A Synchronous-Reference-Frame I-V Droop Control Method for Parallel-Connected Inverters

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***Abstract*-A simple and fast decentralized Current-Voltage (I-V) droop control method under the Synchronous-Reference-Frame (SRF) is proposed to share output current for parallel three-phase inverters with LC filter. The I-V droop characteristic is derived in accordance with the virtual impedance in SRF. Thus, each inverter enables to work in a voltage controlled mode where it controls the filter capacitor voltage. Moreover, a detailed state-space model of two parallel inverters is derived to analyze the control performance. Through the simulation and experiment validation, the proposed method provides accurate current sharing and faster transient response under inverter connection in comparison with the conventional droop control.**

***Abstract*- Parallel inverters, I-V droop, SRF, Current sharing.**

I. Introduction

As a significant operation mode, the islanded microgrid is typically equipped with converters and controlled to provide loads stable voltage and frequency [1], [2]. In order to satisfy the high power requirement, the multi-inverters are required to share load according to their power rating. The power droop control as an effective decentralized strategy has been commonly applied to the islanded mode, even the grid-tied mode. The voltage and frequency can be regulated to realize the active/reactive power sharing. However, the conventional droop technique has obvious drawbacks: active/reactive power coupling, sensitivity to line impedance, and slow dynamic response [3], [4].

To solve these problems, the virtual impedance control theme has been employed, which changes the inverter output characteristic in accordance to the line impedance.[5]-[7] However, these approaches are all based on the active power-voltage and reactive droop characteristics, and instantaneous active and reactive powers should be calculated, which means the low-pass(LPF) is necessary to average. The LPF will affect the transient response. Moreover, the power sharing performance is degraded when short lines with small impedance are used [8].

In order to improve the dynamic performance and stability, the current decoupling control based on droop has been investigated. In [9], a V-I characteristics droop control under SRF has been proposed to obtain the fast dynamics of parallel inverters system, and the SRF voltage and current are decoupled by using a new vector. However, the frequency fixed communication is employed. In [10], a novel and fast autonomous current sharing controller with virtual impedance loop under SRF has been proposed, and it works well with inductive-resistive line impedance. However, the virtual impedance loop needs extra transformations which will burden the controller calculation.

To cope with the all the aforementioned, a simpler and faster controller is proposed in this paper. The I-V droop characteristic has been applied to generate the direct and quadrature current references. The droop coefficients are decided by the virtual impedance to realize the accurate sharing of currents. Moreover, the state-space equations of the two parallel inverters has been derived to model the system.

The paper is organized as follows. Section II introduces the proposed control structure and the control principle. In Section III, the state-space model of SRF I-V droop control is derived in details. In Section IV, the simulation and experiment results are given to validate proposed method under inverter connection. Finally, the conclusion and future works are highlighted in Section V.

II. Proposed SRF I-V Droop Control

The equivalent circuit of parallel multi-inverters system including output impedances, virtual impedances and line impedances are shown in Fig.1. and Fig.2. presents a two-terminal Thévenin equivalent branch in Laplace.

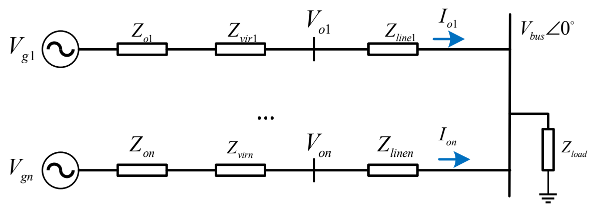

Fig. 1. Equivalent circuit of a parallel inverter system.

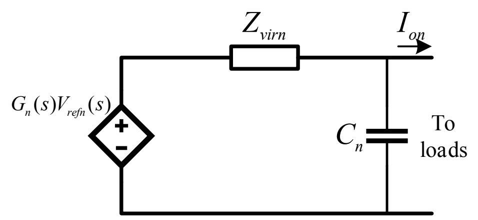

Fig. 2. Thévenin equivalent circuit of closed-loop inverter.

Considering that the $Z_{linen}(s)$ is very small in low-voltage microgrid, and $Z_{virn}(s)$ is the predominant component, according to Thévenin equivalent circuit, the

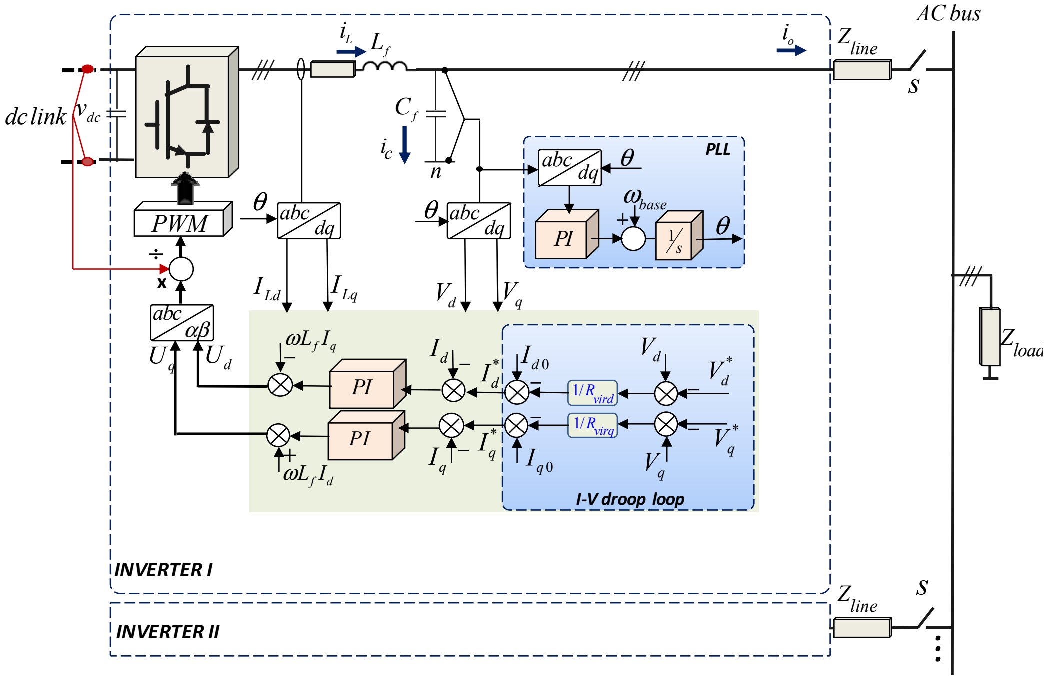

Fig. 3. The proposed control block for parallel inverters

voltage between the generated voltage $\vec{V}_{refn}$ and PCC voltage, $\vec{V}_{pcc}$, can be expressed in SRF:

$$\vec{V}_{refn} - \vec{V}_{pcc} = I_{dn} Z_{virdn} + jI_{qn} Z_{virqn} \quad (1)$$

Where I_{dn} and I_{qn} are the direct and quadrature components of output current respectively. Regardless of line impedance, the relationship of output currents in steady state among the parallel branches can be derived to:

$$I_{d1} : I_{d2} : \cdots : I_{dn} = \frac{1}{R_{vird1}} : \frac{1}{R_{vird2}} : \cdots : \frac{1}{R_{virdn}} \quad (2)$$

$$I_{q1} : I_{q2} : \cdots : I_{qn} = \frac{1}{R_{virq1}} : \frac{1}{R_{virq2}} : \cdots : \frac{1}{R_{virqn}} \quad (3)$$

Where R_{virdn} and R_{virqn} are the direct and quadrature virtual resistances of n-th inverter respectively.

Therefore, in order to share current flow, the d-axis and q-axis currents outputs of each inverter are able to regulated without communication by designing the reciprocals of virtual resistances. Consider that the voltage references of each inverter are equal, the active power P_n and reactive power Q_n of the n-th inverter also can be shared based on the virtual resistances. Consequently, (2) and (3) can be rewritten as:

$$P_1 : P_2 : \cdots : P_n = \frac{1}{R_{vird1}} : \frac{1}{R_{vird2}} : \cdots : \frac{1}{R_{virdn}} \quad (4)$$

$$Q_1 : Q_2 : \cdots : Q_n = \frac{1}{R_{virq1}} : \frac{1}{R_{virq2}} : \cdots : \frac{1}{R_{virqn}} \quad (5)$$

According to the above analysis, a new I-V droop can be obtained based on the direct and quadrature currents and voltage, which can be expressed as:

$$\begin{cases} I_d^* = I_{d0} - \dfrac{1}{R_{vird}}(V_d - V_d^*) \\ I_q^* = I_{q0} - \dfrac{1}{R_{virq}}(V_q - V_q^*) \end{cases} \quad (6)$$

Where V_d^*, V_q^* are the direct and quadrature current reference in SRF respectively, V_d, V_q are the instantaneous voltage components, I_d^*, I_q^* are the direct and quadrature current reference respectively, I_{d0}, I_{q0} are the nominal value of current components.

In case of active loads, the d-axis voltage can be regulated through the virtual resistance, which implies the droop characteristic to adapt the value of the d-axis current. Thus, the amplitude of output voltage can be regulated by the direct voltage reference. On the other hand, the quadrature current will affect the frequency of system. In SRF-PLL, the angular position is regulated through a feedback control loop which drives the V_q component to zero, and the PLL will compel the system to be stabilized at a certain point (50Hz) with zero phase delay if the quadrature voltage reference is zero.

Fig.3. shows the proposed control structure for parallel inverters, in which the system consists of the SRF-PLL, a I-V droop loop and PI current controllers. The direct and quadrature output voltage are independently controlled and rotated to generate the virtual current through the I-V droop relations (6). Then, the current controllers generate voltage references for the PWM signal to drive the IGBT inverter gates.

III. STATE-SPACE MODEL FOR PROPOSED CONTROL

In order to analyze the output characteristics of I-V droop-controlled inverters, the state-space model of single inverter is established for a notional two parallel inverters system. To offer a fixed phase angle, the first inverter's phase angle can be the system reference [11], [12].

Regarding the I-V droop controller, the *dq*-axis current references can be generated by I-V droop relations. Therefore, we can obtain the input-output relationships from (6):

$$\begin{bmatrix} I_d^* \\ I_q^* \end{bmatrix} = \begin{bmatrix} I_{d0} \\ I_{q0} \end{bmatrix} - \begin{bmatrix} \frac{1}{R_{vird}} & 0 \\ 0 & \frac{1}{R_{virq}} \end{bmatrix} \begin{bmatrix} \varepsilon_d \\ \varepsilon_q \end{bmatrix} \quad (7)$$

Where $\varepsilon_d = V_d - V_d^*$, $\varepsilon_q = V_q - V_q^*$.

According to the current PI controllers, the state and output equations can be represented as:

$$\begin{bmatrix} U_d \\ U_q \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_f \\ \omega L_f & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + k_i \begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} + k_p \begin{bmatrix} \dot{\lambda}_d \\ \dot{\lambda}_q \end{bmatrix} \quad (8)$$

Where $\dot{\lambda}_d = I_d^* - I_d$, $\dot{\lambda}_q = I_q^* - I_q$.

According to Fig.3, the LC filter and resistive-inductive loads dynamics can be represented on a SRF as following:

$$\begin{cases} \dot{I}_{Ld} = \frac{1}{L_f}(-R_f I_{Ld} + V_{id} - V_d) + \omega_i I_{Lq} \\ \dot{I}_{Lq} = \frac{1}{L_f}(-R_f I_{Lq} + V_{iq} - V_q) + \omega_i I_{Lq} \\ \dot{V}_d = \frac{1}{C_f}(I_{Ld} - I_{od}) - \omega_i V_q \\ \dot{V}_q = \frac{1}{C_f}(I_{Lq} - I_{oq}) + \omega_i V_d \\ \dot{I}_{od} = \frac{-R_{Load}}{L_{Load}} I_{od} + \omega_i I_{od} \\ \dot{I}_{oq} = \frac{-R_{Load}}{L_{Load}} I_{oq} + \omega_i I_{oq} \end{cases} \quad (9)$$

Where R_f is the parasitic resistance of the inductor, R_{load}, L_{load} is the loads resistor and inductor, and ω_i is the frequency generated by PLL.

Finally, combing the inverters, network and loads, the linearized model of the two parallel inverters system can be built into state-space model, which can be expressed as:

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{BU} \quad (10)$$

The states of the system under consideration are defined as:

$$\mathbf{X} = \begin{bmatrix} x_{inv1} & x_{inv2} & x_{load} \end{bmatrix}^T \quad (11)$$

Where the details of states matrix are:

$$\begin{cases} x_{inv1} = \begin{bmatrix} V_{dq1} & I_{Ldq1} & \lambda_{dq1} \end{bmatrix} \\ x_{inv2} = \begin{bmatrix} V_{dq2} & I_{Ldq2} & \lambda_{dq2} \end{bmatrix} \\ x_{load} = \begin{bmatrix} I_{odq1} & I_{odq2} \end{bmatrix} \end{cases} \quad (12)$$

The input vector of the system is defined as:

$$\mathbf{U} = \begin{bmatrix} V_{dq}^* & V_{loaddq} \end{bmatrix} \quad (13)$$

Therefore, the output admittance of inverters is depending on the inverters' dynamic, the filter and the common AC bus, and small-signal model can be built based on (10). The transfer matrix of state-space model can be derived by:

$$\mathbf{G} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} \quad (14)$$

(10) and (14) can be solved by MATLAB symbolic math toolbox. due to limited contexts.

IV. SIMULATION AND EXPERIMENT RESULTS

The simulation has been conducted to compare the conventional droop control and the SRF I-V control. The system includes two parallel three-phase inverters with an LC filter. The electrical circuit and control system parameters are listed in Table I:

TABLE I
SIMULATION PARAMETERS

	Parameters	Value
Inverter and filter	DC voltage V_{dc}	650V
	Filter inductance L_f	1.8mH
	Filter capacitance C	25μF
	Local load	50+*j*2.83Ω
Droop control	k_{pP}, k_{iP}	5e-7,6e-6
	k_{pQ}, k_{iQ}	1e-5, 0
Proposed I-V droop control	Virtual resistance and inductance	2Ω, 8mH
	PLL proportional coefficient	1.4
	dq-axis inverter#1 virtual resistance R_{vird}, R_{virq}	2Ω,1Ω
	dq-axis voltage references V_d^*, V_q^*	100V,0V
	dq-axis normal current I_{d0}, I_{q0}	0A,0A
	PI controller k_p, k_i	0.0018,0.1

The Fig.4. shows the power-sharing performance of two control methods with resistive-inductive line impedance in the case that inverter2 is connected at 4.2s. From the transient response, the setting time of the conventional droop control is approximately 0.6s in Fig.4. (a) (b), and an offset of reactive current can be observed in Fig. 4. (b). However, the setting time of proposed method is approximately 0.08s, and the offset is well suppressed, which implies that the active and reactive powers are shared accurately, as shown in Fig.4. (b) and (c).

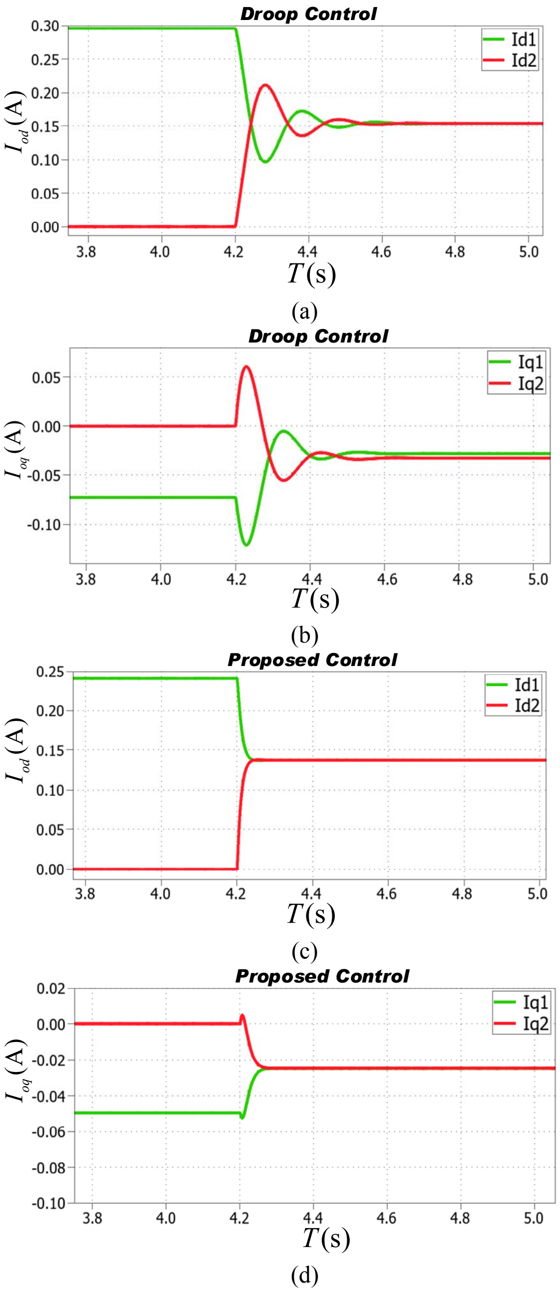

Fig.4. Comparison simulation results when the inverter connection under the conventional droop control ((a) and (b)) and the proposed method ((c) and (d)).

In order to validate the proposed control method, the system platform has been built. An islanded experimental Microgrid setup has been built, which includes two Danfoss 2.2kW inverters, a real-time dSPACE 1006 platform, *LC* filters, resistive load as shown in Fig.5. The experimental parameters are same as the simulation in addition to the *d*-axis voltage reference $V_d^* = 500V$ and the line impedance is 1Ω+1.8mH. The inverter connection case has been considered to test the performances of proposed controller with comparison to the conventional droop controller.

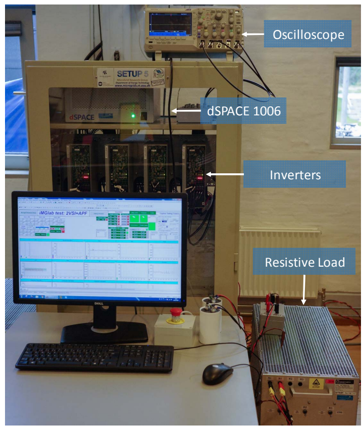

Fig.5. Configuration of the experimental platform

The experiment results of the SRF I-V control are presented in Fig. 6. When the inverter 2 is connected, the setting time of the direct and quadrature output currents is approximately 0.65s to compare with 1.8s setting time of conventional droop control, and the quadrature current is shared via the decoupling control with comparison the q-axis unshared current for droop control. Note that a small overshoot occurs due to inverters voltage error. In conclusion, the proposed method has increased the transient response greatly, and is able to achieve accurate current sharing.

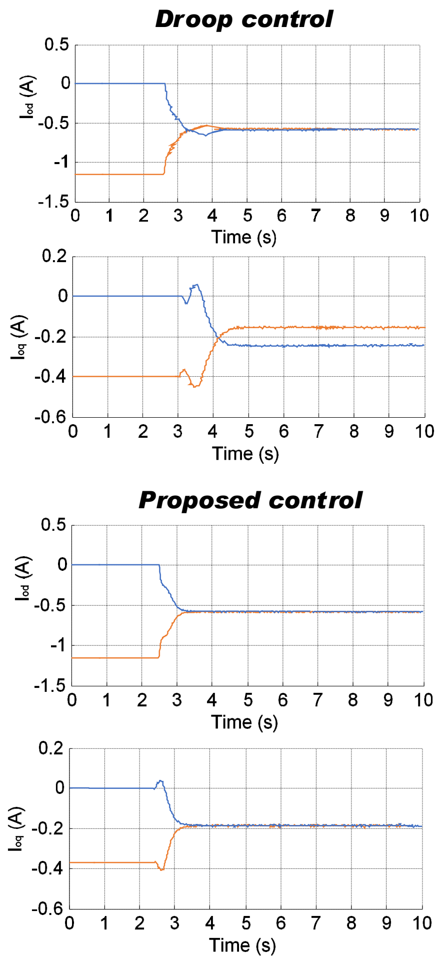

Fig.6 Experimental results of *dq*-axis current output when the inverter connection.

V. CONCLUSION AND FUTURE WORK

A simplified SRF I-V droop control for parallel islanded inverters without communication is proposed, which is able to share the power accurately and get a fast transient response. The state-space model has been derived to analyze the controller performance. The simulation and experiment results verified the merits of the proposed method under the inverter connection situation.

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