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Lu, Jinghang; Savaghebi, Mehdi; Guerrero, Josep M.

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Flexible operation of parallel grid-connecting converters under unbalanced grid voltage

ABSTRACT

Under grid voltage unbalance, grid-connecting converters should be always connected to the grid. However, voltage unbalance has adverse effect on the stable operation of the converters, such as active power oscillation, DC link voltage ripple and overloading. Thus, it is needed to investigate parallel operation of grid-connecting converters interfacing DC and AC buses and propose flexible control strategies to solve the aforementioned issues. In this digest, a thorough study on factors that influence the peak current of single converter is conducted. In addition, based on the principle that total output active power should be oscillation free, a coordinated control strategy is proposed for two parallel converters. Case study has been conducted to demonstrate the effectiveness of this proposed control strategy.

I. Introduction

In the past few years, the high penetration of Renewable Energy Source (RES) and Distributed Generation (DG) systems have been drawing public's increasing attention. DGs and RESs may share a common DC bus for better power management [1], meanwhile, parallel grid-connected inverters are usually adopted to interlink between DC and AC buses for larger power transfer to the grid [2]. According to the grid code [3], these paralleled inverters are required to be connected to the grid under grid voltage unbalance or even grid fault. However, operation of grid-connected inverters in the case with grid voltage unbalance may cause active power oscillation at twice grid-frequency and lead to exceeding limitation of the phase current. Moreover, active power oscillation in turn results in DC link voltage ripple which may damage the DC link capacitor [4].

In order to limit the output current and reduce active power oscillation, [5-16] have investigated various control strategies, among which [12] ensures the minimum peak current values of injected current, but harmonic current was increased to meet the objective, leading to overcurrent. Although in [10] and [12] control strategies are developed to avoid overcurrent tripping, these strategies are only related to reactive power delivery under unbalanced grid and result in active and reactive power oscillation. References [8] and [9] proposed flexible controllers that enable Low Voltage Ride Through (LVRT) by injecting positive and negative sequence current and maintaining the peak phase current to a predefined value, however, this control strategy are too complex to be applicable in practical cases.

On the other hand, the published research on paralleled grid-connecting converters under unbalanced grid voltage is quite limited. References [5] and [17] proposed similar control strategies by defining one control coefficient to set the current reference. Starting from this idea, this digest proposes a more generalized active power control strategy. To the best of author's knowledge, this generalized control strategy for parallel grid-connecting converters has not been reported and investigated yet. In this method, zero active power oscillation while respecting the current limitation is achieved by cooperative control of parallel grid-interfacing inverters. Furthermore, the procedure of control system design is introduced and discussed. The results of a case study are provided to verify the proposed control strategy.

II. Flexible control of parallel grid-connecting converters

Fig.1 shows a typical microgrid with parallel grid-connecting inverters. These inverters are used to achieve high power transfer from DG units to AC grids. According to the grid codes in Europe [3], under unbalance grid voltage condition, DG units that comprised of PV system must only inject active power into the grid. Therefore, only active power transfer is considered in this digest.

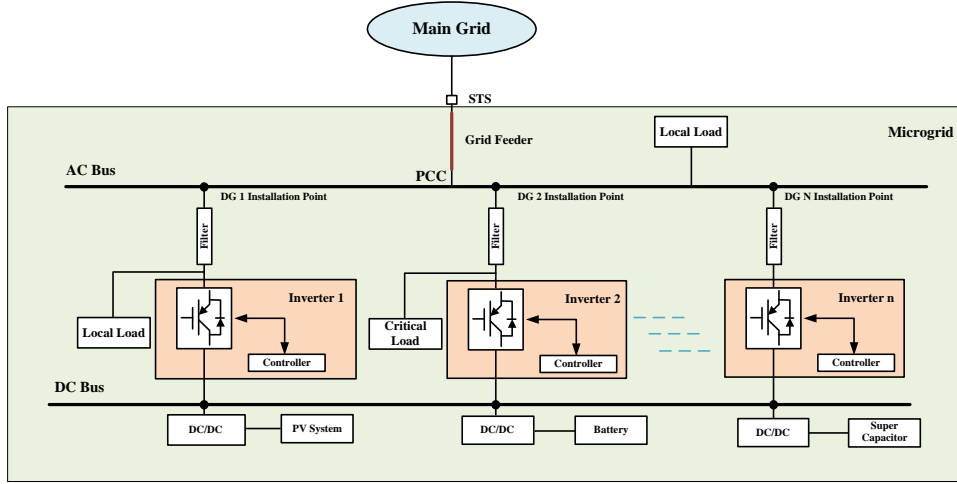


Fig.1 Configuration of microgrid with multiple grid-connected inverters between DC bus and AC bus

Besides, considering operation under unbalance grid voltage, injecting a balanced current may incur the active power oscillation at twice of grid frequency, which may adversely affect the DC link voltage and operation stability. Therefore, based on [6], a set of reference currents that comprise positive

and negative sequence currents and described as follows should be applied:

$$i_p^* = \frac{2}{3} \frac{k_p^+ P^*}{k_p^+ |v^+|^2 + k_p^- |v^-|^2} v^+ + \frac{2}{3} \frac{k_p^- P^*}{k_p^+ |v^+|^2 + k_p^- |v^-|^2} v^- \quad (1)$$

where k_p^+ and k_p^- are the control parameter to generate appropriate positive and negative sequence current. v^+ and v^- are positive and negative sequence vectors. Moreover, the parameter ranges are $k_p^+ > 0$ and $-\infty < k_p^- < +\infty$, which provide flexible current injection strategy. Compare (1) with current reference generation of [5], it is observed that current reference generation of [5] is only one special case of (1). Therefore, (1) will offer a more generalized form of current reference generation. The peak amplitude of abc frame current can be easily calculated by applying the inverse-Clark transformation to (1):

$$I_a^{max} = \frac{2}{3} M \sqrt{(k_p^+ V^+)^2 + (k_p^- V^-)^2 + 2k_p^+ k_p^- V^+ V^- \cos(\delta)} \quad (2)$$

$$I_b^{max} = \frac{2}{3} M \sqrt{(k_p^+ V^+)^2 + (k_p^- V^-)^2 + 2k_p^+ k_p^- V^+ V^- \cos(\delta - \frac{2}{3}\pi)} \quad (3)$$

$$I_c^{max} = \frac{2}{3} M \sqrt{(k_p^+ V^+)^2 + (k_p^- V^-)^2 + 2k_p^+ k_p^- V^+ V^- \cos(\delta - \frac{4}{3}\pi)} \quad (4)$$

where $M = \frac{P^*}{k_p^+ (V^+)^2 + k_p^- (V^-)^2}$, $V^+ = \sqrt{(v_\alpha^+)^2 + (v_\beta^+)^2}$, $V^- = \sqrt{(v_\alpha^-)^2 + (v_\beta^-)^2}$. $\delta = \cos^{-1} \left(\frac{(v_\alpha^+ v_\alpha^- - v_\beta^+ v_\beta^-)}{V^+ V^-} \right)$

Therefore, from (2)-(4) it is clearly seen that if $k_p^- < 0$, the minimum value of the cosine function has the direct relationship with the maximum phase current: $\cos_{min} = \min\{\cos(\delta), \cos(\delta - \frac{2}{3}\pi), \cos(\delta + \frac{2}{3}\pi)\}$ (5)

On the contrary, if $k_p^- > 0$, the maximum value of the cosine function has the direct relationship with the maximum phase current:

$$\cos_{max} = \max\{\cos(\delta), \cos(\delta - \frac{2}{3}\pi), \cos(\delta + \frac{2}{3}\pi)\} \quad (6)$$

As V^+ V^- the voltage amplitudes in the unbalanced case and phase angle δ can be determined by online calculation, the maximum current phase current can be expressed as:

$$I_{max} = \frac{2}{3} M \sqrt{(k_p^+ V^+)^2 + (k_p^- V^-)^2 + 2k_p^+ k_p^- V^+ V^- \cos_{max}} \quad (7)$$

Therefore, considering (5)-(7), the maximum current of each phase depends on amplitude of positive and negative sequence voltages, phase angle difference, and adjustable coefficients k_p^+ and k_p^- . Based on the sign of k_p^- , the following two situations can be considered:

When $k_p^- > 0$ (in the case that $k_p^- = 1$, Fig. 2(a) illustrates a 3-D plot showing the relationship among k_p^+ , theta and peak current and Fig.2(b) provides relationship between peak current and theta when $k_p^- = 1$ and k_p^+ varies from 0.5

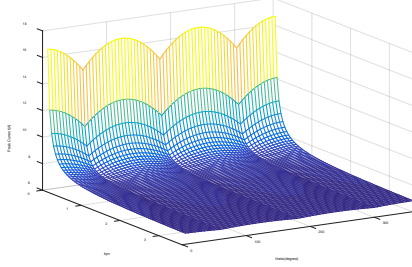


Fig.2 Relationship among k_p^+ , theta and Peak current when $k_p^- = 1$

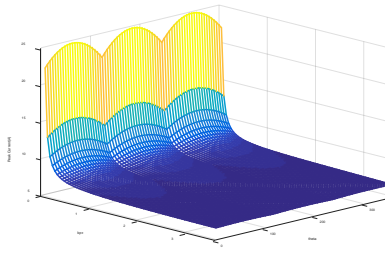


Fig.3 Relationship among k_p^+ , theta and Peak current when $k_p^- = -1$

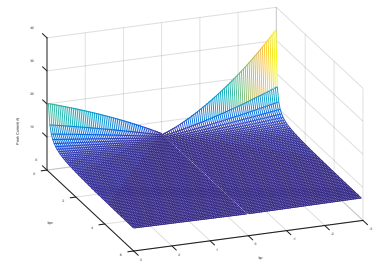


Fig. 4 Relationship among k_p^+ , k_p^- and Peak current

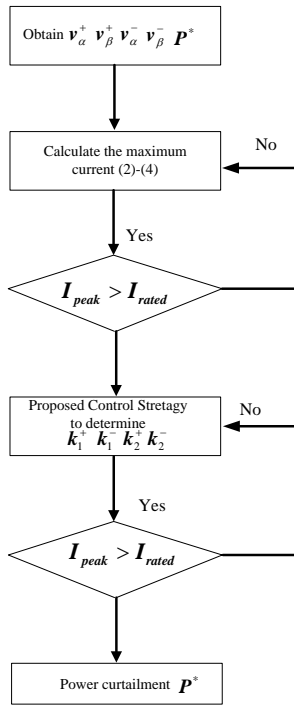


Fig.5 Flow chart of proposed control

to 1.5. It shows that peak current related with theta is a periodic waveform. In addition, peak current value monotonously reduced with k_p^+ increasing from zero.

Moreover, peak current will reach minimum value of $\frac{2}{3} \frac{P^*}{|v^+|}$ when k_p^+ go to infinity.

Fig. 3 shows a similar relationship among k_p^+ , theta and peak current when $k_p^- < 0$ (in this case $k_p^- = -1$). It illustrates that peak current has a periodic waveform as well meanwhile the peak current continuously reduced to the minimum value of

$\frac{2}{3} \frac{P^*}{|v^+|}$ with the k_p^+ increasing. Finally, the relationship among k_p^+ , k_p^- and peak current are shown in Fig. 4, from which it can be observed that with $k_p^- = 0$ the lowest peak current can be achieved.

III. Investigation of active power oscillation

According to the instantaneous power theory [6], during grid voltage unbalance, the instantaneous active and reactive powers injected by converter can be expressed as:

$$p = (v^+ + v^-) \cdot (i^+ + i^-) = P + \tilde{p} \quad (8)$$

where v^+, v^-, i^+, i^- are positive and negative sequence component of voltage and current vectors, and P and \tilde{p} are average value and oscillatory term of active power, respectively. In (8), P and \tilde{p} are equal to $P = v^+ \cdot i^+ + v^- \cdot i^-$ and $\tilde{p} = v^+ \cdot i^- + v^- \cdot i^+$, respectively. By relating (1) and (8), average and oscillatory parts of active power are expressed as:

$$P = \frac{k_p^+(V^+)^2}{k_p^+(V^+)^2 + k_p^-(V^-)^2} P^* + \frac{k_p^-(V^-)^2}{k_p^+(V^+)^2 + k_p^-(V^-)^2} P^* \quad (9)$$

$$\tilde{p} = \frac{(k_p^+ + k_p^-) v^+ v^-}{k_p^+(V^+)^2 + k_p^-(V^-)^2} P^* \quad (10)$$

Therefore, for a single DG unit, making $k_p^+ = -k_p^-$ results in active power oscillation free.

Meanwhile, in the case of multiple DG units, it is needed to deliver as much as possible active power to the grid, therefore, the active power oscillation is expressed as:

$$\sum_{i=1}^n \tilde{p}_i = \tilde{p}_1 + \tilde{p}_2 + \dots + \tilde{p}_n = \left\{ \frac{(k_{p1}^+ + k_{p1}^-)}{k_{p1}^+(V^+)^2 + k_{p1}^-(V^-)^2} + \frac{(k_{p2}^+ + k_{p2}^-)}{k_{p2}^+(V^+)^2 + k_{p2}^-(V^-)^2} + \dots + \frac{(k_{pn}^+ + k_{pn}^-)}{k_{pn}^+(V^+)^2 + k_{pn}^-(V^-)^2} \right\} \quad (11)$$

Considering two parallel converters interfacing into grid, in order to make oscillation-free active power and ripple-free dc link voltage, the following expression should be followed:

$$\frac{(k_{p1}^+ + k_{p1}^-)}{k_{p1}^+(V^+)^2 + k_{p1}^-(V^-)^2} + \frac{(k_{p2}^+ + k_{p2}^-)}{k_{p2}^+(V^+)^2 + k_{p2}^-(V^-)^2} = 0 \quad (12)$$

IV. Proposed Control Strategy for Parallel Grid-connecting converters under unbalanced grid voltage

In this section, a novel control strategy is proposed for the parallel converters to achieve one common objective: active

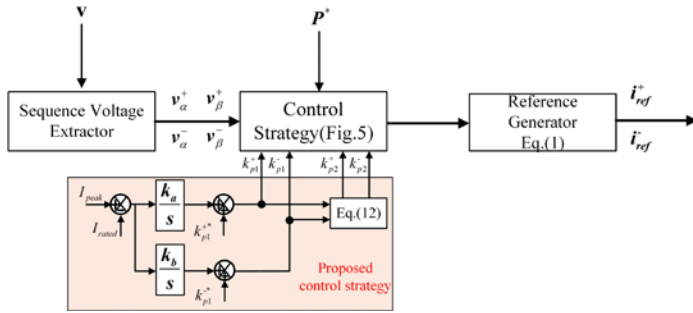


Fig. 6 Block diagram of the proposed control scheme

power oscillation to be zero meanwhile limiting the peak current to the predefined value I_{max} . Therefore, in order to limit the peak current of grid-interfacing converter in the range of current rating, k_p^+ should move towards infinity while k_p^- should move to zero to make sure the peak current reaches its minimum value when voltage unbalance occurs, if it still cannot promise the peak current within the range of current rating,

active power reference should be reduced to guarantee the peak current reduction as is shown in the flowchart of Fig.5.

The proposed control strategy is shown in Fig. 6

V. Case Study

In order to verify the proposed control strategy, operation of two grid-connecting converters in parallel is investigated with Matlab/Simulink (Fig.7). It should be noted the second grid-connecting converter as the complementary converter

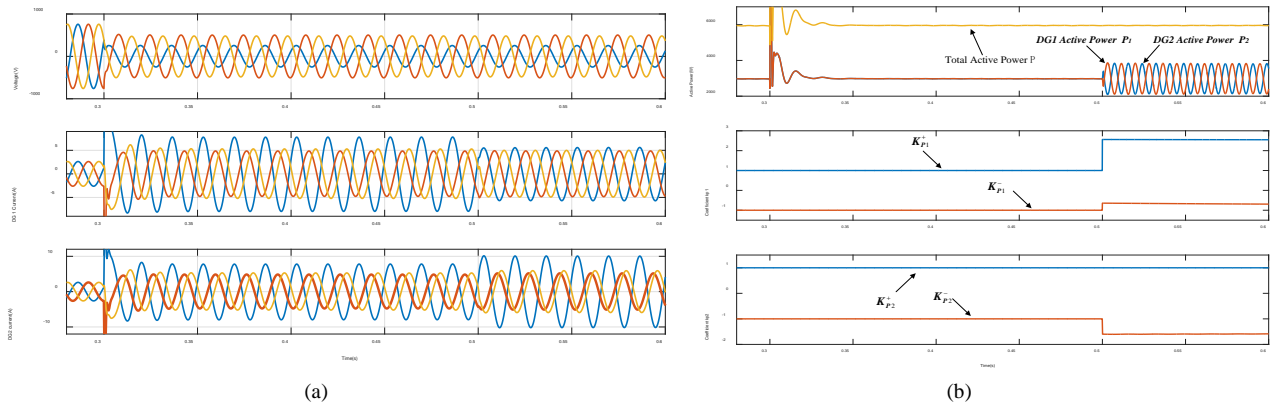


Fig.7 Simulation Results of Parallel converters operation in Voltage Unbalance

should have greater power capacity. First, the current limitation of DG1 is set to 5.8A, and at the normal operation $k_{p1}^+ = 1, k_{p1}^- = -1, k_{p2}^+ = 1, k_{p2}^- = -1$ (see Fig.7(b)). At 0.3s, a grid fault occurs to the system, leading to

voltage unbalance at PCC (see Fig.7(a)), at this time, peak current of DG 1 rises to 6.7A which exceeds the current rating. Meanwhile, due to $k_{p1}^+ = 1, k_{p1}^- = -1$, and $k_{p2}^+ = 1, k_{p2}^- = -1$ (Eq.10), there does not exist active power oscillation (Fig.7(b)). At 0.5s, the proposed current regulation is initiated, from Fig. 7(b) it can be observed that k_{p1}^+ increases from 1 to 2.6 and k_{p1}^- grows from -1 to -0.8 to meet the current regulation requirement. Therefore, DG1's peak current is limited within 5.8A limit. In addition, as the complementary converter, according to (Eq.12), the value of k_{p2}^- is automatically calculated when keeping k_{p2}^+ at 1 (Fig.7(b)). Therefore, although both DG1 and DG2 suffer from active power oscillation at twice of fundamental frequency, the total output active power is still kept free of oscillations.

VI. CONCLUSIONS and FUTURE WORK

This digest proposed a control strategy for parallel grid-connecting converters under unbalanced grid voltage. By adjusting the coefficient of individual converter, the peak current limitation is realized. Moreover, with cooperative operation of the complementary converter, the total active power is free of oscillation. Simulation and Experimental results shows the effectiveness of the proposed control strategy. More detailed analysis and experimental results will be given in the full paper.

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