Iterative droop control strategy for microgrids

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***Abstract*—In this technical report, we will apply the droop control strategy to a microgrid with N sources. In addition, to accommodate optimized reference values provided by a higher level controller, the droop gains are updated at a fixed/periodic interval.**

***Index Terms*—Power systems, Power converters, Droop control, Microgrids.**

I. Introduction

Droop control has served as the foundation for decentralized power sharing among parallel power electronic sources since the method was first formalized for inverter based systems. The original voltage and frequency droop method established the now standard relationship in which active power is regulated through frequency deviation and reactive power through voltage amplitude deviation, allowing multiple inverters to share load proportionally without a communication link between them [1]. Building on this primary control concept, a hierarchical control architecture was later proposed that organizes microgrid control into three levels: a primary droop based loop with a virtual output impedance term, a secondary loop that restores the deviations introduced by droop, and a tertiary loop that manages power exchange between the microgrid and the upstream grid. This hierarchical structure was explicitly designed to apply to both AC and DC microgrids under a unified standardization framework, and remains one of the most widely cited references in the field [2]. Around the same period, mode adaptive droop control with virtual output impedance was introduced to allow a single inverter to operate seamlessly in both grid connected and islanded modes, extending droop beyond purely autonomous operation [3].

On the DC side, conventional droop control suffers from two well-known limitations: line resistance mismatch degrades current sharing accuracy between converters, and the DC bus voltage deviates increasingly from its rated value as load increases. An improved droop control method addressed both issues using low bandwidth communication, restoring the DC bus voltage to its nominal value while simultaneously enhancing current sharing accuracy, and has since become a standard reference point for DC microgrid primary control [4].

More recent work has continued to build on these foundations while addressing the practical demands of renewable dominated, low inertia systems. In AC microgrids, research has concentrated on overcoming the persistent sensitivity of droop control to line impedance mismatch. The distance between connected inverters affects the effectiveness of active power frequency and reactive power voltage droop characteristics, and high impedance from long transmission lines can result in instability, poor voltage tracking, and ineffective frequency regulation [5], motivating finite control set model predictive extensions to the standard droop loop. Comprehensive reviews of this space have cataloged a broader shift toward virtual impedance augmented and adaptive droop techniques as the dominant primary control paradigm at the hierarchical microgrid control level for AC, DC, and hybrid microgrids alike [6].

At the same time, there is renewed interest in purely decentralized, communication free droop for power quality sensitive applications. Recent nanogrid work has demonstrated a parallel hybrid inverter system that enhances power quality using only decentralized droop based primary control, without secondary control or communication links [7], a notable counterpoint to the broader trend toward learning based and model predictive augmentation. Hybrid intelligent approaches have also matured, with artificial neural network based adaptive proportional integral control combined with droop control and virtual impedance techniques reported as a way to improve voltage regulation under high renewable penetration [8].

The most active frontier, however, is at the AC/DC interface itself. Hybrid microgrids, in which an interlinking converter couples an AC subgrid to a DC subgrid, require droop logic that can arbitrate between two physically different regulated quantities, AC frequency and DC bus voltage, using a single bidirectional power flow variable. Recent work normalizes these dissimilar quantities so that they can be compared directly: an adaptive bidirectional droop strategy introduces an adaptive weight coefficient based on normalized AC frequency and DC voltage, prioritizing regulation of whichever side shows the larger deviation, while interlinking converter action thresholds avoid unnecessary frequent switching [9].

Together, these developments mark a clear trajectory: droop control has evolved from a static, locally computed characteristic designed for inverter only AC systems into an adaptively weighted, often model informed coordination layer that must reconcile AC and DC physics directly, rather than treating the two domains as separately regulated subsystems linked by a black box converter.

In this report, the following notation will be followed:

- $\mathbb{1}r, c$ is a matrix of 1s (ones) with r rows and c columns
- $a \otimes b$ is the Kronecker product of a, b.
- $a \circ b$ is the Hadamard product of a, b.
- $a \oslash b$ is the Hadamard division of a, b.
- X^* and $\hat{X}$ are reference and measurement respectively.

II. Droop Control:

A. DC Microgrid:

Define a dc microgrid to consist of N sources/generators (g). Each of these sources/generators has a set of reference voltages which are updated at a fixed time t through the day based on constraints and/or cost optimizations. Let this reference voltage vector based on time for an i^{th} generator be defined as follows:

$$V_{gi}^{*} = \begin{bmatrix} V_{gi}^{*}(1) \\ V_{gi}^{*}(2) \\ \vdots \\ V_{gi}^{*}(t) \end{bmatrix}, \tag{1}$$

such that $V_{gi}^{*}(t)$ may or may not be equal to $V_{gi}^{*}(t-1)$. The voltage reference matrix for N generators concatenated together is then given by:

$$V^{*} = \left[V_{g1}^{*}, \ldots, V_{gi}^{*}, \ldots V_{gN}^{*}\right]. \tag{2}$$

The power drawn from the i^{th} generator at a voltage V_{gi}^{*} is defined as P_{gi}^{*} (reference) such that $0 \leq P_{gi}^{*} \leq P_{gi}^{max}$. We can then formulate a power reference matrix similar to the one seen in (2) as follows:

$$P^{*} = \left[P_{g1}^{*}, \ldots, P_{gi}^{*}, \ldots P_{gN}^{*}\right]. \tag{3}$$

The power generated by each generator at the dc microgrid's voltage setpoint $\mathbb{V}$ is P_{gi}, concatenated together as

$$P = \left[P_{g1}, \ldots, P_{gi}, \ldots P_{gN}\right] \otimes \mathbb{1}_{t\times 1}. \tag{4}$$

The voltage setpoint $\mathbb{V}$ for matrix calculations is then defined as:

$$V = \left[\mathbb{V}\right] \otimes \mathbb{1}_{t\times N}. \tag{5}$$

The relation between the references V^{*} and P^{*}, the dc microgrid's nominal voltage setpoint V (optimal condition) and the respective maximum power generated P across all the generators during nominal operating conditions is

$$V(t) = V^{*}(t) - K_P(t)\Big(P(t) - P^{*}(t)\Big). \tag{6}$$

The droop gain from the above equation is given by:

$$K_P(t) = \Big(V^{*}(t) - V(t)\Big) \oslash \Big(P(t) - P^{*}(t)\Big) \tag{7}$$

Consequently, if the reference power generated P^{*} by the generators at their reference voltage V^{*} is zero, then droop gain is simply given by:

$$K_P(t) = \Big(V^{*}(t) - V(t)\Big) \oslash \Big(P(t)\Big). \tag{8}$$

Note that in the above interpretation, the elements in matrix V are fixed across all N generators and time t, while P is fixed across all time t. This assumes the ideal case that the microgrid parameters, i.e., the setpoint bus voltage and the demand of power at the bus voltage from each generator, do not undergo changes as often as V^{*}, P^{*}. However, the mathematical framing of the microgrid over time t, would still allow us to update $V(t)$ and $P(t)$ accordingly if it's a non-ideal case. Refer to Table:I, to understand the possibility of changes to the parameters discussed.

To incorporate the gain $K_P(t)$ (droop gains for all generators at time t) with the most prominent cascaded PI control strategy [10] at each generator while using only the current and voltage measurements, we define:

$$R_{gi}(t) \approx V_{gi}^{*}(t) K_{P,gi}(t). \tag{9}$$

However, if the microgrid's measured voltage $\hat{V}$ is available, a more accurate approach would be:

$$R_{gi}(t) = \hat{V}(t) K_{P,gi}(t). \tag{10}$$

The outer PI controller's error for each generator is then given by:

$$e_{gi}(\tau) = V_{gi}^{*}(t) - \hat{V}(\tau) - \hat{I}_{gi}(\tau) R_{gi}(t), \tag{11}$$

where τ is updated at the speed of the primary controller's frequency i.e., $\tau \ll t$. Furthermore, it is to be noted that in equation (11), $\hat{V}(\tau)$ is the voltage measurement and $\hat{I}_{gi}(\tau)$ is the measured converter output current, taken positive when flowing from the generator to the bus, so that the droop term $-\hat{I}_{gi}(\tau)R_{gi}(t)$ lowers the reference as the delivered current rises. The same output-current sign convention is used for the dq and $\alpha\beta$ measured currents in the ac case.

TABLE I. Parameter Dynamics in DC Droop Control

Parameter	**Update Rate**	**System Role**
V	Never	Rated bus voltage (design constant)
P	Never	Maximum hardware power limit
V^{*}	Infrequent	Voltage reference for the generators
P^{*}	Infrequent	Power reference at V^{*}

Algorithm 1 DC Droop Gain Computation

Require: Bus voltage V, no-load references $V^{\star}$, power references $P^{\star}$, rated powers P, sources N, time steps t
Ensure: $\mathbf{K}_P,\ \mathbf{R} \in \mathbb{R}^{t\times N}$

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for j = 1 to t do                                  ▷ each row is a time step
    K_P[j,:] ← (V*[j,:] − V) ⊘ (P[j,:] − P*[j,:])
    R[j,:] ← K_P[j,:] ∘ V*[j,:]
end for
for each primary control instant τ do              ▷ runs at fast timescale
    e_gi(τ) ← V*_gi(t) − V̂_gi(τ) − Î_gi(τ) R_gi(t)
end for
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B. AC Microgrid:

In ac microgrids, the droop gains are calculated for $\mathcal{P}$-ω (Active Power – Angular Frequency) and $\mathcal{Q}$-$\mathcal{V}$ (Reactive Power – Voltage). The angular frequency and voltage references for the i^{th} source and their concatenated matrices for N sources follow the same structure as (1)–(2):

$$\omega_{gi}^{*} = \begin{bmatrix} \omega_{gi}^{*}(1) \\ \vdots \\ \omega_{gi}^{*}(t) \end{bmatrix}, \qquad \mathcal{V}_{gi}^{*} = \begin{bmatrix} \mathcal{V}_{gi}^{*}(1) \\ \vdots \\ \mathcal{V}_{gi}^{*}(t) \end{bmatrix}, \qquad \omega^{*} = \left[\omega_{g1}^{*}, \ldots, \omega_{gN}^{*}\right], \quad \mathcal{V}^{*} = \left[\mathcal{V}_{g1}^{*}, \ldots, \mathcal{V}_{gN}^{*}\right]. \tag{12}$$

The reference for active $\mathcal{P}^*$ and reactive $\mathcal{Q}^*$ powers in concatenated matrix form is:

$$\begin{aligned}\mathcal{P}^* &= \left[\mathcal{P}^*_{g1}, \dots, \mathcal{P}^*_{gi}, \dots \mathcal{P}^*_{gN}\right], \\ \mathcal{Q}^* &= \left[\mathcal{Q}^*_{g1}, \dots, \mathcal{Q}^*_{gi}, \dots \mathcal{Q}^*_{gN}\right].\end{aligned} \tag{13}$$

The variables $\mathcal{P}, \mathcal{Q}$ are defined as seen in (4) and the variables $\omega, \mathcal{V}$ are defined as seen in (5). Using the nominal bus frequency/voltage setpoints ω and $\mathcal{V}$, and the active and reactive power references $\mathcal{P}^*$ and $\mathcal{Q}^*$, the droop relations are:

$$\begin{aligned}\omega(t) &= \omega^*(t) - K_{\mathcal{P}}(t)\Big(\mathcal{P}(t) - \mathcal{P}^*(t)\Big) \\ \mathcal{V}(t) &= \mathcal{V}^*(t) - K_{\mathcal{Q}}(t)\Big(\mathcal{Q}(t) - \mathcal{Q}^*(t)\Big).\end{aligned} \tag{14}$$

The droop gains from the above equations are given by:

$$\begin{aligned}K_{\mathcal{P}}(t) &= \Big(\omega^*(t) - \omega(t)\Big) \oslash \Big(\mathcal{P}(t) - \mathcal{P}^*(t)\Big) \\ K_{\mathcal{Q}}(t) &= \Big(\mathcal{V}^*(t) - \mathcal{V}(t)\Big) \oslash \Big(\mathcal{Q}(t) - \mathcal{Q}^*(t)\Big)\end{aligned} \tag{15}$$

TABLE II. Parameter Dynamics in AC Droop Control

Parameter	Update Rate	System Role
ω	Never	Rated grid frequency (design constant)
$\mathcal{V}$	Never	Rated bus voltage (design constant)
$\mathcal{P}, \mathcal{Q}$	Never	Maximum hardware power limits attained at $\omega, \mathcal{V}$ respectively
ω^*	Infrequent	Frequency reference
$\mathcal{V}^*$	Infrequent	Voltage reference
$\mathcal{P}^*$	Infrequent	Active power dispatch target at ω^*
$\mathcal{Q}^*$	Infrequent	Reactive power target at $\mathcal{V}^*$

The droop gains in (15) enter the inverter's cascaded control differently depending on the role of each generator in the microgrid.

1) Grid-forming generator: This generator sets the bus voltage and frequency. Having no grid to lock to, it builds its own angle by integrating the droop-corrected frequency:

$$\theta(\tau) = \int_0^\tau \left(\omega^*(t) - K_{\mathcal{P}}(t)\Big(\hat{\mathcal{P}}(\tau') - \mathcal{P}^*(t)\Big)\right) d\tau'. \tag{16}$$

Algorithm 2 AC Droop Gain Computation

Require: Nominal frequency ω, frequency references $\omega^\star$, voltage references $\mathcal{V}^\star$, rated powers $\mathcal{P}, \mathcal{Q}$, power references $\mathcal{P}^\star$, $\mathcal{Q}^\star$, sources N, time steps t

Ensure: $\mathbf{K}_{\mathcal{P}}$, $\mathbf{K}_{\mathcal{Q}}$, $\mathbf{X} \in \mathbb{R}^{t \times N}$

for $j = 1$ **to** t **do** ▷ each row is a time step
  $\mathbf{K}_{\mathcal{P}}[j,:] \leftarrow \big(\omega^\star[j,:] - \omega\big) \oslash \big(\mathcal{P}[j,:] - \mathcal{P}^\star[j,:]\big)$
  $\mathbf{K}_{\mathcal{Q}}[j,:] \leftarrow \big(\mathcal{V}^\star[j,:] - \mathcal{V}\big) \oslash \big(\mathcal{Q}[j,:] - \mathcal{Q}^\star[j,:]\big)$
  $\mathbf{X}[j,:] \leftarrow \mathbf{K}_{\mathcal{Q}}[j,:] \circ \mathcal{V}^\star[j,:]$ ▷ virtual reactance per generator
end for

Algorithm 3 AC Primary Control — dq and PR Outer Loop

Require: $\mathbf{K}_{\mathcal{P}}$, $\mathbf{K}_{\mathcal{Q}}$, $\mathbf{X}$ from Algorithm 2; references $\omega^\star, \mathcal{V}^\star, \mathcal{P}^\star, \mathcal{Q}^\star$; measurements at each τ

Ensure: Current references $i^*_{d,q}(\tau)$ (dq) or $i^*_{\alpha,\beta}(\tau)$ ($\alpha\beta$)

for each primary control instant τ **do**
  ▷ $K_{\mathcal{P}}$ does its work on the angle/frequency
  Grid-forming:
  $\omega_{gf}(\tau) \leftarrow \omega^\star(t) - \mathbf{K}_{\mathcal{P}}(t) \circ (\hat{\mathcal{P}}(\tau) - \mathcal{P}^\star(t))$
  $\theta(\tau) \leftarrow \theta(\tau{-}1) + \frac{\Delta\tau}{2}\big(\omega_{gf}(\tau) + \omega_{gf}(\tau{-}1)\big)$
  ▷ trapezoidal (Tustin)
  Grid-following:
  $\theta(\tau) \leftarrow \theta_{\text{PLL}}(\tau)$; $\Delta\mathcal{P}_{gi} \leftarrow (\omega^\star_{gi}(t) - \omega_{\text{PLL},gi}(\tau))/K_{\mathcal{P},gi}(t)$
  ▷ $K_{\mathcal{Q}}$ does its work on the voltage magnitude through X
  $\mathcal{V}(t) \leftarrow \mathcal{V}^\star(t) - \mathbf{K}_{\mathcal{Q}}(t) \circ (\mathcal{Q}(t) - \mathcal{Q}^\star(t))$
  ▷ dq outer voltage loop → current refs, Eq. (18)
  $e_{v_d,gi} \leftarrow \mathcal{V}^\star_{gi}(t) - \hat{v}_{d,gi}(\tau) - \hat{i}_{q,gi}(\tau)X_{gi}(t)$
  $e_{v_q,gi} \leftarrow -\hat{v}_{q,gi}(\tau) + \hat{i}_{d,gi}(\tau)X_{gi}(t)$
  $[i^*_d, i^*_q] \leftarrow \text{PI}(e_{v_d,gi},\, e_{v_q,gi})$
  ▷ $\alpha\beta$ outer voltage loop → current refs, Eq. (19)
  $e_{v_\alpha,gi} \leftarrow v^*_{\alpha,gi} - \hat{v}_{\alpha,gi}(\tau) - \hat{i}_{\beta,gi}(\tau)X_{gi}(t)$
  $e_{v_\beta,gi} \leftarrow v^*_{\beta,gi} - \hat{v}_{\beta,gi}(\tau) + \hat{i}_{\alpha,gi}(\tau)X_{gi}(t)$
  $[i^*_\alpha, i^*_\beta] \leftarrow \text{PR}(e_{v_\alpha,gi},\, e_{v_\beta,gi})$
end for

So $K_{\mathcal{P}}$ does its work on the frequency (through this angle) and $K_{\mathcal{Q}}$ does its work on the voltage magnitude, $\mathcal{V}(t) = \mathcal{V}^*(t) - K_{\mathcal{Q}}(t)(\mathcal{Q}(t) - \mathcal{Q}^*(t))$.

2) Grid-following generators: These lock to the bus set by the grid-forming unit through a PLL, which supplies the measured frequency $\omega_{\text{PLL},gi}(\tau)$ and angle $\theta_{\text{PLL},gi}(\tau)$ (used in place of (16)). Here $K_{\mathcal{P},gi}$ turns the measured frequency deviation into a power correction on top of the reference $\omega^*_{gi}(t)$:

$$\Delta\mathcal{P}_{gi}(\tau) = \frac{\omega^*_{gi}(t) - \omega_{\text{PLL},gi}(\tau)}{K_{\mathcal{P},gi}(t)}, \tag{17}$$

giving an effective reference $\mathcal{P}^*_{gi}(t) + \Delta\mathcal{P}_{gi}(\tau)$, while $K_{\mathcal{Q},gi}$ again sets the voltage magnitude. In both cases the inner current loop is tuned independently; the two outer-loop options, dq and PR, follow.

3) dq Control (Synchronous Reference Frame): All signals are moved into a frame rotating at θ (from (16) for grid-forming, or θ_{PLL} for grid-following). In this frame $K_{\mathcal{P}}$ has already done its work by setting the angle, and $K_{\mathcal{Q}}$ does its work as a virtual reactance $X_{gi}(t) = \hat{\mathcal{V}}_{gi}(t)K_{\mathcal{Q},gi}(t)$ (the inductive analogue of the resistance R_{gi}), entering the outer PI voltage error just as R_{gi} does in (11):

$$\begin{aligned}e_{v_d,gi}(\tau) &= \mathcal{V}^*_{gi}(t) - \hat{v}_{d,gi}(\tau) - \hat{i}_{q,gi}(\tau)X_{gi}(t), \\ e_{v_q,gi}(\tau) &= -\hat{v}_{q,gi}(\tau) + \hat{i}_{d,gi}(\tau)X_{gi}(t),\end{aligned} \tag{18}$$

where $\hat{i}_{d,gi}, \hat{i}_{q,gi}$ are the measured dq output currents. The outer PI loop then produces the current references i^*_d, i^*_q, and the inner PI loop tracks them with cross-coupling compensation $\mp\omega^* L\hat{i}_{q,d}$. For grid-following generators, i^*_d carries the extra power correction from (17).

4) Proportional Resonant (PR) Control (Stationary $\alpha\beta$ Frame): PR controllers track the sinusoidal references directly, with no rotating frame. The two gains do exactly the same work as in the dq frame: $K_{\mathcal{P}}$ sets the phase of the voltage reference $v^*_{\alpha,gi}(\tau), v^*_{\beta,gi}(\tau)$ through $\theta(\tau)$ (grid-forming) or θ_{PLL} (grid-following), and $K_{\mathcal{Q}}$ enters as the virtual reactance $X_{gi}(t) = \hat{\mathcal{V}}_{gi}(t)K_{\mathcal{Q},gi}(t)$ in the outer voltage error (same form as (11)):

$$\begin{aligned} e_{v_\alpha,gi}(\tau) &= v^*_{\alpha,gi}(\tau) - \hat{v}_{\alpha,gi}(\tau) - \hat{i}_{\beta,gi}(\tau)X_{gi}(t), \\ e_{v_\beta,gi}(\tau) &= v^*_{\beta,gi}(\tau) - \hat{v}_{\beta,gi}(\tau) + \hat{i}_{\alpha,gi}(\tau)X_{gi}(t), \end{aligned} \tag{19}$$

where $\hat{i}_{\alpha,gi}, \hat{i}_{\beta,gi}$ are the measured $\alpha\beta$ output currents.

III. Conclusion

In this technical report, application of droop control strategy for voltage and/or frequency regulation, and power sharing in a microgrid consisting of N sources is presented. Pseudocode used to tune the droop gains and apply them accordingly is also shared.

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