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New Perspectives on Power Control of AC Microgrid Considering Operation Cost and Efficiency

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***Abstract*—This letter presents new perspectives on power control for AC microgrid considering operation cost and efficiency simultaneously. A multi-objective optimization model is first established. Then optimal operation conditions are derived by Lagrange Multiplier Method. Furthermore, a self-optimization droop control strategy with subject to optimal operation conditions is proposed to improve the overall operation performance. Simulation and experimental results validate the effectiveness of the proposed optimization method and self-optimization droop control strategy.**

***Index Terms*— AC microgrid, efficiency, multi-objective optimization, operation cost, self-optimization droop control.**

I. INTRODUCTION

MICROGRID is one of important components in modern power system [1], where economic operation and energy efficiency are important concerns. To reduce the overall operation cost of microgrid, economic dispatch strategies have been developed in previous works [2]-[4]. The centralized control strategy is proposed to minimize generation cost in [2]. However, the communication facilities can increase hardware cost and mitigate reliability of microgrid. To handle these drawbacks, droop-based power control strategies are developed to perform the economic dispatch without communication requirement [3]-[4].

Apart from the operation cost, energy efficiency is also an important concern. In [5]-[6], the inverter scheduling strategy is developed to improve the system efficiency by optimizing the number of operating inverters. In addition, several efforts have been made to improve system efficiency by dynamically regulating power sharing in DC microgrid [7]-[8] and AC microgrid [9].

In practical operation, the operation cost and efficiency may be highly coupled [3], where the independent optimization for operation cost or efficiency fails to perform the overall optimum performance. However, the twofold optimization for operation cost and efficiency is merely addressed in previous works. Therefore, this letter presents new perspectives on power control strategy of microgrid considering twofold optimization of operation cost and efficiency, and develops a self-optimization droop control strategy to improve system overall performance without using communication channels.

II. PROPOSED OPTIMIZATION MODEL AND ANALYSIS

A. Operation Characteristic Modelling

In renewable energy-dominated microgrid, the cost of renewable distributed generators (DGs) can be represented as [3]:

$$C_i = K_{Ci}P_i = K_{Ci}\left(P_{oi} + P_{loss\_i}\right) \tag{1}$$

where K_{Ci} is the cost coefficient considering maintenance cost, storage replacement and emission cost [3]-[4]. P_{oi} is the active power of the i-th DG. And P_{loss_i} is the power loss caused by converter including conduction loss and switching loss of the semiconductors as well as the power loss on filter inductors, which is a function of output power as [9]:

$$P_{loss\_i} = a_iP_{oi}^2 + b_iP_{oi} + c_iQ_{oi}^2 + d_iQ_{oi} + e_iP_{oi}Q_{oi} + h_i \tag{2}$$

where Q_{oi} is the reactive power of the i-th DG. a_i, b_i, c_i, d_i, e_i and h_i are the power loss coefficients, which can be obtained by fitting experimental data [9].

For a microgrid with N-paralleled DGs, the system efficiency can be defined as (3) [10], where P_{load} is the active load demand.

$$\eta = \frac{P_{load}}{P_{load} + P_{loss\_tot}}, \text{ where, } P_{loss\_tot} = \sum_{i=1}^{N} P_{loss\_i} \tag{3}$$

B. The Proposed Optimization Model and Analysis Method

To establish the multi-objective optimization function, the normalized performance factor considering the operation cost and power loss is first defined as [11]:

$$\begin{aligned} F_i &= \alpha_i\frac{C_i}{C_{\max}} + \beta_i\frac{P_{loss\_i}}{P_{loss\_\max}} \\ &= a_i'P_{oi}^2 + b_i'P_{oi} + c_i'Q_{oi}^2 + d_i'Q_{oi} + e_i'P_{oi}Q_{oi} + h_i' \end{aligned} \tag{4}$$

where

$$\begin{cases} 0 \le \alpha_i \le 1,\ 0 \le \beta_i \le 1,\ \alpha_i + \beta_i = 1 \\ C_{\max} = \sum_{i=1}^{N} C_{i\_\max} = \sum_{i=1}^{N} C_i\big|_{P_{oi\_\max},Q_{oi\_\max}} \\ P_{loss\_\max} = \sum_{i=1}^{N} P_{loss\_i\_\max} = \sum_{i=1}^{N} P_{loss\_i}\big|_{P_{oi\_\max},Q_{oi\_\max}} \end{cases} \tag{5}$$

where α_i and β_i are weight coefficients for operation cost and power loss of the i-th DG, which indicates the priorities of optimization objectives. $C_{\max}$ and $P_{loss\_\max}$ are the operation cost and power loss under maximum load condition, which is used to normalize the two optimization objectives [11]. a'_i, b'_i, c'_i, d'_i, e'_i and h'_i are the coefficients that are related to cost coefficient, power loss coefficients and weight coefficients of the i-th DG, which can be obtained by combining (1)-(4).

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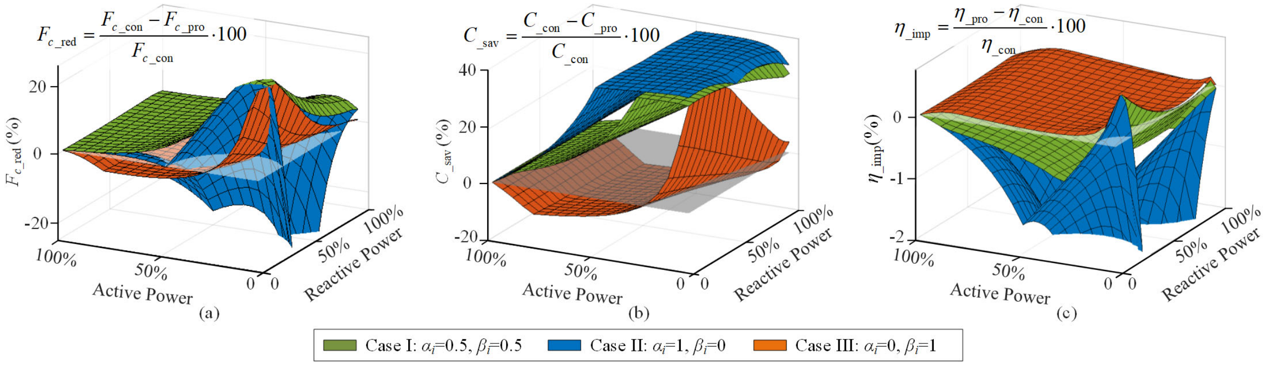


Fig. 1. The optimized results of system performance. (a) Overall performance factor reduction F_{c_red}. (b) Cost saving $C_{\_sav}$. (c) Efficiency improvement $\eta_{\_imp}$.

Then, the multi-objective optimization function of the system can be established as (6). And the Lagrange function is given as (7) to derive the optimal solution.

$$\min\left(F=\sum_{i=1}^{N}F_i\right)\quad s.t.\ \sum_{i=1}^{N}P_{oi}=P_{load},\ \sum_{i=1}^{N}Q_{oi}=Q_{load} \tag{6}$$

$$L=F+\lambda_1\left(P_{load}-\sum_{i=1}^{N}P_{oi}\right)+\lambda_2\left(Q_{load}-\sum_{i=1}^{N}Q_{oi}\right) \tag{7}$$

where λ_1 and λ_2 are the Lagrange multipliers. The necessary conditions of the optimum solution are given as (8) and (9) by Lagrange Multiplier Method.

$$\begin{cases}\dfrac{\partial F_1}{\partial P_{o1}}=\dfrac{\partial F_2}{\partial P_{o2}}=\cdots=\dfrac{\partial F_n}{\partial P_{on}},\ \sum\limits_{i=1}^{N}P_{oi}=P_{load} & (8)\\[2ex] \dfrac{\partial F_1}{\partial Q_{o1}}=\dfrac{\partial F_2}{\partial Q_{o2}}=\cdots=\dfrac{\partial F_n}{\partial Q_{on}},\ \sum\limits_{i=1}^{N}Q_{oi}=Q_{load} & (9)\end{cases}$$

To analyze the overall system performance under different optimization objectives, the overall performance factor F_c is defined as:

$$F_c=F\big|_{\alpha_i=0.5,\,\beta_i=0.5} \tag{10}$$

Fig. 1 shows the optimized results of system performance under different optimization objectives, where $X_{\_con}$ and $X_{\_pro}$ (X=F_c, C and η) are performance indexes under conventional proportional power sharing and the proposed optimum power sharing according to (8) and (9). Some connotations can be drawn from Fig. 1. (1) The overall performance factor (F_c) can be reduced, which means that overall operation performance is improved, within the whole load profile considering operation cost and system efficiency simultaneously. (2) The overall operation performance is not optimum under existing cost- or efficiency-prioritized power dispatch. As a tradeoff, when an individual objective is optimized, another can be weakened, so that the overall operation performance may be reduced.

III. PROPOSED SELF-OPTIMIZATION DROOP CONTROL

To implement the twofold optimization for operation cost and efficiency, a self-optimization droop control strategy is developed according to the derived optimum operation conditions. Fig. 2 shows the diagram of the proposed self-optimization droop controller.

The self-optimization P-ω droop control strategy is developed as (11) according to the first necessary condition (8).

$$\begin{cases}\omega_i^*=\omega'_{0i}-m'_iP_{oi}\\ \omega'_{0i}=\omega_0-k_P\left(b'_i+e'_iQ_{oi}\right),\ m'_i=2k_Pa'_i\end{cases} \tag{11}$$

where ω'_{0i} and m'_i are the retuned droop parameters that are related to coefficients of F_i. k_P is a constant which is equal for all DGs. The output power relationship of DG1 and DG2 can be obtained by (11) as (12), which indicates that the first optimum condition (8) is satisfied under the proposed droop control strategy by combining (4) and (12).

$$2a'_1P_{o1}+b'_1+e'_1Q_{o1}=2a'_2P_{o2}+b'_2+e'_2Q_{o2} \tag{12}$$

To perform the optimum reactive power sharing according to the second optimum condition (9), a nonlinear impedance compensation loop is developed as (13) to reshape the equivalent output impedance of DG.

$$X_{vi}=X^*_{oi}-X_{oi}\text{, where } X^*_{oi}=\left(2c'_i+\frac{d'_i+e'_iP_{oi}}{Q_{oi}}\right)k_Q \tag{13}$$

where X_{oi} is the closed-loop output impedance of the i-th DG [9]. $X_{oi}{}^*$ is the equivalent fundamental impedance. k_Q is a constant that is equal for all DGs. The reference voltage incorporating nonlinear impedance compensation loop is given as:

$$v_{ref\_di}=v^*_{di}+X_{vi}i_{oqi},\ v_{ref\_qi}=v^*_{qi}-X_{vi}i_{odi} \tag{14}$$

where $v_{di}{}^*$ and $v_{qi}{}^*$ are the voltage references derived from droop controller. i_{odi} and i_{oqi} are output currents in dq frame. v_{ref_di} and v_{ref_qi} are the voltage references in dq frame obtained from the impedance compensation loop.

Then, the reactive power sharing ratio of DGs with the proposed impedance compensation method can be given as (15) [9]. And (16) can be obtained in steady state. The second optimum condition (9) can be obtained by combining (4) and (16), which indicates that the second optimum condition (9) can be satisfied with the proposed impedance compensation method.

$$\frac{Q_{o1}}{Q_{o2}}=\frac{X_{o2}+X_{v2}}{X_{o1}+X_{v2}}=\frac{X^*_{o2}}{X^*_{o1}}=\frac{2c'_2+\dfrac{d'_2+e'_2P_{o2}}{Q_{o2}}}{2c'_1+\dfrac{d'_1+e'_1P_{o1}}{Q_{o1}}} \tag{15}$$

$$2c'_1Q_{o1}+d'_1+e'_1P_{o1}=2c'_2Q_{o2}+d'_2+e'_2P_{o2} \tag{16}$$

In addition, desirable operation regions of k_P and k_Q can be obtained by deriving eigenvalues of small signal model of microgrid, which can be found in our previous work [9].

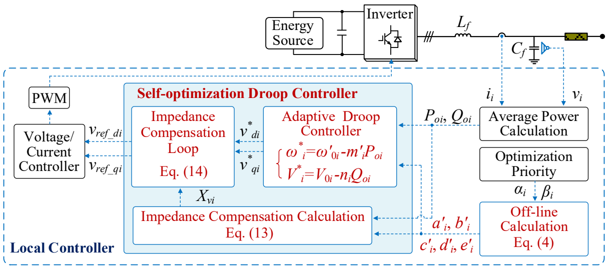


Fig. 2. The diagram of the proposed self-optimization droop controller.

TABLE I
SYSTEM PARAMETERS IN SIMULATION VERIFICATION

<table>
<tr><th></th><th colspan="2">DG1</th><th colspan="2">DG2</th></tr>
<tr><td>Power device</td><td colspan="2">FS6R06VE3_B2</td><td colspan="2">SKiiP 01NEC066V3</td></tr>
<tr><td>Power loss coefficients</td><td colspan="2">a_1=3.29e-6, b_1=-4.28e-3
c_1=2.84e-6, d_1=-1.32e-2
e_1=1.54e-7, h_1=38.14</td><td colspan="2">a_2=1.59e-6, b_2=4.94e-3
c_2=1.79e-6, d_2=1.49e-5
e_2=-5.02e-7, h_2=12.14</td></tr>
<tr><td>Cost coefficient</td><td colspan="2">K_{c1}=5e-5</td><td colspan="2">K_{c2}=1.15e-4</td></tr>
<tr><td colspan="5">Control Parameters</td></tr>
<tr><td>Self-optimization droop coefficient</td><td>k_P=1.5e3</td><td colspan="2">Impedance compensation coefficient</td><td>k_Q=2e8</td></tr>
</table>

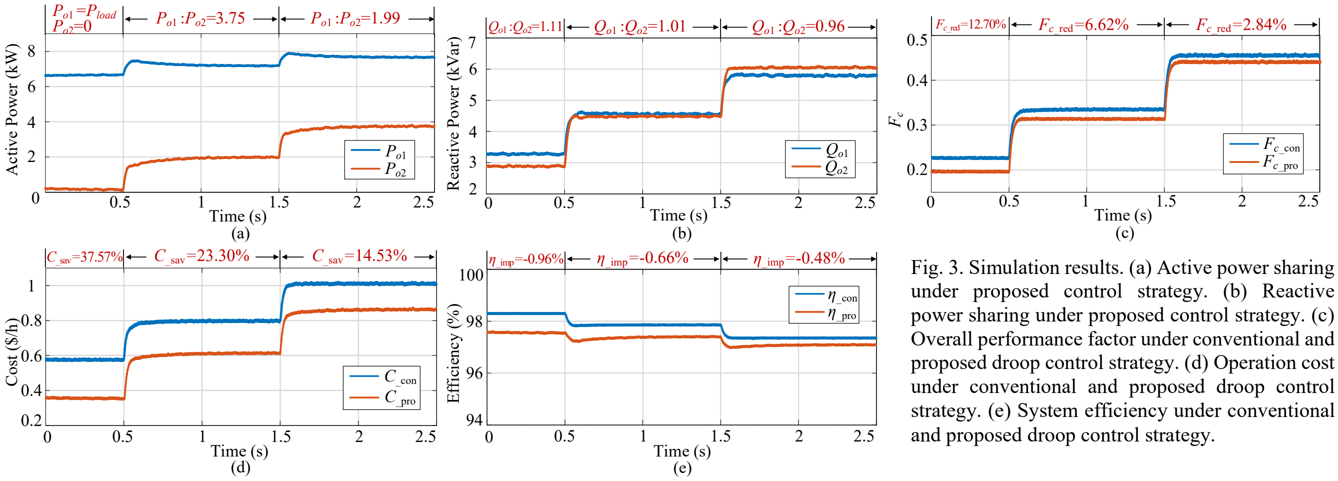


Fig. 3. Simulation results. (a) Active power sharing under proposed control strategy. (b) Reactive power sharing under proposed control strategy. (c) Overall performance factor under conventional and proposed droop control strategy. (d) Operation cost under conventional and proposed droop control strategy. (e) System efficiency under conventional and proposed droop control strategy.

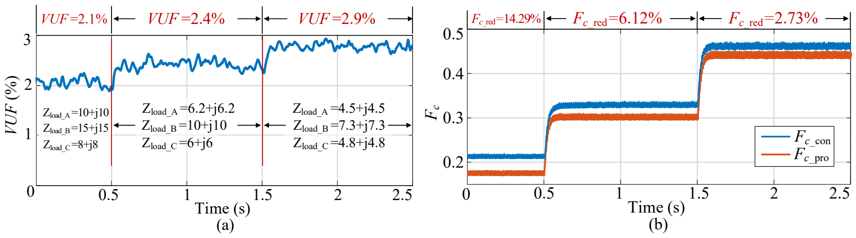


Fig. 4. Simulation results under unbalanced load. (a) *VUF* on the common bus. (b) Overall performance factor under conventional and proposed droop control strategy.

TABLE II
EXPERIMENTAL RESULTS ABOUT OVERALL SYSTEM PERFORMANCE

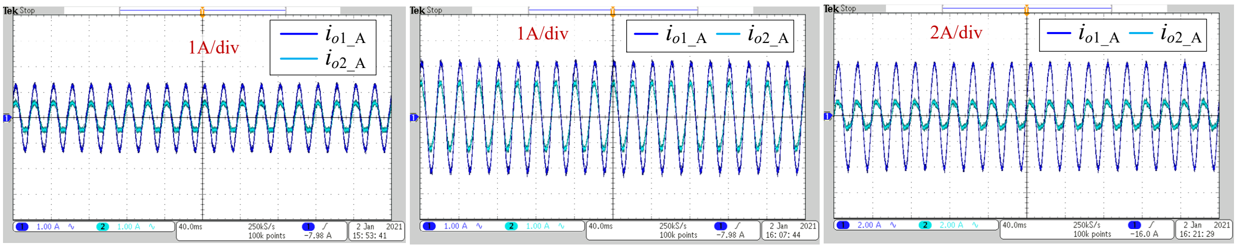
Load profiles (W)	120	300	580
F_{c_red} (%)	2.86	2.82	8.75
$C_{\_sav}$ (%)	13.47	8.18	20.68
$\eta_{\_imp}$ (%)	-0.55	-0.20	-0.31

IV. SIMULATION VERIFICATION

To validate the effectiveness of the proposed analysis and control method, simulation verification is implemented in a scale-down AC microgrid with two DGs in MATLAB with PLECS blockset. Simulation parameters are given in Table I.

Fig. 3 shows simulation results under $\alpha_i=\beta_i=0.5$, where time-varying load is exerted as 40% system capacity during 0-0.5s, 55% system capacity during 0.5-1.5s, 75% system capacity during 1.5-2.5s. It can be seen from Fig. 3(a)-(b) that power sharing performance under the proposed control strategy is regulated adaptively as variation of load profiles for optimum system performance. Fig. 3(c)-(e) show system performance results under conventional droop control and the proposed control strategy. It can be seen that the overall performance is improved dramatically, especially during light load. Also, operation cost is saved under the whole load profile although system efficiency is slightly reduced, which means that an optimum equilibrium point between efficiency and operation cost is captured to improve the overall system performance.

Fig. 4 shows simulation results under unbalanced load. The voltage unbalance factor (*VUF*) is given as $VUF=(V^N_{CB}/V^P_{CB})\times 100$ to indicate the degree of system unbalance [12], where V^P_{CB} and V^N_{CB} are the positive sequence and negative sequence voltages on the common bus. Fig. 4(a) shows the *VUF* which is around 3% due to unbalanced load. Fig. 4(b) shows system performance factor under conventional and proposed control strategy. It can be seen that the overall performance is improved evidently, which means that the proposed self-optimization droop control strategy is still effective under the unbalanced conditions.



(a) (b) (c)

Fig. 5. Experimental results under the proposed self-optimization droop control strategy. (a) Output currents (Phase A) of paralleled inverters as P_{load}=120W. (b) Output currents (Phase A) of paralleled inverters as P_{load}=300W. (c) Output currents (Phase A) of paralleled inverters as P_{load}=580W.

V. EXPERIMENTAL VERIFICATION

To further validate effectiveness of the proposed self-optimization droop control strategy, the experimental verification is implemented in a scaled-down islanded microgrid with two inverters, which is controlled by dSPACE 1006. Fig. 5 shows experimental results about output currents (Phase A) of paralleled inverters under the proposed droop control strategy. The experimental data of improved system performance is given in Table II. It can be seen that the power sharing is aligned with theoretical calculation according to the optimum conditions, which means that the power sharing ratio can be dynamically tuned to optimize the overall system performance as variation of load profiles. The results agree with the theoretical analysis in Section II. Hence, the proposed control strategy can improve overall operation performance of microgrid within a wide load profile.

VI. CONCLUSION

This letter presents new perspectives on power control of microgrid with optimization of operation cost and efficiency, where a self-optimization droop control strategy is presented to improve overall operation performance. The analysis results from optimization model show that there exists an optimum equilibrium point between operation cost and efficiency so as to improve the overall performance in practical operation. Simulation and experimental results are provided to validate the proposed self-optimization droop control strategy. Apart from operation cost and efficiency, the optimization strategy considering other performance indexes such as power quality and long-term reliability will be further investigated in future work.

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