Aalborg Universitet

Active Power Regulation based on Droop for AC Microgrid

Li, Chendan; Coelho, Ernane A. A.; Firoozabadi, Mehdi Savaghebi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.

Link to publication from Aalborg University

Active Power Regulation based on Droop for AC Microgrid

Chendan Li, *Student Member, IEEE,* Ernane A. A. Coelho, Mehdi Savaghebi, *Member, IEEE*, Juan C. Vasquez, Senior *Member, IEEE,* and Josep M. Guerrero, *Fellow, IEEE*

Abstract — **In this paper, two different control strategies are proposed to address the active power regulation issue in AC microgrids. The principle of power regulation in the droop controller is firstly introduced. Frequency scheduling and droop gain scheduling on top of droop control is proposed to successfully follow the active power command. The limitation of each method is discussed in term of small signal stability and light load sharing, respectively. Discussion on the effects of power command is also given. The simulation is carried out for both the strategies to verify the active power control of the system.**

Index Terms —**Active power regulation, droop control, frequency scheduling, droop gain scheduling, AC micrgrid, small signal analysis.**

I. INTRODUCTION

To embrace increasing distributed generation, microgrids become promising technology to fulfil the vision of smart grid. As is defined by US Department of Energy (DoE), a microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and that can working in grid-connected mode and islanding mode .Voltage source converter (VSC) is usually employed as an interface between a DG unit and a microgrid, which can be controlled in current control mode (CCM) or in voltage control mode (VCM) according to the controllability of the DG unit [1].

The major concern of the most previous works is focused on sharing the power among the DGs working in VCM based on their respective kVA ratings. In order to achieve this goal autonomously, droop control and its derivatives are proposed to share the load autonomously through droop controller [2]-[4], virtual impedance [5], adaptive tuning [6], etc. However, with more demanding requirements on efficiency, reliability and sustainability, as well as the diversity of power supply resources, energy management system of the microgrid is highly needed, which calls for more power flow management functions besides only sharing the power according to the rated power of the DG unit. To make the power of each DG unit more flexibly controlled, hierarchical control is proposed to mimic the operation of bulk power system, with primary control achieve the autonomous power sharing while mare advanced power control is implemented by upper level control [7]. This work only tackled the power regulation at the point of power coupling (PCC), which aims at the power generation of total generation of the whole microgrid, yet to accurately control the power of each unit with the microgrid, is not detailed in that work. In [2] and [5], adaptive droop is used to improve the stability of the system, the potential of it for accurate power regulation is not explored. Although for CCM VSC, power regulation is usually the objective, which makes the converter connected with wind turbine and solar panel tracing maximal power point. This is achieved by passing the power command directly to the current control loop. However, without droop controller, this type of converters cannot provide power balance and voltage support in islanding mode, and therefore, a microgrid cannot be formed in islanded mode with converters operating in CCM only. To further regulate the power of VSC converters with droop controller, more research is worthy doing.

In this paper, the active power regulation issue of each DG unit based on droop is addressed. The principle of power regulation in the droop controller is elaborated. Two different ways of active power regulation on top of droop control are proposed to successfully follow the active power command. The limitation of each method is discussed in term of small signal stability and sharing the light load respectively. Discussion on the effects of power command is also given. The simulation verified both the strategies for the power control of the system.

II. PRINCIPLE OF ACTIVE POWER DROOP CONTROL

In the droop mode of operation, active power is regulated by the frequency droop, which introduces droop characteristics towards the frequency of the DG unit output voltage at the PCC [1]–[6] such that

$$\omega_i = \omega_{0i} - K_{P_i} P_i \qquad (1)$$

Chendan Li, Mehdi Savaghebi, Juan C. Vasquez and Josep M. Guerrero are with the Institute of Energy Technology, Aalborg University, 9220, Denmark. (e-mail: che@et.aau.dk; skc@et.aau.dk; mes@et.aau.dk; juq@et.aau.dk; joz@et.aau.dk).

Ernane A. A. Coelho is with Universidade Federal de Uberlândia (UFU) - Faculdade de Engenharia Elétrica (FEELT), Uberlândia, Minas Gerais, Brasil 38400-902, (e-mail: ernane@ufu.br).
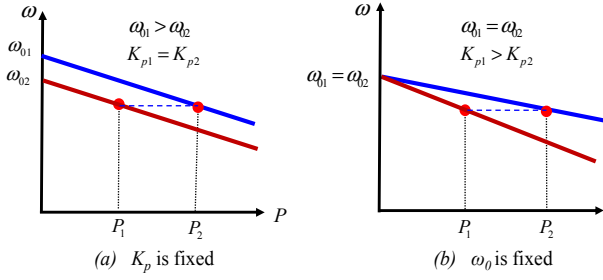
Fig. 1. Active power droop principle

where ω_i, ω_{0i}, K_{Pi} and P_i are the frequency of the output voltage reference, nominal frequency, proportional frequency droop parameter, active power generation of the generator i, respectively.

Not like reactive power, active power sharing is not sensitive to different line impedance and thus can be regulated well by this frequency droop controller [8]. However, in many case, active power of each unit should be regulated according to the specific requirements of the particular applications. For example, in order to achieve state of charge (SoC) balance of the distrusted energy storage system (DES), the active power of droop controlled converters should be regulated according to the SoC of the whole DES [9].

With only the droop controller, however, the specific active power generation cannot be decided accurately. Since according to (1), without communications, the power sharing depends on the choice of proportional frequency droop parameter when ω_{0i} is a constant. Usually, this proportional frequency droop parameter is chosen according to the volume of the converter, so that the active power can be shared proportional to the rating of the distributed generation (DG) units [2]-[4]. In the application which requires accurate power control, only droop controller is not enough.

Considering one DG unit with droop control, according to the frequency droop, there are two possibilities to change the way how active power is shared, which is illustrated in Fig. 2. Under a same system frequency, it can be seen that either changing the frequency droop gain as in Fig.2 (b) or changing frequency given can change the active power sharing. Previous work [2] and [8] has employed adaptive frequency droop gain to achieve SoC balance. Instead of adjusting the droop gain, the adaption of adaptive nominal frequency is also possible to achieve the active power regulation. In the following sessions, these two alternatives are explored and discussed.

III. SMALL SIGNAL STABILITY ANALYSIS OF DROOP CONTROLLED CONVERTERS

In this session, small signal stability analysis of two paralleled converter with droop control is given to show the possible influence of droop gain, and nominal frequency.

In addition to (1), the characteristics of reactive droop is defined as

$$E_i = E_{0i} - K_{Q_i}Q_i \qquad (2)$$

Taking a common d-q reference frame for all the converters, the vector $\vec{E}$ can be represented as

$$\vec{E} = e_d + je_q \qquad (3)$$

The angle and magnitude of the vector can be written as

$$\delta = \arctan(\frac{e_q}{e_d}) \qquad (4)$$

$$E = |\vec{E}| = \sqrt{e_d^2 + e_q^2} \qquad (5)$$

Considering $\Delta\omega(s) = s\Delta\delta(s)$, the state equation for each converter can be obtained as

$$\begin{bmatrix} \Delta\dot{\omega}_i \\ \Delta\dot{e}_{di} \\ \Delta\dot{e}_{qi} \end{bmatrix} = M_i \begin{bmatrix} \Delta\omega_i \\ \Delta e_{di} \\ \Delta e_{qi} \end{bmatrix} + C_i \begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} \qquad (6)$$

where the detailed expressions for matrix M_i and C_i can be obtained from above mentioned equations.

Considering the expressions of active and reactive power supplied by each converter,

$$P_i = e_{di}i_{di} + e_{qi}i_{qi} \qquad (7)$$

$$Q_i = e_{di}i_{qi} - e_{qi}i_{di} \qquad (8)$$

Linearizing the equations above at the equilibrium point, we get the following expression in a symbolic form,

$$\Delta S = I_s\Delta e + E_s\Delta i \qquad (9)$$

where I_s and E_s are constant matrices with respect to the state at equilibrium point , and $\Delta e = [\Delta e_{d1}, \Delta e_{q1}, \Delta e_{d2}, \Delta e_{q2}]^T$, $\Delta i = [\Delta i_{d1}, \Delta i_{q1}, \Delta i_{d2}, \Delta i_{q2}]^T$.

Perturbing the nodal admittance matrix equation of the network, we get

$$\Delta i = Y_s\Delta e \qquad (10)$$

where Y_s is the nodal admittance matrix of the network.

Substituting (22) in (21), we can get

$$\Delta S = (I_s + E_sY_s)\Delta e \qquad (11)$$

The state equation of the whole system can now be obtained as

$$\dot{X} = M_sX + C_s(I_s + E_sY_s)K_sX = AX \qquad (12)$$

where $X = [\Delta\omega_1, \Delta e_{d1}, \Delta e_{q1}, \Delta\omega_2, \Delta e_{d2}, \Delta e_{q2}]^T$, $C_s = \begin{bmatrix} C_1 \\ & C_2 \end{bmatrix}$,

$M = \begin{bmatrix} M_1 \\ & M_2 \end{bmatrix}$,

$K_s = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$,

$A = M_s + C_s(I_s + E_sY_s)K_s$.

The root locus plot of the system for K_{pi} from 0 to 0.005 is shown in Fig. 3, when the damping ratio is 0.24, $K_{pi} \approx 0.002$. Here we chose damping ratio as 0.24 and less damping will make system seriously oscillation during disturbance.
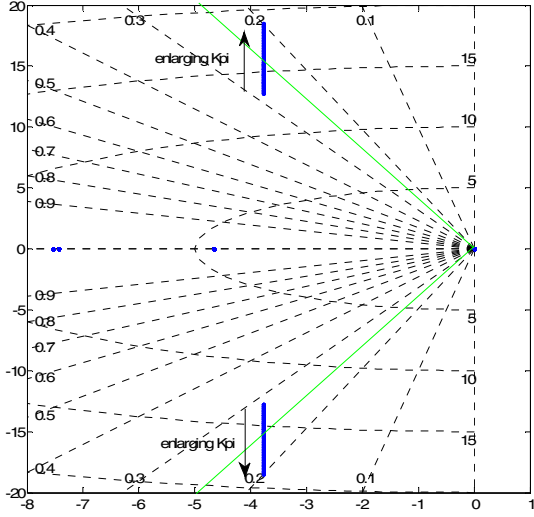
Fig. 2. Eigenvalue trace with different K_{pi}

Since with this model, the nominal frequency doesn't appear in the small signal model, therefore the influence of it is overlooked, except it should be bounded by the frequency variation band of the utility.

IV. STRATEGIES FOR ACTIVE POWER REGULATION BASED ON DROOP

In this section, two strategies based on droop control are proposed to regulate the active power.

A. Frequency scheduling for active power regulation

Since modifying the adaptive droop will change the output characteristic of converter, as is shown in Fig. 1 (a),

it is easy to think out to accurately control the active power in this way. The control diagram of the proposed strategy is shown in Fig. 3. The regulator here chooses the PI controller. The measured active power is compared with the command, and pass through the PI controller. The compensation term is then added to the original nominal frequency.

B. Droop gain scheduling for active power regulation

Similarly, as changing the droop gain K_{pi} can also vary the active power generation of the DG unit, the power regulation loop can be added to this variable. The control diagram of this idea is shown in Fig. 4.

V. SIMULATION RESULTS

In order to test the effectiveness of these proposed distributed control strategies, simulation is carried out in a system with three droop controlled VCM converters based on Matlab SimpowerSystems. Firstly, case study for verification is carried out when the active power command is correctly given. To show that proposed methods also work when the active power command is not correctly given, another case study is added. The system parameters of the tested system are shown in Table I.

A. Case study I

In this session, two strategies are verified in the case of power command change and the case of load and corresponding command changes. At the beginning, the power regulation is cutting in, and the active power command is 1336W, 1000W and 800W respectively for unit 1, unit 2, and unit 3. At the time of 25s, the power regulation command is changing to 1436W, 700W and 1000W respectively. At the time of 50s, one additional
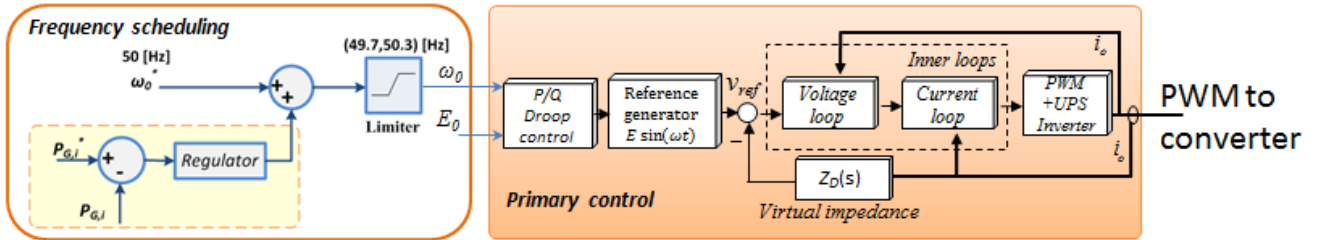

Fig. 3. The control diagram of frequency scheduling for active power regulation
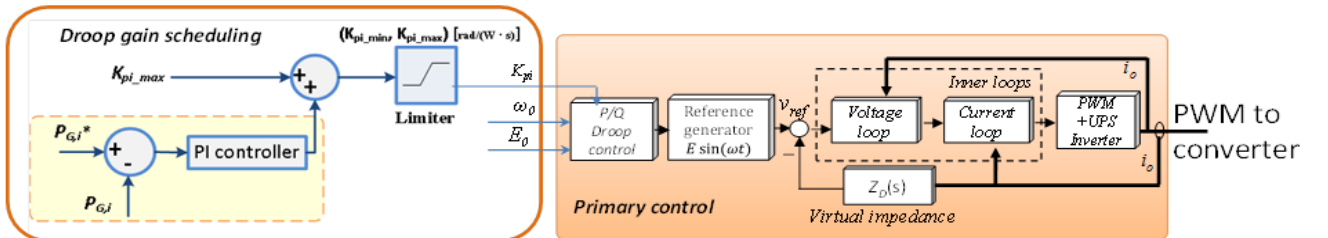
Fig. 4. The control diagram of droop gain scheduling for active power regulation

Parameters	Symbol	Value	Units
Nominal voltage	E_{0i}	230	V
Nominal frequency	ω_0^*	314	rad/s
Cut-off frequency of low pass filter for each DES unit	ω_f	0.7	rad/s
Proportional frequency droop for each DES unit	K_{Pi}	0.002	rad/Ws
Proportional amplitude droop for each DES unit	K_{Qi}	0.02	V/Var
LC filter inductor for each DG unit	L_f	1.8	mH
LC filter capacitor for each DG unit	C_f	27	μF
Initial load impedance	Z_D	89.7904 +20.1555i	Ω

100Ω load is activated, and the corresponding active power command is changing to 1527W, 800W, and 1200W. The active power generation result and the changing of scheduled value is show in Fig. 5 and Fig. 6 for the two methods respectively.

B. Case study II

This session gives the results when the power command is not given correctly. In this case, the proposed method should not jeopardize the merit of the droop control which
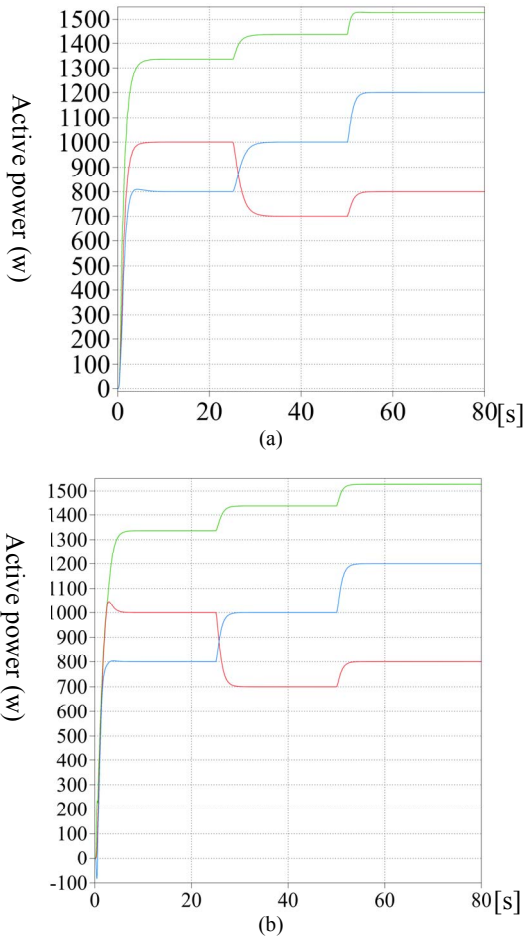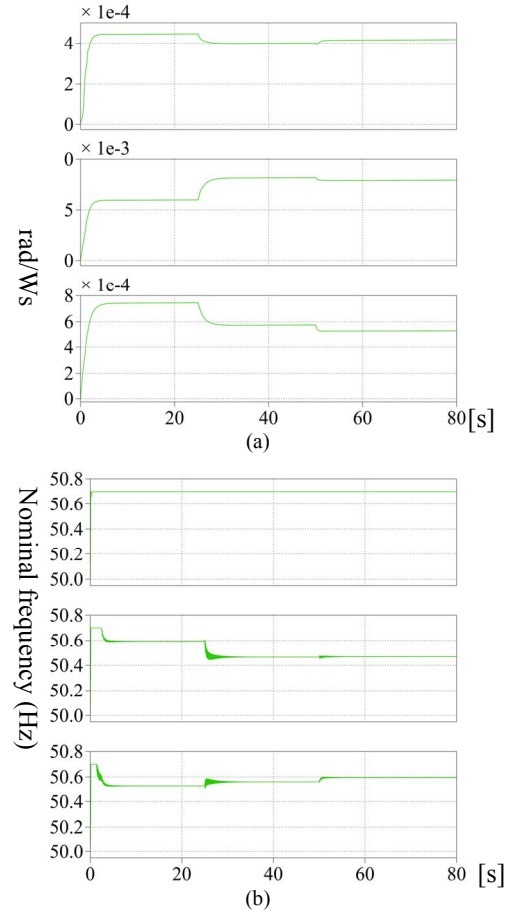

(a)

(b)

Fig. 6. Changing of the control parameters (a) changing of droop gain (b) Changing of nominal frequency

can share the power autonomously. The simulation is done under the same load but with the active power command as 1436W, 1100W and 900W instead of correct command as 1336W, 1000W and 800W. The active power using these two methods is show in Fig. 7. Although the system cannot follow the wrong command, they will stabilize at a nearby value.

(a)

(b)

Fig. 5. Active power generation using (a) droop gain scheduling (b) frequency scheduling

VI. CONCLUSIONS

In this paper, two different ways of active power regulation on top of droop control is proposed and verified.
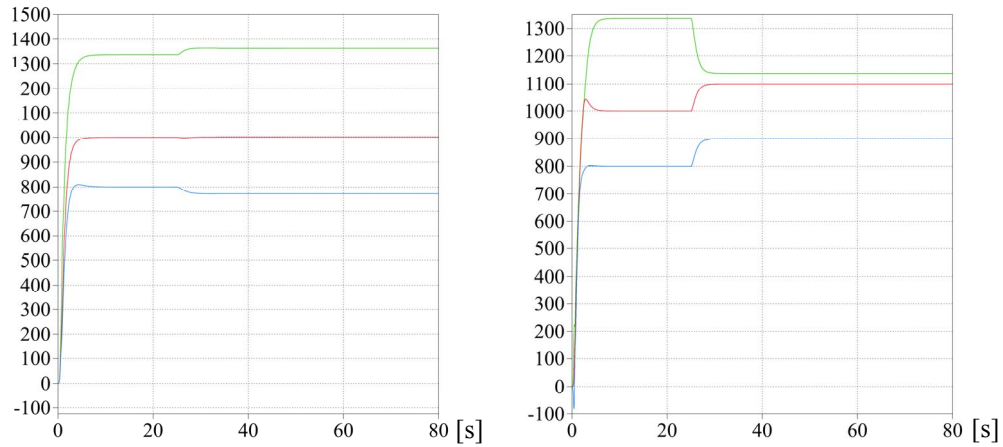
Fig. 7.   Wrong command under (a) droop gain scheduling (b) frequency scheduling

The method based droop gain scheduling has the advantage of no negative power during start up, but is superior to the second method in terms of stability, since the system is more sensitive to the droop gain. The strategy based on frequency scheduling has the advantage of less effect to the stability yet, might not be suitable for irreversible power generation resources which might cause negative power generation during light load or start up.   The proposed methods can also working in the condition where the active power is not correctly given, and thus add more robust to the system.

REFERENCES

[1]   J. M. Guerrero, J. Matas, L. Garcia de Vicuna, M. Castilla, and J. Miret, "Decentralized control for parallel operation of distributed generation inverters using resistive output impedance*," IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 994–1004, Apr. 2007.
[2]   F. Katiraei and M. R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," *IEEE Trans. Power Syst.*, vol. 21, pp. 1821–1831, 2006.
[3]   N. Pogaku, M. Prodanovic, and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," *IEEE Trans. Power Electron.*, vol. 22, no. 2, pp. 613–625, Mar. 2007.
[4]   Y. W. Li and C. N. Kao, "An accurate power control strategy for power-electronics-interfaced distributed generation units operating in a low-voltage multibus microgrid," *IEEE Trans. Power Electron.*, vol. 24, pp. 2977–2988, 2009.
[5]   A. Haddadi and G. Joos, "Load sharing of autonomous distribution-level microgrids," *in Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–9.
[6]   Y. Mohamed and E. F. El-Saadany, "Adaptive decentralized droop controller to preserve power sharing stability of paralleled inverters in distributed generation microgrids," *IEEE Trans. Power Electron.*, vol. 23,
[7]   Guerrero, J.M.; Vasquez, J.C.; Matas, J.; de Vicuña, L.G.; Castilla, M., "Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization," *Industrial Electronics, IEEE Transactions on* , vol.58, no.1, pp.158,172, Jan. 2011
[8]   Xiaonan Lu; Kai Sun; Guerrero, J.; Lipei Huang, "SoC-based dynamic power sharing method with AC-bus voltage restoration for microgrid applications," *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society* , vol., no., pp.5677,5682, 25-28 Oct. 2012
[9]   Chendan Li; Chaudhary, S.K.; Vasquez, J.C.; Guerrero, J.M., "Power flow analysis for droop controlled LV hybrid AC-DC microgrids with virtual impedance," *PES General Meeting | Conference & Exposition*, 2014 IEEE , vol., no., pp.1,4, 27-31 July 2014
[10]   Chendan Li; Tomi, Ernena, Vasquez, J.C.; Guerrero, J.M., "Power flow analysis for droop controlled LV hybrid AC-DC microgrids with virtual impedance," in pressing.