



## Hybrid DC Micro-Grid Modeling and Dynamic Stability Analysis

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### Abstract

DC micro-grids (DC-MGs) have attracted significant attention as a promising solution for integrating distributed renewable sources to main utility. Compared to AC systems, DC-MGs offer higher efficiency; however, their varied structures and control strategies introduce considerable dynamic complexity. This paper investigates the dynamic stability of an islanded DC-MG comprising a photovoltaic (PV) unit, battery unit, and the supercapacitor (SC) unit connected to the main bus through DC-DC power converters. The system is modeled using state-space averaging method, and the linearized equations are analyzed using system eigenvalue analysis method to examine the system stability. The impact of various parameters including capacitor size, inductor values, line resistances, and constant power loads (CPLs) on the system's dynamic behavior is verified systematically. Results indicate that larger capacitors and inductors shift eigenvalues further into the left half-plane, improving damping and stability, whereas resistances and CPLs have a destabilizing effect. All simulations and verifications are conducted in MATLAB/Simulink to ensure analytical accuracy. The presented framework offers valuable insights for designing reliable DC-MGs with hybrid energy storage systems for future modern power grids.

**Keywords:** DC Microgrid; Dynamic Stability; Eigenvalue Analysis; MATLAB/Simulink, Constant Power Load; Battery; Supercapacitor.

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## 1. Introduction

In recent years, the use of DC-MGs has grown rapidly because of the increasing penetration of renewable energy resources and the demand for efficient local power systems. Since many resources and loads are inherently DC, using a DC bus reduces the number of conversion stages and improves overall efficiency. However, DC-MGs exhibit complicated dynamics. Different structures, various control strategies, and the presence of nonlinear elements such as constant power loads (CPLs) can lead to unstable operating points, especially under islanded conditions where

no strong grid is available [1,2]. Many studies have investigated these challenges using both small-signal and impedance-based approaches. Eigenvalue analysis of averaged state-space models is widely applied to evaluate stability margins and dynamic behavior [3,4].

Several control methods have also been suggested for power converters in DC-MGs, including virtual impedance and virtual capacitance strategies, nonlinear stabilizers, and supplementary damping controllers. Results reported in the literatures show improvements in transient performance and robustness of DC-MGs [3,4].

Recent contributions present advanced stabilizer and controller designs, delivering effective transient suppression and enhanced damping in micro-power systems [7,8]. These findings underline the importance of systematic eigenvalue-based analysis and motivate further study of how system parameters influence stability.

While some works focus on control schemes or isolated case studies, fewer papers present a complete parametric analysis showing how eigenvalues move when component values such as capacitance, inductance, resistance, as well as circuit parameters and CPL levels change [9,10]. The integration of hybrid energy storage systems (HESS), which combine batteries and SCs, is an established strategy for managing power, voltage, and current fluctuations in newly developed MGs [11]. While prior research has developed effective control frameworks for these systems, a comprehensive state-space model that captures the full dynamic interactions between the PV, battery, and SC converters remains a critical foundation for stability analysis [12-13]. The state-space model of the system provides a dynamic framework for formally investigating system properties before controller design. Using eigenvalue analysis, the small-signal stability model can be used to characterize the system's dynamic behavior as a function of its parameters [14-15]. The location of eigenvalues in the complex  $s$ -plane directly dictates dynamic performance, where migration toward the imaginary axis signifies reduced damping and potential instability [16]. For a PV-battery-SC DC-MG, this analysis is essential to precisely evaluate how the SC's integration influences the system's dominant modes especially when large signal stability is taken into consideration for controller design [17-18]. Parametric sweeps of controller gains and filter components, guided by eigenvalue loci, allow for the optimization of system parameters to ensure stable, well-damped operation under all conditions [17,19].

This work presents three main contributions:

- 1) while previous papers mainly addressed control design or local converter dynamics, this paper presents an unified small-signal model that captures the coupling among different energy storage and generation units. In this regard, a hybrid DC MG with PV, SC, and battery units, with a ninth-degree nonlinear state-space equation is modeled.
- 2) a detailed parametric sensitivity analysis is performed to show how variations in capacitance, inductance, resistance, and constant power load (CPL) levels influence

system eigenvalues and stability margins a feature rarely covered in earlier works.

All modeling and analysis steps are validated through MATLAB/Simulink simulations, ensuring consistency between theoretical derivations and time-domain results.

This paper is organized as follows: Section 2 describes the system modeling and methodology. Section 3 presents the eigenvalue analysis and sensitivity analysis results. Section 4 discusses the findings and presents the conclusions.

Hence, this study extends the state of the art by linking analytical modeling with simulation-based verification for a complete stability assessment of DC-MGs.

## 2. System Modeling and Methodology

In this section, a sample hybrid DC-MG comprising a PV unit, a battery unit, and a SC unit is considered. This DC-MG provides power to DC loads; two types of loads are taken into account: constant impedance loads and constant power loads, the latter being a well-known nonlinear load. Subsequently, the overall state-space model of the system is derived, and a stability analysis is performed.

### 2-1. Micro-grid Structure and System Time Domain Modeling

The case study is an islanded DC-MG that consists of three main energy sources: a PV array, battery unit and a SC unit. Each power resource is connected to the common DC bus through a dedicated power electronic converter. The PV is interfaced by a unidirectional boost converter, while both the battery and SC units are interfaced using bidirectional DC-DC converters.

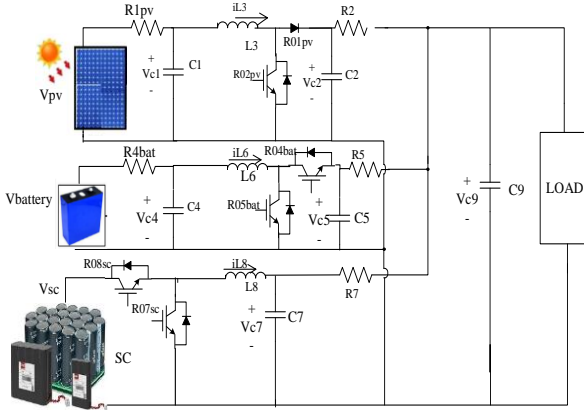
A load is connected at the end of the bus. It is worth mentioning that both the constant impedance loads and constant power loads are discussed in the simulation part.

### 2-2. State-Space Model

To accurately represent the dynamic behavior of the DC-MG, each distributed energy unit including the PV array, the battery storage unit and the SC unit is modeled using the state-space averaging approach described in [3,4]. Inductor currents and capacitor voltages are selected as the state variables to capture the essential dynamic characteristics of the converters. In the modeling approach, to make the results more realistic, the switches in conduction mode are modeled by their on-

resistance. These resistors based on Fig. 1 are shown by

$$R_{01pv}, R_{02pv}, R_{04bat}, R_{05bat}, R_{07sc}, R_{08sc}$$



**Fig. 1. Structure of the islanded DC-MG with PV, battery, and SC units.**

### 2-2-1. PV Subsystem Modeling

As shown in Fig. 1, the PV resource unit is interfaced with the DC bus through a DC-DC converter. By applying the state-space averaging technique, the small-signal dynamic model of this subsystem can be expressed as:

$$\dot{x}_1 = -\frac{1}{R_{1pv} C_1} x_1 - \frac{1}{C_1} x_3 + \frac{1}{R_{1pv} C_1} V_{PV} \quad (1)$$

$$\dot{x}_2 = -\frac{1}{R_L C_2} x_2 - \frac{(1-u_1)}{C_2} x_3 + \frac{1}{R_2 C_2} x_9 \quad (2)$$

$$\dot{x}_3 = \frac{1}{L_3} x_1 - \frac{(1-u_1)}{L_3} x_2 - \frac{1}{L_3} (R_{01pv}) x_3 \quad (3)$$

where  $x_1$  is the voltage across capacitor  $C_1$ ,  $x_2$  is the voltage across capacitor  $C_2$ ,  $x_3$  is the current through inductor  $L_3$ ,  $u_1$  is the duty cycle of the converter switching device.

These equations describe the small-signal dynamics of the PV converter and are derived based on the state-space averaging method presented in [3,4].

### 2-2-2. Battery Storage Unit Subsystem Modeling

The battery energy storage system is connected to the DC bus through a bidirectional DC-DC converter.

Using the state-space averaging approach, the dynamic equations of the battery converter can be written as:

$$\dot{x}_4 = -\frac{1}{R_{4bat} C_4} x_4 - \frac{1}{C_4} x_6 + \frac{1}{R_{4bat} C_4} V_{Battery} \quad (4)$$

$$\dot{x}_5 = -\frac{1}{R_L C_5} x_5 - \frac{(1-u_2)}{C_5} x_6 + \frac{1}{R_5 C_5} x_9 \quad (5)$$

$$\dot{x}_6 = \frac{1}{L_6} x_4 - \frac{(1-u_2)}{L_6} x_5 - \frac{1}{L_6} (R_{04bat}) x_6 \quad (6)$$

where  $x_4$  is the voltage across capacitor  $C_4$ ,  $x_5$  is the voltage across capacitor  $C_5$ ,  $x_6$  is the inductor current  $L_6$ ,  $u_2$  is the duty cycle of the switching device in the bidirectional battery converter.

These equations describe the small-signal dynamics of the battery subsystem derived using the state-space averaging method described in [3], [4].

### 2-2-3. SC Subsystem Unit

The SC unit is interfaced with the DC bus through a bidirectional DC-DC converter, which provides rapid energy exchange and voltage stabilization.

Applying the state-space averaging approach, the dynamic equations of this converter can be represented as:

$$\dot{x}_7 = -\frac{1}{R_L C_7} x_7 - \frac{1}{C_7} x_8 + \frac{1}{R_7 C_7} x_9 \quad (7)$$

$$\dot{x}_8 = -\frac{1}{L_8} x_7 - \frac{R_{08sc}}{L_8} x_8 + \frac{u_3}{L} V_S \quad (8)$$

$$\dot{x}_9 = \frac{1}{C_9} \left[ \frac{x_2 - x_9}{R_2} + \frac{x_5 - x_9}{R_5} + \frac{x_7 - x_9}{R_7} - x_9 \frac{1}{R_L} \right] \quad (9)$$

where:  $x_7$  is the voltage across the SC unit output capacitor denoted by  $C_7$ , and  $x_8$  is the current through the inductor  $L_8$ , and  $u_3$  is the duty cycle of the converter switching device associated with the SC subsystem. These equations capture the fast transient dynamics of the SC converter within the DC-MG.

### 2-2-4. Overall State-Space Model Derivation

By combining the subsystem equations (1)-(9), the complete state-space representation of the DC-MG is obtained. In this formulation,  $x_9$  represents the voltage across capacitor  $C_9$  in parallel with the output load. A general nonlinear, nine-degree-state-space model denoted by  $\dot{\mathbf{x}}_{9 \times 1} = f(\mathbf{x}_{9 \times 1}, \mathbf{u}_{3 \times 1})$  is utilized for derivation of the linearized model. The overall linearized model can be written in compact form as:

$$\dot{\mathbf{X}}(t) = \mathbf{A}\mathbf{X}(t) + \mathbf{B}\mathbf{U}(t) \quad (10)$$

where

$$\mathbf{X}_{9 \times 1}(t) = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9]^T$$

$$\mathbf{U}_{3 \times 1}(t) = [u_1, u_2, u_3]^T$$

The matrices  $\mathbf{A}$  and  $\mathbf{B}$  are obtained by linearizing the nonlinear differential equations around the nominal operating point  $(\mathbf{x}_0, \mathbf{u}_0)$  according to the state-space averaging method

[3,4].

### 2-3. Linearization and Small-Signal Model Deviation

The overall linearized model expressed by (10) is derived by linearization of overall state space model around  $(\mathbf{x}_0, \mathbf{u}_0)$  using first-order Taylor expansion, to this end,  $\Delta \mathbf{x} = \mathbf{x} - \mathbf{x}_0$  and  $\Delta \mathbf{u} = \mathbf{u} - \mathbf{u}_0$ . The small-signal model used for modal analysis is expressed by:

$$\Delta \dot{\mathbf{x}}(t) = \mathbf{A}_{lin} \Delta \mathbf{x}(t) + \mathbf{B}_{lin} \Delta \mathbf{u}(t) \tag{11}$$

$$\mathbf{A}_{lin} = \left. \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \right|_{(\mathbf{x}_0, \mathbf{u}_0)} \tag{12}$$

$$\mathbf{B}_{lin} = \left. \frac{\partial \mathbf{f}}{\partial \mathbf{u}} \right|_{(\mathbf{x}_0, \mathbf{u}_0)}$$

Here  $f(\mathbf{x}, \mathbf{u})$  denotes the right-hand side of the nonlinear state equations (collected in (1)-(9)). The Jacobian matrices  $\mathbf{A}_{lin}$  and  $\mathbf{B}_{lin}$  are evaluated numerically using the operating-point values derived from steady state operation of the system. Eigenvalue analysis of matrix  $\mathbf{A}_{lin}$  is then used to assess local dynamic stability and modal damping.

### 2-4. Simulation Results

The theoretical developed mathematical state space model is validated through MATLAB software. Each converter is modeled with realistic parameters (inductor and capacitor values, line resistances, and controller settings) taken from the literature and practical test cases. The PV is implemented as a controlled DC resource, while the battery and SC units follow their respective charge–discharge dynamics. The CPL is modeled using a negative-impedance representation, which reproduces its destabilizing behavior. These simulations confirm the analytical results and provide time-domain insights into the system response under parameter variations [7-10].

## 3. Results and Discussion

In this section, a set of parameters in the hybrid DC-MG is varied over a range. Based on the eigenvalues derived from the linearized state-space model, the trace of the eigenvalues in the complex plane is drawn to show the effects of the parameter changes on the system's dynamic stability.

### 3-1. Eigenvalue Analysis

The linearized system matrix  $A_{lin}$  was obtained for the operating point corresponding to nominal parameters of the PV, battery storage, and SC units. The eigenvalues of this matrix determine the local

dynamic stability of the DC-MG.

Fig. 2 shows the eigenvalue distribution under nominal conditions. It can be observed that all eigenvalues lie in the left half-plane, confirming that the system is stable in its base case. The relative locations of the eigenvalues also provide insight into damping levels and oscillatory behavior of different modes.

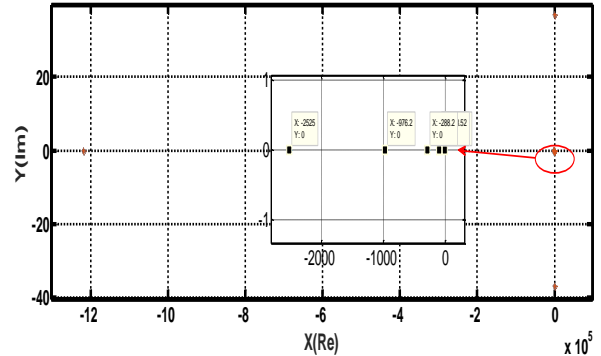


Fig. 2. Eigenvalues of the DC-MG under nominal operating conditions.

### 3-2. Parameter Sensitivity Analysis

To investigate the effect of physical parameters, a systematic sensitivity study was performed. One parameter at a time (capacitor, inductor, line resistance, CPL and linear load) was varied while others were kept constant.

#### 3-2-1. Effect of Capacitance

The DC-MG capacitor values for each converter are varied across several levels. Larger capacitance shifts the eigenvalues leftward, improving damping and enhancing voltage stability. However, very large capacitance values may cause practical limitations in terms of cost and physical size. A representative case with  $C = C_5$  is shown in Fig. 3.

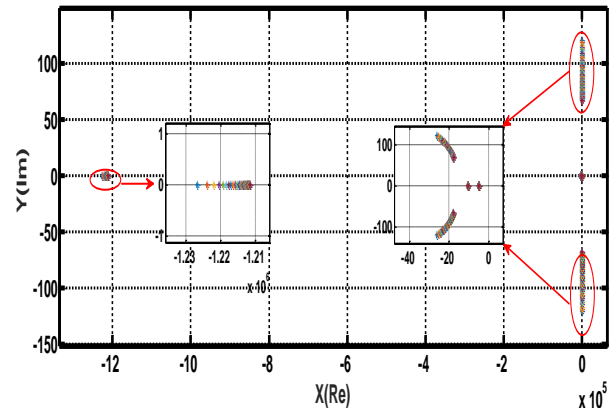
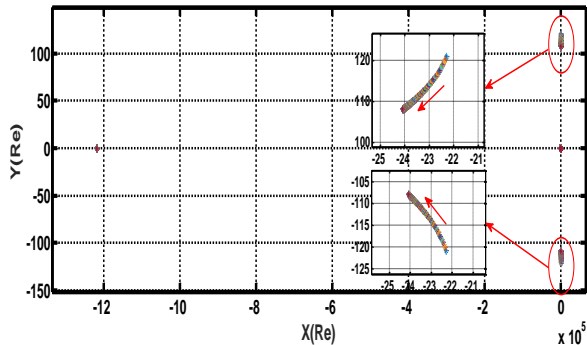


Fig. 3. Eigenvalue trajectories of the DC-MG for a representative case of capacitance variation ( $C_5$ ).

### 3-2-2. Effect of Inductance

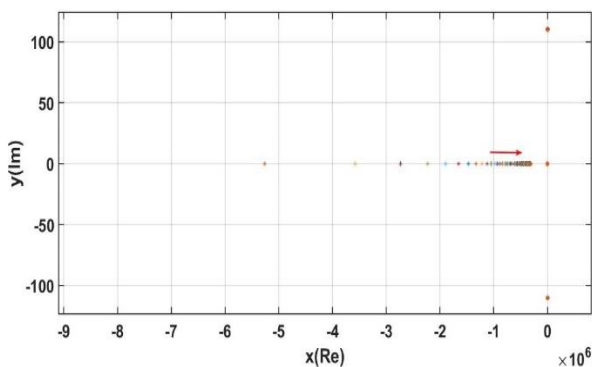
In the second step, the line inductance is varied across three representative levels ( $L_3, L_6, L_8$ ). The results show that increasing inductance moves the eigenvalues further into the left half-plane, which improves current smoothing and enhances overall system stability. However, very large inductance values may slow down the transient response and increase cost. A representative case for  $L_6$  is illustrated in Fig. 4.



**Fig. 4. Eigenvalue trajectories of the DC-MG for a representative case of inductance variation ( $L = L_6$ ).**

### 3-2-3. Effect of Line Resistance

The impact of line resistance on system dynamics was investigated by considering three representative cases, namely  $R_2, R_5$  and  $R_7$ . As the resistance increased from  $R_2$  to  $R_7$ , the eigenvalues gradually shifted to left, showing a reduction in damping and a smaller stability margin. A representative case for  $R_5$  is illustrated in Fig. 5.

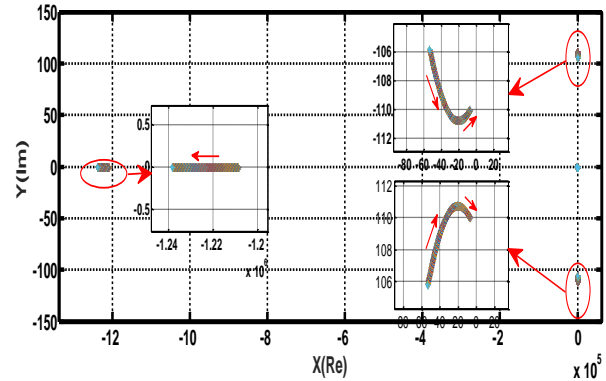


**Fig. 5. Eigenvalue trajectories of the DC-MG for a representative case of line resistance variation ( $R_5$ ).**

### 3-2-4. Effect of Constant Power Loads (CPLs)

The most destabilizing factor in DC-MGs is the constant power loads. As the CPL level increases, the eigenvalues gradually shift toward the right

half-plane. Beyond a certain threshold, one eigenvalue crosses the imaginary axis, leading to oscillations and potential voltage collapse. A representative result is illustrated in Fig. 6.

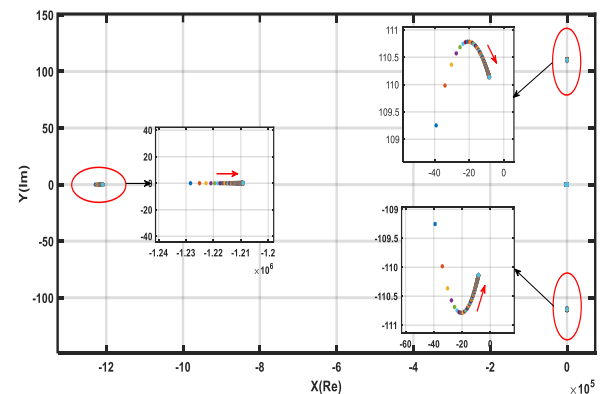


**Fig. 6. Eigenvalue trajectories of the DC-MG under variation of constant power load (CPL).**

### 3-2-5. Effect of Linear Constant Impedance Loads

Changes in the load resistance can have a significant impact on the stability of the DC-MG system. As the load resistance increases, the load current decreases, which may lead to voltage fluctuations and drive the system toward instability. Conversely, when the load resistance decreases, the load current increases, and the system tends to respond more effectively to voltage disturbances, resulting in enhanced stability.

As shown in Fig. 7, variations in the load resistance affect the location of the eigenvalues and cause them to shift toward the positive real axis. This movement indicates a reduction in the system damping, implying that any disturbance may amplify oscillations and eventually lead to the loss of dynamic stability in the DC-MG.



**Fig. 7. Eigenvalue trajectories of the DC-MG for different linear load resistances.**

## 3-3. Summary of Results

The main outcomes of the sensitivity analysis are

summarized in Table 1. It can be observed that larger capacitance and inductance values shift the eigenvalues toward the left-half plane, thereby improving voltage damping and enhancing overall stability. In contrast, higher line resistance or increased CPL power level moves the eigenvalues toward the imaginary or positive real axis, weakening damping and increasing oscillatory behavior. The variation of the linear load resistance  $R_{LL}$  also has a clear impact on system dynamics. As  $R_{LL}$  increases, the eigenvalues slightly move toward the positive real axis, indicating reduced damping and a smaller stability margin. Conversely, smaller  $R_{LL}$  values enhance damping and stabilize the DC-bus voltage. These results confirm that appropriate selection of passive-component values and maintaining a balanced ratio between constant-power and linear loads are essential for ensuring stable operation of DC-MGs.

### 3-4. Discussion

The results demonstrate that proper sizing of passive elements (capacitors and inductors) and adequate load composition play a considerable role in the dynamic performance of DC-MGs. Larger capacitance and inductance values strengthen damping and suppress oscillations, whereas excessive line resistance or higher CPL penetration reduce system robustness. The influence of the linear load resistance  $R_{LL}$  further validates this observation. As shown in Fig. 7, increasing  $R_{LL}$  weakens the natural damping effect and causes some eigenvalues to shift toward the positive real axis, which may result in slower transient recovery or even instability under disturbances. On the other hand, decreasing improves damping characteristics and enhances voltage-regulation capability. These findings are consistent with previous analytical and experimental studies [7,8], which reported similar eigenvalue movements under parameter variations. By integrating eigenvalue-based analysis with

MATLAB/Simulink verification, the proposed framework bridges the gap between theoretical modeling and practical implementation. It provides useful insight for selecting optimal component values and load configurations to ensure robust and stable operation of islanded DC-MGs.

### 4. Conclusion and Future Works

This paper presented a comprehensive dynamic stability analysis of an islanded DC-MG composed of a PV unit, a battery unit, and a SC unit. The system was modeled using a state-space averaging approach, and the linearized equations were applied to perform eigenvalue-based small-signal stability analysis. The sensitivity of eigenvalues to major parameters—including capacitance, inductance, line resistance, CPL level, and constant impedance loads was thoroughly investigated. The results showed that increasing capacitance and inductance improves damping and voltage stability, whereas higher line resistance and larger CPL penetration reduce stability margins and may lead to oscillatory behavior. Additionally, the variation of linear load resistance was found to have a noticeable effect on system dynamics: smaller enhances damping and stabilizes the DC bus voltage, while larger decreases damping and may shift eigenvalues toward the positive real axis. All analytical findings were validated through MATLAB/Simulink simulations, confirming the accuracy of the proposed theoretical framework. The main contributions of this study are as follows:

- 1) Development of a systematic modeling and linearization approach for hybrid-storage DC-MGs;
- 2) Comprehensive eigenvalue-based sensitivity analysis considering passive elements, CPL, and linear load effects.
- 3) Verification of analytical predictions through MATLAB/Simulink simulations.

**Table 1. Sensitivity of Eigenvalues to Parameter Variations in DC-MG.**

| Parameter change                           | Eigenvalue shift                           | Impact on stability                               | Practical note                                 |
|--|--|---|--|
| Capacitance (increase)                     | Eigenvalues move leftward                  | Improves damping and voltage stability            | Limited by cost and physical size              |
| Inductance (increase)                      | Eigenvalues move leftward                  | Enhances current smoothing, better stability      | Very large $L$ increases system inertia        |
| Line resistance (increase)                 | Eigenvalues move toward imaginary axis     | Reduces damping, weakens stability                | Higher losses and voltage drop                 |
| CPL power (increase)                       | Eigenvalues move rightward                 | Destabilizing effect, may cause oscillations      | Requires supplementary control schemes         |
| Linear load resistance $R_{LL}$ (increase) | Eigenvalues move toward positive real axis | Decreases damping, increases oscillatory tendency | Excessive $R_{LL}$ may reduce stability margin |

Future research could extend this work in several directions. First, advanced nonlinear and adaptive control strategies could be designed to mitigate the destabilizing effects of constant power loads (CPLs) and enhance system robustness against parameter uncertainties. Second, experimental validation on a hardware testbed would strengthen the findings of this study. Finally, the integration of renewable generation forecasting and intelligent energy management algorithms could significantly improve the stability and operational efficiency of DC-MGs.

#### Appendix A:

| System parameters of the DC-MG |             |        |          |
|--------------------------------|-------------|--------|----------|
| Parameter                      | Symbol      | Value  | Unit     |
| PV unit capacitor              | C1          | 0.01   | F        |
| PV unit inductor               | L3          | 0.033  | H        |
| Battery unit capacitor         | C4          | 0.01   | F        |
| Battery unit inductor          | L6          | 0.033  | H        |
| SC unit C7                     | C7          | 0.01   | F        |
| SC unit inductor L8            | L8          | 0.0033 | H        |
| SC C9                          | C9          | 0.0001 | F        |
| SC Line resistance             | R2          | 0.1    | $\Omega$ |
| Line resistance                | R5          | 0.01   | $\Omega$ |
| Line resistance                | R7          | 0.1    | $\Omega$ |
| CPL power (nominal)            | P_CPL       | 1      | MW       |
| Linear load                    | P- $R_{LL}$ | 1      | MW       |
| DC bus voltage (nominal)       | V_bus       | 1000   | V        |

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## Biography

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