

Optimal Power Flow and Short-Circuit Analysis in Hybrid Renewable-Powered DC Microgrids using Modular Multilevel Converters

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ABSTRACT

Modern power systems require an increased use of renewable energy, which drives the acceptance of DC microgrids because they reduce conversion needs and directly support battery storage for improved performance. Combining several renewable energy sources and fault protection reliability proves to be a significant operational challenge. This paper examines an integrated approach to studying optimal power flow and short-circuit analysis within renewable energy-powered DC microgrids incorporating a modular multilevel converter (MMC). The main goal involves achieving optimal daily decision-making for solar and wind power, battery capacity, and safeguarding the system against excessive transient currents. The model has been set up in MATLAB to integrate critical components like charge restrictions of battery-powered generation, real-time generation capacity, and MMC-defined voltage and current constraints. An optimum power flow solver sets dispatch levels to minimise losses and hold the DC bus at stable levels. Short-circuit conditions of fault current reactions and voltage drop examinations were also performed after defining the dispatch setpoint at which the MMC submodule bypass acted as a protective device. Most power generation from renewable sources minimises battery intervention, considering that the device offers a lot of current assistance for faults in the event of DC faults. The holistic approach involved both an economic analysis and the nature of a fault response, which proved that the protective parameters needed to be directly analysed, as well as the operational effectiveness.

1. Introduction

1.1 Background and Motivation

Global power systems are quickly evolving toward higher levels of renewables (notably solar photovoltaics and Wind) due to the demand for greenhouse-gas emissions reduction and a reduction in reliance on traditional fuels [1,2]. To provide clean and distributed electricity with high efficiency and power quality, DC microgrids are attracting a lot of attention due to their facilitating power conversion with lower harmonic distortion in converter-dominated environments [3]. However, integrating

many intermittent sources presents nontrivial operational issues, such as DC-bus voltage regulation under variability and fault current control to protect the network. The large-scale integration of intermittent renewable energy sources—such as photovoltaic arrays and wind energy systems—introduces significant operational challenges in DC power networks. One major issue is DC-bus voltage regulation, as the stochastic and rapidly varying nature of renewable generation leads to frequent power imbalances between sources and loads. Sudden changes in irradiance or wind speed can cause voltage fluctuations on the DC bus, potentially resulting in

instability, degraded power quality, or even disconnection of sensitive equipment if not properly controlled. In addition, fault current control becomes increasingly complex in DC systems with high renewable penetration. Unlike AC systems, DC networks lack natural current zero-crossings, causing fault currents to rise rapidly and persist unless actively limited. Power electronic converters interfacing renewable sources can contribute to high fault currents, which may exceed the ratings of cables, converters, and protection devices. Without effective fault detection, isolation, and current-limiting strategies, such faults can propagate quickly and compromise the safety and reliability of the entire network.

Therefore, advanced control strategies, fast-acting protection schemes, and coordinated converter control are essential to ensure stable DC-bus voltage regulation and robust fault current management in renewable-rich DC power systems. This can result in an exponential growth in low-inertia networks with power-electronic components [4].

Optimal power flow (OPF) methods have provided practical solutions for economic dispatch and coordinated resource utilisation of solar, Wind and energy storage. Still, conventional OPF formulations are generally steady-state and do not automatically protect against fast transients or short-circuit events of converter-controlled DC systems [5]. Meanwhile, modular multilevel converters (MMCs), which are nowadays used mainly for their scalability and their low harmonic content, need to be constrained in real time from their operating point to stay within maximum current limits, as they are prone to an overcurrent stress in case of a fault [6]. The existing literature has tended to consider economic dispatch and fault behaviour as independent problems: OPF is solved without reference to the network protection and transient response, while fault studies are done independently of the operating point at which dispatch decisions are made. This separation may unintentionally lead to cost-optimised setpoints that increase the susceptibility to microgrid-to-instantaneous-DC-bus-fault currents [7].

Motivated by these gaps, the present work aims for a unified operational paradigm where an OPF solver schedules renewable generation and storage subject to MMC constraints, and the resulting operating point is directly stressed by short-circuit analysis that accounts for high-current transient effects. The goal is to achieve fault-tolerant behaviour economically within the same computing environment, for improved technical performance and cost results [8]. By implementing fault detection, diagnosis, and

mitigation mechanisms within the same computational platform used for control and monitoring, the need for additional dedicated hardware or parallel protection systems is significantly reduced. This integrated approach minimizes system complexity, lowers capital and maintenance costs, and simplifies system architecture. By implementing fault detection, diagnosis, and mitigation mechanisms within the same computational platform used for control and monitoring, the need for additional dedicated hardware or parallel protection systems is significantly reduced. This integrated approach minimizes system complexity, lowers capital and maintenance costs, and simplifies system architecture. This research trend is timely and of great importance: DC microgrids are expected to become one of the pillars of decentralised power architecture, and should be tightly integrated with renewable resources and intelligent dispatch strategies to avoid unnecessary increase of fault currents and maximise the reliability and security of supply [9].

1.2 Literature Review

This section examines the research on optimal power flow and short-circuit analysis of renewable-powered DC microgrids, focusing on modular multilevel converter systems. Research papers review new converter topologies, control strategies, and fault modeling methods and show a common practice of isolating operational dispatch from fault response. The discussion demonstrates the requirement for a single methodological approach that integrates economic optimisation methods with safe fault management procedures for responding to rising renewable power generation in complex microgrids.

1.2.1 DC Microgrid Optimal Power Flow Approaches

The article by Chen (2024) provides extensive coverage of optimal power flow methods that integrate renewable energy resources. The article extensively examines Wind- and solar-powered uncertainty, yet briefly addresses DC microgrids' specific constraints, which are mainly encountered in systems that implement advanced converter designs. According to Chen, future OPF frameworks must develop solutions that address computational speed and real-time supply adjustment capabilities. The author fails to discuss short-circuit modelling even though it remains critical in DC networks where fault currents rapidly increase. Many studies provide optimal power flow solutions through nominal operating conditions while overlooking their performance during transient or fault events [1]. Figure 1 shows the general architecture of a DC microgrid, highlighting the integration of multiple renewable energy sources, energy storage

systems, and converter-based interconnections to support efficient and decentralised power flow [10].

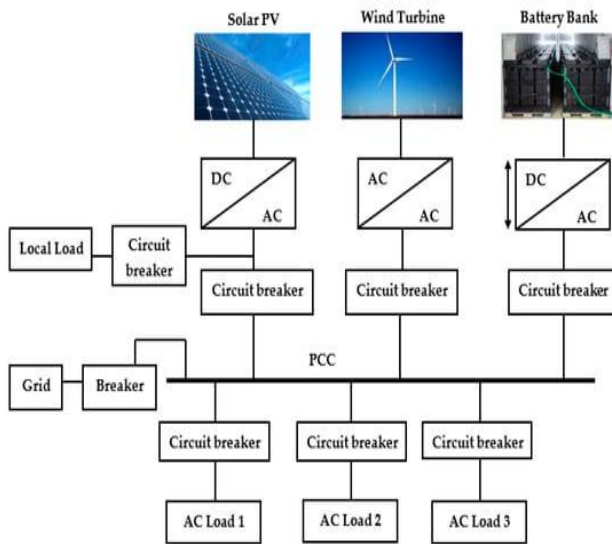


Fig. 1. A general Architecture of MG [11]

Vijay (2022) evaluates how circulating currents behave and the power distribution aspects in multiple DC converters linked across distributed energy resource DER clusters. The main objective of this research is to focus on real-time power balancing and converter efficiency improvement, but the conceptual foundations could serve an OPF environment receiving converter constraints. Vijay recognises the need for advanced dispatch in cost and reliability-focused applications, yet his publication does not implement a structured OPF framework. The models fail to include short-circuit events, indicating the requirement for a combination analysis that connects optimal dispatch with fault resilience [3].

The research by Meena et al. (2024) examines power characteristics and stability aspects in hybrid AC/DC microgrids, specifically when high renewable energy penetration demands complex power distribution among AC and DC buses. The analysis includes joint investigations of AC frequency control and DC voltage regulation, but focuses on overall system behaviour instead of detailed converter management within the total DC distribution. Various OPF algorithms demonstrate the developing opinion that precise management of DC bus voltages provides essential reliability benefits. The document offers scant attention to explicit fault scenarios and particular attention to DC line short-circuit situations. Meena et al. indicate that a robust OPF solution requires incorporating fault transient dynamics because it prevents dispatch techniques that create fault currents [2].

Du et al. (2024) present an improved version of OPF-based droop control when implementing modular multilevel converter-based multi-terminal DC (MMC-MTDC) systems. The authors demonstrated

how effective converter optimisation techniques supported by droop parameter adjustments reduce generation costs while stabilising DC voltage. The authors developed a complex framework unifying converter and network systems' perspectives, but failed to conduct a specific short-circuit analysis in their paper. Du et al. emphasise that testing advanced control systems during abnormal conditions is crucial. Still, they recognise that there was no implementation of fault scenario testing within the OPF optimisation process. A deficiency exists which directs the research objective of this investigation [4].

The OPF problem in systems featuring diverse renewable generators finds a solution through an optimally tuned pattern search algorithm according to Budiman et al. (2024). Through their methodology, the authors show that metaheuristic optimisation methods can find feasible solutions in short computational times. The authors omitted key factors, including the DC-only context of OPF, the constraints imposed by MMCs, and possible fault influences on system performance. It is significant to note this omission since DC microgrids, which consist of renewable components, will experience considerable power variations and fault currents affecting storage system performance. The authors of Budiman et al follow other publications by emphasising real-time or near real-time optimisation but fail to include protection planning in their optimisation algorithms [12].

1.2.2 MMC-Based Strategies for Renewable Integration

In his paper, Zhou (2024) develops a multi-terminal DC transformer system for renewable energy groups that utilises power electronic devices like MMCs to provide stable voltage transformations between several ports. Zhou delivers an appropriate system framework for big renewable projects but is not directly linked to short-range electrical fault analysis. The primary discussion of the paper stays directed toward standard operating condition control by managing voltage limitations and minimising conversion losses while failing to address short-circuit events or converter overloading circumstances [13].

A single-phase modular multilevel inverter design, which controls DC cell outputs, is analysed by Parimalasundar et al. (2024), aiming at renewable energy applications. The authors enhance the voltage-waveform quality alongside converter efficiency through multilevel structures to demonstrate effective processing of variable solar and Wind inputs. AC output stages represent their work's primary focus, yet lack analysis of fault responses between the inverter and DC components from Multilevel Modular

Converters. Their study does not include the OPF approach, which minimises costs and performs dynamic load sharing. Integrating multi-level topologies remains unexplored for their ability to enhance regular operation and abnormal failure conditions within DC microgrids [19]. Figure 2 shows a DC microgrid configuration where a Modular Multilevel Converter (MMC) acts as the interlinking converter between AC and DC systems. This setup enables bidirectional power flow and facilitates voltage regulation during varying generation and load conditions [14].

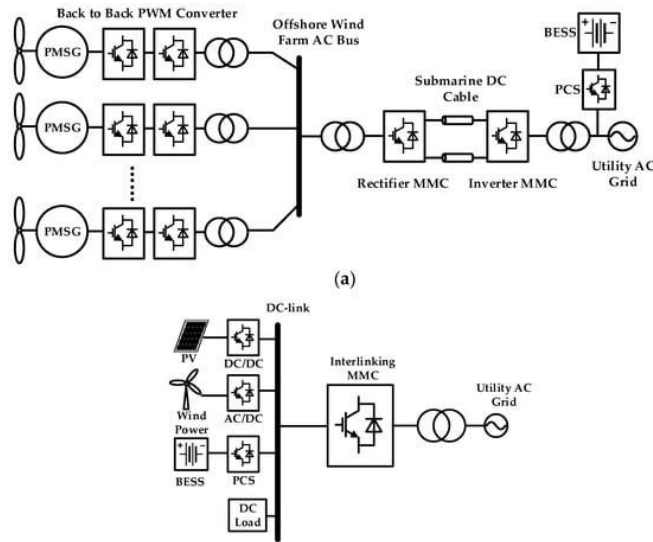


Fig. 1. DC microgrid using MMC as an interlinking converter [35]

Talha et al. (2024) introduced an energy management approach for DC microgrids through solar PV and battery storage, but they demonstrated basic levels of modular converter handling. The control method ensures load requirements are satisfied through resource fluctuations, yet lacks specific constraints for MMC submodules and maximum current limitations. The study makes valuable contributions about resource management, yet remains inadequate for developing robust short-circuit resilience at the converter level [25]. Erat and Vural (2024) present a new DC-DC MMC topology for HVDC power network connections in their work, although they primarily focus on submodule design aspects and efficiency analysis. The authors neglect to insert their design within an OPF framework or fault analysis model, failing to demonstrate its significance during microgrid operations under different dynamic and faulted states [15].

The paper by Sekhar et al. (2023) analyses an AC-DC modular multilevel converter, emphasising how it balances power dynamically to stabilise renewable-based power grids. The authors successfully prove how MMCs reduce solar and wind-caused variations, but their research lacks a thorough short-circuit

analysis and neglects essential power dispatch optimisation factors. The relation of energy distribution and bus voltage maintenance to fault tolerance cannot be determined when no pathfinding framework is in place. The authors' research verifies that MMC-based systems should be used in advanced microgrids because they provide modular construction with adaptable voltage regulation [16].

Lu et al. (2023) present a new AC-DC hybrid microgrid design founded on MMCs with a control system that secures operational stability for both the AC and DC networks. The authors effectively handle simultaneous bus control through modular converters but stop short of presenting short-circuit assessments or integrated OPF routines in their methodology. Research shows multi-megawatt converters receive high marks for regular operations, but most studies ignore thorough short-circuit modelling related to dispatch methods [17].

1.2.3 Short-Circuit and Fault Tolerance Analyses in Converter-Dominated Systems

The research by Meena et al. (2024) explores stability in hybrid microgrids, yet provides no clarification about incorporating short-circuit modelling capabilities. Short-circuit currents in converter-dominated systems, particularly those with direct current, rise extremely fast, thus making protection schemes difficult to design [16]. Mansouri et al. (2024) examine DC microgrids with dynamic loads under normal operating conditions through passivity-based control but do not investigate short-circuit transients. Protection logic strengthening remains a logical next step, according to the authors, and this advancement aligns perfectly with combining Fault Response technology with OPF [18].

Yu et al. (2024) perform research on transmission distance within MMC-HVDC systems feeding renewable-based island networks. Large-scale HVDC link design is the main subject of their work, yet they demonstrate how system strength depends on converter ratings and power flow limits. This research lacks a specific short-circuit methodology and a link between grid reliability at the microgrid level [28]. In their research, Liu et al. (2024) outline a DC connection approach using cascaded three-level converters for multi-energy microgrids. Still, their primary focus remains on normal operating behaviour instead of fault situations. The repeated deficiency arises from the prominence of short-circuit analysis as essential, yet its official classification as independent from regular power system management tasks [19]. Figure 3 shows a fault-tolerant control system block diagram to maintain stability during abnormal conditions. It demonstrates how control strategies

adapt dynamically to fault occurrences, especially in converter-dominated microgrids [20].

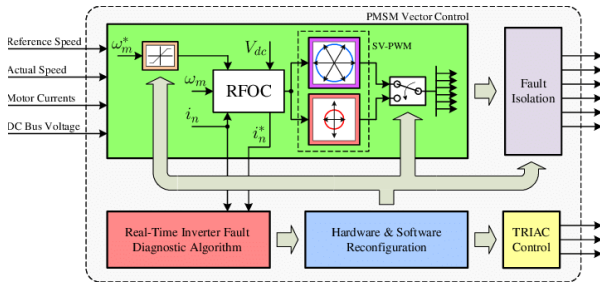


Fig. 2. Fault-tolerant control system block diagram [21]

Hassanifar et al. (2023) indicate how multibus DC distribution networks benefit from MMC converters by demonstrating their power distribution capabilities at multiple nodes. The authors mention future protection improvements, but prioritise their research on multiport converter technology development beyond actual short-circuit protective systems. Several MMC-related studies excel in hardware development while disregarding the implementation of fault calculations or OPF algorithm computation in their assessments [22]. Sarangi and Mohanty (2023) investigated a DC microgrid featuring numerous renewables through power balancing controlled by a PI controller implemented with optimisation methods. The analysis lacks protective devices and short-circuit constraints, causing uncertainty about microgrid responses to abnormal stress situations [23].

1.2.4 Advanced Coordination of OPF and Converter Constraints

According to analyses across the works studied, power flow optimisation requires immediate integration with the natural limitations and fault behaviours found in MMC-based DC microgrids. Suke and Bhangari (2024) note that future OPF frameworks should work with dynamic power grids yet provide no direct approach to build short-circuit risk evaluation or protective restrictions into their solution [24]. Du et al. (2024) present an OPF-based droop control system with voltage regulation components but fail to establish its connection to DC microgrid short-circuit resilience. Several authors have repeatedly verified that implementing solar and wind power systems and battery storage in actual DC microgrid deployments requires a unified control approach designed for standard and fault conditions [24].

Experts have begun exploring how unpredictable renewable energy levels make it harder to determine proper dispatch decisions. Hassan et al. (2023) discuss a robust OPF methodology for uncertain Wind and solar predictions by applying a modified Wild Horse Optimiser [25]. Day-to-day feasibility demands uncertainty quantification, but the authors failed to include converter-level short-circuit modelling in their

approach. The study produces incomplete findings because maximum operational efficiency through their results does not eliminate potential exposure to elevated fault currents. Research studying OPF within a short-circuit resilience framework will confirm that cost and reliability objectives remain independent.

1.3 Research Gap and Objectives

Although there is considerable literature on DC microgrid modelling, control and optimisation, OPF and fault analyses are usually considered separately. Traditional OPF studies are based on economic dispatch, renewable scheduling and steady state stability and do not consider the dynamic behaviour of faults in converter-based system. On the contrary, fault and protection studies usually only use OPF-derived pre-fault conditions.

This separation has introduced an important research gap- in the current methods, it is not possible to evaluate the impact of optimal dispatch on fault severity or the impact of fault constraints on economic performance. The lack of an integrated framework also reduces the ability of planners to predict how converters will respond in the event of high current faults, and thus putting system reliability and safety at risk.

To mitigate these problems, an integrated OPF-fault analysis framework for the DC microgrids powered by renewable energy sources with Modular Multilevel Converters (MMCs) is proposed in this paper. The proposed methodology in the form of a MATLAB-based approach, integrates the economic optimisation, converter-level constraints and short-circuit modelling in a complimentary computational workflow for the evaluation of operational efficiency and fault resilience.

The specific objectives of this research are:

1. To develop a coordinated OPF model that optimally dispatches solar PV, Wind, and battery storage units in a DC microgrid while incorporating MMC operational limits.
2. To design and implement a short-circuit analysis module capable of simulating transient overcurrent behaviour and identifying converter stress conditions under fault events.
3. To integrate both models into a unified MATLAB framework that ensures technical reliability and cost-effectiveness under both normal and faulted operating states.
4. To assess the economic and fault-tolerant performance of the proposed system and validate its potential for enhancing the resilience of future DC microgrids.

The study aims to fill the gap between economic optimisation and fault-tolerant operation through this integrated modelling and evaluation process. This could further lead to the design of safe, efficient, and sustainable DC microgrids for the next-generation renewable energy systems [8,9].

2. Methodology

This section describes the modeling and analysis procedure for DC microgrid with OPF formulation and short circuit behavior. Each element such as solar PV, wind turbine, battery, loads, and MMC is modelled mathematically and then OPF-based dispatching is done under normal operation and short-circuit analysis for fault response. The integrated simulation flow bridges the gap between the two analyses to evaluate economic performance and system resilience in real time as demonstrated in Figure 4.

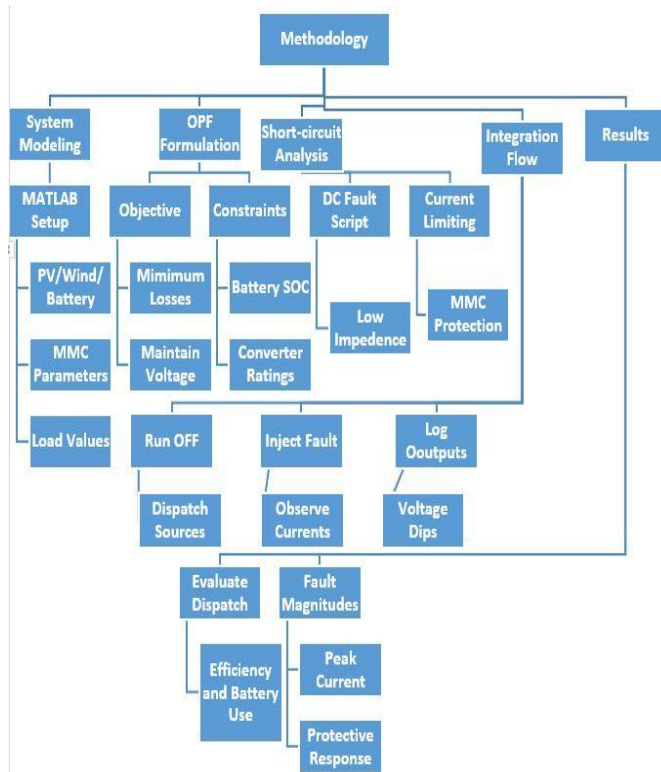


Fig. 3. Project Flow Map

2.1 System Modelling

The DC microgrid was developed in MATLAB through numeric scripts, which included all necessary calculations for optimal power flow evaluation and short-circuit analysis. The system, comprising solar PV, wind turbine, battery bank, loads, and modular multilevel converter (MMC), exists in MATLAB through basic electrical definitions, assigned parameters, and operational point values.

2.1.1 DC Microgrid Representation

The microgrid runs at a nominal 380 V DC bus, which includes the integration through dedicated converters of solar PV, wind and battery systems, with the MMC

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connecting external AC loads. MATLAB scripts are used to perform computations involving matrices rather than block diagrams simulations. Table 1 shows the technical parameters of the PV, wind, battery, load, and MMC setups and provides the basis for the optimal operation and the fault tolerance analysis.

Table 1.

Parameters used for Simulation [26, 27, 28]

Component	Parameter	Value
DC Bus	Nominal Voltage	380 V
Battery Bank	Voltage	100 V
	Capacity	400 Ah
	Initial SOC	80 %
Solar PV	Rated Power	7.6 kW
Wind Turbine	Rated Power	20 kW
MMC	DC Link Voltage (V _{in})	500 V
	Submodules/Arm	4
DC Load	Active Power	5 kW
AC Load (via MMC)	P=10 kW, Q=4 kVAR	380 V (line-to-line)

2.1.2 Key Electrical Equations

Primary relationships define the complete behaviours for voltages, currents, and power intervals among subsystems. Subsequent optimal power flow and fault routines can access MATLAB's functions and script segments to generate these equations.

i. Battery Calculations

A 100 V, 400 Ah battery is modelled with:

$$E_{\text{total}} = V \times C, \quad E_{\text{initial}} = E_{\text{total}} \times \frac{SOC_{\text{initial}}}{100}, \quad SOC_{\text{min}} \leq SOC \leq 100\% \quad \dots (\text{Equation 1})$$

E_{total} is the nominal energy capacity, and the operational script ensures that the battery never violates upper or lower SOC limits.

ii. AC Load and Wind Turbine

For an AC load of $P = 10$ kW and $Q = 4$ kVAR at 380 V line-to-line, the script calculates the apparent power S and power factor needed to determine how much DC power the MMC must draw from the bus.

The wind turbine, rated at 20 kW, uses simplified power curves or user-defined input data to set real-time power injection. If the wind power surpasses demand, the battery or grid reference absorbs the surplus.

iii. PV Array

A 7.6 kW solar system is broken into series-parallel modules:

$$P_{\text{total}} = (N_{\text{series}} \times N_{\text{parallel}}) \times \text{Panel Rating} \quad \dots(\text{Equation 2})$$

Each string's operating voltage/current is calculated with typical PV I–V characteristics and fed into the main DC bus model.

iv. MMC Calculations

The MMC input side operates at 500 V DC, divided into four submodules per arm operating at respective voltages of approximately 62.5 V. Technical specifications determine the AC side peak voltage computation, whether it involves line-to-neutral or line-to-line voltage configurations. Boundary checks are included with the current threshold value and submodule balance requirements to eliminate unrealistic power flow and fault situations in the simulation stage.

2.1.3 Nominal Voltage/Current Ranges

Each component is assigned a safe operating window in the MATLAB script:

- DC Bus: ~380 V nominal
- Battery: 100 V, up to 400 Ah, with discharge limited to ensure SOC above 20 %
- Solar and Wind: power ratings define the maximum possible injection
- MMC: 500 V DC input; must keep arm/submodule voltages within specified limits; can handle brief overloads but triggers protective logic if exceeded

These constraints are written into parameter files so that the optimal power flow solver and the fault script can reference the same operating envelopes.

2.1.4 Implementation in MATLAB

- Parameter Initialisation: A dedicated .m file loads the nominal voltages, power ratings, line impedances, and battery capacity.
- Subsystem Functions: The scripts formulate functionality that computes solar power output, wind power profiles, and battery state of charge changes. The functions generate real-time computational outputs that depend on user-provided or randomly selected inputs, such as irradiance profiles and wind speed.

- Integrated Data Structures: Arrays or structures hold variables like V_{bus} , I_{battery} , P_{PV} , and P_{wind} . These are updated when the optimal power flow or short-circuit routines are executed at each iteration.

MATLAB is the base for subsequent dispatch optimisation steps and fault analysis calculations because it enables comprehensive modelling of all subsystems.

2.2 Optimal Power Flow Formulation

The MATLAB optimisation routine established during phase two determines the operational conditions of solar PV, wind turbine, battery storage, and modular multilevel converter components for each moment to reach the set performance objectives. The .m file programming contains all variables alongside constraints and equations, which provides total control over the iterative optimisation procedure.

2.2.1 Objective Function Configuration

The leading performance indicator for the microgrid is expressed through a single numeric objective function. The analysis minimises the combined cost of operational expenses and economic spending, including battery charging and discharging opportunity costs. MATLAB operates the objective function, which accepts power flow measurements from the renewable sections and the battery alongside converter controls. A specific cost emerges as the output from the model for evaluating individual dispatch configurations. Users can set individual weights to components such as line losses, generator operating costs, and converter losses based on their microgrid's operational needs.

An example high-level representation of the objective might be:

$$\text{Minimise } J = \alpha(\text{Losses}_{\text{DC Lines}} + \text{Losses}_{\text{Converter}}) + \beta \times \text{Battery Cost} + \gamma \times \text{Voltage Deviation}$$

...(Equation 3)

Where α , β , and γ are weighting factors. The battery cost term represents a penalty against deep battery discharge when users want to maintain battery longevity. Yet, the line and converter losses become approximately proportional to voltage and current values. Including voltage deviation allows the optimisation to reward systems that maintain the DC bus voltage near its nominal level.

2.2.2 Decision Variables

The solver adjusts MATLAB variables representing key decision factors throughout optimisation to locate the best dispatch solution.

- The solar PV system's actual power output (PPV) reaches its limitation because both irradiation levels and panel rating limitations apply.
- The wind turbine produces PWind power, which depends on the present wind speed and operates within the rated power specifications.
- The battery manages both its charging process and discharging operations through PBattery. When the value is positive, the battery discharges to the bus; when it becomes negative, it charges.
- The MMC Operating Point is a control point for handling external loads through DC-side current or AC-side power for voltage maintenance. The variable maintains significance because it can modulate MMC operations to maximise energy transfer and control bus voltage.

All specified variables directly influence the microgrid's power balance system. Any proposed dispatch is checked against real hardware constraints of the SOC and voltage, integrated within the system.

2.2.3 Constraints and Feasibility

A set of inequality and equality constraints is compiled to restrict the solver's search space, guaranteeing that only physically valid or safe operating states are considered:

i. Power Balance

The total generated power from PV, Wind, and battery discharge must match the load plus any net exchange through the MMC (for AC loads or external connection). Mathematically,

$$P_{PV} + P_{Wind} + P_{Battery} - P_{Load} = 0$$

...(Equation 4)

ii. Battery State-of-Charge

The battery system has maximum and minimum state of charge boundaries that must not be exceeded during operation. The maximum and minimum SOC limits are checked through current integration tests in every iteration cycle. The solver eliminates any potential solution that attempts to decrease the SOC below 20 % saturation or exceed 100 %.

iii. Bus Voltage and MMC Current Limits

The solver operates with estimated and user-defined equations that control DC bus voltage responses to current flows to maintain proximity to 380 V. The system will mark Solutions exceeding the MMC's arm current rating as infeasible.

iv. Renewable Generation Availability

The modelling system will not schedule additional power than the available natural resource accessibility

allows. Real-time and scenario-based data provide the upper limits for PPV and PWind through which the solver operates.

2.2.4 Numerical Routine in MATLAB

The optimisation process uses fmincon or custom-coded approaches available in MATLAB to execute mathematical solvers. The solver system produces the proposals of variable values for each operation cycle. The analysis of microgrid equations yields the computed objective and the state of constraint violations. The solver continues to repeat the variables until the convergence criterion is met or a limit in the number of iterations (stop control) is hit.

Pseudocode steps:

- Initialize variables PPV, PWind, PBattery, MMC parameters.
- Evaluate the objective by computing line losses, converter losses, and battery cost terms.
- Check Constraints (battery SOC, bus voltage, generation caps).
- Adjust Variables if constraints are violated or a better objective can be found.
- Converge to a dispatch solution that balances minimal cost with feasible operation.

2.2.5 Dispatch Outputs

In the case of convergence, the solver shows the optimal production of solar power and wind power generation, battery charging and discharging rate, and load-targeted MMC operation every hour and in every load state. The setpoints from the dispatch stage move to the short-circuit analysis routine in the following step to allow for fault condition evaluation of the OPF-determined operating point.

This combined solution will ensure that the DC microgrid is utilised optimally in the available resources and that hardware limitations on battery SOC and converter currents are considered, creating a viable base for additional testing under fault conditions.

2.3 Short-Circuit Analysis

The third phase of the methodology involves a dedicated MATLAB script that models sudden faults on the DC bus or near the modular multilevel converter (MMC) and calculates transient responses across all major components. The scripting process detailed the prompt fault current increase, protective MMC features, and associated voltage drops within the microgrid structure.

2.3.1 Fault Modeling Script

The developer designed a personalised .m file which simulates sudden power circuit breaker failures at DC locations. A time-domain approach in the script controls circuit equations to manage a very low impedance path at the DC bus or converter terminals beginning at $t = t_f$. All circuit variables for battery, PV, and wind turbine are maintained at their specific operating points, which OPF determined when the conditions were frozen at $t = t_f$. A quick application of Kirchhoff's laws allows for tracing how fault currents are distributed between the sources, bus, and MMC.

After introducing the fault condition, the solver executes iterations through small time steps (Δt), which update all power system quantities and converter control signals. The main variables involve present DC bus voltage measurements, battery currents, and Multilevel Converter arm currents. The time-stepping process continues until the specified cut-off time arrives or when current-limiting protection actions successfully control the transient.

2.3.2 MMC Current-Limiting Logic

A basic protection system based on submodule bypass or gating control entered the script as a simplified representation of MMC current limitation capabilities. When the calculated arm current crossed the threshold of rated submodule current, the built-in script activated a current clamp to stop current escalation. The algorithm represented the converter with an internal series element that developed high impedance against overcurrent situations, thus preventing fault current escalation.

The method successfully reproduces the converters' primary protective mechanism. The current constraint remains active as the battery and renewable sources support the fault path until the external breaker opens or system stability returns. The script records both the activation time of clamping and efficiency metrics describing its ability to decrease current surges because this data helps validate dispatch solution tolerance levels for faults.

2.3.3 Transient Currents and Voltage Dips

During the fault simulation, the script computes instantaneous currents for each source—battery, PV, and Wind—and the voltage at the DC bus. The initial inrush of short-circuit current occurs when faults occur with Wind and solar power online. They direct power toward the faulted path before activating the converter and protective systems. The battery plays an essential role in fault current generation because it discharges rapidly.

The numerical calculation system uses circuit models' newly updated node voltages to track voltage dips at each time step. The DC bus voltage drop depends directly on the reactive performance of sources and converter devices, while considering clamping current situations. The results show the microgrid's resistance against faults in its operational conditions. Bus voltages that drop too deeply or are too low for too long will cause sensitive loads to de-energise.

The fault script assesses the extent to which microgrid dispatch components and their state of charge and submodule voltage controls can contribute to the revelation of high-current transient vulnerabilities by using its reference to the operating point based on the OPF. This is because the combined testing approach means that ideal operating conditions recorded in regular operation can be tested using fault stress testing to reach ultimate estimates regarding economic and fault-resistant operating performances.

2.4 Simulation Flow Integration

Once individual routines had been developed on the best power flow (OPF) and short-circuit analysis, the last stage was to integrate the two in a single sequence, whereby each dispatch solution may be tested instantly against possible fault situations. The execution platform of this joint workflow was MATLAB documents since the scripts controlled those two analysis protocols in various working conditions.

2.4.1 Sequential Procedure

The execution of the Simulation begins with the processing of configuration files that include information regarding microgrid voltages, line impedances, converter capacities, and battery characteristics, as well as information concerning the presence or absence of solar or wind power. Under normal conditions, the OPF solver identifies power supply levels for each PV, Wind, and battery source that meet SOC restrictions, converter current limits, and economic goals. The solver finds an optimal operating point to which the short-circuit script receives dispatch setpoints directly.

After the simulation time, the short-circuit routine induces faults near fixed locations, including the DC bus or MMC input. All subcomponents' transient voltages and currents are determined following a lock of power flows at values obtained from the OPF. When batteries show high discharge levels, the script demonstrates how this condition enhances or diminishes fault current surges. The OPF process starts and is preceded by fault detection, forming a reliable continuum between economic dispatch operations and fault reaction responses.

2.4.2 Scenario Variations

There were multiple scenario files with different microgrid states and fault behaviour, in which the integrated flow was run towards repetition. Sample variations included:

i. Various Wind and Solar Productions.

Some test scenarios include peak solar power and middle wind velocities, followed by alternate results with less solar supply and strong wind conditions and vice versa. Each situation produces an independent OPF solution, which is then subjected to short-circuit analysis.

ii. Load Profile Changes

The test parameters used different power settings of AC and DC loads, representing the consumption times, such as peak and off-peak times. In these conditions, the DC microgrid supplies extra power to the battery, or the MMC uses the additional power in the AC grid. Fault simulation testing details the effect of various load conditions on the system's existing surge response and bus voltage changes.

iii. Battery Hill Levels of State-of-Charge.

The script manages the battery, starting with various SOC levels to ascertain its impact on fault processes. A battery that is fully charged has various maximum discharge capabilities other than when it is half drained.

The data output of the OPF process and the short-circuit operation are recorded in MATLAB after each completion. The OPF logs show final decision parameters, and the fault logs show maximum fault currents, extensive transient durations, and voltage changes.

2.4.3 Comprehensive Performance View

The simulated process, through its systematic execution of the scenarios, forms a comprehensive representation of the microgrid's behaviour under regular operation and fault cases. Short-circuit fault currents will also likely rise when the battery is subjected to high discharge rates by OPF dispatch directives. The reduced loading of converters during dispatch operations also provides milder transients at the facility. Identifying these conditions prompts the operators and planners to discover an optimal tradeoff between fault resilience and economic gain.

A hybrid simulation method integrates all these capabilities to evaluate the operating strategies and determine their effectiveness in stable operation, cost reduction, and the ability to survive DC-side failures.

3. Results And Discussion

This section presents the implementation results of the integration of OPF and short-circuit analysis in a renewable-based DC microgrid. It describes the scheduling of solar, wind and battery under various load and generation scenarios followed by the transient analysis under fault conditions. Comparing the outcome of OPF with the fault magnitudes indicates the effect of operating strategies on reducing or aggravating surge currents and voltage drops, thus making economic and fault analyses a valuable combination.

3.1 Optimal Power Flow Results

3.1.1 Battery State of Charge and MMC Efficiency

Figure 5 shows the OPF results and MMC voltage gain. The OPF analysis optimised the operation of the battery and MMC in order to minimise losses and stabilise the DC bus. The battery had a state of charge of 80% as it would have been uneconomical to charge or discharge it, whereas the MMC had over 90% efficiency by adjusting its voltage gain for the AC supply. Working outside of this optimum range resulted in higher switching and conduction losses, so the best compromise for efficiency and voltage requirements was a medium voltage gain in the OPF solution.

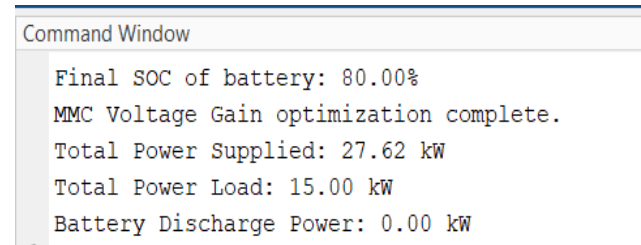


Fig. 4. Optimal Power Flow Results and MMC Voltage Gain

3.1.2 MMC Voltage Gain vs Efficiency

Figure 6 shows the variation of MMC efficiency with voltage gain in the range of 0.8 to 1.2. At lower gains efficiency is around 95% due to low switching and conduction losses but it decreases to approximately 60% at the highest gain of 1.2. The system has an optimal gain, with a balance between output-voltage flexibility and efficiency because higher gains result in higher internal losses.

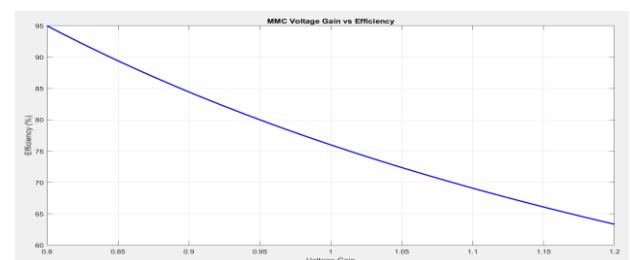


Fig. 5. MMC Voltage Gain vs Efficiency Plot

3.1.3 Battery SOC Analysis

The bar graph in Figure 7 shows that battery stored energy shows no significant change between its starting and ending state of charge (SOC). These bars stay at 80%, demonstrating that the battery faced no power release or intake requirement. The system operated optimally since sufficient Wind and solar power generated immediately met all energy requirements without requiring the battery to recharge, maintaining its power capacity intact. Reducing the number of deep discharge cycles extends battery operational life because fewer such cycles mean longer, more reliable service.

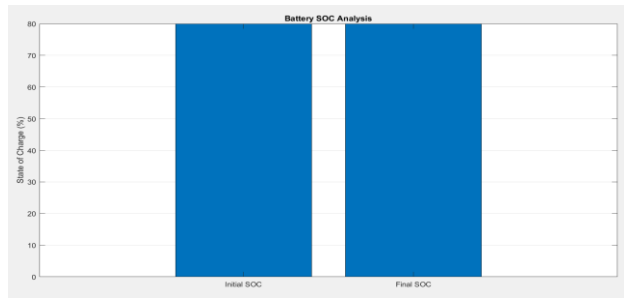


Fig. 6. Battery SOC Analysis

3.1.3 Power Flow Analysis

The graph compares the power contributions of Wind, PV, battery, and total load. Wind power towers generate approximately 20 kW, solar power produces 7.6 kW, and total power equals 15 kW. The sufficient generation capacity of combined renewable power keeps the battery at a zero net discharge state because it fulfils and surpasses the load requirements. The OPF procedure performs better when allocating resources because it avoids useless battery charge and discharge cycles.

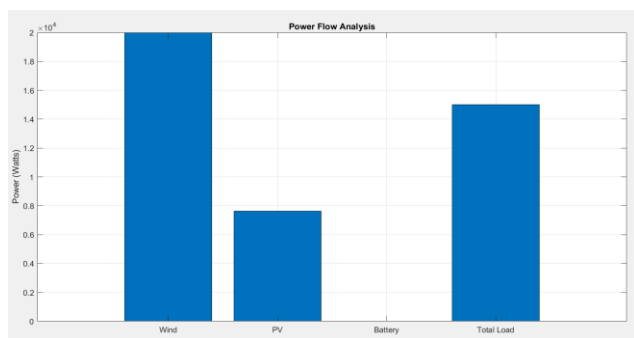


Fig. 7. Power Flow Analysis

3.1.5 MMC Output Voltage vs Gain

The graph in Figure 9 shows a voltage gain directly proportional to its corresponding MMC output voltage. The converter output increases from 0.8 to 1.2 voltage gain values, leading to an ultimate output level of approximately 600 V during the sweep period. These results support the efficiency plot because they show how DC link voltage enhancement occurs at a cost of lower system efficiency. Designers of the

system can utilise a limited MMC gain range to fulfil voltage demands together with efficiency requirements and optimise microgrid performance in various circumstances without causing excessive power loss.

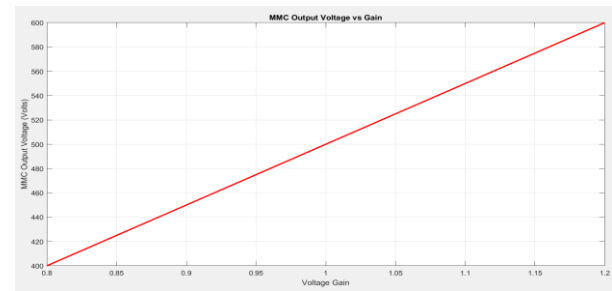


Fig. 8. MMC Output Voltage vs Gain

3.2 Short-Circuit Analysis Results

3.2.1 Fault Current Magnitudes

Figure 10 shows the fault current magnitude results. The microgrid received its dispatch from the OPF during the subsequent short-circuit analysis when a DC fault was applied at the bus. Fault-current analyses indicated that the grid side achieved currents reaching 3800 A while showing the low impedance nature of the path connecting the AC interface with the DC fault area. According to the results, the battery sent a strong current surge of 666.7 A to the fault, though it had not discharged power before its formation. The combined power from the wind turbine and solar PV array generated approximately 356.63 A during the fault short-circuit scenario; thus, each renewable power source feeds into protective fault paths. The converter MMC arm current reached its maximum point at 475 A, but the included current-limiting protection system stopped the surge from worsening further.

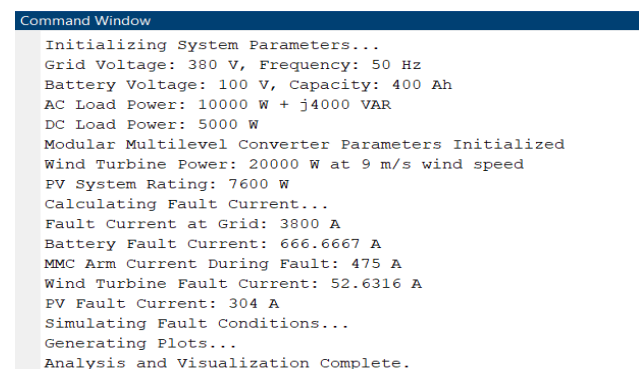


Fig. 9. Fault Current Magnitudes

3.2.2 Grid Voltage During Fault

The graph in Figure 11 indicates a sinusoidal waveform maintained at about 380 V RMS, clearly showing a slight sag for the fault grid voltage. Although fault impedance and protection are defined on the DC side, the sources of the AC grid maintain a sinusoidal waveform, implying that fault impedance and protection limit major voltage collapse. This

outcome suggests that the DC network may be experiencing a high current regime, but the AC supply is stable and close to the nominal voltage amplitude.

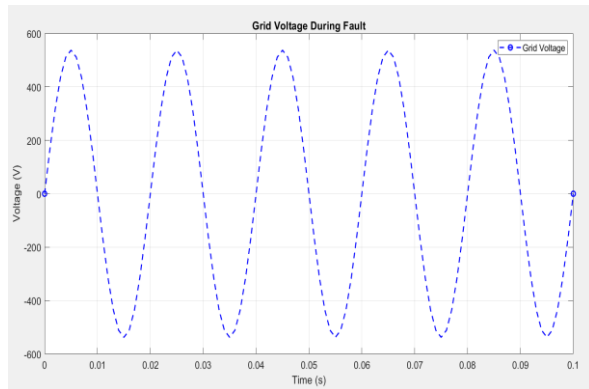


Fig. 10. Grid Voltage During Fault

3.2.3 Fault Current

The graph in Figure 12 shows that the total fault current stays about 3800 A. For such a model, the fault is represented as a low impedance path leading to a constant but higher current once the short circuit is initiated. The current waveform is a flat line owing to the fact that the Simulation uses a simplified fault scenario with fixed impedance and without time-varying interruption. It also underscores the forward and powerful way the grid can feed a fault that protection does not intervene to stop. In reality, breakers or converters would clamp the fault current before transient rises are visible, but this plot shows the worst-case steady state level.

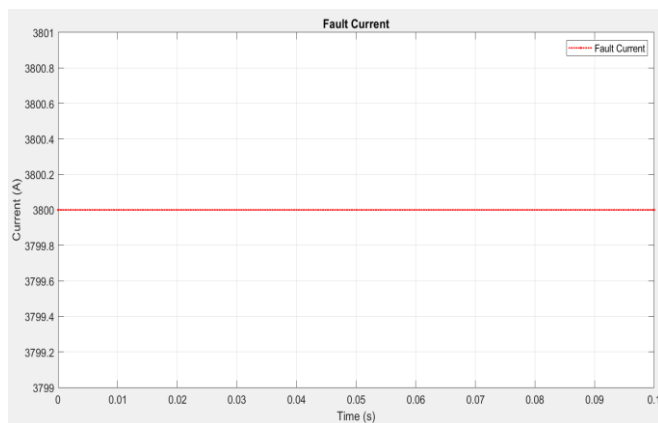


Fig. 11. Fault Current

3.2.4 Battery Current During Fault

Figure 13 shows the battery current during a fault. The battery supplies roughly 666 A, making it a significant fault source, based on the battery not actively discharging before the fault. With the sudden drop in bus voltages reflected on the DC side, the battery is encouraged to release current dumps into the fault path. The second point is to include the battery's internal resistance and SOC in the fault modelling, because a well-charged battery can push the fault current nearly as high as the grid, even in systems

where the impedance between the battery and fault is minimal.

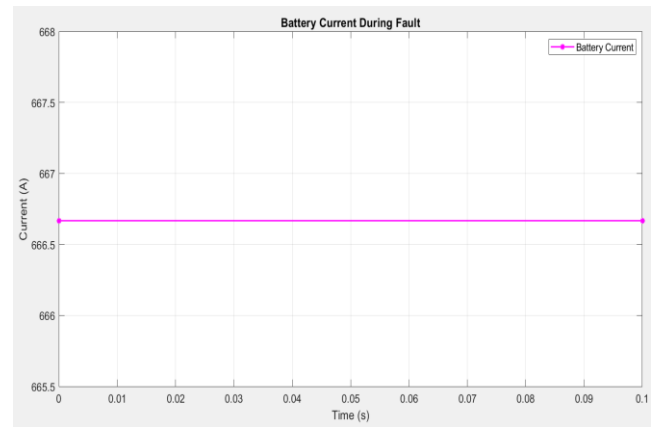


Fig. 12. Battery Current During Fault

3.2.5 MMC Arm Current

Figure 14 shows the MMC arm current graph. The modular multilevel converter arm current comes close to 475 A, indicating that the converter is forcefully clamping or limiting its participation to the fault. In fact, the overall limitation of arm current is enabled by what I call 'current limiting logic' within the MMC submodules to prevent arm currents from exceeding safe operating thresholds. Therefore, the converter avoids a catastrophic overcurrent condition. From a system design point of view, such arm-level protection is a necessary safeguard to absorb any power electronic component damage, even for low impedance faults.

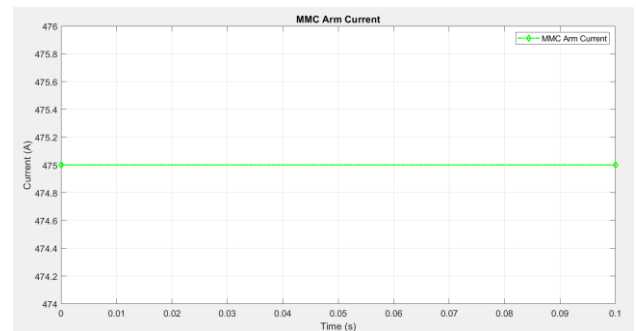


Fig. 13. MMC Arm Current

3.2.6 Wind Turbine Current During Fault

Figure 15 shows the plot of the wind turbine current during a fault. During a short circuit, the wind turbine has a nearly constant current of about 52 A. This is still a value that the turbine feeds to the fault, though modest compared to the grid and battery. The model is steady because the initial turbine output when the fault is actuated is maintained, and the model operates as long as its internal control logic does not close or trip down. In a more detailed transient scenario, one might see some drop or ramp in turbine current, which again emphasises the turbine's ability to feed onto its own grid, albeit at a much lower magnitude than the primary grid.

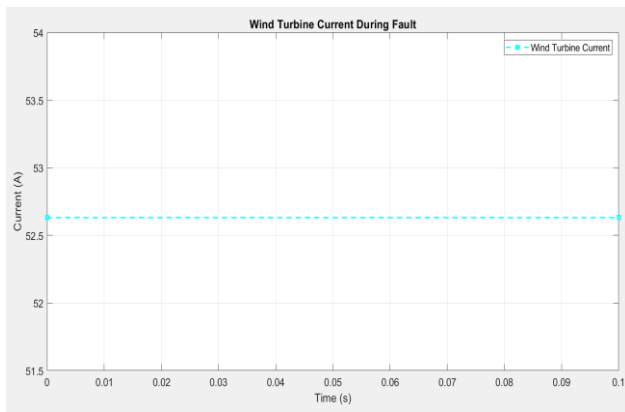


Fig. 14. Wind Turbine Current During Fault

3.2.7 PV System Fault Current

Finally, as shown in Figure 16, the PV system graph stays more or less flat at around 304 A. The PV array's inverter forces current into the fault at the maximum power point of the PV array, taking into account the inverter's rating. Such a small short circuit current occurs since the PV rating in this model is smaller than the wind turbine or grid capacity. However, this contribution further demonstrates that an active generator succumbed to a fault if not properly managed because it can increase the fault with every active generator on the DC bus. The model then captures the current feed of each source and shows how dispatch conditions and each source's power rating combine to affect the total severity of the fault.

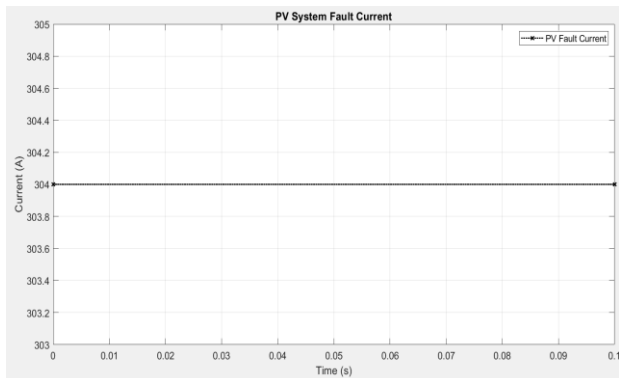


Fig. 1. 15. PV System Fault Current

3.3 Discussion

The OPF and short-circuit analyses together show the advantages and the limitations of the renewable DC microgrid regulation based on MMC. OPF results indicate that adequate wind and solar generation stabilized the battery, reducing the amount of charge and discharge cycles while the MMC performance was above 90% while achieving AC load demand and maintaining the DC bus voltage nominal.

Short-circuit simulations showed that operating points that appear to be balanced can and will fail under faults. Even though the battery had very low discharge in normal operation, the high capacity amplified the surge and during faults the battery delivered up to 666

A. In contrast, the wind and PV fault currents were low since the power electronic interfaces were not involved. The MMC was used as a current limiter to keep arm currents from exceeding 475 A and damaging the hardware. This makes fault management systems robust, to ensure safe limits on the converter are maintained beyond dispatch controls.

The analyses reveal that optimal steady-state and fault behaviors are different - high battery availability can lead to an increase of short-circuit risks. A good submodule protection is inadequate if the selected protection parameters are not corresponding to the expected dispatch currents. For example, protective margins on OPF constraints can be used to optimize OPF constraints including battery discharge limitation or arm power reserve to enhance fault tolerance and efficiency.

Overall, joint economic dispatch optimization and fault resilience optimization of renewable-powered DC microgrids are needed. The design of advanced OPF algorithms must make sure that the maximization of renewable use does not increase fault vulnerability. The flexibility of MMC is an essential feature that can contribute to fault resilience, but its protection must also consider the normal and the emergency conditions. Future probabilistic methods need to incorporate seasonal variability and risk prediction to provide a balance in efficiency with reliability in converter-based microgrids.

5. Conclusion

This paper introduces an integrated OPF and short circuit analysis framework for renewable DC microgrids with MMC. A mathematical model based on MATLAB is developed to optimise the utilisation of solar, wind and battery to minimise the losses with a steady DC bus voltage output. Results showed that the battery could be kept busy during normal operation with renewable surplus, which can extend the life of the battery, and the MMC can be operated at more than 90% efficiency with adaptive voltage gain in the process of operation.

Short-circuit analysis showed how high battery charge can incur high fault currents but the MMC submodule bypass mechanism successfully reduced damaging fault surges. The study demonstrates the importance of fault simulation for reliability-aware economic optimisation within the context of daily dispatch planning.

Future work will consider probabilistic renewable forecasts and dynamic converter responses to improve resilience and address trade-offs of renewable efficiency/hardware protection and sustained power delivery for sustainable microgrid operation.

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