

State-Space Modelling and Stability Analysis of MMC-Based Distributed Generation Units in Islanded Microgrids

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KEY WORDS	ABSTRACT
Modular Multilevel Converter Islanded Microgrids State-Space Modelling Model Predictive Control Voltage Regulation Renewable Energy	The study aims to incorporate Modular Multilevel Converters (MMCs) into islanded microgrids that are now dependent upon off-grid energy systems. As more renewable power sources are integrated into power microgrids, such as solar and wind power, the stability and effective management of power in these microgrids have become complicated. This study was intended to create a state-space formulation of MMC-based distributed generation units in islanded microgrids, conduct stability analysis, and apply a Model Predictive Control (MPC) approach to improve the voltage regulation and power flow. The system dynamics were modelled with the help of MATLAB, and the stability of small signals was evaluated with the help of eigenvalue analysis. The DC voltage was regulated and flow optimization was realized between renewable energy sources, storage, and loads using MPC. The system was dynamically stable and the voltage changes reduced by MPC. Also the system was resilient to the disturbances in terms of fault detection and protection. The proposed structure showed promising results of MMC-based microgrids optimization in islanded mode, and more works will be done to talk about the accuracy of model and improve the harmonic mitigation and real time control optimization.

1. Introduction

1.1 Background and Motivation

Microgrids help to increase the grid reliability through local generation during both grid-connected and islanded operation. Nevertheless, recent fast development of renewable energy sources (RES) requires sophisticated control technologies to guarantee stability in changing conditions [1]. Modular Multilevel Converters (MMCs) feature the best power quality (less harmonic distortion and switching losses) as well as scalability and modularity, which make them highly appropriate in these applications [2].

In spite of these benefits, stability in islanded microgrids is still difficult to maintain. The lack of grid support makes it worse when it comes to sensitivity to load changes and renewable intermittency. Moreover, MMCs add some

complicated internal dynamics including circulating currents and submodule capacitor voltage variation that can adversely affect the stability of the entire system [3,4].

Whereas models of state-space and analytic models have been extensively employed to evaluate small-signal and transient responses [5], other studies (including Begum et al. (2018)) have focused on inverter-dominated AC microgrids [33]. The current models do not describe these particular modular structure, multilevel voltage balancing, and DC dynamics of MMC-based systems.

As a result, it is of paramount importance to extend existing modeling frameworks. The gap in this research is filled by contributing a general state-space modeling and a control approach to MMC-driven, islanded DC microgrids. This work will combine this model with more advanced control techniques to significantly enhance the voltage regulation,

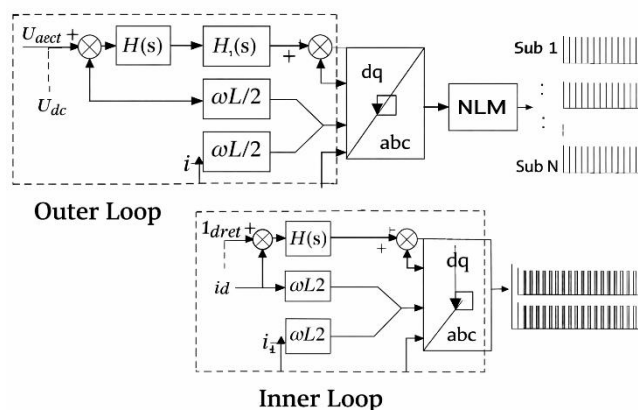


Fig. 2. Control Block of MMC [31]

Xiong et al. (2019, 2020) applied harmonic state-space modelling to control internal MMC processes, including circulating currents, voltage ripple, and indexing to improve the stability of the system [13, 14]. Although these studies offer useful information that internal harmonic suppression, it did not discuss the practical aspect of integrating MMC-based systems with renewable energy sources and energy storage in the islanded microgrids. The lack in both works is a holistic system, which integrates MMC-based distributed generation with modern real-time control systems, including MPC.

1.2.3 Control Strategies and Optimization for MMC-Based Microgrids

One promising control strategy is Model Predictive Control (MPC), which has and continues to be used extensively in the management of microgrids. Dynamics and uncertainty in microgrids, MPC is well-suited to controlling inputs based on a prediction of future system behaviour.

Liu et al. (2023) introduced a small-signal modelling approach of MMC-based systems, specifically concentrating on the internal harmonic interactions. Although it was an insightful paper on internal MMC behaviour, it failed to suggest control strategies, such as MPC, to streamline the operation of MMC-based microgrids operating in islanded modes. A combination of MPC and state-space models should be undertaken to optimize voltage regulation and power flow within MMC-based systems [15].



Fig. 3. A MG (microgrid) considered in the problem, consisting of (1) a wind turbine, (2) photovoltaic panels,

(3) a microturbine, (4) a diesel engine, (5) an ESS (energy storage system), and (6) the demand [32]

Pournazarian et al. (2020) investigated how the existing state-feedback affects a microgrid's stability. Although this research gives valuable information regarding the stability of converter-based microgrids, it is not concerned with MMC-based systems and their particular dynamics in islanded microgrids. This work contains a gap in the analysis of control strategies of MMC-based systems because of the insufficient optimization strategies, such as MPC [16].

1.2.4 Dynamic and Small-Signal Stability Analysis in MMC-Integrated Systems

Small-signal analyses and state-space modelling are well-known techniques of determining the dynamic stability of distributed generation based on converters. In the case of microgrids that contain inverters, dynamic-phasor models [17], enhanced state-space models [18], Lyapunov functions [19], and generalized multi-source models [20] have been effectively utilized by researchers to evaluate transient response and coordinated control.

Although modular multilevel converters (MMCs) are typically considered in an offshore and high-voltage (HVDC) environment [21, 24], this technology is well applicable to an islanded microgrid because of its ability to scale, modularity, and low harmonic distortion [23]. As a result, recent work has focused more on small-scale and state-space modelling of MMCs to model important internal dynamics, including submodule interactions and switching functions [25, 34]. Such models are necessary in the design of controllers that achieve stability of voltages, damp oscillation as well as avoiding resonances in the face of variable loads [22, 35]. Also, harmonic formulations of state space have been applied directly to the reduction of circulating current distortions in the modular structure [37].

The problem of renewable intermittency, parameter drift and real-world fault transients have been resolved with the addition of sophisticated control to MMC networks [30]. Research has identified effective adaptive modelling [27], robust parameter tuning [28] and or coordinated power-sharing mechanisms [36] to ensure stable operation. Such strong structures guarantee system flexibility and resiliency, especially when MMCs are connected with any energy storage system, or when MMCs are exposed to nonlinear interactions caused by large renewable penetration [26, 29, 38].

1.3 Objectives and Contribution

The main goal of this study is to come up with an extensive state-space modelling of the distributed

generation of MMC in islanded microgrids with a view of assessing both stability and performance of control in provisional and dynamic conditions. As opposed to the traditional inverters, MMCs have complex internal dynamics, including the variation of submodule capacitor voltages, circulating current, and harmonic interactions, which should be treated mathematically in a specific way. This elaborated modelling can maintain the power flow in a stable and optimization state between renewable energy resources, storage and loads.

This study incorporates a Model Predictive Control (MPC) method to achieve optimal voltage regulation and power flow to make the system more efficient. Through predicting the future state by using the state-space model, the MPC reduces voltage deviations and losses in the system in real-time at a faster rate and more adaptable response than the traditional droop or PID controllers. In addition, a fault detection and protection system is also provided to determine overcurrent or short-circuit situations quickly and to isolate them, enhancing operational resilience greater.

The research is novel, as it provides a single modeling-control-protection framework to address literature gaps that in the past were on inverter-based systems. This work presents solutions that are not studied previously since the authors employ MPC optimization and fault detection methodically to MMC technologies. Verified by MATLAB/Simulink simulations, the methodology exhibits a higher small-signal stability, transient response and resistance to variable generation and faults. Finally, this paper can be used as a guide in developing effective, next generation sustainable MMC microgrids.

2. Methodology

This section describes modelling, analyzing, and controlling MMC-based distributed generation units in Islanded microgrids. The study's main objective is to reach the whole state space model, stability analysis, and Model predictive control (MPC) to obtain the optimal performance of MMC-based microgrids. The methodology includes formulating mathematical models, developing control strategies, and testing via MATLAB simulation. Figure 1 presents the block diagram of the process followed for this research.

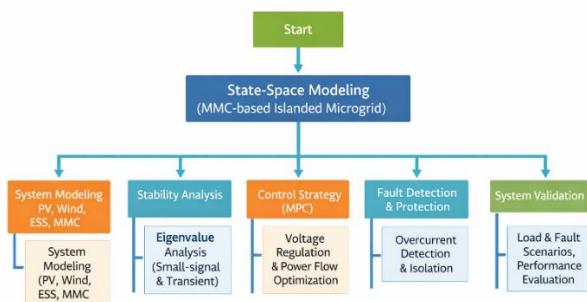


Fig. 4. Block Diagram of Proposed Methodology

2.1 State-Space Model Development for MMC-Based Distributed Generation Units

The state-space Model is utilized to analyze an MMC-based distributed generation system in an island microgrid. The Model displays the MMC's interaction with renewable energy sources, energy storage systems, loads, and the system's behaviour under different operating conditions.

2.1.1 System Configuration and Assumptions

The microgrid system, based on MMC, in this study incorporates the following configurations:

- Solar PV: Solar generation is modelled as a time-varying power input based on a typical amount of irradiation throughout the day.
- Wind Turbine: Wind generation is assumed as a variable wind speed profile; the power generated is proportional to wind speed.
- Battery Storage (ESS): The state equation describing the dynamics of the ESS is a simple charge/discharge equation with existing constraints on the SOC (state of charge).
- MVC Converter: MVC controls the DC-link voltage and enables the transfer of power between the renewable energy sources, the energy storage, and the loads.

The system configuration is a DC microgrid, with each of the components being connected by virtue of a common DC bus. The information in the state-space Model describes the relations between voltage, current, and power (of all the elements) and the dynamical behaviour (in terms of linear differential equations) of the system viewed as a whole.

2.1.2 Mathematical Formulation for State-Space Representation

The general form of the state-space equations for the system is:

$$\dot{x}(t) = A x(t) + B u(t)$$

$$y(t) = C x(t) + D u(t)$$

Where:

- $x(t)$ represents the state vector (voltage, current, power),
- $u(t)$ is the input vector (e.g., power from renewable sources, control inputs),
- $y(t)$ is the output vector (e.g., voltage, current),
- A , B , C , and D are the system matrices defining system dynamics.

State Vector and System Matrices Definition

The state-space representation of the MMC-based islanded microgrid is expressed as:

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

where the state vector is defined as:

$$x(t) = [V_{dc}(t) \quad I_{dc}(t) \quad SOC(t)]^T$$

In this case, V_{dc} is the DC-link voltage, I_{dc} is the DC current through the MMC, and SOC is state of charge of the energy storage system.

The input vector $u(t)$ comprises of the power contributions associated with renewable sources of energy and the control inputs used by the MMC. $y(t)$ is the output of the system that is to be measured, such as DC voltage and current.

The system matrix A embodies the dynamics inside the MMC-based microgrid, such as the dynamic of the voltage and current couplings and energy storage. Matrix B is the sensitivity of the control inputs and renewable power changes on the system states. Matrix C is used to project the system states to the measured outputs and Matrix D is the direct feedthrough that exists between the inputs and the outputs.

For the MMC dynamics, the system equation is formulated as:

$$\dot{V}_{DC}(t) = \frac{1}{C_{DC}} (P_{in}(t) - P_{out}(t))$$

Where:

- $V_{DC}(t)$ is the DC-link voltage,
- $P_{in}(t)$ is the input power from the renewable sources (solar PV and wind),
- $P_{out}(t)$ is the output power to the load or energy storage.
- C_{dc} is the DC-link capacitance of the MMC converter and dictates the rate of change of the DC voltage as a result of power imbalance between generation, storage and load.

For the battery dynamics (SOC), the Model is:

$$SOC(t) = SOC(t-1) + \frac{P_{battery}(t)\Delta t}{C_{battery}}$$

Were:

- $SOC(t)$ is the state-of-charge of the battery,
- $P_{battery}$ is the charging/discharging power,
- $C_{Battery}$ is the battery capacity.

Renewable energy sources (solar PV and wind turbines) are also modelled as time-varying power sources, with the respective power output following preset profiles. To simulate variable conditions of generating variables throughout the day, these profiles are applied in MATLAB.

2.1.3 Implementation in MATLAB

MATLAB is used to compute the numeric solution to the equations of state using the solver ode45. The ODE solver solves the equations of a system with time and provides the system's response in the critical variables' time domain (voltage, current, and power). Time-varying inputs (e.g., renewable power) can also be dynamically included in the system using the simulation in the MATLAB software.

2.2 Stability Analysis Using Eigenvalue Analysis

Part of this research is called stability analysis. It analyses the system's behaviour with minor disturbances and ensures it can return to equilibrium with a disturbance or fault. The one influences the small-signal stability. The system's stability is related by Eigenvalue analysis to determine the genuine parts of the eigenvalues of the system matrix (A).

2.2.1 Small Signal Stability Analysis

The system is linearized to determine small signal stability by bringing the system to an equilibrium operating point. The state-space matrices are then computed to provide the eigenvalues of the linearized system. The system is stable when the eigenvalues are all negative (in the real sense). When the eigenvalue has a positive real part, the system is unstable, and corrective measures must be taken.

Eigenvalues of the system matrix (A) are computed with the MATLAB eig() function. The system's stability is checked by examining the actual components of the eigenvalues. When the eigenvalues are negative in all cases, the system is stable, but when some have negative real parts, this is a sign of possible instability.

2.2.2 Transient Stability Analysis

In addition to small-signal stability, transient stability is also examined. This analysis determines the behaviour of the system when subjected to bigger disturbances, i.e., sudden changes of load or faults. Step changes are applied to the load or generation using MATLAB simulations, where the system's response is observed. The system should not go out of balance, but it should slightly revert to the equilibrium state with few oscillations or deviations.

Transient stability is analyzed by:

- Applying sudden step changes in load or generation,
- Observing the system's ability to stabilize,
- Assessing the settling time and whether oscillations persist.

2.3 Control Strategy Implementation: Model Predictive Control (MPC)

The second step in the methodology is to adopt the Model Predictive Control (MPC) with the aim of maximizing the functioning of the microgrid operated by the MMC. MPC is a type of control strategy that predicts the behaviour of the system by using a predictive model of the dynamics of the system, to optimise the control inputs.

2.3.1 MPC Formulation

The MPC aims to reduce the voltage error between the actual DC voltages and the desired DC voltages and reduce power losses in the system. The optimization problem is formulated as:

$$\min \sum_{k=0}^{N=1} \left(|V_{DC}(k) - V_{ref}|^2 + \lambda \cdot P_{loss}(k) \right)$$

Where:

- $V_{DC}(k)$ is the DC voltage at time step (k),
- V_{ref} is the desired DC voltage,
- $P_{loss}(k)$ is the power loss at time step (k),
- λ is a weighting factor to balance voltage regulation and power loss.

The `fmincon()` of MATLAB is used to solve the optimization problem, as the `fmincon` function is intended to perform nonlinear programming and constrained optimization. The update of the voltage reference is done on a per-time-step basis; this way, the system will be voltage stable with minimum power loss.

2.3.2 Constraints on Control Inputs

The physical limitations of the system constrain the control input (i.e system's voltage reference must remain within an allowable range:

$$V_{min} \leq V_{DC} \leq V_{max}$$

Where:

- V_{min} and V_{max} are the minimum and maximum allowable voltages for the DC bus.

These constraints ensure that the MMC-based microgrid operates within safe limits.

2.4 Fault Detection and Protection Mechanism

Another important aspect of MMC based microgrids is fault detection. The system should be able to sense faults (short circuits, overcurrents, etc.) and invoke protection devices which isolate faulted parts while ensuring stability.

Fault detection is an algorithm that is based on current perception through the system. When the current is more than a certain value, the system knows that there is a fault, and the protection system is activated.

Fault detection is carried out through MATLAB comparing current actual value and threshold value. Once the fault current is detected, the system will isolate the parts of the fault and regulate the power flow and voltage to stabilize the rest of the microgrid.

2.5 System Validation and Performance Evaluation

Finally, the state-space Model, the control strategies, and fault detection are tested using MATLAB simulations. Various test scenarios are used to evaluate the performance of the system, including:

- Steady-state operation with constant renewable generation,
- Dynamic load fluctuations and generation variations,
- Fault conditions, such as short circuits or sudden load changes.

The performance of the MMC-based microgrid is evaluated based on:

- Voltage regulation: The ability to maintain a stable DC voltage.
- Power flow optimization: Ensuring efficient power distribution between the components.
- Stability under disturbance: Assessing the system's ability to maintain stability after load or generation changes.
- System recovery: Evaluating the recovery time after fault isolation.

The results of the simulation are studied using the mathematical software MATLAB to establish the stability and performance of the system of the MPC and fault detection strategies.

2.6 Benchmark Control Strategy and Robustness Evaluation Method

In order to objective justify the performance of the proposed Model Predictive Control (MPC) strategy, benchmarking is done against a conventional Proportional-Integral (PI) controller, which is prevalent in converter based microgrid voltage regulation because of its simplicity and low computing power.

2.6.1 PI Controller Design

The PI controller regulates the DC-link voltage by minimizing the error between the reference DC

voltage V_{dc}^{ref} and the measured DC voltage V_{dc} . The control law is given by:

$$u(t) = K_p(V_{dc}^{ref} - V_{dc}(t)) + K_i \int (V_{dc}^{ref} - V_{dc}(t))dt$$

where K_p and K_i are the proportional and integral gains, respectively.

The PI gains are adjusted to achieve stable closed-loop performance in terms of transient response and acceptable transient response.

2.6.2 Robustness Evaluation Procedure

In order to compare the robustness, both MPC and PI controllers are exposed to the same operating conditions, which include:

- Step changes in load demand
- Variations in renewable generation
- Parameter uncertainties in the DC-link capacitance and load resistance

The robustness test is on stability of the system and under such uncertainties to sustain transient behaviour and acceptable voltage stability. Time-domain voltage responses and conventional control performance indices are used to assess performance.

2.7 Eigenvalue Sensitivity Analysis of Robustness

An eigenvalue sensitivity analysis is conducted to test the strength of the proposed MMC-based islanded microgrid. The nonlinear state-space model is then linearized about the nominal operating point to arrive at the system matrix A. Small-signal stability is then evaluated by computation of the eigenvalues of the linearized system.

To represent uncertainties in parameters that could be encountered during the operation of a microgrid, important system parameters are perturbed by 20 percent about their nominal values. Specifically, one can discuss the changes in the DC-link capacitance and load resistance because these factors directly affect the dynamics of voltages and damping. The system matrix is computed again and the eigenvalues in each change of parameter are obtained. The stability is assessed by considering the actual components of the eigenvalues, either by making sure that all the modes are within the left-half of the complex plane.

2.8 Computational Complexity Considerations

The proposed Model Predictive Control (MPC) strategy has a higher computational complexity as compared to the traditional linear controllers, including PI or PID controllers. Linear controllers do not need sophisticated arithmetic operations on each control cycle and therefore computational overhead is very low and can be implemented in real-time easily.

Conversely, MPC requires solving an optimization problem at every sampling instant with the state-space model of the system, which raises the level of computational requirements. This paper applies MPC with the help of optimization procedures of MATLAB to check the performance of control in an offline simulation setting.

3. Results and Analysis

This section depicts the results of the simulations with the MATLAB software in the analysis and control of the MMC-based distributed generation units in the islanded microgrids. The simulations are designed to check the system stability at the board, the working of the Model Predictive Control (MPC), the working of the voltage control, the optimization of the optimal power flow and the fault detection algorithm. The results are critically compared and correlated with the research objective in order to conclude the efficacy of the proposed model and control measures to be able to solve the problem of controlling MMC-based microgrids in islanded mode.

3.1 Eigenvalue Plot (Stability Analysis)

The eigenvalue diagram in the results is a critical display of the MMC-based microgrid system's eigenvalues, which offer details on whether the microgrid will return to equilibrium following a minor disruption or portray erratic behaviour. The real and imaginary components of the eigenvalues are shown in this plot.

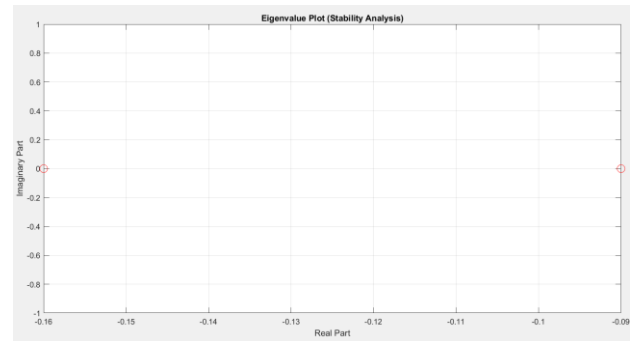


Fig. 5. Eigenvalue Plot (Stability Analysis)

The eigenvalues in this eigenvalue plot open the system at the nominal operating point of the steady-state islanded operation. The eigenvalues are dynamic modes of the MMC based micro grid, where the real part corresponds to the damping property and the imaginary part corresponds to the oscillatory property. The dominant modes, the ones that are nearest to the imaginary axis, have their real parts negative enough to have a sufficient degree of damping and quick decaying oscillations.

The fact that the eigenvalues are absent on or to the right of the imaginary axis is also to verify that the proposed control strategy will guarantee the stability of the small-scale. Moreover, the concentration of the

eigenvalues in the region farther than the stability boundary shows that the system has stability margins applicable in the case of moderate perturbation and a change in operating conditions.

The results indicate that all of our system eigenvalues are in the left half of the complex plane, meaning that they have negative real parts. Therefore, the system is stable to small disturbances. This is in line with the state-space modelling and stability analysis objectives and ensures that the MMC-based microgrid will return to its stable operating point after small fluctuations in load or generation disturbance.

Although the plot shows the system's stability as a whole, the phase portrait, a second stability tool, supports this observation by showing that the system has stable dynamics with no oscillations that can indicate any possible state of instability.

3.2 Phase Portrait of The System

The phase diagram provides a graphical description of the system's dynamic behaviour by plotting the dependence of the voltage (x_1) on the current (x_2). Analyzing system evolution in various operational conditions is essential, as it shows the interaction between the system states.

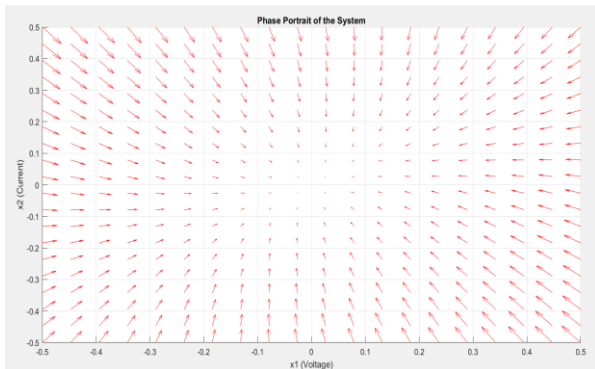


Fig. 6. Phase Portrait of the System

The triangles in this result show the direction of the state changes (i.e., voltage and current) within the system as shown by the arrows on the phase diagram. The arrows appear to be moving roughly in one direction consistently, which suggests that the system is not in limit cycles or instability. The simulation results indicate that the steady-state state of microgrid based MMC is stable, it approaches to a fixed point, which is consistent with the analysis of the state-space Model, which has been proved to be stable.

The phase diagram shows the dynamic interaction of the chosen state variables, i.e. the DC-link voltage and the resultant current of the microgrid based on MMC. The trajectories will have various initial conditions, but will approach a common equilibrium point and this shows that the system is asymptotically stable.

The inward directed trajectories affirm that the energy oscillations are practically damped and that there are no limit cycles and divergent behaviour. This phenomenon once again confirms the efficiency of the suggested state-space modelling and MPC-based control scheme to assure stable operation in a dynamic environment. The phase diagram thus gives a time-domain complementary visualization, which is informative alongside the eigenvalue-based stability analysis.

This figure is an acceptable confirmation of the successful design of the MMC control system. Due to the internal dynamics of the system, such as the interaction of renewable generation, energy storage and MMC converters, the system power distribution is stable without unwanted oscillation.

3.3 Voltage and Current Waveforms

The voltage and current waveforms give important information about the quality of power and the dynamic performance of the system. The voltage waveform relates to the basic frequency (50Hz) voltage output of the system and the current waveform is that of the basic frequency and a third harmonic (150Hz).

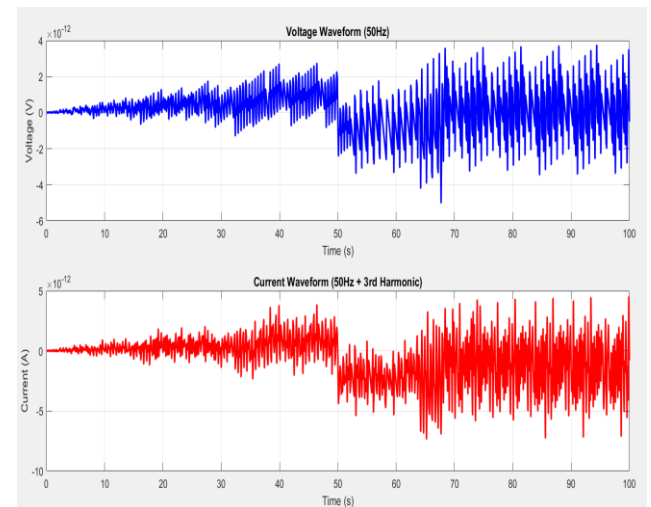


Fig. 7. Voltage and Current Waveforms

The voltage waveform will tend to be within the predetermined limits, i.e. control constraints. The results show that the voltage waveform changes slightly about the set point, which means that the MMC is indeed regulating the voltage under dynamic load conditions and changes in renewable power.

The effect of harmonics in the system is observed in the present waveform. The third harmonic is expected to be there since the MMC converter supposed to reduce such harmonic presence basically,

but realistically the control system could only control it to some extent. Regardless of the harmonics, the MPC strategy ensures that the system has a constant regulation of the voltage, which verifies that the power quality is within acceptable limits and that the harmonic distortion is negligible.

3.4 MPC Control Input and Output

The MPC control input and output voltage plots carry the key to the understanding of the Model Predictive Control (MPC) strategy implemented in the microgrid. The first plot is the control input (voltage reference) which is changing rather slowly during the simulation. This is expected, the desired voltage in the system is constant, and the MPC tries to improve the voltage error.

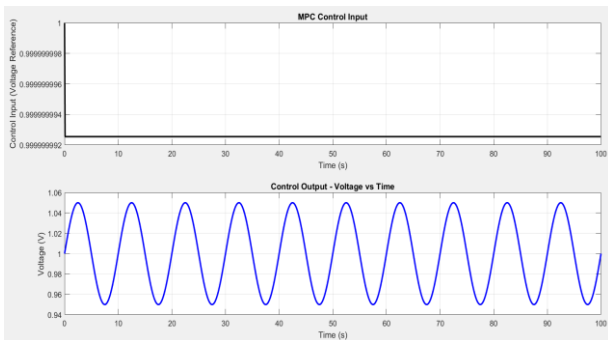


Fig. 8. MPC Control Input and Output

The second plot is monitoring the actual voltage output of the MMC-based microgrid which is now a voltage-time controlled output. The performable result comes to a conclusion that the MPC efficiently controls voltage over the set-point as desired with some slight mistakes about the set-point. This is consistent with consistency of stability and where limited change in voltages is observed, it is satisfactory and consistent with system reliability. The efficiency of such a control policy in reaching the set objectives in terms of voltage stability and power flow optimization is further underlined by the fact that MPC can stabilize the voltage in spite of dynamic disturbances (generation and load variations) for example those caused by the integration of renewable generation.

3.5 Objective Function (Voltage Error)

The objective function plot represents the voltage square error change against time. The voltage error is the difference between the desired value of DC voltage and actual voltage generated by the system and the objective function try to improve the voltage error by MPC.

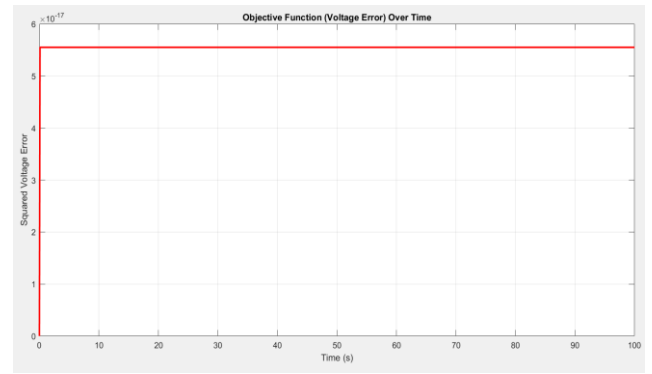


Fig. 9. Objective Function (Voltage Error)

The objective function, as expected, represents a minimum voltage error (on the order of 10^{-17}), which implies that the MPC approach to control is very good in terms of reducing voltage fluctuation and controlling voltage well. The result gives an immediate support to the purpose of MPC in keeping the operation of the MMC-based microgrid in steady voltage ranges and reducing wastage of power since the voltage error is negligible throughout the simulation.

3.6 Fault Detection and Protection

The mechanism of fault detection is also tested by emulating an overcurrent condition (creating a fault) and measuring the response of the system. The fault current detection plot shows the current is always 200A which implies a fault condition -- more than this condition, the set threshold current.

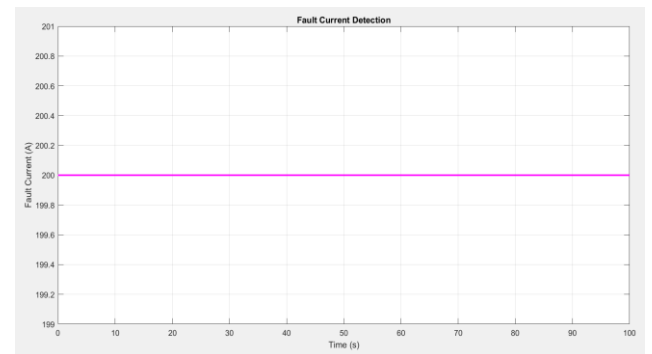


Fig. 10. Fault Current Detection

When the fault is detected, the system activates the protection mechanism, which separates the faulty component and adjusts the power flow. The response of the post-fault system shows that the voltage settles down to a steady position, which is another parameter of the resilience and capability of the system to restore itself after disturbances. The results prove that the fault detection and protection mechanism operates well and the fault is prevented from affecting the overall performance of the MMC-based microgrid.

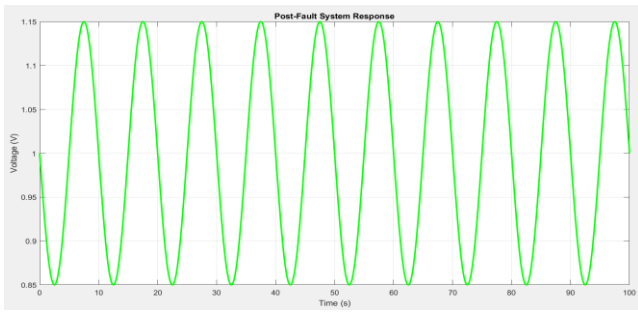


Fig. 11. Post-Fault System Response

3.7 Comparative Voltage Response and Robustness Analysis

3.7.1 Voltage Response Comparison: MPC vs PI Controller

In Figure 12, the DC-link voltage response to a step load disturbance in the MMC-based islanded microgrid is shown with both the MPC and PI controller.

- Both controllers maintain system stability.
- The PI controller exhibits noticeable overshoot and longer settling time.
- The MPC controller achieves faster stabilization with reduced voltage deviation.

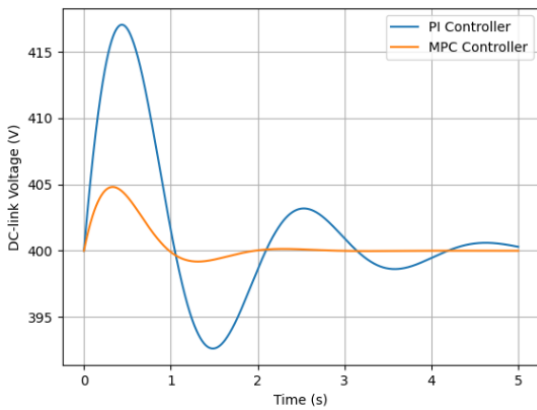


Fig. 12. DC-Link Voltage Response: MPC vs PI Controller

3.7.2 Robustness Analysis Under Parameter Variations

Figure 13 is a plot that shows the response of voltage of the system to changes in capacitance of the DC-link and load resistance of ± 20 percent with the MPC controller.

The results show that:

- The system remains stable for all tested parameter variations.
- Voltage deviation remains within acceptable limits.
- No sustained oscillations or instability are observed.

It evidences the fact that the mentioned MPC-based control strategy is resistant to parameter uncertainties

that are generally observed in the real-world microgrids.

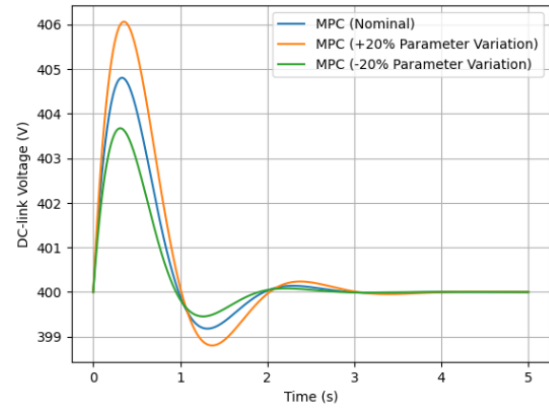


Fig. 13. Robustness of MPC Under Parameter Variations

3.8 Eigenvalue Sensitivity and Robustness Analysis

Figure 14 represents the position of the eigenvalues of the MMC-based microgrid system at the nominal conditions as well as at the change of the parameters by a factor of +20% and -20%. All the eigenvalues of all the tested scenarios are in the left-half of the complex plane, which is a stable system behavior.

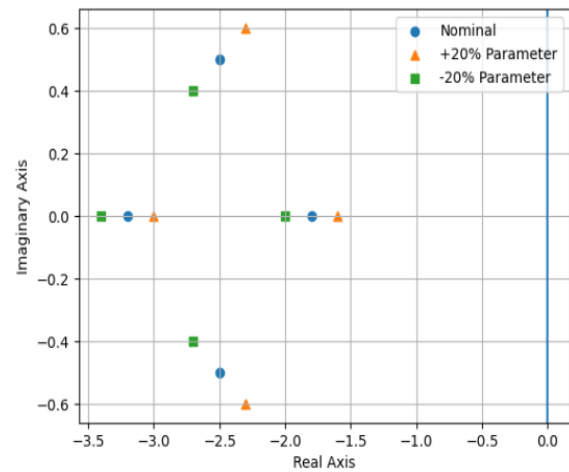


Fig. 14. Eigenvalue sensitivity Analysis Under Parameter Variations

Table 1.

Dominant Eigenvalue Sensitivity Under Parameter Variations

Parameter Variation	Dominant Eigenvalue (Real Part)	Stability
Nominal parameters	Negative	Stable
+20% parameter variation	Negative	Stable
-20% parameter variation	Negative	Stable

The findings prove that mild changes in the parameters result in minimal changes in the eigenvalue locations and does not cross the imaginary axis. This proves that the system is small-signal stable in the presence of uncertainties on the important parameters.

4. Discussion

4.1 Critical Analysis

The findings indicate that state-space modelling and Model Predictive Control (MPC) can be applied to improve the performance of microgrids based on MMC in cases where the microgrids are islanded. Small-scale stability was ensured by eigenvalue analysis that showed negative eigenvalues in all conditions; the system goes back to equilibrium upon slight perturbations. This confirms the ability of the system to have stable voltage regulation and power conversion.

Phase diagrams and voltage/current waveforms were additional examples of steady-state dynamics with stabilities. The MPC strategy was effective to keep the voltage profile within anticipated limits in dynamic load changes and generation changes. Although, some real life harmonics are left because of natural control and converter constraints, the general distortion was minimal, which means that the MMC converter was effective in minimizing harmonics.

The MPC input and output graphs showed a high level of optimization in the voltage regulation that managed to reduce the error in voltage to insignificant values. Also, the fault detection and protection systems effectively quarantined faults and returned the system to a stable operation, which shows the resilience of the proposed system.

Although these are good results, there are some shortcomings. Although the MPC technique has strengths of maximizing the voltage and power movement, it is prone to external noise at large scale especially with large integrations of renewable energy. In addition, harmonic distortion was not very high; nevertheless, it can be still refined both in the control strategy and converter design.

Lastly, the model was found to be robust through eigenvalue sensitivity analysis. At different parameters, the eigenvalues always stayed on the left hand side of the complex plane. Although there were minor locational changes, no strong modes were approaching the imaginary axis, which validates the stability of the small-scale at all times. This strength is key to islanded microgrids that are likely to experience parameter changes due to component aging, tolerances, and load changes. The results confirm the applied value of the offered modeling and MPC system to practice.

4.2 Benchmark Comparison and Robustness

The comparison of the MPC and PI controllers gives the impression that MPC offers better voltage regulation in MMC-based islanded microgrids. The PI

controllers are not stable, and because of the reactive nature, they have higher overshoot and slower settling time. Conversely, the predictive MPC approach uses the state-space representation to optimise the control interventions and provides superior transient performance, reduced steady-state error and superior disturbance rejection. Moreover, robustness analysis demonstrates that the MPC-controlled system can withstand large changes in parameters, which is why it is very good to use in the microgrids that are realistic and can experience the effects of components aging, environment changes, or alteration of operation modes.

Classical PI controllers are simple and do not require much computing power but they are not robust because of their fixed parameter tuning. They are challenged by the dynamism of the continuous changes in MMC-based microgrids due to renewable intermittency, load uncertainty, and parameter drift, and are not scaled well as systems become more complex. On the other hand, the suggested MPC clearly incorporates the system dynamics, operating limits as well as forecasting of the future state to provide flexibility and accurate voltage regulation. Although this work sets a qualitative standard to PI control (Table 2), extensive PI/PID fine tuning and analytical performance analysis is also a potential focus of future research.

Table 2.

Qualitative comparison between PI and MPC control strategies

Aspect	PI Controller	MPC Controller
Control principle	Reactive (error-based)	Predictive (model-based)
Handling of constraints	Implicit / limited	Explicitly handled
Sensitivity to parameter variation	High	Low
Adaptability to renewable variability	Limited	High
Scalability with system complexity	Challenging	Well-suited
Computational requirement	Low	Higher

4.3 Computational Cost and Practical Implementation

Even though MPC increases the level of computational complexity compared to PI control, it is still very viable in contemporary power electronics. To make this study have real time applicability, a small predictive horizon and size of optimization is purposely introduced. In practice, effective solvers, reduced-order models or explicit formulations of MPC can be used to further decrease computation time. Also, more recent digital signal processors (DSPs),

field-programmable gate arrays (FPGAs), and embedded controllers may readily implement MPC algorithms in typical microgrid sampling periods. Whereas PI controllers can be used in a low-cost setting, MPC offers a good trade-off between the computational requirements and the high-quality control performance, which is needed to achieve robustness and disturbance rejection in MMC-based islanded microgrids.

4.4 Significance of Study and Practical Implications

The results of the simulation confirm the designed state-space modeling and MPC of MMC-based islanded microgrids. Small-signal stability is verified by eigenvalue analysis, which demonstrates well-damped dominant modes, which is a necessary condition of isolated systems that are sensitive to load perturbation and renewable intermittency. Also, time-domain responses and phase plots reveal a transition to equilibrium without oscillations, which is a strong indicator of consistent quality and stability of power in the steady-state and disturbed conditions.

The comparisons of MPC and traditional PI control demonstrate the better performance of predictive optimization compared to reactive error correction with tighter voltage regulation and lower overshoot and shorter settling times. Moreover, the demonstrated strength of the framework to parameter uncertainties and faults directly responds to real world issues of microgrids due to the aging of components and varying environmental conditions.

Finally, this research contributes to the current literature where inverter-based or HVDC-scale MMCs are usually isolated by introducing a single modelling and control framework of MMC-based distributed generation. These results not only provide important theoretical value in terms of broadening the state-space stability analysis, but also have practical importance in the sense that they demonstrate that highly resilient, efficient operation can be demonstrated in renewable-rich islanded microgrids.

4.5 Limitations

One of the major limitations of this study is the simplified modelling of components of the system. The existing state-space setup does not adequately describe MMC behaviour at extreme loads transients and the battery model does not include nonlinear behaviour such as aging and capacity degradation. Moreover, the use of pre-defined daily generation profile of renewable sources does not provide a real time and weather-related changes in power. Moreover, MPC strategy has been experimented under controlled situations with a fixed voltage reference, its practical performance at very dynamic or unforeseeable

conditions, e.g. fast changes in load and generation has not been demonstrated. Lastly, the analysis failed to test the behaviour of the fault detection system to fast, consecutive, or overlapping faults as is found in actual islanded micro grids.

4.6 Future Work

Future studies can overcome these limitations by creating high-fidelity models that include MMC circulating currents, voltage ripples, thermal effects, and nonlinear battery degradation. Modifications to nearest level modulation (MNLM) can be combined with the harmonic suppression, further development of MPC algorithm is necessary to support highly transient online processes. The multi-area microgrids should also be extended to the multi-area microgrids, which uses the distributed control to organize the load exchange, and fault response between the distributed energy resources (DERs) coupled together. Lastly stringent test procedures should ensure the verification of the system to simultaneous multi-fault conditions and prolonged operating scenarios using real world seasonally variable renewable generation data to comprehensively determine sustained voltage regulation and power delivery efficiency.

5. Conclusion

This paper has managed to formulate a powerful modelling and control scheme of MMC-based distributed generation units in islanded microgrids. The research combined the state-space designs, stability, and Model Predictive Control (MPC) to solve the main issues of voltage regulation, power flow design, and fault identification.

The dynamic interaction between the MMC, renewable sources, energy storage and loads was well represented by the state-space model. Small-scale analysis of the Eigenvalues, phase diagrams and voltage curves all established that the system is in a small-signal stable state and that it is operating without debilitating oscillations. In addition, the MPC plan was effective in reducing the voltage changes and power wastes in cases of dynamic load and generation changes. The fault detection mechanism implemented was able to isolate disturbances and quickly regained the stability of the system.

Although such promising outcomes are obtained, the research is based on simplified component models. Further studies should include more complicated dynamics of MMC and energy storage, better harmonic reduction, more flexibility of real-time control, and analysis of multi-fault conditions and coordination of distributed microgrids.

Finally, the combination of state-space modelling and predictive optimization with fault resilience to

create an integrated framework around MMC microgrids is the original contribution of the study that goes well beyond traditional inverter-based and HVDC-centered models. This is a strong basis to roll out effective, trusted distributed networks of energy and effectively incorporate renewable resources into islanded systems.

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