the load sharing capability is very good when supplying nonlinear loads. And the measured source voltage THD is also in a acceptable range.

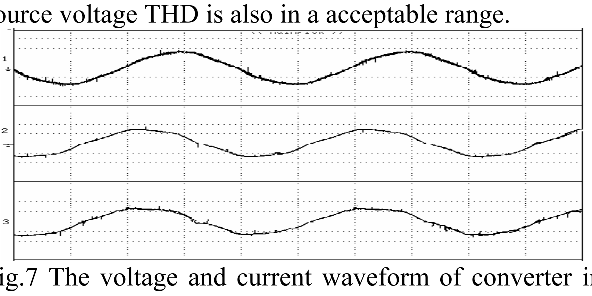

Fig.7 The voltage and current waveform of converter in interconnect mode（1）Voltage of phase A (v_a 200*V/div*)（2）DG1 output current of phase A ($i_{a,DG1}$ 10*A/div*) (3) DG2 output current of phase A ($i_{a,DG2}$ 10*A/div*)

Another experimental test is to test the transition performance from interconnect mode to islanding mode (Only use L output filter). Fig.8 shows the voltage and current waveform of source. These results show a good dynamic response of the proposed controller strategy.

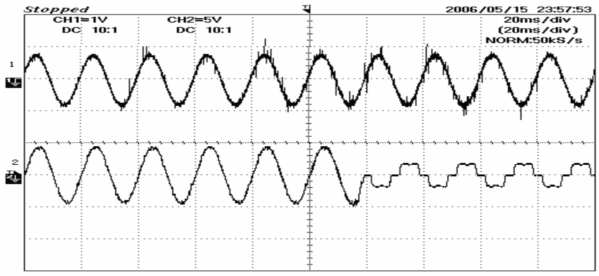

Fig.8 The voltage and current waveform of source from interconnect mode to islanding mode only using L output filter（1）Voltage of phase A (v_a 100*V/div*)（2）DG1 output current of phase A (i_a 18*A/div*)

Ⅳ CONCLUSIONS AND FUTURE WORK

A novel control strategy for distributed generation to improvement power quality in distribution network has been proposed in this paper. The technique make converter of DG operate both in microgrid islanding mode and in grid-interconnection mode, and share the real power, the reactive power and the harmonic power without any communication. Moreover, the transition from interconnect mode to islanding mode is smooth. Experimental results from a prototype system consisting of two 2-*k*VA inverter modules verified the efficiency.

This study is just a first step for the proposed control strategy applied in the converter of DGs in distribution networks. Future research will focus on the relation between the change of circuit parameters and dynamic performance, and the delay of communications from MCC to the controller of DGs impact on transition dynamic performance.

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