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Conditional Droop Adjustment for Reliability-Oriented Power Sharing in Microgrids

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***Abstract* – Power electronic systems are facing the challenge to function more safely and reliably. Reliability-oriented power sharing is thereby employed in multi-converter systems to reduce the cost of end-of-life maintenance. One typical approach is to adaptively adjust the droop gains of the converters solely based on the accumulated damage to the power devices. However, this does not always hold throughout the entire loading profile, possibly ending up with a contradiction from higher reliability. Hence, this paper generalizes the reliability-oriented power sharing by necessitating the adjustment of active droop gains considering the nominal power. Two operation regions are formalized by the nominal point, where the adjustment goes into opposite directions. The principle is validated by short-term experiments and long-term simulations estimating the B_{10} lifetime (10% probability of failure), revealing the improvement of system-level reliability especially under fluctuating loads or operator commands.**

***Index Terms* – Power electronic systems, AC microgrids, reliability, active power, droop control, power distribution.**

I. Introduction

Power electronics are enabling miscellaneous types of power conversion and industrial applications [1], and the semiconductors and passive components are playing dominant roles in terms of controlling. However, due to the increasing number and diversity of components, the degradation of components appears to be more critical, and could lead to serious loss of functionality of the entire system. It is consequently practical to model the reliability performance of power electronic systems, which describes the ability of the system to perform desired functions within a desired time span [2]. Reliability is commonly evaluated by the probabilistic combination of component-level indices [2], [3], and the estimated lifetime implies when it is highly probable for a functional failure to appear. By improving the performance of power electronics systems, the costly maintenance can be reduced, which thereby contributes to a lower cost in the long run.

Reliability-oriented control in power electronics systems is then introduced, e.g., adaptively adjusting the operation points [4], the switching strategies [5], or the control gains [6], [7]. In [7], reliability-oriented droop control is implemented in multi-converter systems like microgrids, such that the converters consuming more lifetime share less loading. The stresses on converters are supposed to be distributed as evenly as possible, where the converter with the least available lifetime determines the lower bound of the system time-to-failure. However, the adjustment should not be entirely one-way like in [7], especially for active power sharing in AC microgrids. When the load fluctuates, the existing method could contradict the averaging of lifetime among converters and in turn lower the system-level reliability. Thus, the adjustment needs to be reformatted.

In this paper, formal restrictions are revealed on active power droop assignments for an improved reliability-oriented power sharing seen from a practical perspective. It is revealed that the adjustment is related to both the consumed lifetime and the nominal operation points of converters, wherein the latter is ignored in prior-art studies and can be decisive in the proposed adjustment strategy. The improved guideline for the reliability-oriented active power sharing is thereby established, which can effectively enhance the system-level reliability of a multi-converter power electronics system as illustrated by experimental results and long-term evaluations.

II. Conditional Reliability-Oriented Power Sharing

A. Reliability-Oriented Power Sharing

A three-phase AC microgrid is exemplified in Fig. 1 as the study case, consisting of two DC-AC converters with the same capacity and a resistive load at the point of common coupling (PCC). Droop controllers are adopted for both converters. The active power droop equation is given in (1) [8].

$$f = f_0 - m_{p0}\left(P - P_0 \right) \tag{1}$$

where $m_{p0} \geq 0$ is the initial droop gain and (P_0, f_0) is the nominal

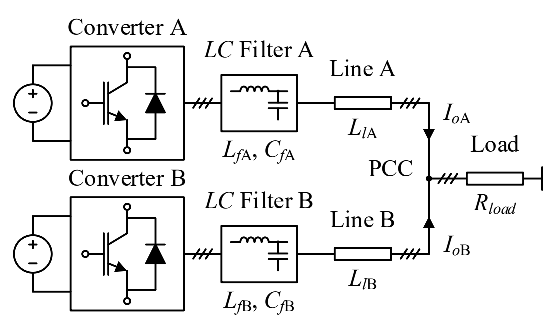

Fig. 1. Schematic of the exemplified three-phase AC microgrid.

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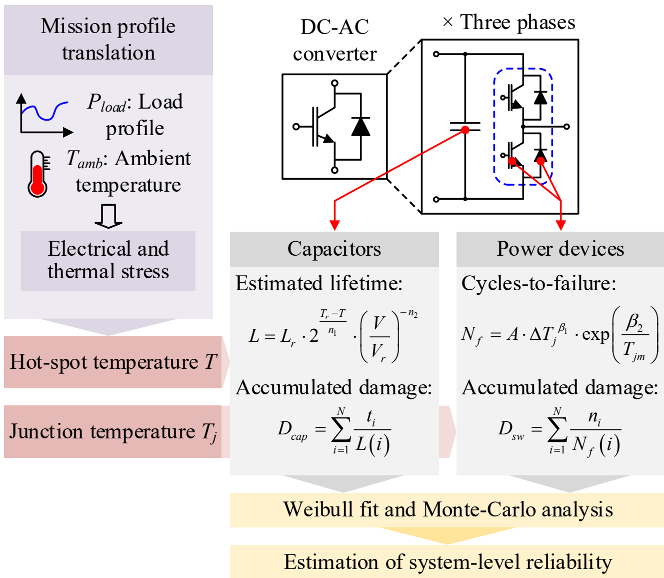

Fig. 2. Procedure of the system-level reliability evaluation of a three-phase DC-AC converter or multi-converter system [2]. The system reliability is evaluated based on the probabilistic combination of component reliabilities.

operation point (frequency and active power). The droop gain m_{p0} is normally designed based on the maximum frequency deviation with respect to the maximum loading capacity.

Remark I: If the system has reached steady-state operation, the frequencies of converters should be equal, i.e., $f_A = f_B$.

According to [2], the overall reliability of a converter or a system can be evaluated following the procedure shown in Fig. 2, where the failures of capacitors and power devices are considered. The reliability can be assessed by the *consumed lifetime* (*CL*) or *accumulated damage* (*D*), reflecting the degradation of components when stresses accumulate. The two metrics are formulated in Fig. 2, and they can be normalized into a per-unit value between 0 and 1 on the basis of estimated lifetime, e.g., D = 1 if a component is completely worn out. With this, the accumulated damage of a converter can be represented by the average or the maximum of all the critical components considered [7], [9]. Generally, the availability of the system is normally limited by the converters inside the system with the least lifetime or the lowest reliability.

In [7], the power between converters is re-distributed to compensate for the stresses of more *fragile* converters such that the converters consuming more lifetime share less loading. The power sharing strategy in [7] is given as:

$$m_p = m_{p0} \cdot \left[\alpha + (1-\alpha) \cdot \left(\frac{D_i}{D_0}\right)^{\lambda}\right] \tag{2}$$

where $0 \le \alpha \le 1$ is a weighting factor between the proportional and reliability-enhanced power sharing, $\lambda > 0$ indicates the role of D_i in affecting the droop gain, D_i is the accumulated damage of the i-th converter, and D_0 is the reference value of D_i.

As $0 \le \alpha \le 1$, $1–\alpha \ge 0$. For all converters in the system, the highest D_i will always correspond to the largest droop gain m_p:

$$m_p \le m_{p0} \cdot \left[\alpha + (1-\alpha) \cdot \left(\frac{max\{D_i\}}{D_0}\right)^{\lambda}\right] = m_{p,maxD} \tag{3}$$

Therefore, this one-way adjustment strategy of (2) can actually contradict the objective of reliability enhancement when, e.g., system operators update P_0 by tertiary functions. The difference P–P_0 can trigger reliability considerations apart from the droop gains, and thus, a two-conditional adjustment is derived to generalize the power sharing for all cases.

B. Two-Conditional Adjustment of the Active Droop Gain

In Fig. 1, it is assumed that the droop gains of both converters are initially equal and the nominal operation points (P_0, f_0) are also identical. Based on Remark I, the following holds:

$$\Delta f = m_{pA}\,(P_A - P_0) = m_{pB}\,(P_B - P_0) \Rightarrow \frac{m_{pA}}{m_{pB}} = \frac{P_B - P_0}{P_A - P_0} \tag{3}$$

With this, given that Converter A is consuming more lifetime, or $D_A \ge D_B$, then $P_A \le P_B$, as illustrated in Fig. 3.

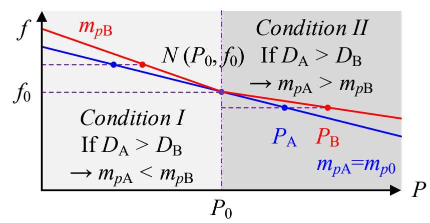

Fig. 3. Illustration of the two conditions. N (P_0, f_0) is the nominal operation point. Droop gains are adjusted oppositely under the two conditions.

- *Condition I:* If $P_A \le P_B < P_0$: $P_A - P_0 \le P_B - P_0 < 0$, then

$$\frac{P_B - P_0}{P_A - P_0} \le 1 \Rightarrow m_{pB} \ge m_{pA} > 0 \tag{4}$$

When a converter is operating on the left side of the nominal point, its droop gain should be *reduced* to share less loading.

- *Condition II:* If $P_0 < P_A \le P_B$: $P_B - P_0 \ge P_A - P_0 > 0$, then

$$\frac{P_B - P_0}{P_A - P_0} \ge 1 \Rightarrow m_{pA} \ge m_{pB} > 0 \tag{5}$$

When a converter is operating on the right side of the nominal point, its droop gain should be *increased* to share less loading.

- *Condition III:* If $P_A \le P_0 \le P_B$, to achieve the same frequency, the only operation point is that $P_A = P_0 = P_B$.

Therefore, compared to the prior-art methods, the droop gain should normally be adjusted according to Conditions I and II, as also illustrated in Fig. 3.

Accordingly, the proposed adjustment rules for droop gains are generalized as:

$$m_p = m_{p0} \cdot \left[\alpha + (1-\alpha) \cdot \beta^{\lambda}\right] \tag{6}$$

where β is the adjustment coefficient with respect to the *CL*. The droop gains can be updated as frequently as the tertiary change of power, but the adjustment of droop gains should not violate the stable operation of the system. Certain examples of the adjustment strategies are given in Table I.

TABLE I
ADJUSTMENT STRATEGIES FOR ACTIVE DROOP GAINS BASED ON THE PROPOSED TWO-CONDITIONAL PRINCIPLE

Strategies of active power droop adjustment	Value of β under Condition I	Value of β under Condition II
Proportional adjustment	$\beta_{\mathrm{I}} = D_0/D_i$	$\beta_{\mathrm{II}} = D_i/D_0$
Complementary adjustment	$\beta_{\mathrm{I}} = 1 - D_i$	$\beta_{\mathrm{II}} = D_i$
Composite adjustment	$\beta_{\mathrm{I}} = (1-D_i)/(1-D_0)$	$\beta_{\mathrm{II}} = (1-D_0)/(1-D_i)$

III. CASE STUDIES

A. Experimental Tests on Short-Term Performance

To validate the short-term performance of the proposed method, experimental tests have been conducted according to the system in Fig. 1. The experimental setup is shown in Fig. 4. Two racks with three-phase 7-kW DC-AC converters are employed, and the key parameters are listed in Table II.

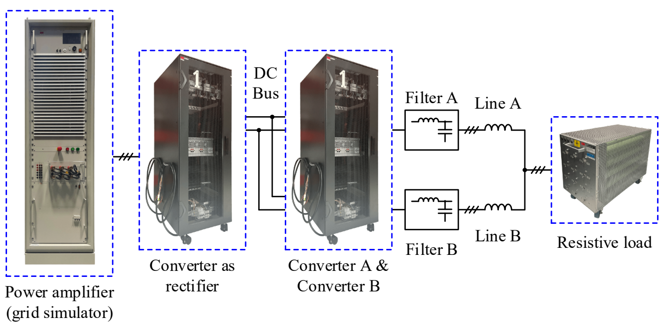

Fig. 4. Structure of the experimental setup. Two three-phase DC-AC converters are installed in each converter rack.

TABLE II
KEY PARAMETERS OF THE STUDY CASE IN EXPERIMENTS

Parameters	Values
Rated phase voltage and frequency	110 V rms, 50 Hz
Rated power of converters	7 kW
Initial active droop gain m_{p0}	9.4×10^{-5} [Hz/W]
Initial reactive droop gain n_{q0}	1.3×10^{-3} [V/Var]
Rated power of Load P_{load}	1.38 kW
Parameters of the LC filters	$L_{fA} = L_{fB} = 2.0$ mH $C_{fA} = C_{fB} = 10$ µF
Parameters of line inductances	$L_{lA} = L_{lB} = 0.5$ mH

The experimental results are shown in Fig. 4. It is assumed that the CLs of the two converters are D_A and $D_B = 0.6D_A$ respectively, and the reference value $D_0 = D_A$. Four stages are studied, as marked in Fig. 5. In Stage II, the adjustment of active droop gains is activated, where $\alpha = 0$ and $\lambda = 1$. In Stage III, the nominal active power P_0 is increased from 300 W to 1000 W, and in Stage IV, the modified adjustment strategy is employed in the form of *proportional adjustment* in Table I.

In Fig. 5, when the operation points are above the nominal power in Stage II, Converter B shares more loading since $D_A > D_B$. However, the load-sharing relationship reverses in Stage III where the nominal power is higher than the operation points, which contradicts the objective of reliability improvement. By employing the proposed adjustment strategy, Converter B with less CL takes more loading. Therefore, the two-conditional droop control strategy can effectively accommodate the nominal active power updates to attain an improvement in the reliability.

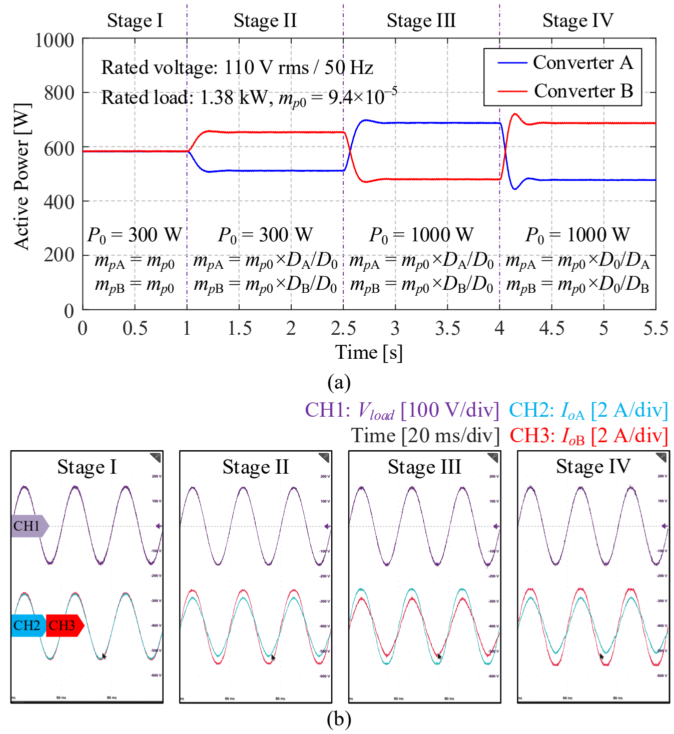

Fig. 5. Experimental results illustrating the two-conditional load sharing over four stages. (a) the active power and (b) the load voltage and respective output currents of the two converters at the PCC are presented.

B. Simulation Results on Long-Term Performance

To reveal the long-term effect of the proposed strategy, a study case is illustrated in Fig. 6. The example system consists

TABLE III
KEY PARAMETERS OF THE STUDY CASE ON LONG-TERM PERFORMANCE

Parameters	Values
Type of the power devices	FS100R12KT3 for Converter 1 FS25R12KT3 for Converter 2, 3, 4, 5
Initial active droop gain m_{p0}	1.9×10^{-5} [Hz/W] for Converter 1, 2, 3, 5 9.5×10^{-6} [Hz/W] for Converter 4
Power cycling period t_{on}	0.01 s
Number of cycles per month	(24×60×60×30) ×50

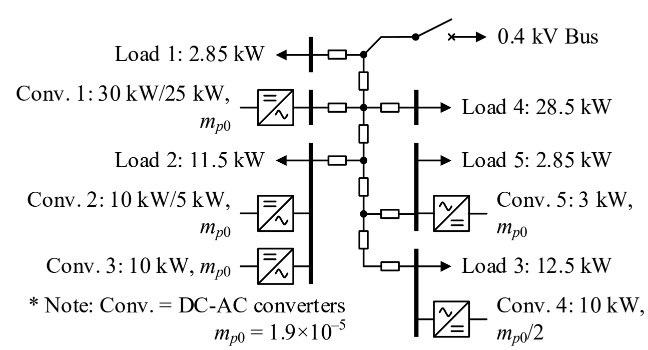

Fig. 6. Layout of the system used for long-term reliability evaluation. It is based on the CIGRE LV benchmark model and is operating in islanded mode.

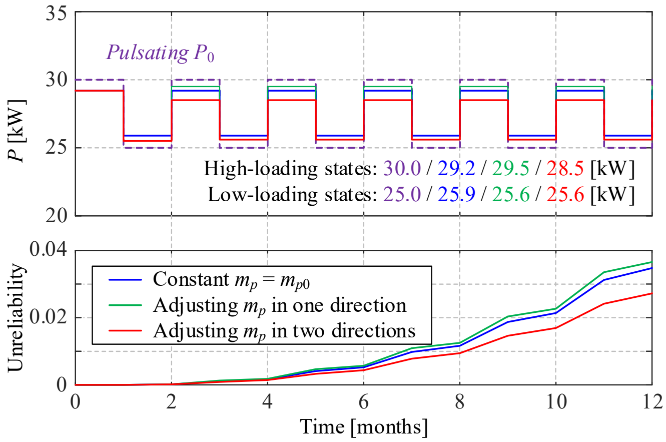

Fig. 7. Comparison of active power of Converter 1 under different droop policies. The nominal P_0 of Converter 1 is pulsating between 30 kW and 25 kW by month, and the shared active power converges as illustrated.

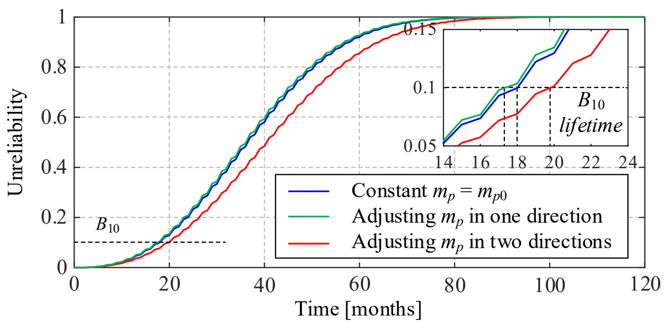

Fig. 8. Unreliability of the microgrid system. The B_{10} lifetime (10% probability of failure) of the system can be prolonged from 18 months to nearly 20 months.

of 5 DC-AC converters and 5 resistive loads and operates in the islanded mode. Key parameters for evaluating the reliability of the system are listed in Table III. To better show the essence of the two conditions, the reference active powers of Converters 1 and 2 are set to be pulsating by month, corresponding to a periodic load variation.

The performances of the system along 12 months are shown in Fig. 7. Three cases are studied, namely the cases with constant droop gains, adaptive droop gains in one direction and the proposed two-conditional droop adjustment. The droop gains are updated by month according to the *proportional adjustment* in Table I, with $\alpha = 0.5$ and $\lambda = 1$, and the droop gain is limited by a maximum of $5m_{p0}$. To simplify the analysis, the degradation of capacitors and the error of component parameters are not included, and all devices are assumed to have zero *CL* in the beginning.

Converter 1, which shares the most active power, shapes the system-level reliability. Thus, in Fig. 7, the active power of Converter 1 is illustrated, and the operation points eventually converge to two levels. When Converter 1 is in Condition II (corresponding to the 2nd, 4th, … months), both methods can reduce the stress on power devices, but in other conditions (corresponding to the 1st, 3rd, … months), the curtailment of load can only be achieved by the proposed strategy followed by a higher overall reliability of the system.

The evaluation of system performances is also extended to longer time scale in the same pattern, as shown in Fig. 8. With

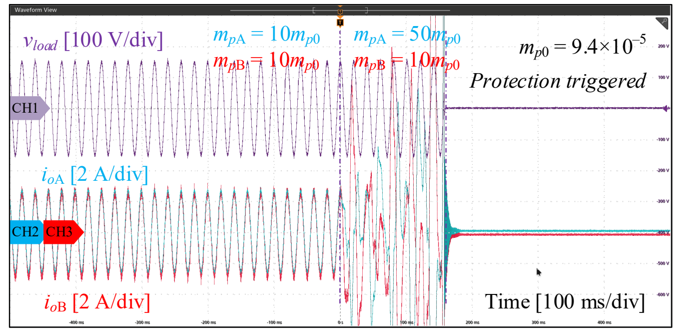

Fig. 9. Experimental results when the system becomes unstable after increasing the droop gains.

the proposed strategy, the B_{10} lifetime of the system can be prolonged by about 10%. Therefore, the proposed two-conditional droop adjustment can be more effective under practical circumstances with fluctuating loads or operator commands.

C. Boundary of the Droop Adjustment

As it is mentioned in Section II-B, the boundary of droop adjustment, however, is determined by the stability of the system. In Fig. 9, a case also based on the topology in Fig. 1 is presented to illustrate this point, where the droop gains of the converters are initially set as 9.4×10^{-4}. When one of the droop gains is increased to 5 times of the initial value, the system shows instability immediately and the hardware protection is triggered. The results indicate that there should be a limit for the adjustment coefficient β, which will be the future focus of our study.

IV. Conclusions

In this paper, the issue of droop gain adjustment in reliability-oriented active power control of multi-converter power electronic systems is pointed out. The adjustment should not be judged only by the consumed lifetime, whereas the nominal operation points are also important. The two-conditional adjustment principle is thereby proposed together with several examples of strategies, which is validated to better enhance the system-level reliability especially through fluctuating loads or operator commands. The proposed principle can then be employed to further reduce the cost of maintenance and help to optimize the power distribution actively.

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