www.ijbar.org
ISSN 2249-3352 (P) 2278-0505 (E)
Cosmos Impact Factor-5.86

FLC based droop controller for enchancement of Islanded DC Microgrid

Veeranjaneyulu Gopu [1],V.Vyshnavi[2], T.Meghana[3] ,T.Sukanya[4] ,P.Sai Hareesh Kumar[5] , Y.Shanmukh[6]
[1]Assistant Professor, Department of Electrical & Electronics Engineering
[2,3,4,5,6] UG Students, Department of Electrical & Electronics Engineering
R.V.R & J.C. College of Engineering, Guntur (Dt), AP, India.

Abstract:

This study examines the impact of droop control implementation on the voltage stability of DC power systems operating in islanded mode, particularly in the presence of active and nonlinear loads such as constant power loads (CPLs). The system setup consists of parallel sources with associated transmission lines, modeled as ideal voltage sources in series with equivalent resistance and inductance. To enhance analysis efficiency, an approximate model is utilized to conduct nonlinear stability analysis, allowing for the prediction of system behavior with a reduced set of differential equations. Furthermore, fuzzy controller methodologies are integrated to evaluate their effect on system stability and improve dynamic performance. Based on analytical stability conditions and system parameters, this study provides design guidelines for developing resilient microgrids and defining safe operating regions, ensuring robust and stable operation under varying load conditions.

Index Terms—DC microgrid, droop control, nonlinear stabilityanalysis, constant power load (CPL), bifurcation analysis, FLC.

1. Introduction:

Networks are becoming increasingly pervasive across a wide range of autonomous systems—from ships to portable electronics—driving a growing interest in the use of small-scale DC microgrids (MGs) for energy distribution. This renewed attention to DC power distribution is largely due to its compatibility with renewable energy sources and the rising prevalence of electronic loads, making DC systems a compelling choice for building more efficient energy infrastructures [1], [2].

A key challenge in designing DC MGs is ensuring system stability. Power converters, which act as the core interface between sources and loads, are instrumental in achieving this goal, as illustrated in Fig. 1. These converters isolate disturbances, regulate voltage levels, and enable seamless interaction between various network components. In islanded DC MGs that lack centralized communication, distributed control strategies are employed, where each unit operates independently using locally available information [4]. In such decentralized systems, stability is typically managed through cooperative control of the common bus voltage by parallel-connected sources.

To prevent overloading of individual sources, a widely used technique is *droop control*, which involves adding virtual resistance to the output of power converters [5]–[8]. This approach increases each source's effective output impedance, deliberately moving away from ideal voltage source behavior and enhancing source-load interactions. As a result, the stability of the bus voltage becomes heavily dependent on the characteristics of the connected loads.

Importantly, DC MGs often include nonlinear active loads, such as constant power loads (CPLs), which maintain fixed power consumption through tightly regulated point-of-load (POL) converters [9], [10]. These CPLs introduce additional complexity into stability analysis.

Traditional stability assessments of DC systems often rely on linear techniques like the Middlebrook and Cuk criteria [11], which evaluate system behavior based on the ratio of source output impedance (\(Z_s\)) to load input impedance (\(Z_L\)) [12]–[14]. However, the nonlinear behavior of CPLs requires linearization around a nominal operating point to make such methods applicable [15], [16]. This approach becomes insufficient in droop-controlled systems, where voltage levels can vary significantly outside the linearization range [20], [21]. As a result, linear negative-resistance models fail to fully capture system dynamics, highlighting the need for more comprehensive nonlinear analysis methods.

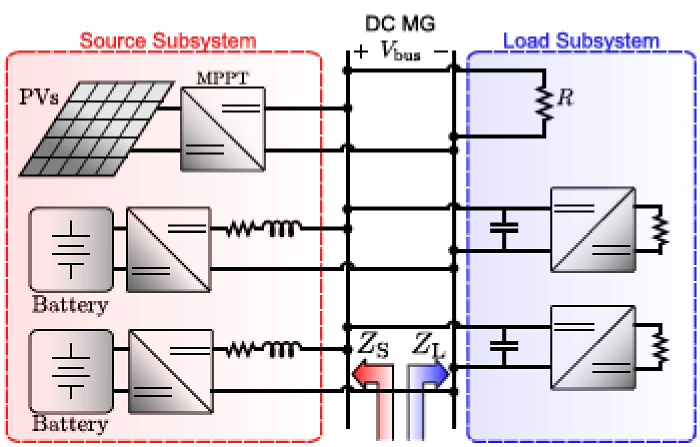

Fig.1 Single line diagram of Test system

To address this challenge, nonlinear stability analysis is employed to forecast the system's global qualitative behavior. This approach models POL converters with a constant power characteristic at any operating voltage using the ideal CPL model, which assumes constant input power equal to the load's demanded power. Despite its conservative nature, this model retains nonlinearities and is thus adopted in this study. Nevertheless, nonlinear stability analysis poses challenges due to the high number of differential equations involved, often rendering it excessively complex or providing limited insights into the variable interactions affecting stability.

In this context, the integration of fuzzy logic controllers offers a promising avenue for enhancing the stability of DC microgrids. By incorporating fuzzy logic methodologies, the control system can adaptively respond to changing operating conditions and load dynamics, potentially mitigating stability challenges posed by nonlinear loads and facilitating the construction of more resilient microgrid systems. This paper investigates the synergistic effects of droop control and fuzzy logic integration on the voltage stability of DC microgrids, aiming to provide comprehensive insights and practical guidelines for designing robust and reliable energy distribution systems.

2. Control Design:

In a distributed control scheme, sources collaborate to regulate the bus voltage effectively. However, an essential challenge arises in ensuring equitable load sharing among the sources, where each source must contribute power to the load in proportion to its capacity. Failure to maintain balanced load sharing can lead to source overloading, compromising the reliability of distributed power systems (DPSs).

To grasp the dynamics of power distribution among parallel sources, a simplified circuit featuring two sources supplying power to a designated load is examined. The static analysis of this simplified circuit involves modeling the power sources as voltage sources (Vi) in series with output droop resistances (Rdi), as depicted in Fig. 2.

$$I_1 - I_2 = \frac{2(V_1 - V_2)}{R_{d_1} + R_{d_2}} + \frac{(R_{d_2} - R_{d_1})}{R_{d_1} + R_{d_2}} I_o.$$

Thus, the main idea of droop control is to increase the outputresistance to reduce the difference between the currents.It is depicted in Fig. 3(a) the current sharing of two powersources as the output resistances are increased gradually bya factor of _. The power sources feed a 10A load with thesame reference voltage (V1 = V2) and output resistances ofRd1 = (1 + _) and Rd2 = (9 + _).It is noteworthy in Fig. 3(a) that the currents of each sourceget closer as the output resistances are increased. On theother hand, increasing the output resistances degrades the busvoltage regulation (Vbus) because the Th´evenin resistance Rdis increased, as it becomes explicit by the equation obtainedfrom the Th´evenin equivalent circuit in Fig. 2

$$V_{bus} = \underbrace{\frac{V_1 R_{d_2} + V_2 R_{d_1}}{R_{d_1} + R_{d_2}}}_{V_{ref}} - \underbrace{\frac{R_{d_1} R_{d_2}}{R_{d_1} + R_{d_2}}}_{R_d} I_o.$$

www.ijbar.org
ISSN 2249-3352 (P) 2278-0505 (E)
Cosmos Impact Factor-5.86

The microgrid (MG) structure examined in this paper comprises multiple sources operating in parallel and connected to a shared load via transmission lines, as depicted in Figure 4. Each source, controlled through droop control, is represented by an ideal voltage source Vi in series with a virtual droop resistance Rvi. Additionally, each transmission line is modeled as a resistance Rti in series with an inductance Lti. The resulting model from the circuit with n sources in Figure 4 is referred to as the n-sources model.

Multi input droop:

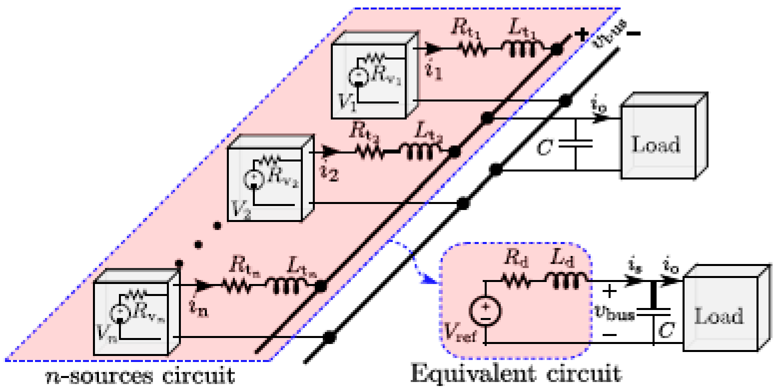

Fig. 4. A dc MG composed by n sources in droop scheme (n-sources model) and the proposed equivalent circuit (equivalent model).

The aim is to regulate the output resistance of the source, thus the virtual resistance Rvi is designed to be greater than the transmission line resistance Rti, implying that the source subsystem can be approximated by an equivalent resistance Rd and inductance Ld in series with an ideal voltage source, as illustrated in Figure 4. This simplified circuit is henceforth termed the equivalent model.

$$R_{d_i} = R_{v_i} + R_{t_i}$$

$$\frac{R_{d_1}}{L_{t_1}} \approx \frac{R_{d_2}}{L_{t_2}} \approx \ldots \approx \frac{R_{d_n}}{L_{t_n}},$$

In systems without droop control (Rvi = 0), they often meet condition (6) because Rti and Lti typically maintain a constant ratio regardless of the line length. However, even with droop control, the equivalent model closely resembles the n-sources model (which involves n differential equations) if the lengths of the lines and the power capacities of the sources are similar. This scenario is common in small DC microgrids.

$$\begin{aligned}\frac{\mathrm{d}i_1}{\mathrm{d}t} &= \frac{1}{L_{\mathrm{t}_1}}(V_{\mathrm{ref}} - v_{\mathrm{bus}}) - \frac{R_{\mathrm{d}_1}}{L_{\mathrm{t}_1}} i_1\\ \frac{\mathrm{d}i_2}{\mathrm{d}t} &= \frac{1}{L_{\mathrm{t}_2}}(V_{\mathrm{ref}} - v_{\mathrm{bus}}) - \frac{R_{\mathrm{d}_2}}{L_{\mathrm{t}_2}} i_2\\ &\vdots\\ \frac{\mathrm{d}i_{\mathrm{n}}}{\mathrm{d}t} &= \frac{1}{L_{\mathrm{t}_{\mathrm{n}}}}(V_{\mathrm{ref}} - v_{\mathrm{bus}}) - \frac{R_{\mathrm{d}_{\mathrm{n}}}}{L_{\mathrm{t}_{\mathrm{n}}}} i_{\mathrm{n}}.\end{aligned}$$

To demonstrate that the source subsystem can be approximated by just one differential equation, we utilize condition (5) in conjunction with the n-sources model.

$$R_{\mathrm{d}_\mu} = \frac{\sum_{i=1}^{n} R_{\mathrm{d}_i}}{n} \quad \text{and} \quad L_{\mathrm{t}_\mu} = \frac{\sum_{i=1}^{n} L_{\mathrm{t}_i}}{n}.$$

$$L_{\mathrm{d}} \frac{\mathrm{d}i_{\mathrm{s}}}{\mathrm{d}t} \approx (V_{\mathrm{ref}} - v_{\mathrm{bus}}) - R_{\mathrm{d}} i_{\mathrm{s}},$$

$$R_{\mathrm{d}} = R_{\mathrm{d}_\mu} \frac{L_{\mathrm{d}}}{L_{\mathrm{t}_\mu}}.$$

The proposed model aims to simplify the analysis by reducing the complexity of the system from n differential equations, corresponding to the n transmission lines in parallel, to just one equation. This simplification facilitates the determination of system equilibrium points and their stability, as depicted in Figure 4. To validate this approach, the total output impedance of three sources operating in parallel, including the internal dynamics of the power converters, is compared among the equivalent model, the n-sources model, and the complete model.

Source V1 is configured with a virtual resistance Rv1 = 0.2 and is connected to the bus via transmission line TL1 = [28.5m, 436.5μH]. The parameter values of sources V2 and V3 are derived from those of source V1, as outlined in Table I.

Table I
Parameters of V2 and V3 as a function of V1.

Sources Parameters	R_{v_2}	R_{v_3}	T_{L_2}	T_{L_3}
Values	$0.5R_{\mathrm{v}_1}$	$2R_{\mathrm{v}_1}$	$1.4T_{\mathrm{L}_1}$	$1.8T_{\mathrm{L}_1}$

In this paper, the distributed generation (DG) units were initially modeled as ideal sources. However, real sources possess internal dynamics that can impact the dynamic behavior of the microgrid. Typically, the control of these sources follows a cascade control loop structure, comprising an inner current loop and an outer voltage loop. While the inner loop has a minimal effect on microgrid stability, the outer voltage loop must exhibit slow dynamics to avoid destabilizing the system.

Given these considerations, the proposed DG units model proves effective. To validate this model, Figure 5 illustrates the Bode diagrams of the output impedance of the sources (including the transmission lines) for three scenarios: (i) the complete model, incorporating the internal dynamics of the DG units; (ii) the n-sources model; and (iii) the equivalent model. The comparison reveals that for short transmission lines with similar lengths and small droop resistance values, the approximation provided by the equivalent model is sufficiently accurate for stability analysis.

3. System Model:

The evaluated DC microgrid (MG) operates in island mode during emergency situations, lacking communication with a microgrid central controller (MGCC) or among its sources, as depicted in Figure 1. Therefore, each power converter controller relies solely on locally available variables. The configuration includes:

- An intermittent source employing maximum power point tracking (MPPT).

- Two batteries of equal capacity using droop control.

- Transmission lines.

- Active loads comprised of POL converters.

- Resistive loads.

- Bus capacitance.

In DC MG modeling, the most critical components are the sources, whose behavior is contingent upon their controllers, and the loads, particularly the POL converters. The following subsections detail the modeling of sources and loads to facilitate stability analysis.

Fixed Load

Each load in a DC MG requires a specific voltage level for proper operation, necessitating the use of POL converters tightly controlled to maintain a constant output voltage, as shown in Figure 6(a). Assuming the output power of the POL converter equals the input power (P), it behaves akin to a Constant Power Load (CPL), as the control action adjusts the input current with changes in input voltage [22]–[24], [26].

There are two primary differences between an ideal CPL and a POL converter. Firstly, when the input voltage is less than or equal to the designed output voltage Vth (buck converter with voltage control loop), the control saturates the duty-cycle, causing the switch to remain closed. Consequently, the POL converter transitions to a passive load, losing its CPL characteristic, as depicted in Figure 6(b). Thus, an ideal CPL is mathematically represented as a voltage-controlled current source (VCCS).

$$i(v) = \begin{cases} \dfrac{P}{v}, & \text{if} \quad v > V_{\text{th}} \\ \dfrac{P}{V_{\text{th}}^2} v, & \text{if} \quad v \leq V_{\text{th}}. \end{cases}$$

$$\begin{aligned} i(v) &= i(V_{\text{op}}) + \frac{\partial i}{\partial v}[v - V_{\text{op}}] + O(v^2) \\ i(v) &\approx 2\frac{P}{V_{\text{op}}} + \frac{v}{-\frac{V_{\text{op}}^2}{P}}. \end{aligned}$$

The second difference arises at high frequencies. While ideal CPLs respond uniformly to all frequencies, POL converters can only react to frequencies within their closed-loop bandwidth. However, this characteristic is not captured in the piecewise function in equation (21).

Due to the nonlinearity of the ideal CPL model, it's common to linearize it. This linearization typically results in a current source in parallel with a negative resistance [15], [16].

It's important to note that linear stability analysis is only applicable for small deviations around the operating point. Moreover, it cannot forecast the global system behavior, which is crucial for defining a safe operating region. Therefore, in this study, bus voltage stability is determined through analytical bifurcation analysis using the ideal CPL model.

Source:

The sources connect to the microgrid (MG) via power converters, and their behavior is governed by their respective control strategies [4]. Sources operating under maximum power point tracking (MPPT) aim to maximize power injection into the MG regardless of the network status. Under constant weather conditions, the photovoltaic (PV) system and its power converter can be represented as a constant power source (CPS) when observed from the bus terminals, as depicted in Figure 8(a). This implies that despite variations in bus voltage, the power converter adjusts its current output to maintain a constant power injection.

www.ijbar.org
ISSN 2249-3352 (P) 2278-0505 (E)
Cosmos Impact Factor-5.86

In contrast, batteries operating under droop control collaborate to maintain bus voltage stability. The resistive output characteristic of the droop controller is modeled as an ideal voltage source in series with a resistance, as shown in Figure 8(b).

4. Fuzzy Design

Fuzzy logic introduces a flexible approach to reasoning, especially when faced with situations where statements may not be definitively true or false. In real-life scenarios, uncertainties often arise, and fuzzy logic allows for the consideration of these uncertainties during decision-making processes. This method mimics human decision-making by exploring possibilities between digital values of true and false.

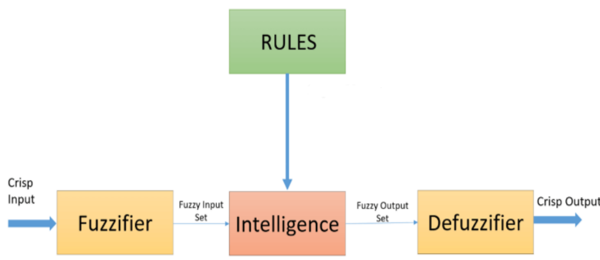

Fig.5 Schematic diagram of fuzzy.

Using a fuzzy logic algorithm involves analyzing all available data to make the best possible decision given the input. It integrates rules and if-then conditions provided by experts to control decision-making systems. Recent advancements in fuzzy theory have led to various methods for designing and fine-tuning fuzzy controllers, resulting in a reduction in the number of fuzzy rules needed.

The process of fuzzy logic involves several key steps:

Fuzzification: This step converts crisp numbers, obtained from sensors measuring inputs such as room temperature or pressure, into fuzzy sets. It allows for the representation of uncertainty in the input data.

Inference Engine: The inference engine evaluates the degree of match between fuzzy inputs and predefined rules. Based on the percentage match, it determines which rules to implement for the given input. These rules are then combined to generate control actions.

Defuzzification: In the final step, defuzzification is performed to convert fuzzy sets into crisp values. Various techniques are available for this process, and the choice depends on the specific application and expert system used.

www.ijbar.org
ISSN 2249-3352 (P) 2278-0505 (E)
Cosmos Impact Factor-5.86

Overall, fuzzy logic offers a powerful approach to decision-making in complex and uncertain environments, allowing for the consideration of all possibilities and uncertainties in the data.

5. Results and Analysis:

In this section, simulation results are presented to validate the stability analysis under load variations in a DC microgrid (MG) setup. The system consists of two sources in parallel, connected through dc-dc boost converters and transmission lines to a bus with resistive and Constant Power Load (CPL) loads, as illustrated in Fig.6.

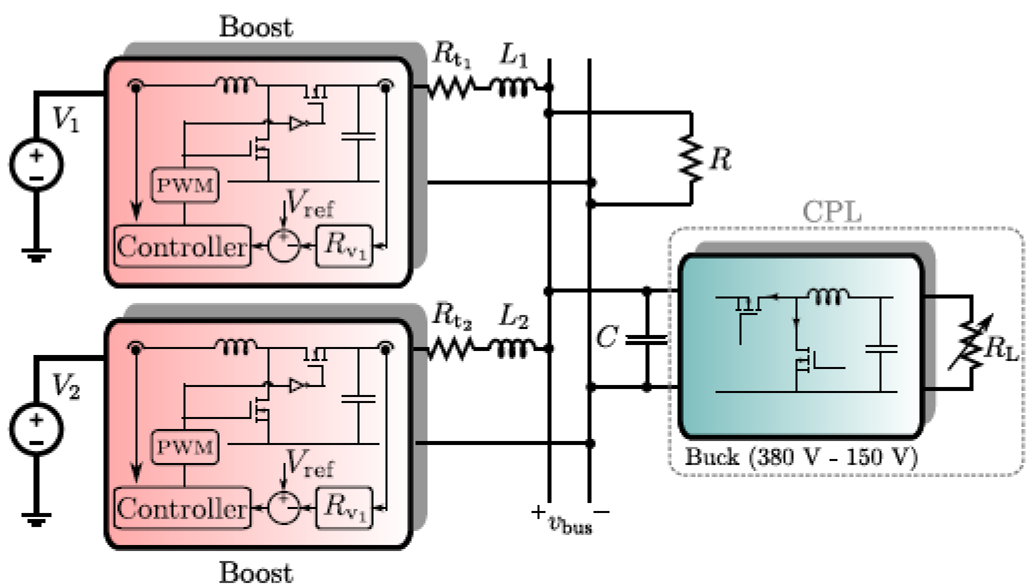

Fig.6 Circuit used in the simulation to validate the stability analysis of a380V island dc microgrid.

The bus voltage maintains a nominal value of 380V, and the CPL load is represented by a POL buck converter (380V-150V) driving a variable resistance RL. This setup corresponds to a Case II system with Rd = 0.11 and Ld = 291μH. Using these values in equation (30), it's determined that the system remains stable for P < PII = 49.72kW, beyond which a Hopf bifurcation occurs, causing the system to oscillate.

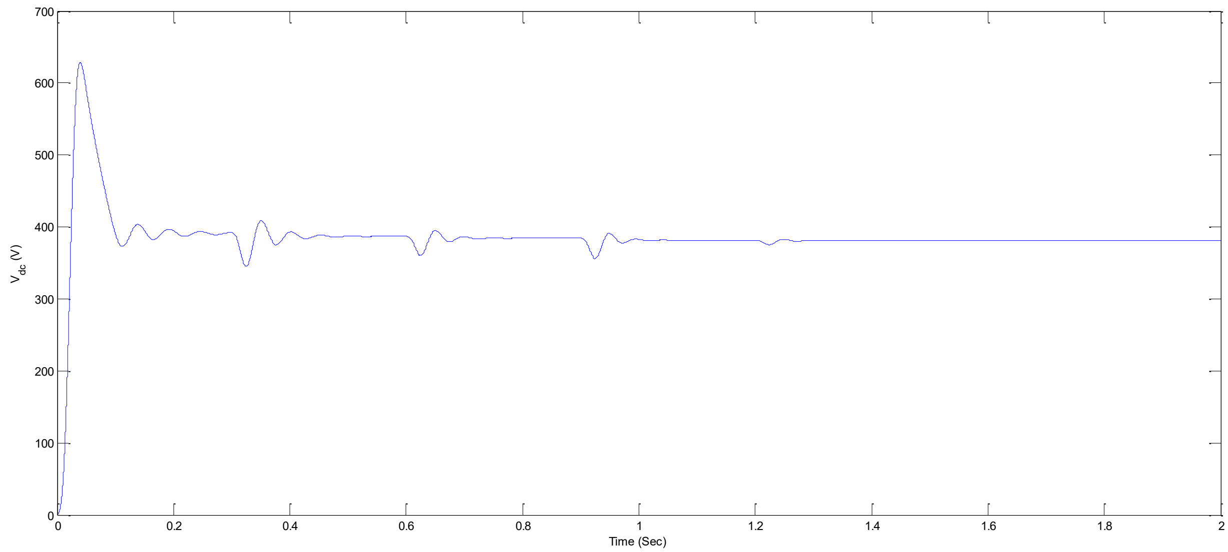

Fig.7 DC link voltage of Proposed droop controller with FLC basedMicrogrid

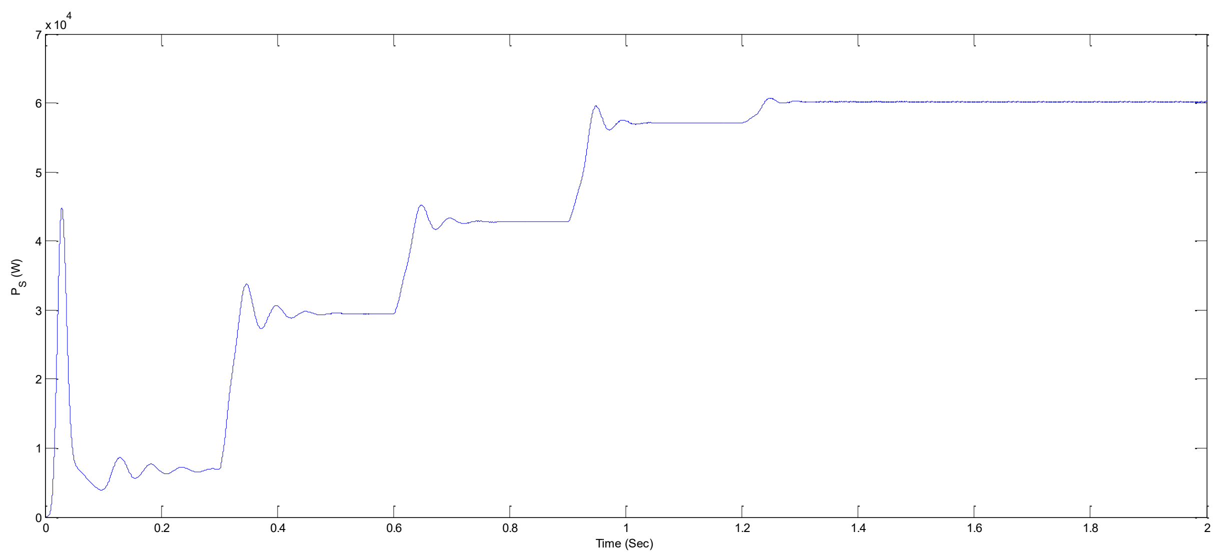

Fig.8DC grid Active Power of Proposed droop controller with FLC basedMicrogrid

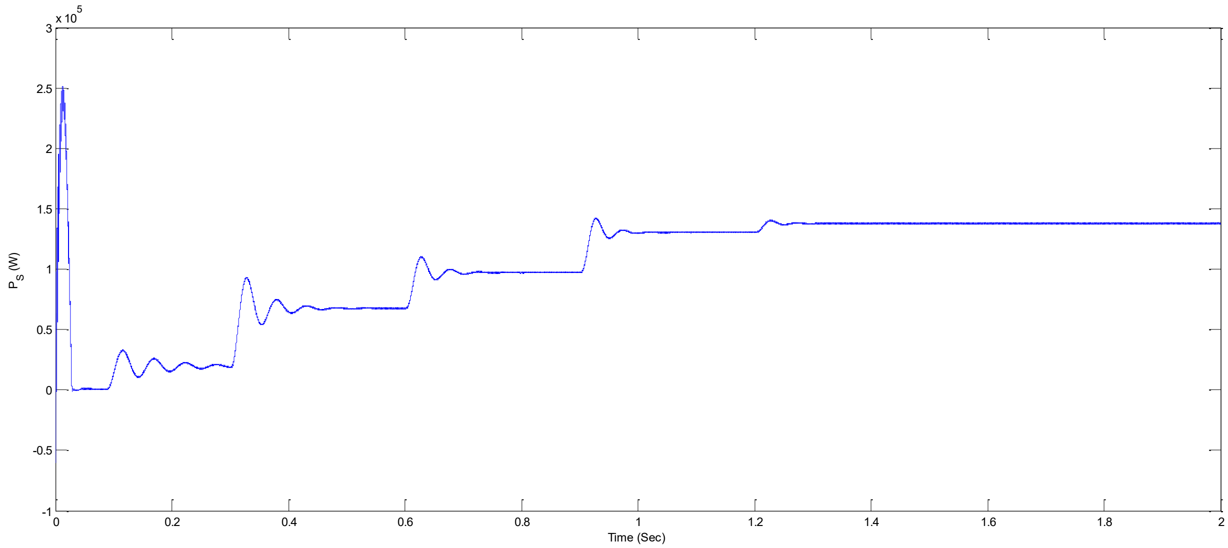

Fig.9 Source Active power of proposed droop controller with FLC based Microgrid

To validate the stability analysis, CPL variations are introduced to the system and compared with mathematical analysis. The system is evaluated by gradually decreasing the resistance RL driven by the POL converter, equivalent to CPL power variations (P). The resistance is decreased incrementally until the system becomes unstable. This incremental method is chosen to prevent large variations that could potentially destabilize the system even when initially stable.

The phase portrait depicted in Figure 18 illustrates the system behavior for P within the unstable region (Pu), showing how the system becomes attracted to a stable limit cycle when disturbed. As a result of this analysis, microgrids should be designed to operate within the safe region to ensure stability, even when intermittent sources are connected.

To enhance stability further, a fuzzy controller can be integrated into the system. The fuzzy controller would adjust the control parameters of the sources and loads based on fuzzy logic reasoning, considering factors such as bus voltage variations, load fluctuations, and system dynamics. This adaptive control approach can help maintain stability even under varying conditions and uncertainties in the microgrid operation.

Conclusion:

DC microgrids (MGs) are increasingly recognized as effective distributed generation systems, offering both efficiency and reliability. This paper presents a reduced-order model that simplifies the nonlinear stability analysis of small-scale DC MGs operating under droop control without relying on communication networks. The proposed model captures the essential dynamics of the system while significantly reducing the analytical burden.

To further enhance system performance, a fuzzy controller is incorporated to dynamically adjust source and load control parameters. Leveraging fuzzy logic, the controller responds to variations in bus voltage, load conditions, and overall system dynamics, providing adaptive stability control under diverse and uncertain operating scenarios.

The nonlinear analysis, grounded in bifurcation theory, reveals critical relationships between microgrid parameters and system behavior. The resulting bifurcation diagrams serve as practical tools for identifying stable operating regions and guiding the design of resilient microgrids. By integrating the simplified modeling approach with adaptive fuzzy control and bifurcation-based analysis, this study offers a comprehensive framework for developing robust, high-performance DC MGs tailored to a wide range of applications.

References:

[1] F. Blaabjerg, Z. Chen, and S. Kjaer, "Power electronics as efficientinterface in dispersed power generation systems," IEEE Trans. PowerElectron., vol. 19, no. 5, pp. 1184–1194, Sept 2004.
[2] H. Kakigano, Y. Miura, and T. Ise, "Low-voltage bipolar-type dc microgridfor super high quality distribution," IEEE Trans. Power Electron.,vol. 25, no. 12, pp. 3066–3075, Dec 2010.
[3] D. Boroyevich, I. Cvetkovic, D. Dong, R. Burgos, F. Wang, and F. Lee,"Future electronic power distribution systems a contemplative view,"in Optimization of Electrical and Electronic Equipment (OPTIM), 12thInternational Conference on, May 2010, pp. 1369–1380.
[4] D. Chen, L. Xu, and L. Yao, "Dc voltage variation based autonomouscontrol of dc microgrids," IEEE Trans. Power Del., vol. 28, no. 2, pp.637–648, 2013.
[5] J. Guerrero, J. Vasquez, J. Matas, L. de Vicuna, and M. Castilla,"Hierarchical control of droop-controlled ac and dc microgrids a generalapproach toward standardization," IEEE Trans. Ind. Electron., vol. 58,no. 1, pp. 158 –172, jan. 2011.
[6] S. Anand, B. G. Fernandes, and M. Guerrero, "Distributed control toensure proportional load sharing and improve voltage regulation in lowvoltagedc microgrids," IEEE Trans. Power Electron., vol. 28, no. 4, pp.1900–1913, April 2013.
[7] X. Lu, J. Guerrero, K. Sun, and J. Vasquez, "An improved droop controlmethod for dc microgrids based on low bandwidth communication withdc bus voltage restoration and enhanced current sharing accuracy," IEEETrans. Power Electron., vol. 29, no. 4, pp. 1800–1812, April 2014.
[8] T. Dragicevic, J. Guerrero, J. Vasquez, and D. Skrlec, "Supervisorycontrol of an adaptive-droop regulated dc microgrid with battery managementcapability," IEEE Trans. Power Electron., vol. 29, no. 2, pp.695–706, Feb 2014.
[9] A. Rahimi and A. Emadi, "Active damping in dc/dc power electronicconverters: A novel method to overcome the problems of constant powerloads," IEEE Trans. Ind. Electron., vol. 56, no. 5, pp. 1428 –1439, may2009.

[10] P. Liutanakul, A.-B.Awan, S. Pierfederici, B. Nahid-Mobarakeh, andF. Meibody-Tabar, “Linear stabilization of a dc bus supplying a constantpower load: A general design approach,” IEEE Trans. Power Electron.,vol. 25, no. 2, pp. 475–488, feb. 2010.

[11] R. Middlebrook and S. Cuk, “Input filter considerations in design andapplication of switching regulators,” in IEEE Industry Applicationsannual meeting, 1976.

[12] B. Cho, J. Lee, and F. Lee, “Large-signal stability analysis of spacecraftpower processing systems,” IEEE Trans. Power Electron., vol. 5, no. 1,pp. 110 –116, jan 1990.

[13] C. Wildrick, F. Lee, B. Cho, and B. Choi, “A method of defining the loadimpedance specification for a stable distributed power system,” IEEETrans. Power Electron., vol. 10, no. 3, pp. 280 –285, may 1995.

[14] J. Liu, X. Feng, F. Lee, and D. Borojevich, “Stability margin monitoringfor dc distributed power systems via perturbation approaches,” IEEETrans. Power Electron., vol. 18, no. 6, pp. 1254 – 1261, nov. 2003.

[15] C. Rivetta, G. Williamson, and A. Emadi, “Constant power loads andnegative impedance instability in sea and undersea vehicles: statement ofthe problem and comprehensive large-signal solution,” in IEEE ElectricShip Technologies Symposium, july 2005, pp. 313–320.

[16] A. Emadi, A. Khaligh, C. Rivetta, and G. Williamson, “Constantpower loads and negative impedance instability in automotive systems:definition, modeling, stability, and control of power electronic convertersand motor drives,” IEEE Trans. Veh. Technol., vol. 55, no. 4, pp. 1112–1125, july 2006.