Research Report:

Flexible Consensus Mechanism for Current Allocation in DC Microgrid

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Ho Chi Minh City, Saturday, September 6, 2025

Table of Contents

1. Motivation & Problems

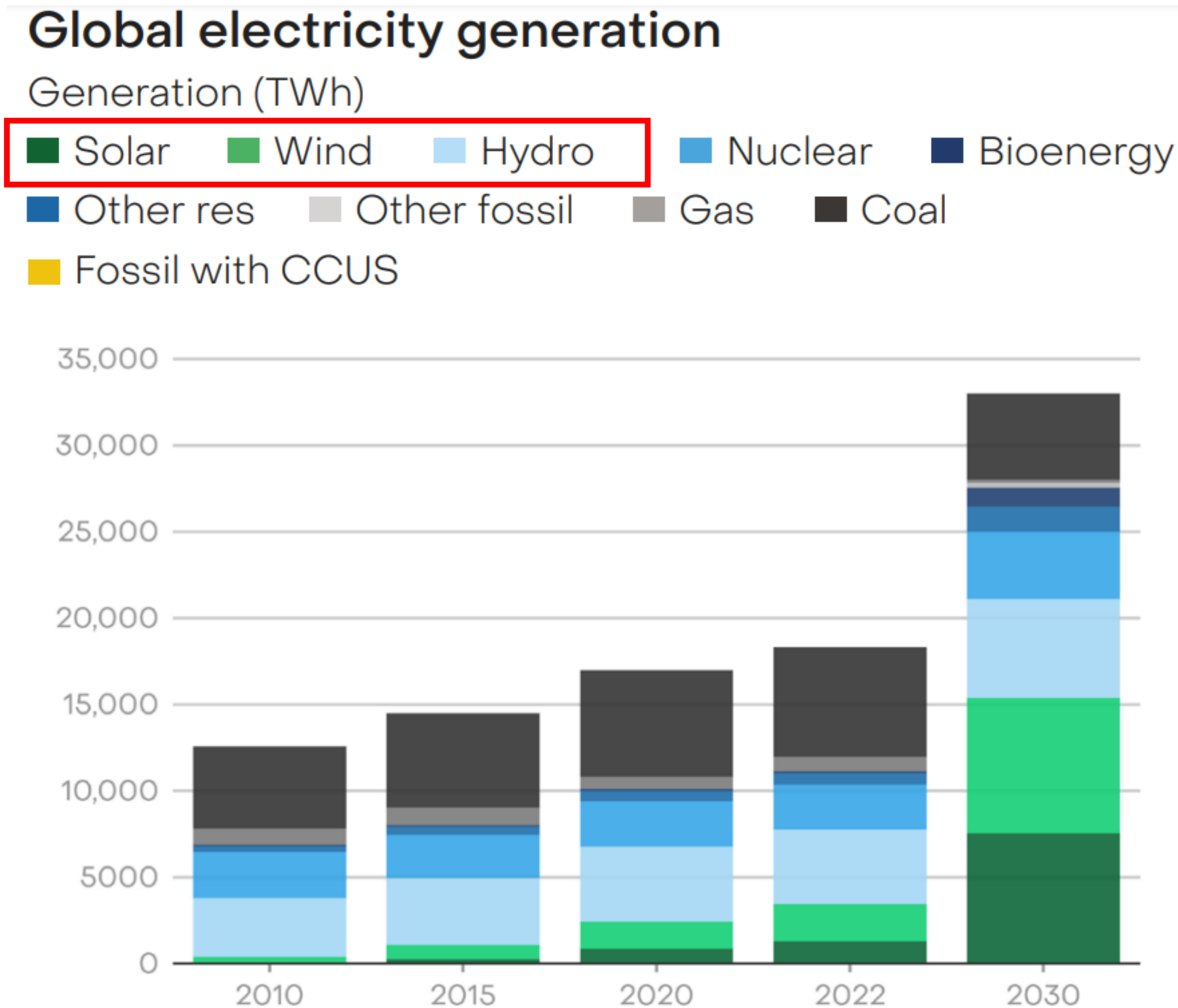
2. Proposed method & Consensus Algorithm

3. Simulation Results

4. Conclusions

5. Acknowledgement

6. References



Global-Electricity-Review-2023

Renewable energy sources (RESs) like Solar, Wind or Hydro have become the predominant trend in the development of energy systems in many countries.

Motivation & Problems

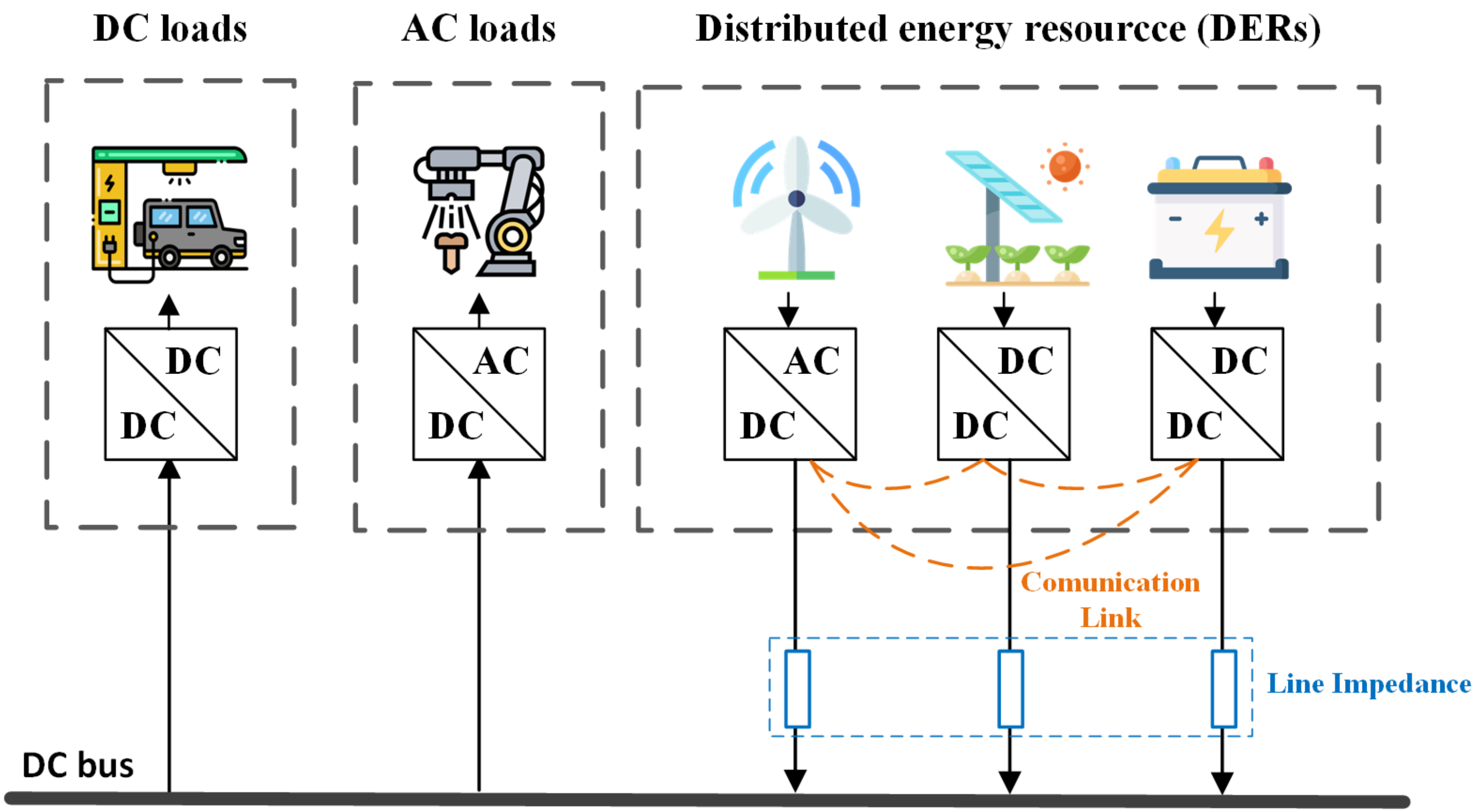


Fig. 1. Simplified diagram of Microgrid with communication link.

To coordinate RESs, microgrids have emerged as an efficient and optimal solution. However, the microgrid is facing the problem of inaccurate power sharing between the generators

Proposed method

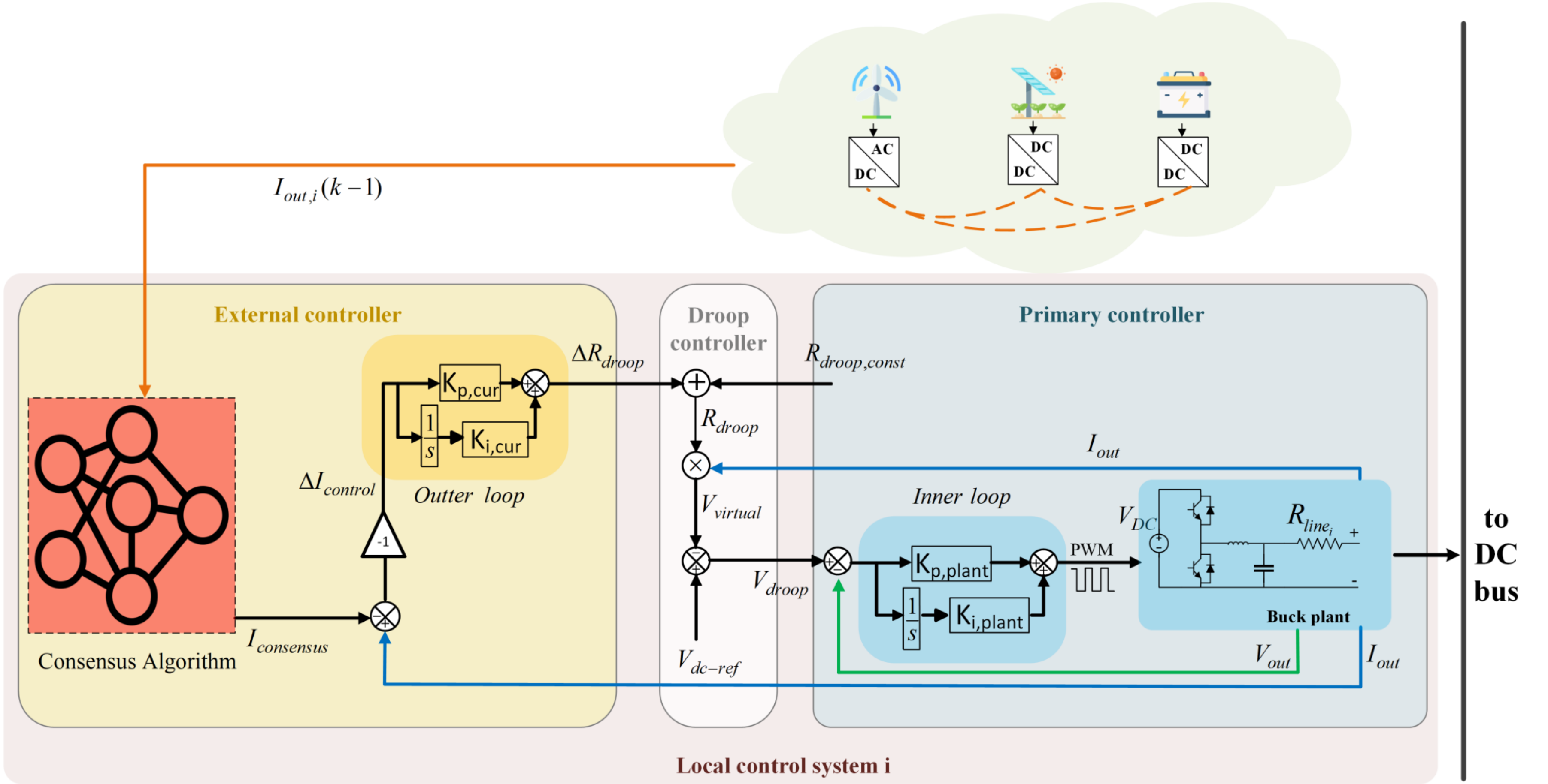


Fig. 2. Block diagram of the combined Consensus-Droop control loop.

Order of analysis :

Droop Control → Consensus Algorithm → Combination Droop Control & Consensus Algorithm

Droop Control

To analyze the characteristics of the droop control method, the Microgrid circuit with Thevenin transformation is established as :

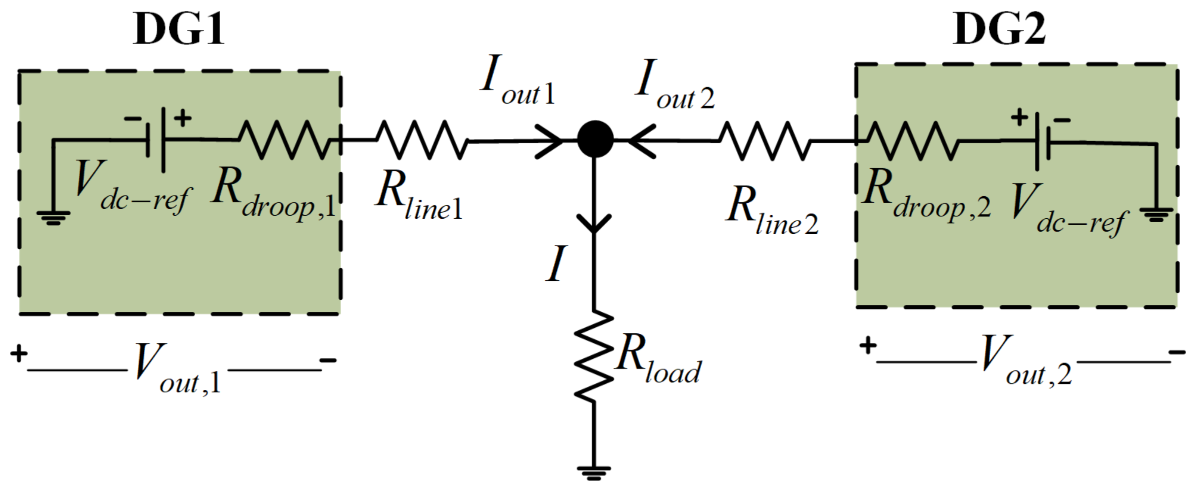


Fig. 3. Microgrid ciruit with thevenin transformation

Where $V_{dc-ref}, R_{droop\,i}$ are the control parameters, and $V_{out\,i}, I_{out\,i}$ represent the sensor feedback values.

In the conventional droop control, the relationship between voltage and current at the output of each generator is expressed as follows:

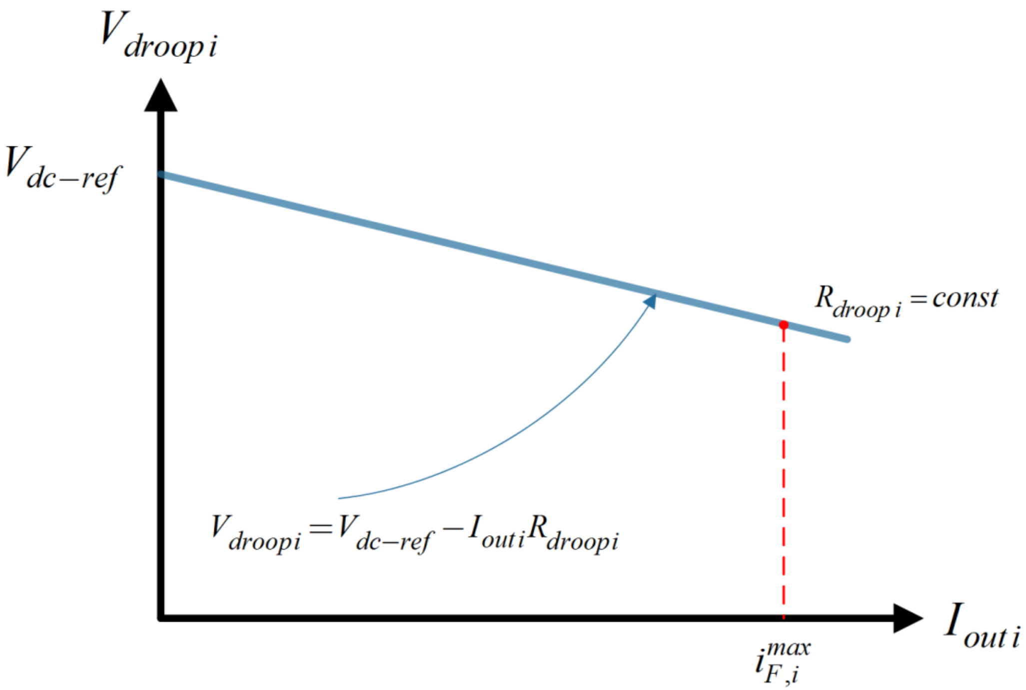
$$V_{droop\,i} = V_{dc-ref} - I_{out\,i} R_{droop\,i} \quad i = 1,2 \tag{1}$$

$$I_{out,i} = \frac{V_{dc-ref} - V_{bus}}{R_{droop,i} + R_{line,i}} \tag{2}$$

Proposed method

Droop Control

Autonomous power sharing is achieved by regulating the power output of each generator according to its deviation from the operating point, which is expressed as



$$\begin{cases} R_{droop,i} \le \dfrac{\Delta V_{dc,max}}{i_{F,i}^{max}} \\ \Delta V_{dci} = \left| V_{dc}^{*} - V_{out,i} \right| \le \Delta V_{dc,max} \end{cases} \quad (3)$$

Fig. 4. Droop curve in a DC microgrids with conventional Droop controller.

Where $i_{F,i}^{max}$ is the maximum current that the source converter can provide, and $\Delta V_{dc,max}$ is the maximum voltage deviation.

Droop Control

It is important to note that the line impedance values are varied depending on the electricity grid area. From droop control theory for microgrid , the mismatched current sharing is inevitable due to the microgrid configuration. Thus, the feasible solution to deal with the problem of unequal current sharing is to modify the droop resistance. The adjustment of the droop resistance required a calculation of the current difference among generation units, which is estimated with the aid of a **consensus algorithm**

Proposed method

Consensus Algorithm

Consensus algorithm is a mechanism used in distributed systems to achieve agreement among multiple nodes on a specific outcome. In a distributed system, where multiple generation units interact and collaborate to perform grid voltage support, consensus algorithms ensure that all nodes reach a consistent state and agree on validity

Consensus Algorithm

The consensus algorithm employing the **continuous time** domain can be characterized as :

$$\dot{u}_i(t) = \sum_{j \in N_i} a_{ij}\left(u_j(t) - u_i(t)\right) \quad (4)$$

Where a_{ij} is a gain that represents the connection state from distributed generation unit i^{th} to j^{th}. $u_i(t)$ and $u_j(t)$ are the sent data in the generation unit i^{th} and j^{th}, respectively.

When taking the derivative of the equation in continuous time domain to the discrete-time domain, the following equation is obtained:

$$\begin{array}{ccc} \left[\dot{u}_{i(t)}\right] & \Leftrightarrow & \left[u_i(k+1) - u_i(k)\right] \\ (real - time) & & (discrete - time) \end{array}$$

$$u_i(k+1) = u_i(k) + \varepsilon . \sum_{j \in N_i} a_{ij}\left(u_{j(k)} - u_{i(k)}\right) \quad (5)$$

$i = 1, 2, \ldots, n$

N_i : the total number of agents

ε : the gain of the consensus algorithm

Consensus Algorithm

Because the communication delay for processing is inevitable, the suitable discrete time equation for the consensus control algorithm is rewritten as :

$$u_i(k) = u_i(k-1) + \varepsilon . \sum_{j \in N_i} a_{ij}\left(u_j(k-1) - u_i(k-1)\right) \quad (6)$$

$u_i(k-1)$: stored data of the 1st generation

$u_i(k)$: current data to be calculated

Proposed method

Consensus Algorithm

Considering a scenario where three distributed generation units are considered in the microgrid system :

Initial values	$u_1 = 75$
	$u_2 = 75$
	$u_3 = 75$
Gain coefficient	$\varepsilon = 0.5$
Time sampling	$T_s = 0.01s$

Proposed method

Consensus Algorithm

$$u_1(k) = u_1(k-1) + 0.5\Big[\big(u_1(k-1) - u_1(k-1)\big) + \big(u_2(k-1) - u_1(k-1)\big) + \big(u_3(k-1) - u_1(k-1)\big)\Big]$$

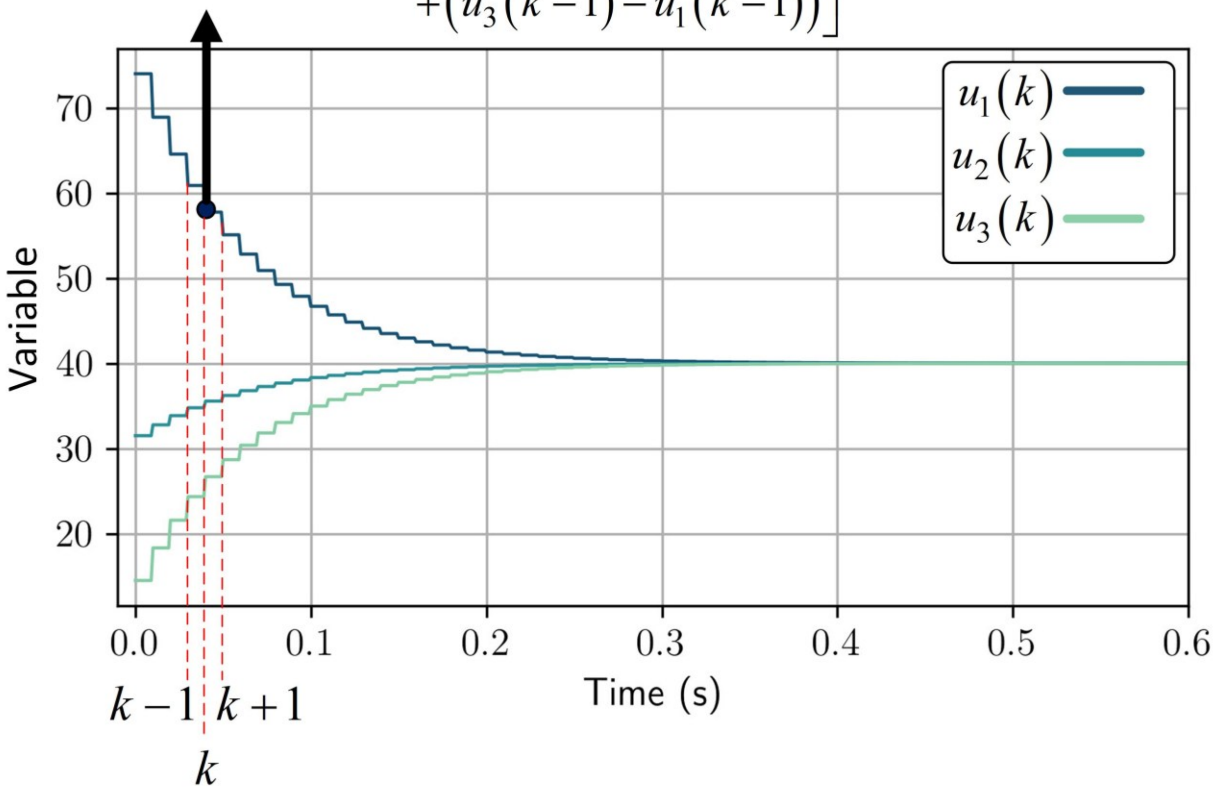


Fig. 7. Simulation example of data convergence in the consensus algorithm

After a convergence time of 0.3s, the three variables u_1, u_2 and u_3 converge to the **average value**.

These variables change gradually until they approach the convergent value, and their performance is maintained **in a steady state.**

Proposed method

Combination Droop Control & Consensus Algorithm

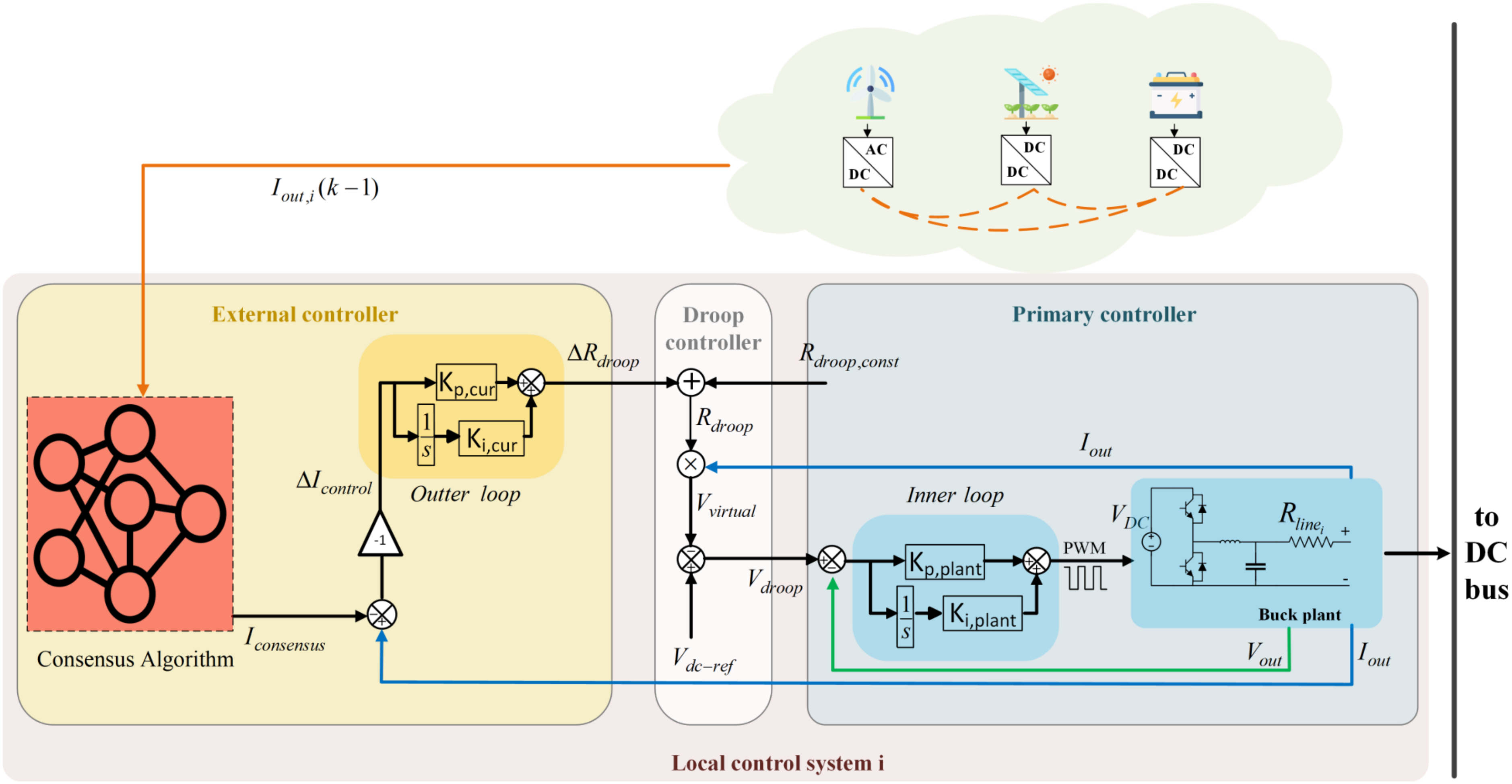
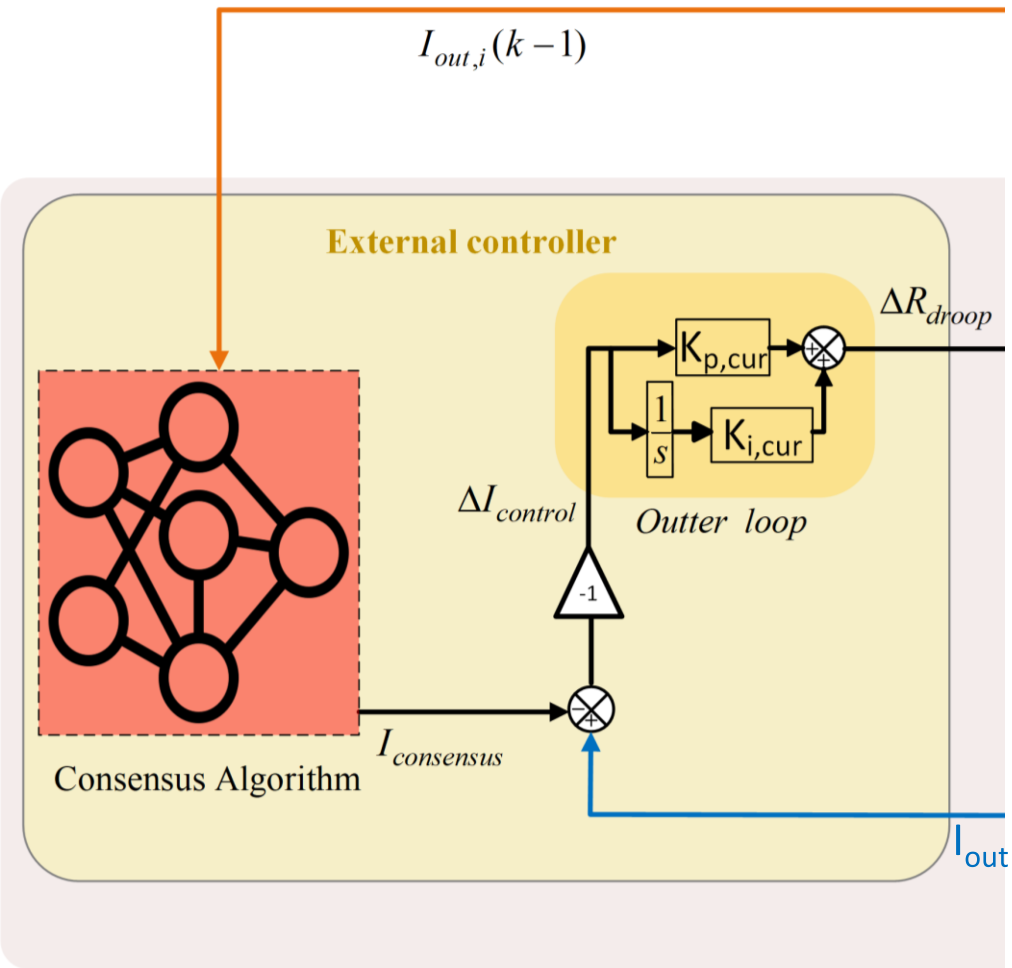


Fig. 8. Block diagram of the combined Consensus-Droop control loop.

Combination Droop Control & Consensus Algorithm



The first part is the external controller, which is calculated using the consensus algorithm. The sent data is $I_{out,i}\;k-1$, and the consensus output variable is defined as $I_{consensus} = I_{out,i}\;k$

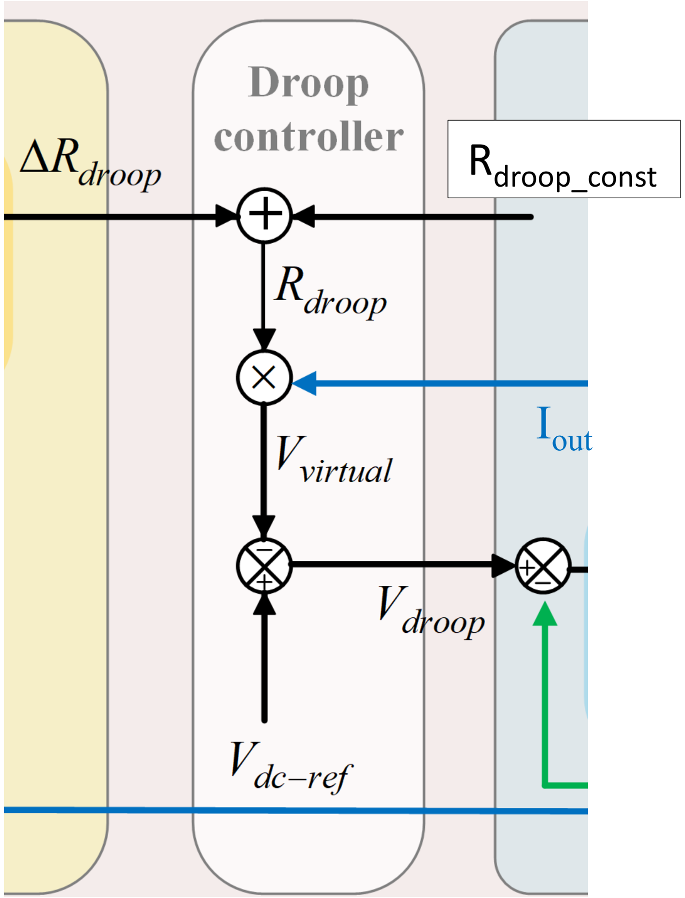
By applying the consensus algorithm, the current error in the external controller is calculated as :

$$\Delta I_{control} = I_{consensus} - I_{out} \qquad (7)$$

Fig. 8.1 Block diagram of the combined Consensus-Droop control loop – External control

Proposed method

Combination Droop Control & Consensus Algorithm



The second part is the modified Droop control,

where ΔR_{droop} from the external controller is added to the droop constant $R_{droop,const}$ to generate the modified R_{droop}

$$R_{droop} = R_{droop,const} + \Delta R_{droop} \quad (8)$$

Virtual voltage drop on the droop resistor, as defined in the following equation:

$$\begin{aligned} V_{virtual} &= I_{out} R_{droop} \\ V_{droop} &= V_{dc-ref} - V_{virtual} \end{aligned} \quad (9)$$

Fig. 8.2 Block diagram of the combined Consensus-Droop control loop – Droop controller.

Proposed method

Combination Droop Control & Consensus Algorithm

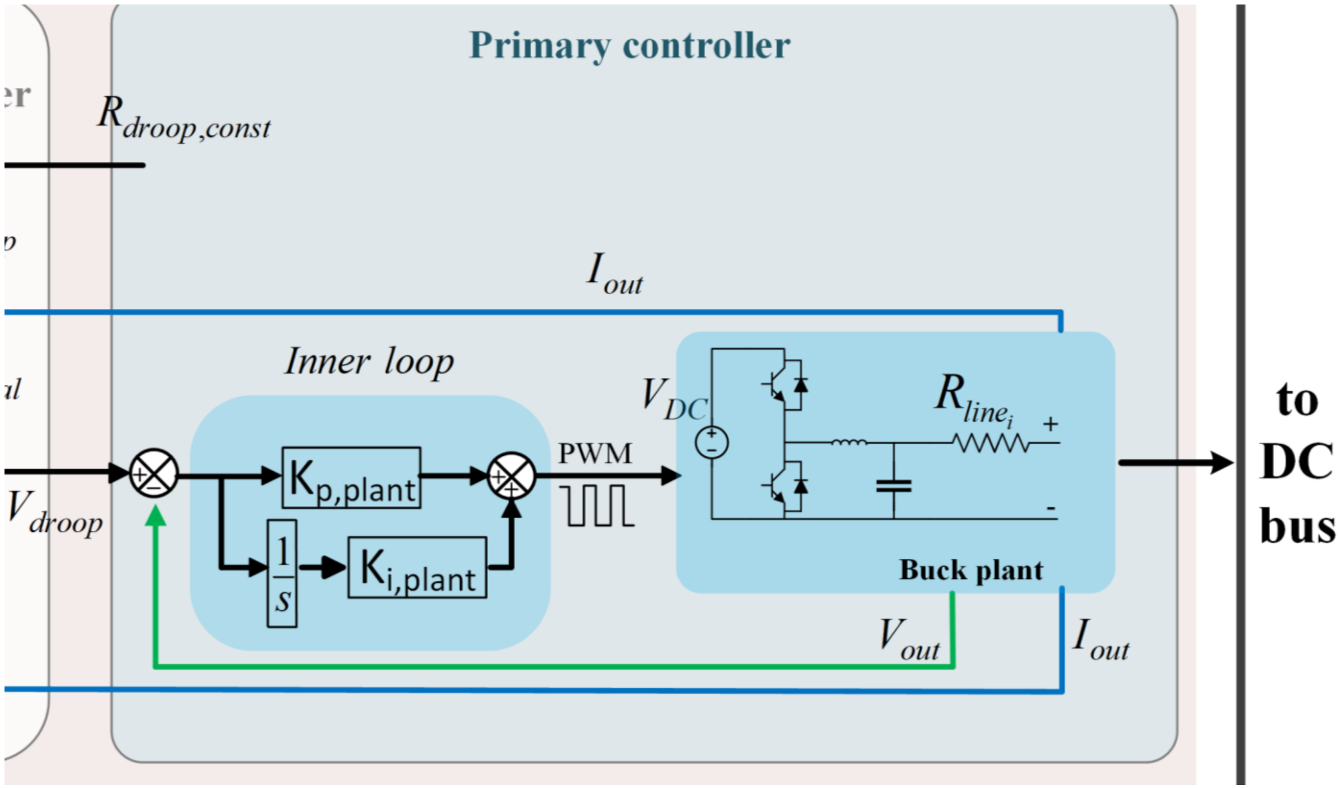


Fig. 8.3 Block diagram of the combined Consensus-Droop control loop – primary controller

To control the output voltage according to the droop voltage, the primary controller is applied. The deviation between the desired voltage V_{droop} and V_{out} is fed into the inner loop of the primary controller. Then the output PWM duty is generated to control the DC-DC converter.

Simulation Results

Consensus Simulation Only with PLECS

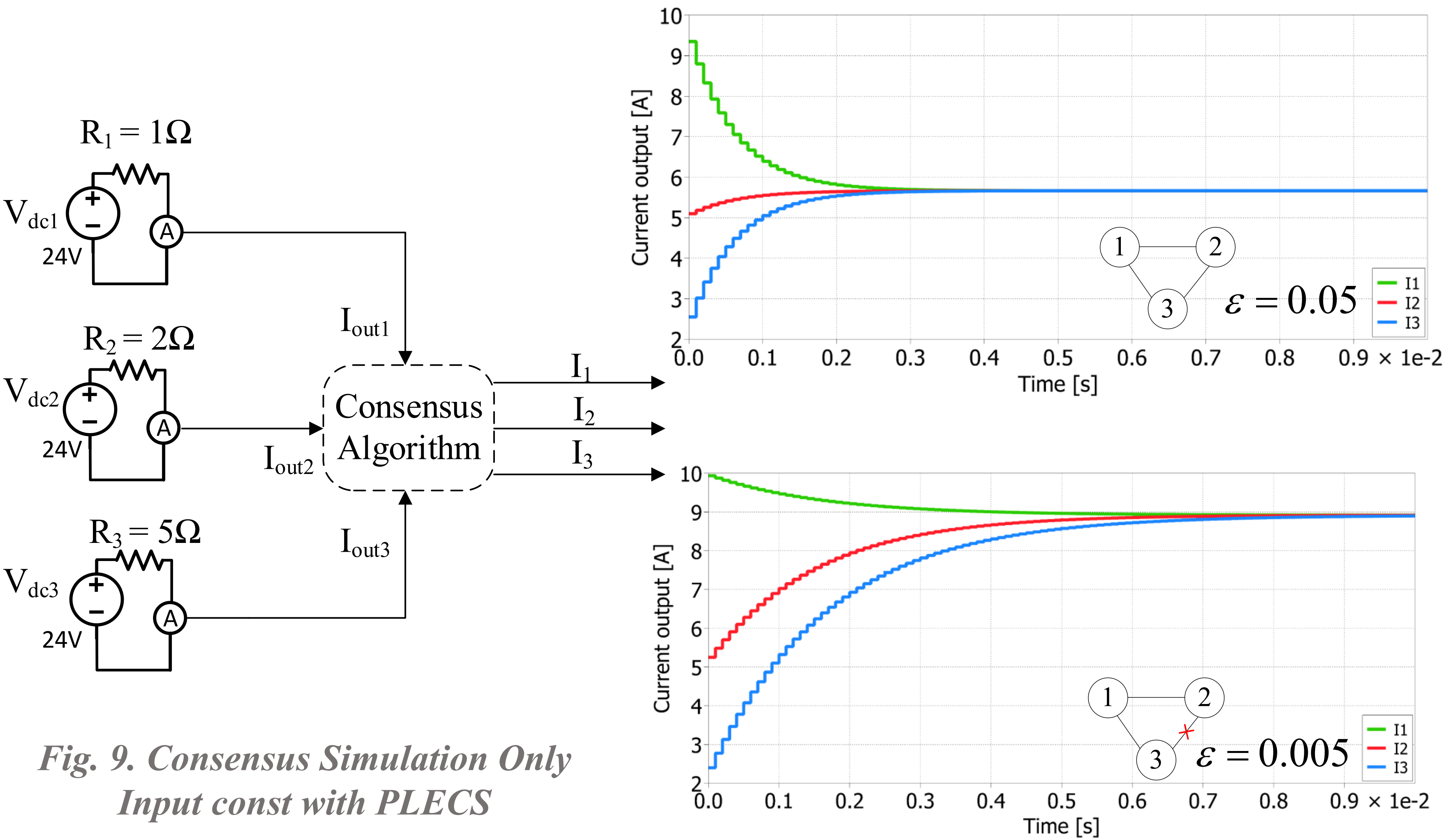
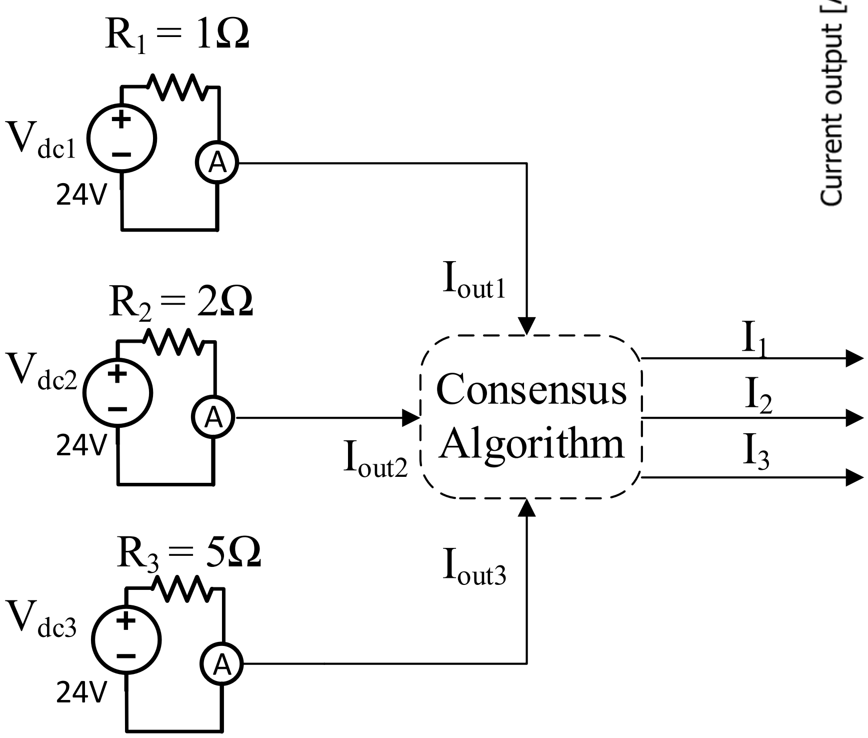


Fig. 9. Consensus Simulation Only Input const with PLECS

Consensus Simulation Only with PLECS



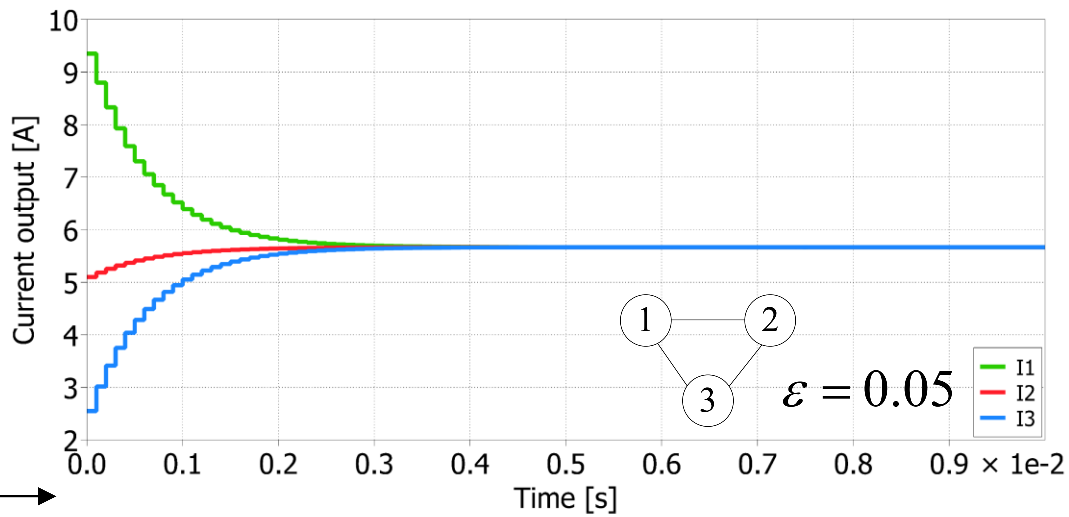


Fig. 9.1 Consensus Simulation Only Input const with PLECS – 0.05 gain

In Fig. 9.1, the convergence performance of the Consensus algorithm is illustrated when $\varepsilon = 0.05$. With the adoption of the Consensus algorithm, the control variables are gradually updated over time. After 30 steps (0.3s), these variables converge to their average values, indicating that a consensus is achieved among the generators.

Simulation Results

Consensus Simulation Only with PLECS

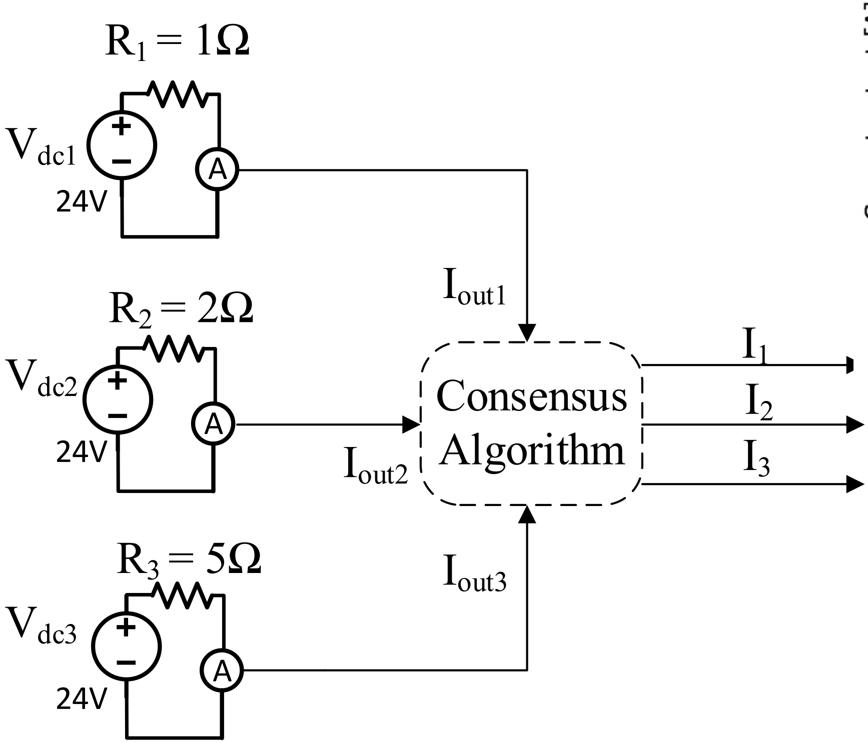
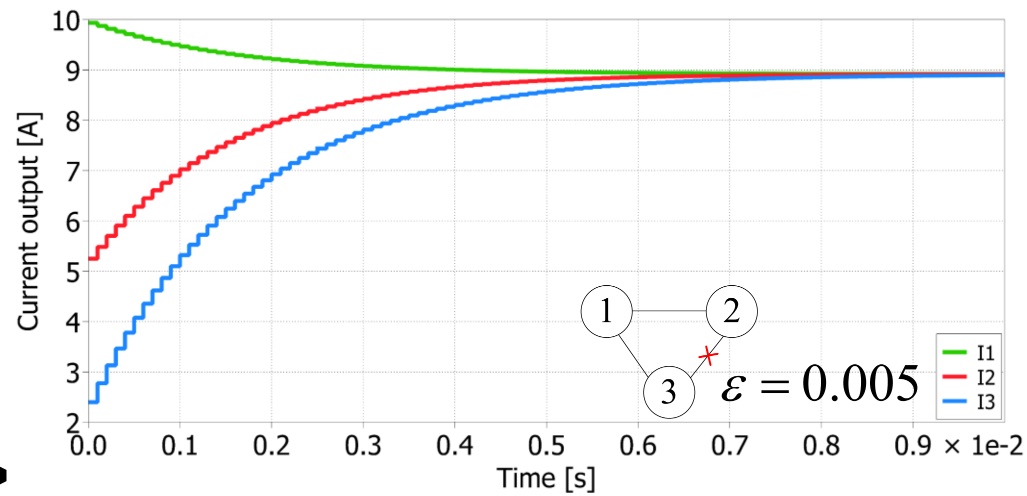


Fig. 9.2 Consensus Simulation Only Input const with PLECS – gain 0.005 – not all connected



In Fig. 9.2, the convergence performance of the Consensus algorithm is depicted when $\varepsilon = 0.005$ In this specific scenario, DG1 is assumed to have superior infrastructure investment and minimal errors during surveys. Furthermore, there is no exchange of information between DG2 and DG3 ($a_{23} = a_{32} = 0$).

Combined Consensus-Droop Control Simulation with PLECS

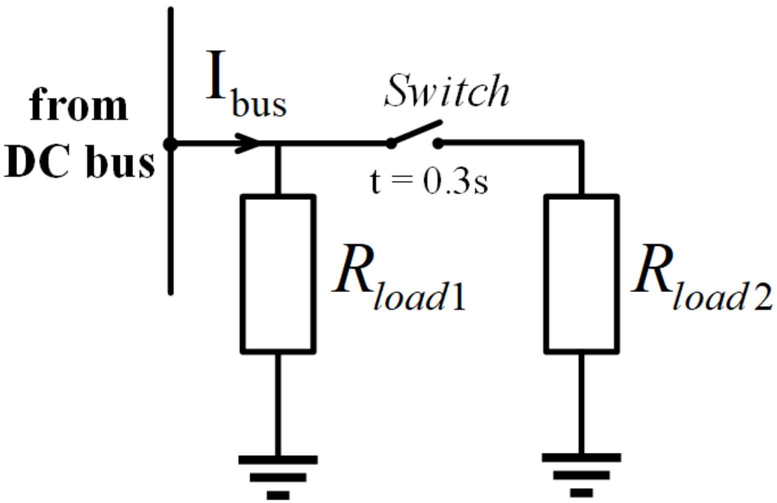


Fig. 10. Detail schematic of load connection at DC bus.

Load 1 remains connected to the DC bus throughout the simulation, while Load 2 is connected to the DC bus at 0.3 seconds to investigate the system stability characteristics

Simulation Results

Combined Consensus-Droop Control Simulation with PLECS

DC Bus : Connection of DGs

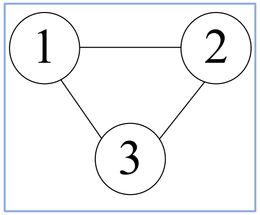


TABLE I. PARAMETER INFORMATION

Parameters	Value
Line Resistors	$R_{Line1} = 0.5$ $R_{Line2} = 0.75$ $R_{Line3} = 0.25$
DC source of DG1, DG2, DG3	$V_{dc} = 10V$
Desired Voltage	$V_{dc-ref} = 24V$
Resistor of Load 1	$R_{load1} = 10\Omega$
Resistor of Load 2	$R_{load2} = 10\Omega$

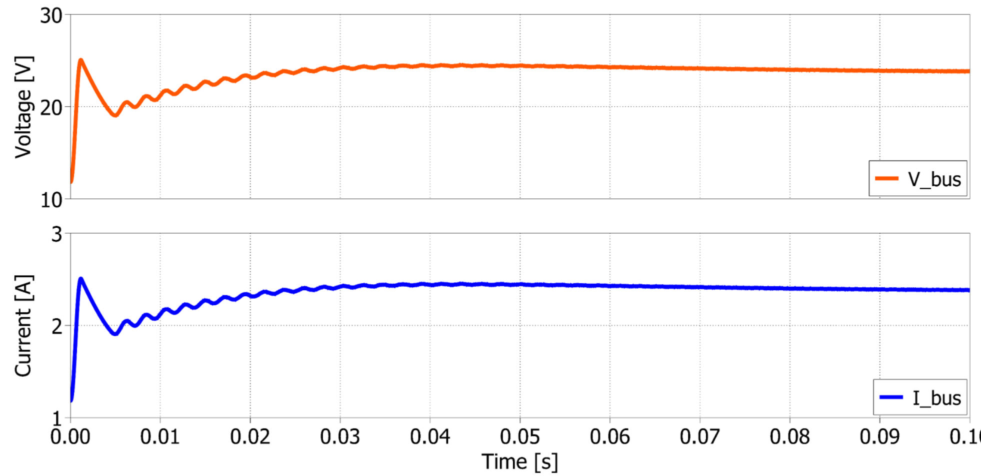


Fig. 11. Voltage and Current output at the DC bus during the system startup.

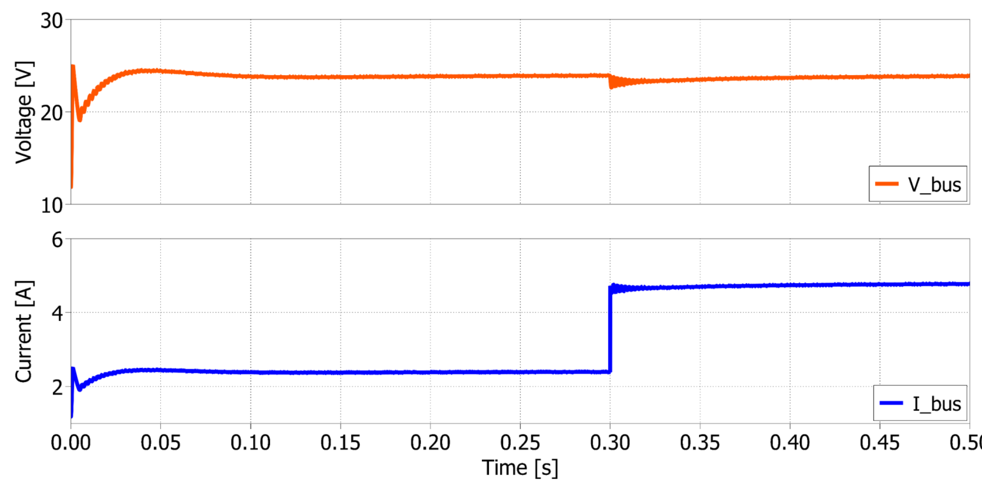


Fig. 12. Voltage and Current output at the DC bus during the load change period.

Combined Consensus-Droop Control Simulation with PLECS

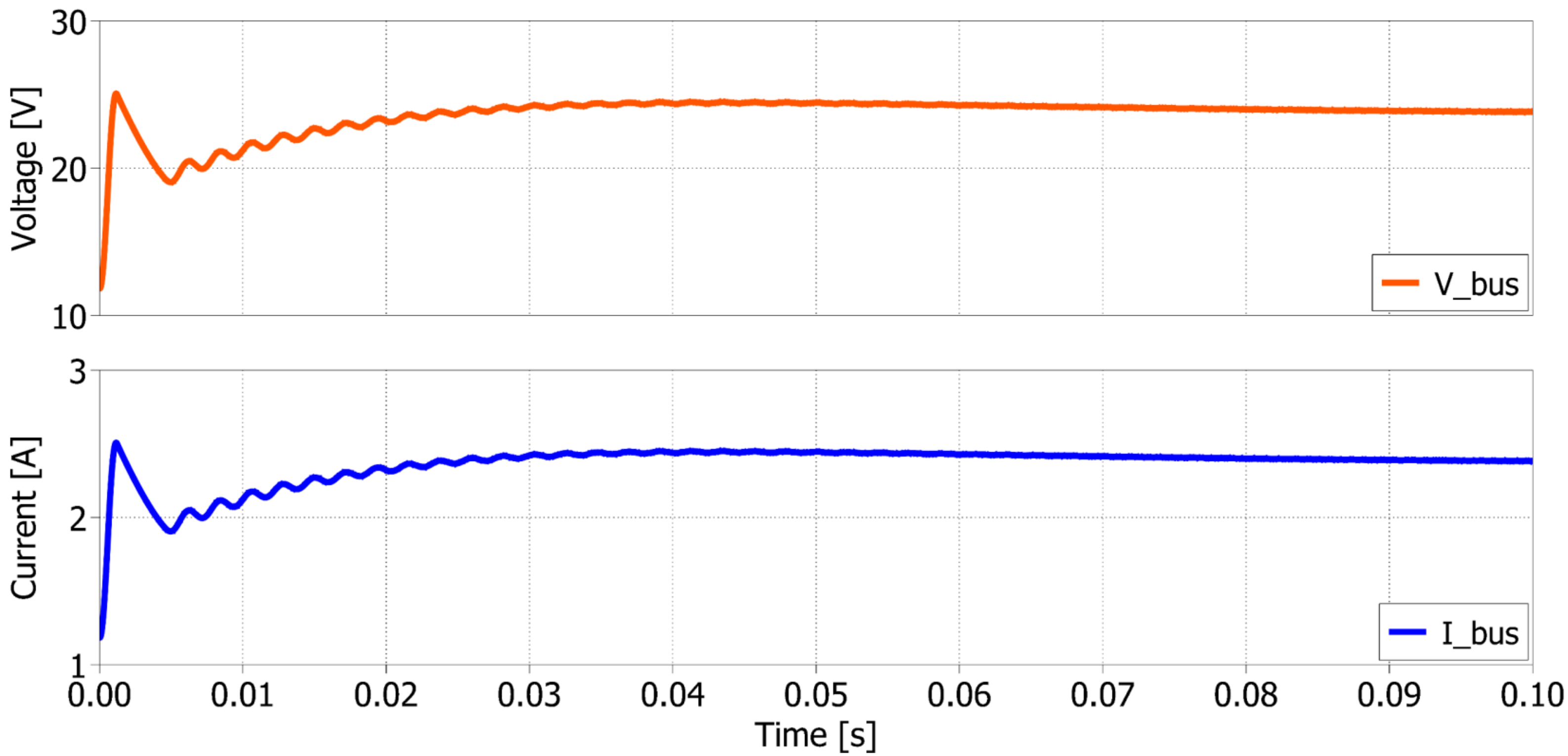


Fig. 11. Voltage and Current output at the DC bus during the system startup.

During the startup process, both the DC bus voltage and current reach a steady state within a short transient period of 0.015 seconds. Notably, there are no oscillations or overshoots observed during the startup, indicating a stable initial state

Simulation Results

Combined Consensus-Droop Control Simulation with PLECS

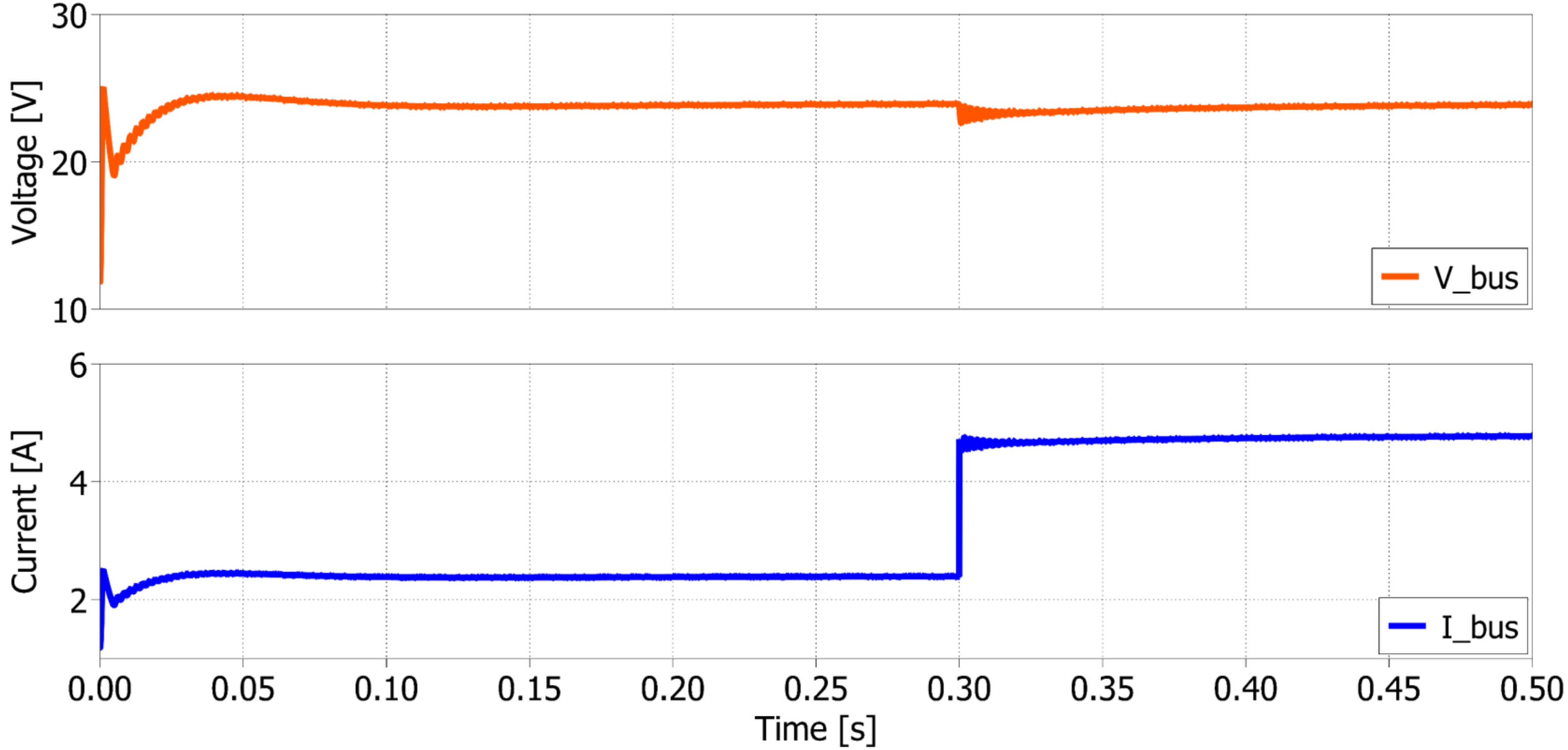


Fig. 12. Voltage and Current output at the DC bus during the load change period.

At 0.3 seconds, when Load 2 is connected to the system, there is a slight voltage drop; however, this drop quickly diminishes after 0.05 seconds.

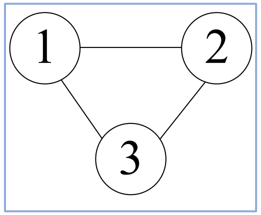
Combined Consensus-Droop Control Simulation with PLECS

Based on the results presented in Figs. 11 and 12, it can be concluded that the combination of the consensus algorithm and droop control has effectively maintained the quality of the DC bus voltage and supported the load demand without significant disturbances or deviations

Combined Consensus-Droop Control Simulation with PLECS

Output Current of DGs :

Connection of DGs



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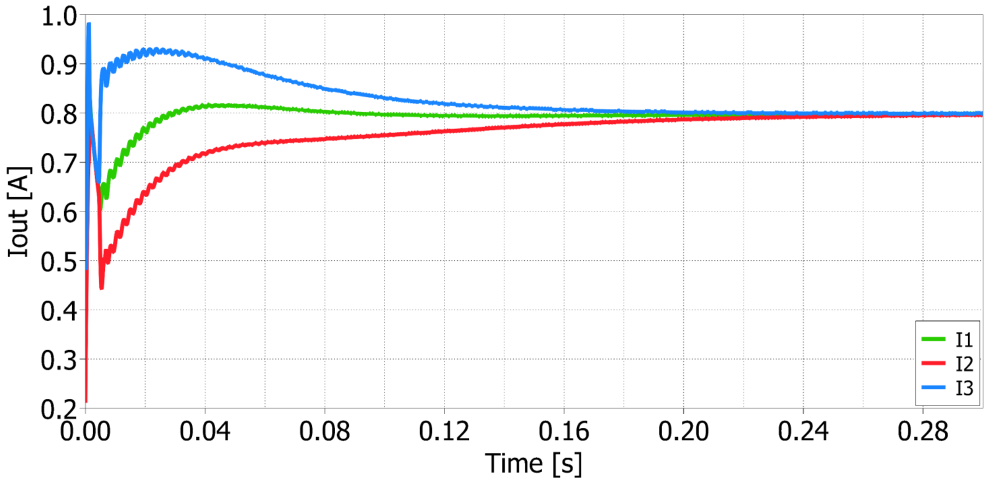

Fig. 13. The waveforms of the output currents during the start-up transient period.

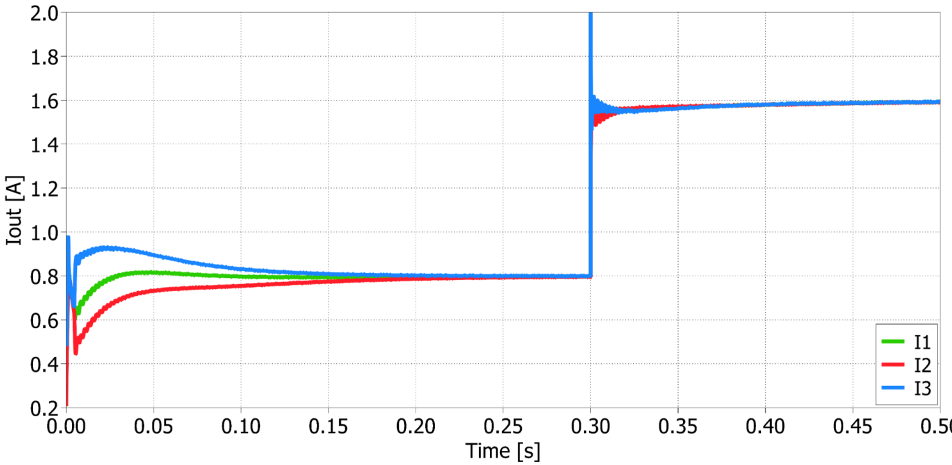

Fig. 14. The waveforms of the output currents during the load change period

Simulation Results

Combined Consensus-Droop Control Simulation with PLECS

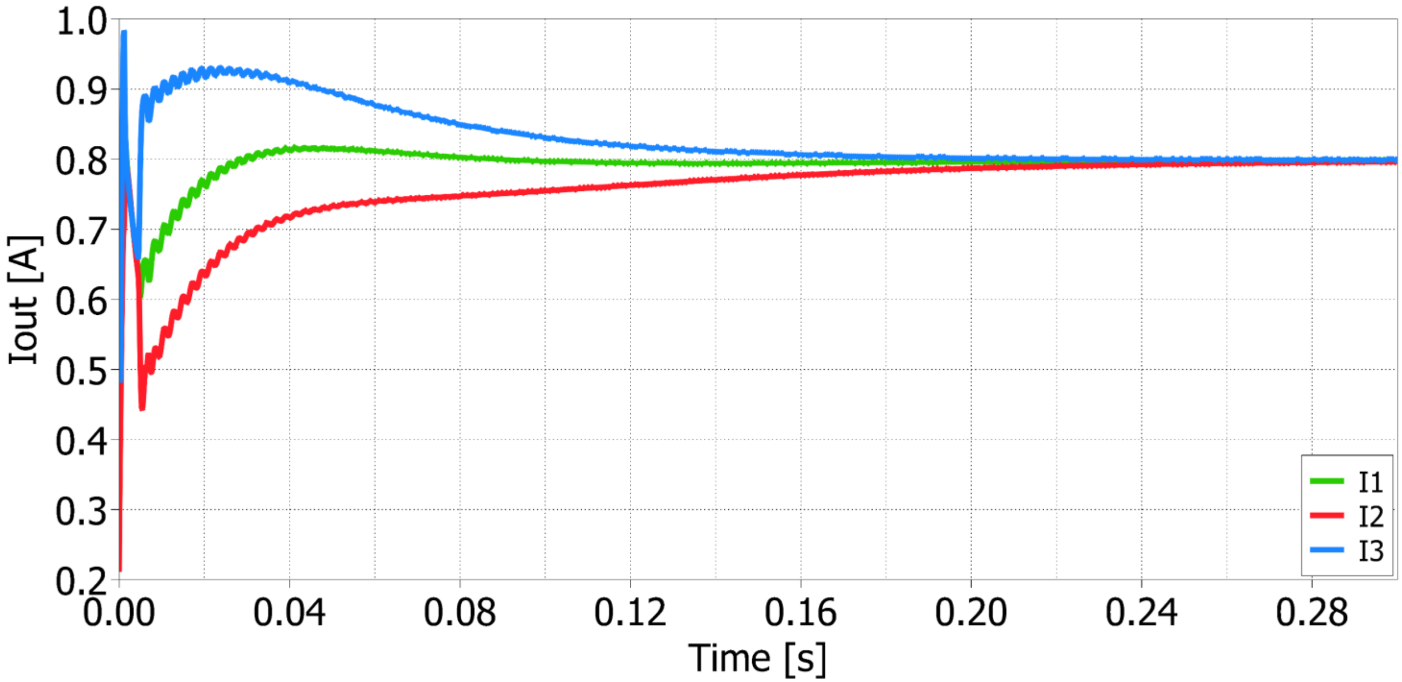

Fig. 13. The waveforms of the output currents during the start-up transient period.

The current sharing mismatch caused by line impedance mismatches has been resolved using the consensus algorithm combined with droop control. All three output currents reach the same established value after approximately 0.25 seconds.

Simulation Results

Combined Consensus-Droop Control Simulation with PLECS

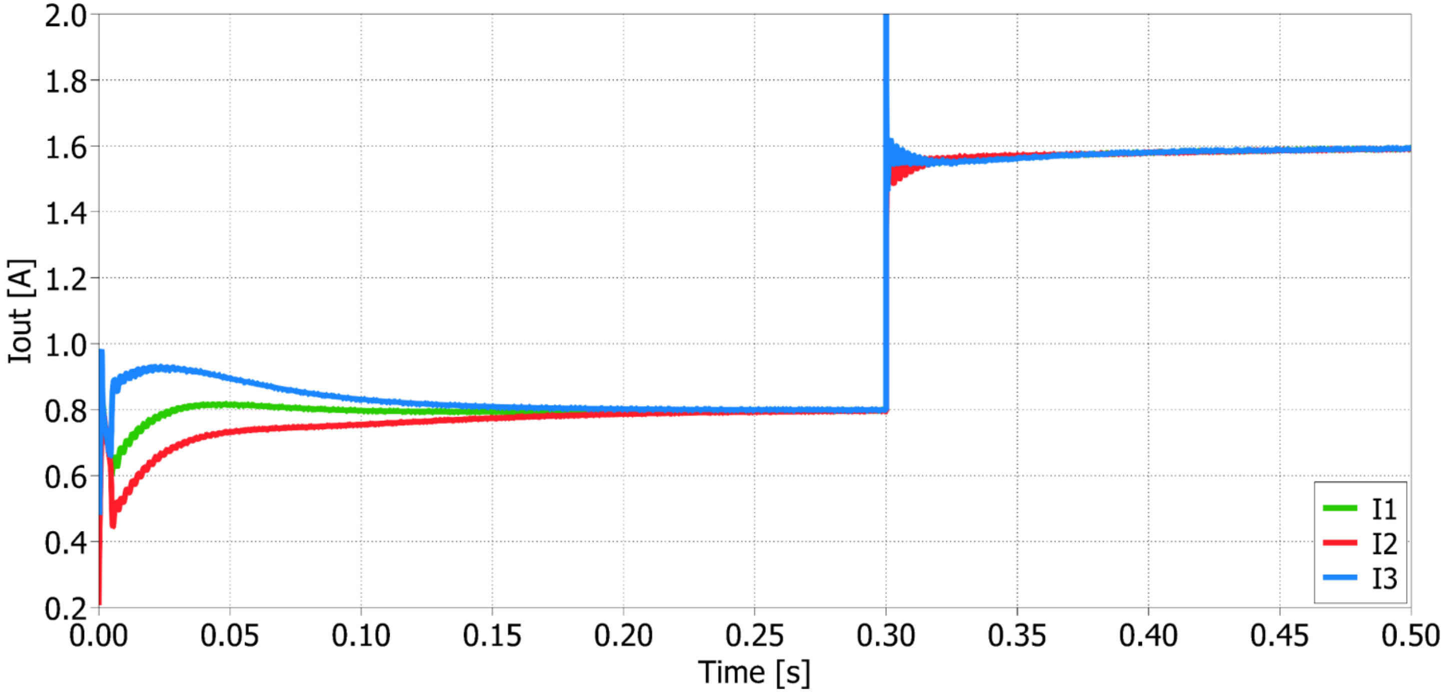

Fig. 14. The waveforms of the output currents during the load change period

Upon connecting Load 2 to the system at 0.3 seconds, a small current overshoot occurs in the generators to compensate for the load change. Importantly, it should be noted that the overshoot current remains within the maximum allowable current limit of the system, as illustrated in Fig. 14. Subsequently, a minor current sharing mismatch persists after 0.35 seconds.

Combined Consensus-Droop Control Simulation with PLECS

Based on the results depicted in Fig. 13 and 14, it is evident that the proposed method effectively mitigates current sharing errors in the microgrid. Furthermore, its performance remains stable even under load condition changes, demonstrating its suitability for maintaining power-sharing accuracy in practical scenarios.

Conclusions

- This paper proposes an improved approach that combines droop control with a consensus algorithm to tackle current sharing mismatches and enhance synchronization among distributed generation units. By integrating these two techniques, we have addressed the single point of failure issue often encountered in conventional methods.
- The consensus algorithm plays a crucial role in achieving convergence of the control variables, even in the presence of diverse communication network configurations. Through simulations conducted under various scenarios, the effectiveness of the z-domain discrete-time consensus algorithm has been demonstrated.
- This combined method offers a promising solution for improving power-sharing accuracy and maintaining synchronization in microgrids. Further research and Hardware-in-the-loop implementations will be valuable to validate and extend the effectiveness of this study

Acknowledgement

We acknowledge Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

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