Real-Time Fault Detection and PI Controller Optimization in DC Microgrids Using Artificial Bee Colony

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Abstract: The stable integration of renewable energy sources into DC microgrids (DCMGs) is hindered by significant challenges in fault detection and control, often leading to system-wide instability. This study addresses these issues by introducing a novel, integrated framework. We propose a resistance-based fault identification strategy for swift fault detection and precise localization, effectively containing faults and mitigating the risk of cascading failures. To manage the resulting voltage-current (V-I) variations, this paper further develops a Proportional-Integral (PI) controller whose parameters are dynamically optimized using an Artificial Bee Colony (ABC) algorithm. The ABC algorithm is selected for its superior control capabilities in complex, nonlinear systems, ensuring operation within required limits for voltage, current, and power ripple. The applicability and correctness of the proposed methodologies were rigorously validated through extensive digital simulations, with performance benchmarked against unoptimized conditions. This research offers a significant advancement in DCMG technology by demonstrably increasing operational efficiency, enhancing dynamic stability, and improving overall control performance for future-oriented, resilient power systems.

Keywords: DC Microgrid (DCMG); Fault Detection; Proportional-Integral (PI) Control; Fuzzy Logic Control; Artificial Bee Colony (ABC) Algorithm

1. Introduction

The escalating demand for sustainable and efficient power systems drives a global shift toward decentralized renewable energy infrastructures [1], [2]. DC microgrids (DCMGs) emerge as valuable platforms supporting renewable sources, distributed generators, and battery storage systems [1], [2]. DCMGs offer inherent advantages like simplified source interfacing, greater energy efficiency, and reduced power conversion losses versus AC microgrids [3]. Furthermore, DC operation avoids issues such as phase synchronization and reactive power management, ensuring smooth integration of diverse units [3]. Various renewable sources, including solar photovoltaic (SPV) and wind energy (WE), can be effectively integrated, along with fuel cells (FC) and the utility grid (UG) [4]. DCMGs reliably accommodate both linear loads and modern nonlinear loads, such as electric vehicles (EVs), within the distributed DC framework [4]. Nonetheless, nonlinear converter dynamics and constantly changing sources complicate stability, demanding advanced protection and control for reliable DCMG operation.

A critical barrier to widespread DCMG deployment arises from fault detection and protection complexities, especially under dynamically evolving operating environments [2]. Unlike AC grids, DC networks lack current zero-crossings, creating significant challenges in arc interruption and subsequent fault clearance procedures. Low-impedance faults (LIF) and high-impedance faults (HIF) severely disturb DC link voltage–current (V–I) dynamics, threatening operational reliability and system survival [3], [5]. Robust protection approaches are therefore vital for maintaining safe V–I levels and guaranteeing continuous microgrid reliability [5], [6]. Fault protection systems commonly utilize relays and circuit breakers to isolate faulty segments quickly, reducing propagation effects [3], [4]. Relays initially sense abnormalities and transmit information to circuit breakers, which then achieve rapid clearance and isolation [3], [4]. However, identification accuracy remains difficult because DC fault currents often show minimal deviation from normal operation due to PI controller current-limiting properties[7]. This phenomenon particularly complicates detection of line-to-ground (LG) disturbances, demanding advanced detection and adaptive control mechanisms [6].

Several strategies addressing fault detection and DCMG control have been recently proposed to mitigate operational instabilities. Differential protection frameworks for SPV-based DC systems were developed in [1], while outlined limitations of hardware detection relying heavily on sensors and communication. To reduce detection latency, neural network-assisted schemes were proposed in [2], though these approaches necessitate extensive training datasets and efficient data management platforms. Studies in [4]promoted localized measurement-based detection to minimize dependence on communication networks, while emphasized fault isolation through combined power regulation and breaker coordination. Despite these advances, inadequate consideration of PI parameter adaptation under dynamically evolving scenarios persists as a major limitation. Control-oriented investigations demonstrated that Fuzzy Logic Controllers (FLCs) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) provide improved resilience compared to conventional PI controllers [8]. Yet, fractional-order PI and fuzzy controllers [9], [10] lacked integrated optimization algorithms, limiting precision tuning and hardware-in-the-loop validation.

Recent studies examined met aheuristic optimization techniques for tuning PI parameters in complex nonlinear multi-variable DCMG environments [11]–[12]. Approaches including ABC, Genetic Algorithms (GA), Arithmetic Optimization (AO), and Equilibrium Optimization (EO) exhibited significant improvements in dynamic performance [13]-[18]. Despite these advancements, research has rarely investigated integrated frameworks combining resistance-based detection with optimized PI control under real-time faulted conditions. Addressing this deficiency forms the central motivation for the present study. The objectives are fourfold: first, modeling LG faults across multiple DCMG terminals and analyzing their V–I impacts; second, evaluating PI and FLC controllers under healthy and faulty conditions; third, proposing a resistance-based detection strategy utilizing localized V–I measurements without reliance on communication infrastructures; and fourth, optimizing PI controller gains ($\mathbf{K_p}$ and $\mathbf{K_i}$) using an ABC algorithm inspired by honeybee foraging. The proposed hybrid framework is validated through MATLAB/Simulink offering a robust, optimized, and practically realizable control methodology [6], [12].

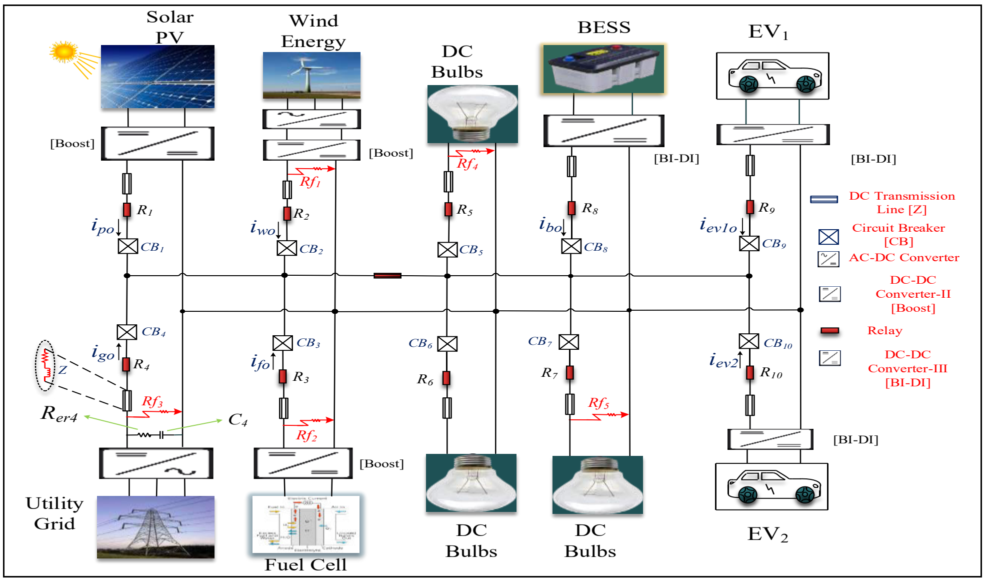

Fig. 1: Schematic diagram of the DCMG, which includes diverse sources, loads, and CBs ($\mathbf{CB_1}$-$\mathbf{CB_{10}}$)

2. Overview of the Proposed DC Microgrid

The developed DCMG system integrates renewable energy sources, including SPV, WE, FC, and UG, to ensure flexibility and reliability. A BESS, multiple loads, and two EV batteries are also incorporated, with the network configuration detailed in Fig. 1 [3].The SPV, FC, and WE sources are connected to the DC bus via DC-DC converters controlled with maximum power point tracking (MPPT) for optimal energy extraction [4]. The proposed DCMG employs DC cabling over distances of 82–100 meters [5] and uses multiple DC circuit breakers for segmenting lines and isolating faulty sections, as detailed in Table 1. While PI controllers and FLCs are conventionally used, an ABC optimization ensures superior control of DC-link V-I fluctuations.

Table 1: A comprehensive list of DCMG Key Elements and their respective Configurations

Key Elements	Configurations
Frequency of Switching Operations (f_s)	5000Hz
Specified terminal output voltage (V_{out})	325 V
Typical input voltage of the converter (V_{in})	200-400 V
Converter efficiency (η)	85%
Load resistance (R_{l1}, R_{l2})	50 Ω
Required Inductance for the Converter (L)	7.14 mH
Input Stage Capacitor (C_{in})	473.4693μF
Output capacitor (C_{out})	473.4693μF
Resistance Fault range (Rf_1, Rf_2,Rf_3, Rf_4)	1-20 Ω
BESS DC-DC Converter	4 kW
SPV, WE, FC, Grid DC-DC Converter	4 kW
EV_1, EV_2 DC-DC Converter	4 kW
EV_1, EV_2 voltage	12 V
EV_1, EV_2 capacity	35 Ah
Cable Resistance (R_c) Cable length	12.1 Ω/Km 90

3. DC microgrid is disrupted by faults, and a proposed control technique is presented

DC microgrid systems are susceptible to various faults, with line-to-ground (LG) faults being notably frequent and impacting system reliability [3]. The mathematical model of the DC link under an LG fault is crucial for the accurate detection and characterization of these events. The proposed scheme for fault identification behavior involves intentionally introducing LG faults at specific terminals to meticulously observe system responses. This working method utilizes relays to activating circuit breakers, which enables the isolation of faulty sections for systematic observation of system responses.

A defective circuit's reaction in a transitory condition: When an LG fault occurs in the DCMG, the discharge of capacitors C_1 and C_2takes place for a few seconds due to the low time constant. The discharge stage is primarily responsible for transmitting the frequency domain of the transient RC circuit through the cable, as shown in Figure 2(b). When a fault occurs, the resistance in the fault zone is less than that of the parallel load branches [5]. The circuit configuration shown in Figure 2(b) is being analysed using nodal analysis at a specific point labelled A.

$i_1(s) + i_2(s) = i_{f4}(s)$(1)

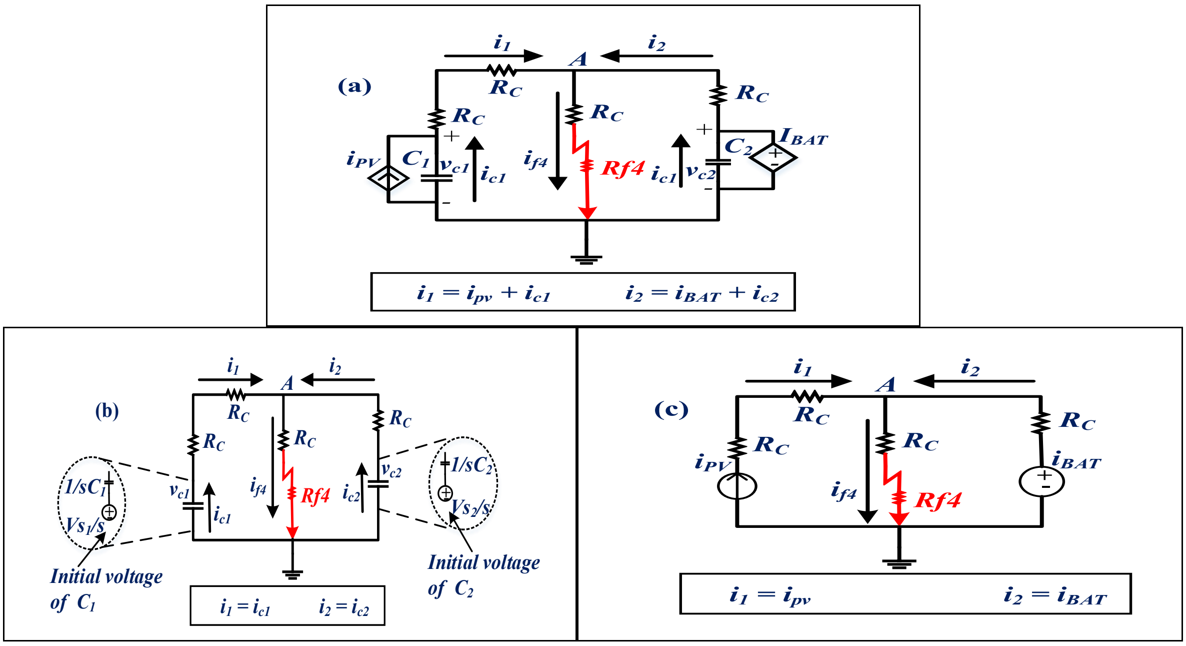

Figure 2: (a) The fault circuit within a DCMG system. (b) The transient RC equivalent circuit of a DCMG. (c) The steady-state circuit during the LG fault at resistive load 1 of DCMG

The frequency domain response of an RC circuit during a fault event can be mathematically expressed as follows:

$$\begin{bmatrix} i_{C1}(s) \\ i_{C2}(s) \end{bmatrix} = [A] \begin{bmatrix} V_{s1} \\ V_{s2} \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} v_{C1}(s) \\ v_{C2}(s) \end{bmatrix} = [B] \begin{bmatrix} V_{s1} \\ V_{s2} \end{bmatrix} \qquad (3)$$

Where i_{c1}, i_{c2} and i_{f4} Represent the capacitor currents of C_1, C_2 and the I_f At the load zone 1. And V_{s1}, V_{s2} Represent the starting capacitor voltages.

The validity of these mathematical representations describing the system's response has been confirmed through digital simulations. Based on these expressions and responses, it can be inferred that capacitors primary energy supply to the fault for the transitory period. After the completion of this period, the entire system transitions into a steady-state region, where the average influence of the capacitor on the fault becomes insignificant. A comparable analysis can also be conducted for the capacitor C_2.

A defective circuit's reaction in steady state: After the transient period, the system stabilizes with zero average currents through the capacitor, and only the system sources impact the fault. Figure 2(c) shows the circuit arrangement under the faulty situation. The sources are the only cause of the I_f In the steady state. Figure 2(c) shows the network in a steady state, with both SPV and BAT sources supplying current to the fault. By applying Kirchhoff's Current Law (KCL) at node A, the i_{f4} Can be calculated.

$$i_{PV}(s) + i_{BAT}(s) = i_{f4}(s) \qquad (4)$$

The fault identification technique relies on measuring the terminal resistance across different branches. The resistance is calculated using accurate V-I values for each sample. On-ship between voltage, current, and resistance is expressed as:

$$R_k(t) = \frac{v_k(t)}{i_k(t)} \qquad (5)$$

Where $R_k(t)$, $v_k(t)$ and $i_k(t)$ Are the values of k^{th} A terminal of the resistor, voltage, and current.

4.5 Proposed PI Controllers

A PI-C is fundamental for adjusting the variables within the proposed DCMG by tuning parameters according to its specific transfer function. Distinct from standard proportional components, the behavior of these elements changes based on their respective transfer functions (TFs). A consistent gain term is essential for reducing long-term operational errors [19]-[21]. The transfer function for the PI-C is provided in Eq. (22):

$$\frac{C(s)}{E(s)} = K_p + \frac{K_i}{s} \qquad (6)$$

In this formula, C(s) represents the PI controller's output for a given input signal E(s). The terms K_p and K_i Denote the proportional gain constant and the integral constant, respectively. The application of PI-Cs enhances the frequency results of distributed systems, leading to more effective regulation.

As illustrated in Figure3, the PI-C architecture processes an input signal, e(t), through its PI differential controller, which in turn generates an output, u(t). This operation allows the PI-C to efficiently tune the proposed controller [18], [22]-[23]. The accompanying block diagram demonstrates that an ABC algorithm is used to derive the PI parameters. This is achieved by using a sum of weighted combination of the Integral of Time-weighted Absolute Error (ITAE), Integral of Absolute Error (IAE), and Integral of Squared Error (ISE) as an objective function, defined below:

$$\begin{cases} \text{ITAE} = \int_0^\infty t|e(t)|dt. \\ \text{IAE} = \int_0^\infty |e(t)|dt. \\ \text{ISE} = \int_0^\infty |e^2(t)|dt. \end{cases} \qquad (7)$$

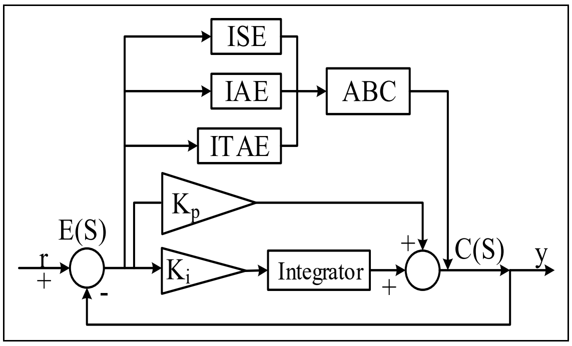

Figure 3. Structure of a PI controller tuned using ABC-based optimization

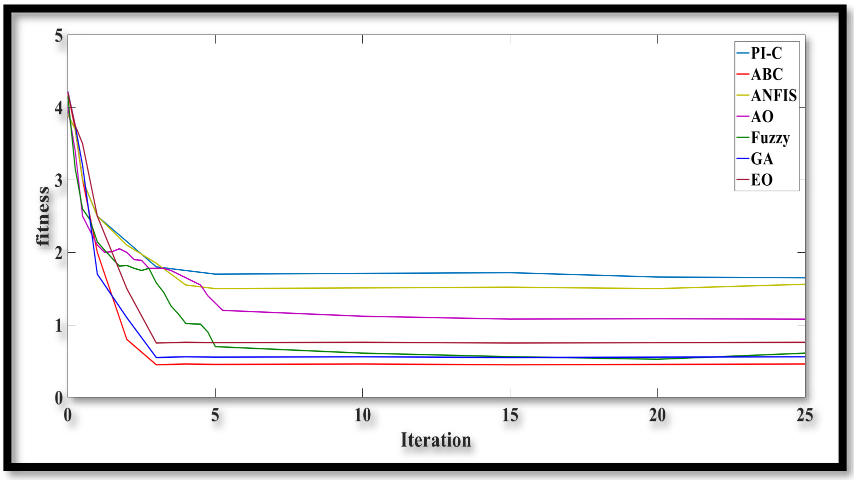

Fig. 4: Characteristic of Artificial Bee Colony algorithm

A proposed control technique addresses operational challenges through a hybrid framework for enhanced system stability [5], [6]. This framework integrates an FLC with a PI controller to mitigate V-I fluctuations and manage multiple sources and loads [9], [10]. The system also utilizes an MPPT algorithm and a bidirectional controller for the BESS, aiding in voltage regulation and balancing supply-demand [4]. The PI controller parameters are optimized using a bio-inspired ABC algorithm, which is detailed in Fig. 4 to explain its functionality [7]. The method's effectiveness is validated through simulations and rigorous real-time testing on an Opal-RT platform.

4. Results and Discussion

Initial simulations within the MATLAB/Simulink framework revealed the significant vulnerability of the DCMG to various fault conditions. A critical observation was the severe impact of LG faults, which consistently caused voltage drops and risked system collapse. The conventional PI control strategy proved inadequate in handling these transient conditions, leading to substantial V-I variations. The results of PI controller's limited ability to effectively damp oscillations and maintain stability.

The application of ABC optimization significantly enhanced the DCMG's fault tolerance by identifying optimal converter parameters. The optimized FLC effectively reduced the transient V-I variations observed with the unoptimized PI controller. Quantitative performance benchmarking showed a significant reduction in peak dV/dt and limited voltage sags [7]. This direct comparison, validated by Opal-RT real-time simulations, provides robust evidence of the optimized FLC's ability to maintain better control.

4.1. Comparative analysis

This section provides a rigorous comparative analysis of three control strategies—PI, FLC, and ABC-optimized FLCto enhance DC microgrid fault resilience. Conventional PI control exhibits significant vulnerability, showing drastic voltage dips and poor damping during faults at source terminals. The FLC, however, improves fault confinement through its adaptive logic, reducing current oscillations. The ABC-optimized FLC further refines this performance by dynamically tuning parameters to surpass both standard FLC and PI. The superior fault mitigation at source terminals is visually confirmed in Fig. 5.

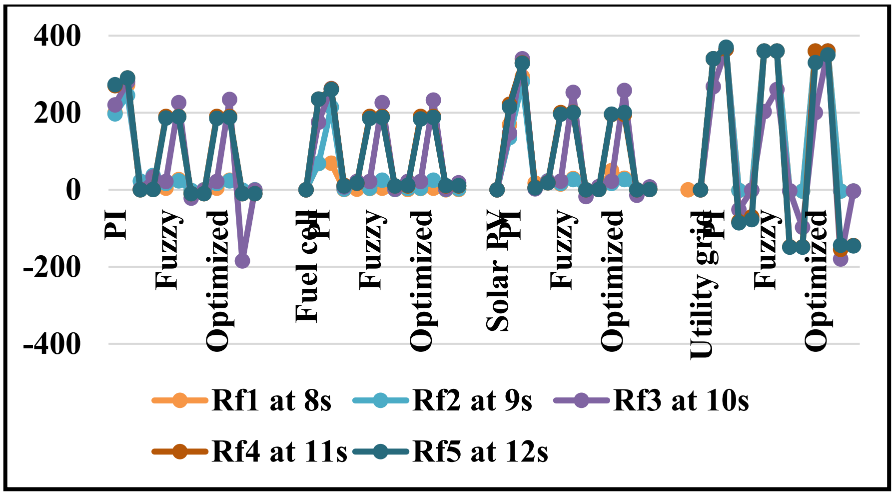

Fig. 5. A comparative analysis of this protection technique for power sources

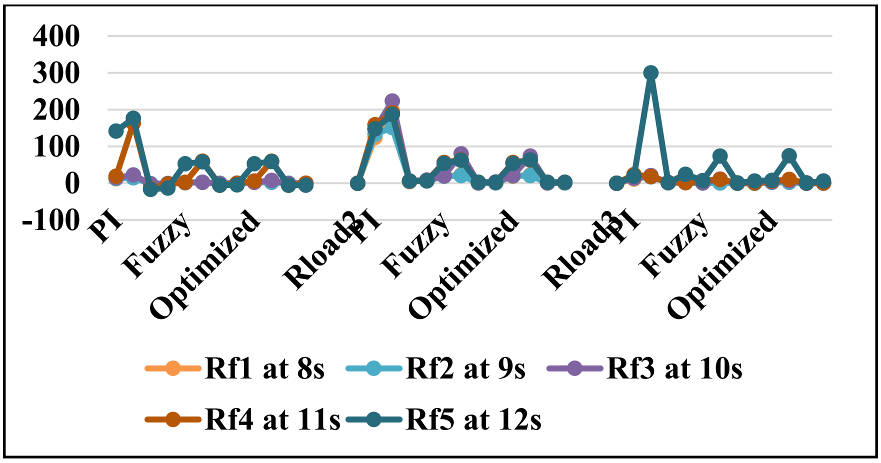

Fig. 6. A comparative analysis of this protection technique for Resistive Loads

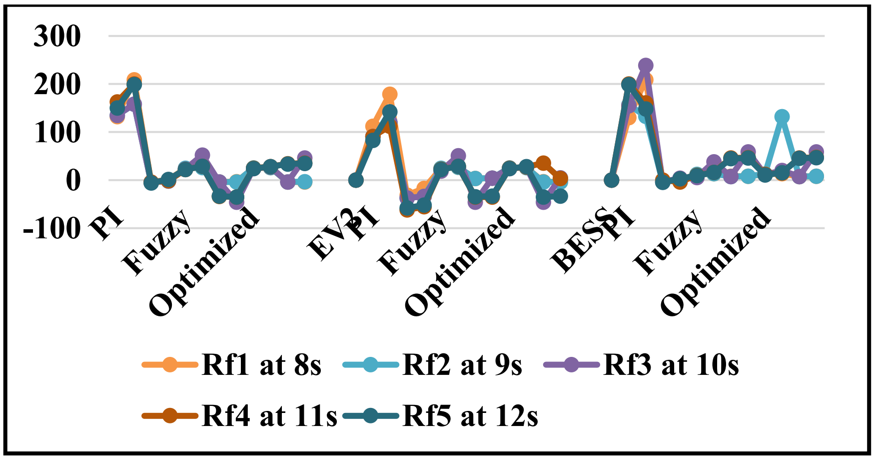

Fig. 7. A comparative analysis of the protection technique for EV batteries

At load terminals, Fig. 6 shows the PI controller's limited ability to localize fault impact, severely affecting other microgrid terminals. The FLC provides superior fault isolation by substantially reducing fault levels. For EV and BESS integration, Fig. 7 confirms that the ABC-optimized FLC consistently yields more stable and minimal deviations. Its superior performance is rigorously benchmarked against established methods in the literature, as detailed in Table 2.

Table 2: Comparative analysis of fault detection and optimization methods

Parameters	Various fault detection and location methods					
	PS	[15]	[16]	[13]	[17]	[18]
FD	C-C	FC-C	L-C	C-C	C-C	L-C
No. of sources	5	4	4	1	4	6
R_f	10	0.1	2	1	25	50
v, i	v,i	i	i	v,i	i, v	i,v
FD time (ms)	2.3	1.98	2	0.402	1.25	2
FL (TL, LS)	LS	TL	TL	TL	TL	TL
Fault classification	Yes	No	No	Yes	Yes	Yes
errors in D (%)	2.59	x	8.32	3	7.1	3.59
DCMG with the EV station	Yes	Yes	No	No	Yes	Yes
FL calculation	Yes	Yes	No	Yes	Yes	No
Optimization	Yes	No	No	Yes	Yes	No

In Table 2, PS=Proposed Scheme, L-C = line current, FC-C = filter capacitor current, C-C = capacitor current, x = not given, FD =Fault detection, FL=Fault location, TL=Transmission line, LS=Load side, D= Fault distance.

5. Conclusion

This study successfully developed and validated a resistance-based methodology for the detection and isolation of LG faults within DCMGs. A primary finding confirmed the significant limitations of conventional PI control, which induced considerable V-I variations and risked systemic instability during fault events. In contrast, the integration of an ABC optimized FLC profoundly improved fault ride-through capability. This optimized strategy consistently achieved a marked reduction in both the magnitude and duration of short-circuit currents, enhancing stability and preventing cascading failures. The developed methodology offers tangible advantages in rapid fault containment, improved efficiency, and prevention of critical errors, significantly enhancing overall system reliability and safety.

Future Scope

Future research should include a comprehensive DC microgrid analysis to assess the feasibility of advanced control strategies for power systems. Investigations will focus on integrating sophisticated fault detection and location techniques to further enhance overall system robustness and reliability. This work will also involve exploring novel controllers to improve the system's resilience and dynamic performance in a real-world setting. Such efforts are crucial for the development of resilient and efficient microgrid solutions for future energy infrastructure.

Author Contributions

Banothu Somanna: Writing – review & editing, Writing – Original draft, Visualization, Methodology, Investigation, Conceptualization.

Sushma Gupta: Visualization, Validation, Supervision, Investigation.
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