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Enhanced Model Predictive Control for V2G Enabled Grid Using Z-Source Inverters: A Comparative Analysis with ANN Integration for EV Application

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Abstract*— The paper postulates a new approach in energy management through 'Vehicle-to-Grid' in the context of the micro-grid where the Electric Vehicle battery acts as storage for both storing and supplying energy from a DC fast charger architecture. This system allows a bi-direction flow of energy between the Grid and the Vehicle for active power stability management in the context of energy demand management in the micro-grid setting. A Model Predictive Control strategy incorporated with Artificial Neural Network enhances responsiveness, stability, and the power quality of the system by reducing harmonic distortion in the grid-injected current. Simulation results have been quite robust in dynamic performances that signify the possibility of increasing micro-grid resilience and V2G-enabled grid-connected EV systems.

Index Terms*— Model Predictive Control, Z-Source Inverter, Electric Vehicle Systems, Artificial Neural Network, Variable Cut-Off.

I. INTRODUCTION

Electric Vehicles Transitioning into Electric Vehicles seems to be an exciting move toward sustainable energy with EVs holding promise for using their batteries for effective energy storage. When plugged into charging stations, EVs can self-recharge while feeding power back into the grid to participate in energy management in micro-grids. V2G technology is a very useful solution, which can enable power flow in both directions and charge during low demand and discharge during peak demand. Integration with renewable energy sources is possible to achieve peak shaving, voltage regulation, and energy stability in micro-grids.

This paper examines a DC fast charging station model for V2G within a micro-grid, using off-board chargers and grid-connected inverters for seamless power exchange. This implies that with the proposed MPC strategy aimed at optimizing dynamic performance and reducing disruptions in the power grid, the approach will be improved with an ANN. This study focuses on finding a balance in achieving effective voltage stability along with the regulation of the active power through the MPC-ANN integration towards improved energy efficiency and stability within grid-connected EV systems.

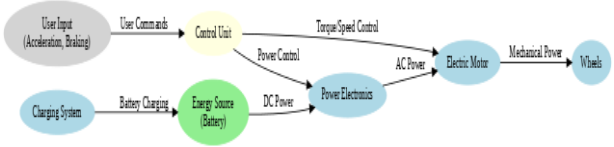


Figure 1. Basic EV System Elements

This figure presents the elements and operation of a basic EV system.

On the other hand, the efficiency of EV systems is influenced by the power management and control systems. Variations in load demands, state of charge of the battery, and interactions with the grid may affect the stability and efficiency of EV operations, and therefore sophisticated control strategies are required. Quick response to changes in load demands and ability to stabilize the voltage and current outputs of power management are crucial to optimizing EV performance under varying operating conditions.

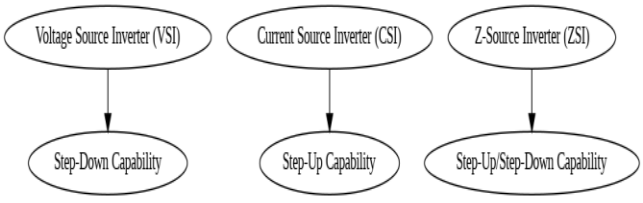


Figure 2. Comparison of Inverters This Figure compares the characteristics and functionalities of different types of inverters, including VSIs, CSIs, and ZSIs.

Two categories of inverters are largely used in a conventional EV system: VSIs and CSIs. In the case of VSIs, the DC is stepped down from the batteries and is converted into an AC power suitable for the EV motor. On the contrary, CSIs can only step up the voltage and therefore are not very flexible for applications in EV systems that require both step-up and step-down functions. ZSIs have been developed to overcome this limitation, with the ability to perform

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step-up and step-down functions through an impedance network called Z-network placed between the DC source and the inverter circuit. This functionality makes ZSIs highly suited for EVs, whose load requirements may vary a lot during driving and charging.

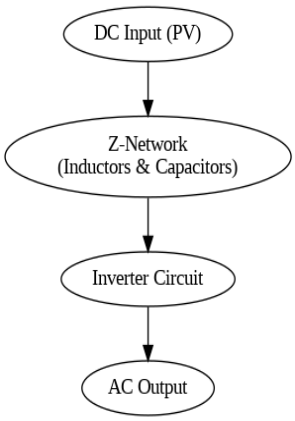


Figure 3. Z-Source Inverter Circuit This Figure presents the circuit configuration of a Z-Source Inverter.

This feature of handling variable voltage conditions makes ZSIs an ideal candidate for EV applications where voltage and current requirements can vary with motor load and battery charge levels. Therefore, ZSIs seem to be a promising solution for the integration of renewable energy sources and grid interactions in EV systems, with enhanced power management and efficiency.

A. Problem Statement

Electric Vehicles (EVs) are gradually turning into plausible energy storage resources for micro-grids, primarily because technologies like V2G and G2V now permit bi-directional power flows. However, the adaptability and responsiveness that are employed in regulating the power dynamics of this micro-grid with fluctuating power demands are not found in traditional methods especially when they integrate them with renewable energy sources. Also, contemporary systems have issues with problems like harmonic distortion and mere inability to deal with fast changes in load and grid demand during voltage stabilization. Advanced control strategies should be utilized to efficiently and stably manage energy in micro-grids with DC fast charging stations for electric vehicles.

B. Motivation

The opportunity of using EVs as grid support systems lies in the balance, they can offer in dynamic energy supply and demand. Properly stored excess energy, when released during peak demand, helps provide a flexible, reliable, and sustainable power infrastructure. However, to achieve this vision, it requires an advanced control system capable of harmonious operation in the variation conditions of the grid. There is a very promising capability inherent in the combination of ANN and MPC that has been and will lead to the robust and adaptive solution by learning response to dynamic conditions that minimize harmonic distortion and enhance grid stability and power quality.

ZSIs have a dual voltage-control functionality. Their advantages in handling integration and interactions between battery management and grid interactions in the electric vehicles are unique. Advances of hybrid ANN-MPC algorithms enhance high-performance ZSI operating under a dynamic environment of handling nonlinear changes in power electronic circuits. In contrast, this hybrid approach should further increase the adaptability of the control system without reducing its stability or at least its response time but by reducing energy consumption only by that margin. This research develops a control system that can manage the power of an electric vehicle intelligently under fluctuating load demands. As such, it will enhance reliable energy output and the robustness of the system.

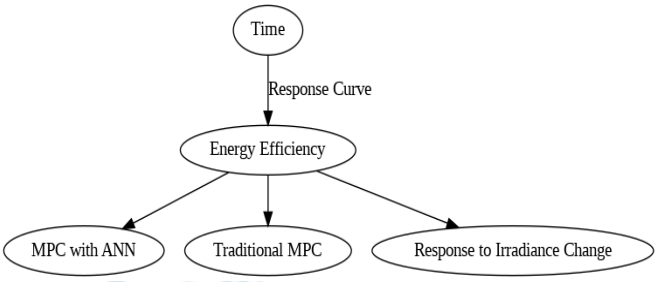


Figure 4. System Response This Figure depicts the expected system response of the proposed control strategy under dynamic conditions.

C. Objectives

- Developing Adaptive MPC-based control system-An advanced MPC system with ANN integration for micro-grids for controlling bidirectional power flow within the micro-grid with optimal responsiveness and minimum losses.
- Reduce Harmonic Distortion-The proposals of the work try to maintain good quality of power by making efforts to reduce harmonic distortion and oscillation at the grid-injected currents in any of the rapid load change scenarios.
- Improve Stability and Efficiency: Determine the stability in voltage and current outputs of the EV charging station under shifting grid conditions so that the reliability of V2G/G2V would be improved.
- Feasibility Demonstration Through Simulation: Simulations shall be used in establishing the viability of the proposed system so that the performance would be compared with traditional MPC when ANN-based MPC is implemented in handling the dynamic load variations.

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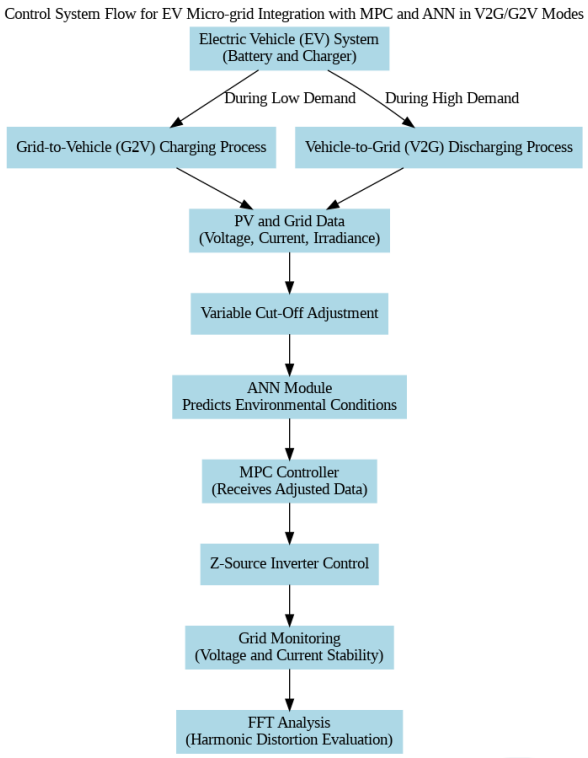


Figure 5. Ev_Control_System_Flowchart

II. RELATED WORKS

Chincholkar et al. discussed the overview of PV control systems in regard to advancements in inverters. It primarily lay emphasis on shifting from conventional to innovative solutions, their efficiency as well as integration with renewable energy as well as underlined the role of inverter technology across diverse environmental conditions [1].

Dhaked et al. (2022) present the MPPT technique, including P&O, Incremental Conductance, and ANN-based methods. They state its merits and demerits with a high recommendation for improved algorithms that enhance the efficiency of tracking, particularly at variable solar irradiance [2].

Guisso et al. (2019) reviews the applications of MPC for PV systems, which, they report, have its merits and demerits in comparison to ZSIs. They also reported that a good control strategy is needed to overcome MPC in the presence of rapid changes in environmental conditions [3].

Irfan et al. (2021) describes the applications of ANN in control systems for nonlinear applications. They describe how ANNs can learn to adapt themselves to various conditions enhancing efficiency besides stability in complex PV setups [4].

Al Essawy et al. (2021) introduce a grid-connected PV system that adopts a ZSI for the maximum power extraction. There, they mention some merits of a ZSI that include step-up and step-down capabilities with effective strategies in control for increased energy extraction [5].

Jamal et al. (2022) developed an overview of the grid-connected PV system using an impedance source inverter, which improves the quality of supply with the control of fluctuation from renewable energy sources [6].

Ahmed et al. (2007) focus on three-phase inverter design for a distributed generation and emphasize the need to eliminate harmonic distortion in order to maintain power quality with steady state inverter operation [7].

Kalaiarasi et al. (2023) identify some ZSI configurations for PV systems with the support of AI-based MPPT methods. They found that AI supports the dynamic condition-based energy extraction efficiency to be a reasonable amount [8].

de Oliveira-Assis et al. (2020) have discussed a quasi-ZSI-based large-scale PV power plant. They also reported that large-scale quasi-ZSI-based PV power plants may provide a possibility of achieving more energy conversion efficiency by incorporating more sophisticated control techniques [9].

Wang et al. (2021) discussed a fast charging station's influence on a grid for electric vehicles with the urgency of effective integration of renewable energy to address the increasing demand for charging [10].

Chuang and Hong (2019) analyzed ZSI control in PV using active disturbance rejection technology for better stability and performance under non-ideal operation conditions [11].

Elmorshedy et al. (2023) discuss the grid-connected PV system having a quasi-ZSI with maximum power extraction, mentioning that this method has provided good performance using advanced control algorithms [12].

III. PROPOSED SYSTEM

System Architecture

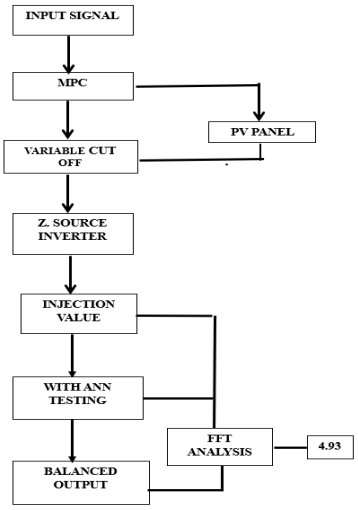


Figure 7. proposed model

A. PV System with Z-Source Inverters (ZSIs):

- **Overview of Z-Source Inverter**: The Z-Source Inverter (ZSI) is a type of power inverter specially designed to handle variable input voltages, ideal for

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photovoltaic (PV) applications where solar irradiance can fluctuate significantly. Unlike traditional Voltage Source Inverters (VSIs) and Current Source Inverters (CSIs), which can only step up or down the voltage, ZSIs provide both step-up and step-down voltage conversion using an impedance network (Z-network). This flexibility is achieved by utilizing a unique topology with two inductors and capacitors arranged in an X-configuration between the DC source (PV array) and the inverter switches, as shown in Figure 3

- **Advantages of ZSIs for PV Systems**: The ZSI enables single-stage power conversion, which simplifies the system architecture and improves efficiency. ZSIs are well-suited to handle PV modules' variable voltage output by supporting a wide range of input voltages, making it ideal for direct grid connection applications where fluctuations in irradiance require adaptive control
- **Operation and Control**: ZSIs operate with shoot-through states (where switches in one inverter leg are ON simultaneously), allowing voltage boosting without additional converter stages. This capability is critical for maintaining the Maximum Power Point (MPP) of the PV system across different irradiance conditions, thus ensuring optimal energy capture and efficiency in power conversion as shown in Figure 7.

B. Model Predictive Control (MPC) Algorithm Integrated with Variable Cut-Off Technology:

- **MPC Overview**: Model Predictive Control (MPC) is a control strategy that uses a system's predictive model to optimize its performance. In PV systems, MPC is used to maintain the inverter's output within optimal limits by anticipating changes in irradiance and adjusting the inverter's control inputs. This predictive nature helps to maintain stability and efficiency, especially when irradiance levels change rapidly.
- **Implementation of Variable Cut-Off Technique in MPC**: The Variable Cut-Off technique enhances the MPC by dynamically adjusting the prediction horizon, which is the duration over which future states are predicted and optimized. This dynamic horizon adapts to real-time environmental conditions—such as fluctuations in irradiance—by shortening or lengthening as needed to avoid delays in response and reduce system oscillations. In highly variable conditions, a shorter prediction horizon improves response time, while in more stable conditions, a longer horizon conserves computational resources as shown in Figure 7.
- **Advantages of Variable Cut-Off in MPC for PV Applications**: By dynamically modifying the prediction horizon, the Variable Cut-Off technique mitigates the response time lag typically encountered in traditional MPC implementations. This leads to faster tracking of the MPP and improved stability under rapid changes in solar irradiance, resulting in reduced harmonic distortion and minimized oscillations at the inverter output. This enhancement is particularly beneficial in grid-connected PV systems where power quality and response time are crucial as shown in Figure 7.

C. Adaptation of MPC to ANN Module:

Role of ANN in PV System Control: An Artificial Neural Network (ANN) module is integrated with the MPC to provide adaptive and non-linear predictive capabilities. ANN's role is to learn from historical data on irradiance and load variations, enabling the system to predict future environmental conditions and adjust MPC parameters accordingly. This hybrid approach allows for real-time adjustments to MPP tracking based on irradiance and load conditions, making the system more resilient and responsive to environmental changes as shown in Figure 7.

Integration Process: The ANN is connected as a pre-processor to the MPC, feeding predictions of future irradiance and load conditions into the MPC's model. This input allows MPC to adjust its predictions, thus fine-tuning the control signals it sends to the ZSI. By proactively adjusting these parameters, the ANN-enhanced MPC system reduces tracking errors and enhances system stability.

Flow Diagram of Integrated MPC+ANN Control System: As depicted in the flow diagram as shown in Figure 7, the control system starts with input signals from the PV panel (voltage, current, and irradiance data). These signals are fed into the Variable Cut-Off, where prediction horizons are adjusted based on current environmental conditions. The ANN module provides additional predictive data to the MPC, which processes the signals and sends control commands to the ZSI. The outputs are monitored to verify system stability and balanced grid injection. With FFT analysis, the system minimizes harmonic distortion, maintaining power quality within acceptable limits and ensuring seamless integration with the grid.

This detailed architecture highlights the integration of MPC with Variable Cut-Off and ANN modules, creating a robust and adaptive control strategy for grid-connected PV systems. The combined approach optimizes energy capture, maintains system stability, and ensures power quality, making it an ideal solution for dynamic PV applications.

IV. METHODOLOGY

A. Data Collection and Initialization

- **Data Collection**:

Collect PV panel data, including voltage (V_PV), current (I_PV), and irradiance levels across varying conditions (simulated and experimental). This data is crucial for initializing the Z-Source Inverter (ZSI) and for training the ANN module.

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- **Initialization of Z-Source Inverter Parameters:**

Initialize ZSI parameters according to grid and PV specifications from the **Survey Main**. Include Z-network values like inductances and capacitances based on grid requirements to achieve impedance matching, essential for optimal power transfer to the grid.

B. MPC Algorithm with ANN Integration

- **MPC Equations for ZSI Control:**

MPC predicts the future states of PV output, enabling real-time control based on desired grid power output. The discrete-time model of the ZSI for MPC is defined as:

$x(k+1) = A \cdot x(k) + B \cdot u(k)$

where x(k) represents the state vector (e.g., PV voltage and current), and u(k) is the control input, typically the duty cycle for the inverter switches.

- **Integration of ANN with MPC:**
  - ANN is integrated as a module that learns from historical data on irradiance and load. Its role is to predict future irradiance conditions, feeding this prediction into the MPC to preemptively adjust ZSI parameters for optimal response. ANN thus dynamically modifies MPC parameters, improving adaptability under variable irradiance conditions.

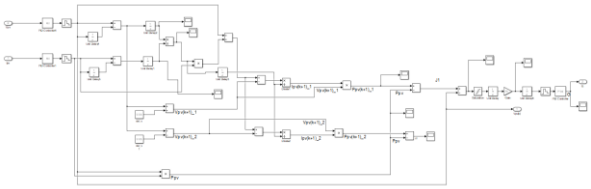


Figure 9. showing ANN and MPC flow

In the Figure 9 highlighting the data exchange pathways (PV data input → ANN prediction → MPC adjustment → ZSI).

C. Variable Cut-Off Technique

- **Enhancement of MPC Response:**

The Variable Cut-Off dynamically alters MPC's predictive horizon based on environmental feedback. This horizon adjustment optimizes response speed: a shorter horizon for rapid irradiance changes and a longer one for stable conditions, reducing oscillations and tracking errors.

- **Calculation of Variable Cut-Off:**

The cut-off is computed by evaluating the rate of change in irradiance *dI/dt*. If *dI/dt* exceeds a threshold, the horizon H is shortened:

$H = H_{min} + k \cdot dI/dt$

where H_{min} is the minimum horizon and k a tuning constant based on empirical data from.

D. Implementation and Simulation in MATLAB/Simulink

- **Algorithm Implementation:**

Step-by-step implementation of the MPC+ANN control algorithm in MATLAB/Simulink. Code each component (data input, ANN, MPC, ZSI control) as outlined in the survey.

- **Simulation Conditions:**

Simulate under varying irradiance, with conditions of 1250 W/m² and a transition to 750 W/m². **Compare MPC-only and MPC+ANN** performance to demonstrate improvements in response time and tracking efficiency.

V. STATEMENT OF CONTRIBUTIONS

- **Development of Combined MPC+ANN Strategy**: Novel integration of ANN and MPC to adjust MPC parameters based on predictive irradiance conditions, enhancing MPP tracking and system resilience.
- **Variable Cut-Off Technique**: Implementation of a dynamic cut-off in MPC to improve real-time adaptability, crucial for managing rapid irradiance shifts.
- **Reduced Harmonic Distortion and Improved MPPT Tracking**: Validation through simulations and experimental results showing that ANN-enhanced MPC reduces oscillations and harmonics, enhancing grid compatibility.

VI. RESULTS AND DISCUSSION

This section presents the simulation and experimental results of the proposed MPC+ANN control strategy under varying environmental conditions. Figures and tables illustrate key performance metrics, comparing traditional MPC control with the ANN-enhanced MPC.

A. Simulation Analysis

1. System Response under Different Conditions:

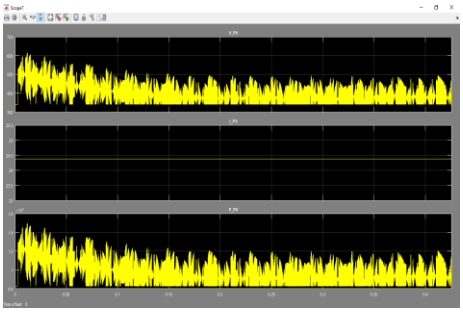


Figure 10. Graph For V_PV, I_PV, P_PV For Irradiance 1250 W/M2

This Figure 10. displays the PV output parameters—voltage (V_PV), current (I_PV), and power (P_PV)—at a stable irradiance level of 1250 W/m². The graph demonstrates the system's ability to track the Maximum Power Point (MPP) under ideal conditions with minimal oscillations, showing the stability of the control system in maximizing energy capture without significant

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fluctuations in V_PV, I_PV, or P_PV.

2. Comparison of Output Performance (MPC-only vs. ANN-Enhanced MPC):

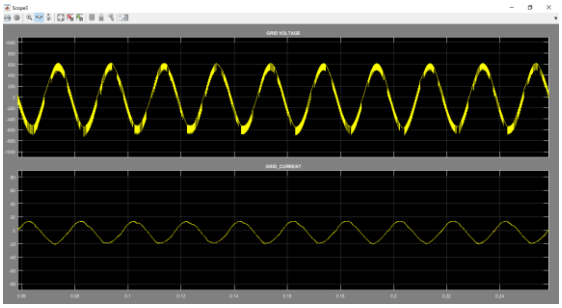


Figure 11. Grid Voltage and Current

This Figure 11. provides the grid voltage and current waveform when using traditional MPC without ANN support. During changes in irradiance, the Figure reveals fluctuations in the current waveform, reflecting the limitations of MPC-only control in handling dynamic conditions effectively.

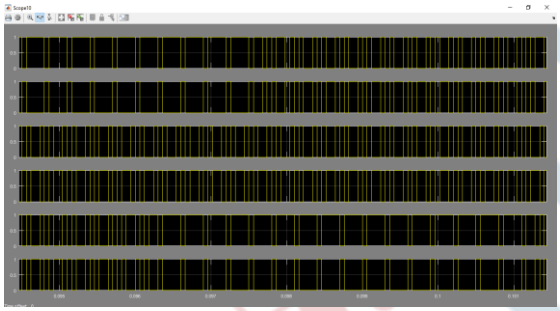


Figure 12. PULSES

This Figure 12. illustrates the pulse signals in the Z-Source Inverter (ZSI) under MPC-only control, showcasing the switching behavior as the inverter attempts to maintain MPP tracking without ANN support. The pulse response shows delay-induced oscillations, which affect efficiency during rapid irradiance changes.

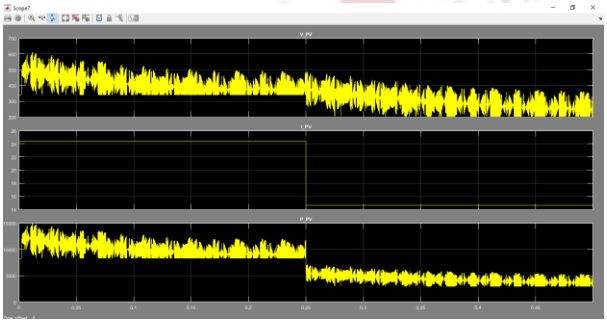


Figure 13. Changing Irradiance From 1250w/M2 To 750 W/M2

This Figure 13. compares the response of V_PV and I_PV as irradiance changes from 1250 W/m² to 750 W/m², highlighting the differences between MPC-only and ANN-enhanced MPC control. The ANN-enhanced system shows a smoother transition with fewer oscillations, enabling quicker adaptation to changing irradiance, which improves tracking accuracy and efficiency.

3. FFT Analysis for Grid Current:

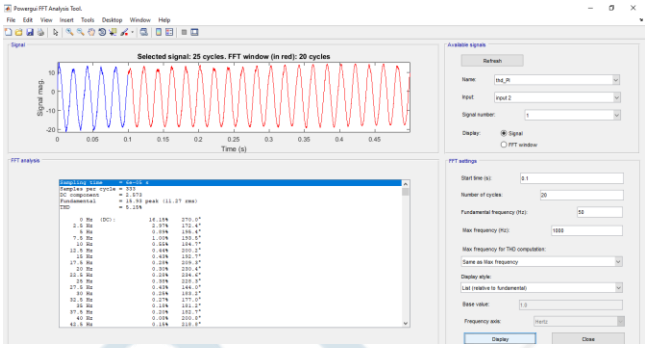


Figure 14. FFT for Grid Current

FFT analysis in this Figure 14 compares the Total Harmonic Distortion (THD) of the grid current for MPC-only versus ANN-enhanced MPC. ANN integration shows a notable reduction in THD, indicating improved power quality. Lower harmonic distortion supports grid stability and reduces stress on the inverter, which is crucial for longevity in grid-connected PV systems.

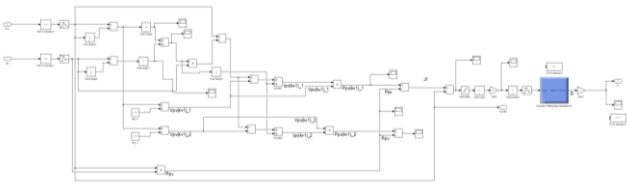


Figure 15. Inside MPC

The experimental setup, illustrated in Figure 15, consists of a PV simulator, Z-Source Inverter (ZSI), grid connection, and data acquisition tools, allowing real-time monitoring of PV voltage (V_PV), PV current (I_PV), grid voltage, and current under varied irradiance conditions. This configuration effectively simulates real-world scenarios to test the robustness of the MPC+ANN control strategy.

B. FFT and Harmonic Distortion Analysis:

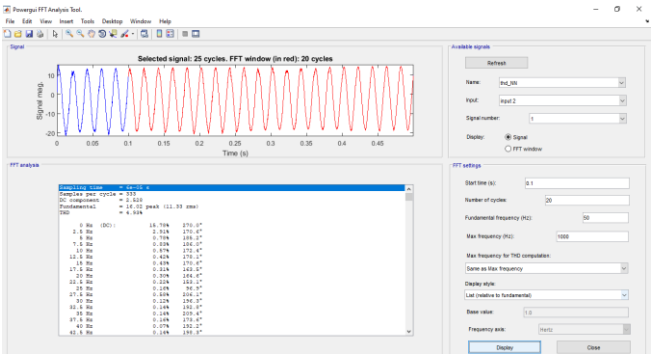


Figure 16. FFT Window

Figure 17 shows FFT analysis, revealing a reduction in

Total Harmonic Distortion (THD) with ANN-enhanced MPC versus traditional MPC-only control. The ANN module enables fast adjustments that mitigate harmonic distortion during abrupt irradiance changes. These THD reductions improve power quality, supporting grid standards compliance and enhancing system reliability.

C. Performance Metrics for ANN-Based MPC for EV

The key performance metrics of reduced oscillations and system stability validate that ANN-enhanced MPC is really capable of managing the power dynamics of the EV. HIL testing reveals that the integration capability of ANN into the MPC has made the control system much more responsive and stable in comparison to the pure MPC. The ANN also makes for real-time adjustments resulting in swift response times along with power stability to major improvements, especially for the load conditions that are fast-changing. The new MPC system allows for a smoother transition and faster convergence to the optimal power points with stability in case of fluctuations in demand. Besides, the Variable Cut-Off technique improves the adaptability of the control system, reduces the response delay in case of sudden changes in load, thus reducing energy losses and increasing efficiency. But at the same time, certain challenges do exist, which include having a large training data in order to get optimal ANN performance and more computing demands. This should then be kept in balance for achieving real-time responsiveness requirements of the system.

VII. CONCLUSION

This paper proves the feasibility of the integration of EVs within the micro-grid setting while operating on a DC fast charging station for V2G and G2V power flows. With this application of MPC strategy along with an ANN, there is an evident improvement in the power quality and responsiveness of the overall system. Simulation results indicate that the proposed architecture improves not only active power regulation but also maintains grid stability through dynamic adjustments of power demand. The future direction of research on the topic is focused on developing comprehensive ANN training techniques in order to improve adaptability toward different load profiles and micro-grid environments to realize wide applications in renewable integrated micro-grids. This approach opens up the path to efficient, responsive EV energy storage solutions within micro-grid systems and puts EVs at the center of managing grid energy and integrating renewables.

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