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Improving LVRT Capability in Grid-Connected PV System Using DRL-Based Controller

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ABSTRACT: This project addresses the challenge of maintaining grid stability in photovoltaic (PV) systems during voltage disturbances caused by grid faults. Low Voltage Ride Through (LVRT) requirements ensure that PV inverters remain connected to the grid and support voltage recovery, but conventional controllers with fixed parameters often struggle to perform effectively under severe and dynamic voltage sag conditions. To overcome these limitations, a Deep Reinforcement Learning (DRL) based control strategy is proposed for grid-connected PV inverters. The controller continuously monitors real-time grid conditions such as voltage variations and current limits, and dynamically regulates active and reactive power output. Through learning-based decision making, the system adapts to different fault scenarios without relying on detailed mathematical models, improving flexibility and performance. Simulation studies conducted under various voltage sag levels demonstrate that the DRL-based controller enhances LVRT capability, reduces inverter stress, and accelerates post-fault voltage recovery. Overall, the proposed approach improves grid support, robustness, and reliability, making it a promising solution for smart grids with high renewable energy penetration.

Keywords-Photovoltaic systems, Low Voltage Ride Through, Deep Reinforcement Learning, Grid connected inverter, Smart grid.

1. Introduction

The rapid growth of renewable energy has transformed modern power systems, with photovoltaic (PV) generation becoming widely adopted due to its sustainability, scalability, and declining costs. However, higher PV penetration introduces challenges for grid operators, including voltage regulation, power quality, and system stability during disturbances such as faults, switching events, To address this, grid codes mandate Low Voltage Ride Through (LVRT), requiring PV systems to stay connected and support the grid during short-term voltage sags. LVRT helps prevent cascading failures and large-scale blackouts by ensuring inverters inject reactive current, limit fault currents, and aid voltage recovery while maintaining protection constraints. Achieving these objectives is challenging due to the nonlinear and time-varying nature of power systems. Conventional controllers, like PI or rule-based methods, are limited to nominal conditions and may perform poorly under severe or unexpected faults, leading to slow voltage recovery, excessive current stress, or grid code violations. Recent advances in artificial intelligence, particularly Deep Reinforcement Learning (DRL), offer intelligent solutions for PV control. DRL learns optimal control policies through interaction with the system, adapting to real-time conditions without requiring precise system models. Applied to LVRT, DRL enables PV inverters to dynamically regulate active and reactive power, prioritize reactive support during voltage sags, limit inverter currents, and adjust actions according to fault severity and duration. Over time, the controller learns strategies that better balance grid support and inverter protection than fixed rule-based approaches.

2. Recent Works

The main objectives of the proposed system are:

- To analyze the behavior of grid-connected photovoltaic (PV) systems under low-voltage and fault conditions and to identify the limitations of conventional control methods such as PI controllers.
- To design a Deep Reinforcement Learning (DRL) based intelligent controller capable of adapting to dynamic grid conditions and enhancing Low Voltage Ride Through (LVRT) performance.
- To improve voltage stability and provide effective reactive power support during grid voltage sag conditions to ensure continuous grid connection.
- To compare the dynamic performance of the proposed DRL-based controller with a conventional PI controller in terms of voltage recovery, power quality, and system stability.
- To validate the effectiveness of the proposed control strategy through simulation studies under different grid fault scenarios.

2.1 Literature Review

Several researches have been conducted to improve LVRT capability in grid-connected PV systems using DRL-based controllers. In simple terms, researchers use artificial intelligence methods like Deep Q-Network (DQN) and other learning algorithms to make the inverter “learn” how to react properly during voltage sag or faults. Along with this, smart inverter control and automatic reactive power support techniques are used to keep the voltage stable and prevent the system from disconnecting from the grid.

2023 – S. Wang et al. Implemented DRL-based LVRT enhancement for grid-connected PV systems. Improved voltage stability and fault ride-through capability. 2021 – Y. Zhang et al Applied DRL for grid-connected converter control. Achieved better dynamic response compared to PI controller.2015 – V. Mnih et al. Introduced Deep Reinforcement Learning (DRL) framework. Demonstrated adaptive learning in dynamic environments.2010 – H. Bevrani et al. Discussed intelligent control techniques for renewable energy systems. Compared adaptive and conventional control strategies.2007 – J. Morren& S.W.H. de Haan. Analyzed LVRT performance during voltage dip conditions. Highlighted importance of reactive power support.2006 – F. Blaabjerg et al. explained conventional control of grid-connected converters. Identified limitations of PI controllers under faults.

3. Proposed Methodology

The proposed system introduces a Deep Reinforcement Learning (DRL) based control framework to enhance the Low Voltage Ride Through (LVRT) capability of grid-connected photovoltaic (PV) systems. The learning agent observes important parameters such as voltage, current, and power references to maintain stability, support voltage recovery, and protect inverter components during voltage disturbances.

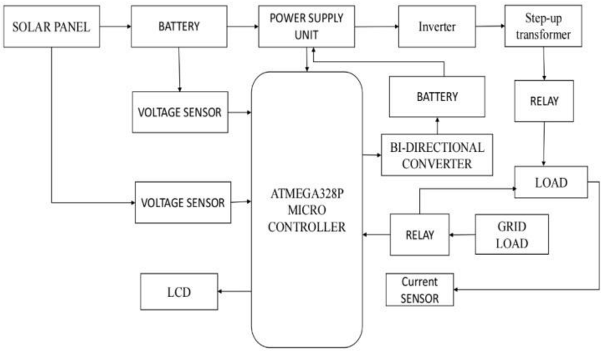


Figure1: *Block diagram of proposed System*

At the core of the system, the DRL agent is integrated into the inverter control architecture and makes decisions using a reward-driven learning process. During voltage sags, the controller intelligently prioritizes reactive power injection to support grid voltage while limiting inverter current to reduce stress on power electronic components. This adaptive capability enables the system to respond effectively to faults of varying depth and duration without relying on predefined control rules or accurate mathematical models of complex grid dynamics.

The proposed controller can balance multiple objectives simultaneously, including voltage support, system stability, and inverter protection. By continuously updating its learning policy based on system feedback, it ensures faster voltage recovery, smoother post-fault transitions, and improved overall performance compared to conventional control methods.

Extensive simulation studies under different fault scenarios demonstrate that the DRL-based controller improves LVRT compliance, robustness, and grid support. Overall, the proposed system provides an intelligent, flexible, and scalable solution for smart grids with high renewable energy penetration, contributing to reliable and sustainable power system operation.

3.1 Hardware Requirements

A regulated power supply is an essential part of electronic systems as it provides a stable and reliable DC voltage required for the proper operation of various circuit components. In this system, the widely used linear voltage regulators 7812 and 7805 are employed to generate regulated outputs of +12 V and +5 V, respectively, from a higher unregulated DC input source. The 7812 voltage regulator is designed to provide a constant +12 V output and typically requires an input voltage slightly higher than the output level, generally in the range of 14–16 V, to maintain effective regulation. Similarly, the 7805 voltage regulator produces a regulated +5 V output, which is commonly used for powering digital circuits such as microcontrollers and sensors, and it generally operates with an input voltage between 7 V and 25 V, with an optimal operating range of 7–20 V. To improve voltage stability and reduce noise in the power supply, appropriate filtering capacitors are included in the circuit. A 1000 µF, 25 V electrolytic capacitor is connected at the input side of the regulators to smooth the incoming voltage and suppress fluctuations or transient disturbances. In addition, a 10 µF, 63 V capacitor is connected at the output side to reduce ripple voltage and enhance the dynamic response of the regulators. Although resistors are not required for the basic operation of these voltage regulators, they may be incorporated in certain circuit designs for auxiliary functions such as voltage division, current limiting, or feedback control. The integration of 7812 and 7805 regulators along with appropriate filtering capacitors therefore forms a reliable dual-output regulated power supply capable of delivering stable +12 V and +5 V DC voltages for different sections of the electronic system.

3.2 Circuit Considerations

Decoupling capacitors play a significant role in maintaining the stability and reliability of the regulated power supply. Capacitors such as C1000/25 and C10/63 are commonly used to filter electrical noise and smooth voltage fluctuations within the circuit. The larger capacitance capacitor (1000 µF, 25 V) is typically placed at the input stage to suppress supply variations and store temporary charge during transient conditions, while the smaller capacitor (10 µF, 63 V) is connected at the output stage to reduce ripple voltage and improve the dynamic response of the regulator. Proper decoupling ensures that the voltage regulators deliver a clean and stable DC output, which is essential for sensitive electronic components. Another important consideration in linear voltage regulators such as 7812 and 7805 is heat dissipation. When the input voltage is significantly higher than the regulated output voltage, the excess energy is dissipated as heat within the regulator device. Therefore, adequate thermal management, such as the use of heat sinks, is often required to prevent overheating and to maintain reliable operation. Additionally, the current handling capability of the regulators must be carefully considered during circuit design. The selected regulators should be capable of supplying sufficient current to meet the load requirements of the system. In applications where higher current demand exists, improved thermal management or alternative regulator configurations may be necessary. Overall, the integration of 7812 and 7805 voltage regulators with appropriate decoupling capacitors provides a simple and effective approach for generating stable +12 V and +5 V DC outputs, which are widely used in electronic systems including microcontrollers, sensors, and analog interface circuits.

3.3 Communication

The Arduino Uno (Genuino Uno) microcontroller board provides several communication and interfacing capabilities that enable interaction with computers, other microcontroller boards, and embedded systems. The board is based on the ATmega328 microcontroller, which supports UART-based TTL serial communication operating at 5 V logic levels. This serial interface is accessible through digital pins 0 (RX) and 1 (TX) and is commonly used for communication with external devices or other controllers. To facilitate communication with a computer via USB, the board incorporates an ATmega16U2 microcontroller, which functions as a USB-to-serial converter. This component translates the UART signals from the ATmega328 into USB communication, allowing the board to appear as a virtual COM port on the host computer. The firmware programmed in the ATmega16U2 utilizes standard USB communication drivers, enabling compatibility with most operating systems without requiring additional drivers, although in certain cases, such as Windows environments, a configuration file (.inf) may be required. The Arduino Integrated Development Environment (IDE) includes a built-in serial monitor that enables users to transmit and receive textual data between the computer and the board for debugging and data monitoring purposes. During serial data transmission, the RX and TX indicator LEDs on the board flash to indicate active communication. In addition to communication features, the Arduino Uno provides several general-purpose pins and power interface functions. A built-in LED connected to digital pin 13 allows users to easily test digital output functionality; the LED illuminates when the pin is set to a HIGH logic level and turns off when the pin is LOW. The VIN pin serves as an input for supplying external voltage to the board when it is powered through an external power source rather than the USB interface. The 5 V pin provides regulated output voltage from the on board voltage regulator and can be used to power external components. The board can receive power from the DC power jack (7–20 V), USB connection (5 V), or the VIN pin, although applying voltage directly to the 5 V or 3.3 V pins bypasses the on board regulator and May potentially damage the board. A 3.3 V output pin is also available, generated by the on board regulator, with a maximum current capacity of approximately 50 mA. Multiple ground (GND) pins are provided to establish a common reference point for the circuit. The IOREF pin supplies the reference voltage level at which the microcontroller operates, enabling compatible shields to detect the operating voltage and adjust their logic levels accordingly. Additionally, a reset pin is available, allowing external circuits or shields to reset the microcontroller when necessary. The board also provides an analog reference (AREF) pin, which can be used to supply an external reference voltage for the analog input pins, thereby improving the accuracy of analog-to-digital conversions in specific applications.

4. Results and Discussion

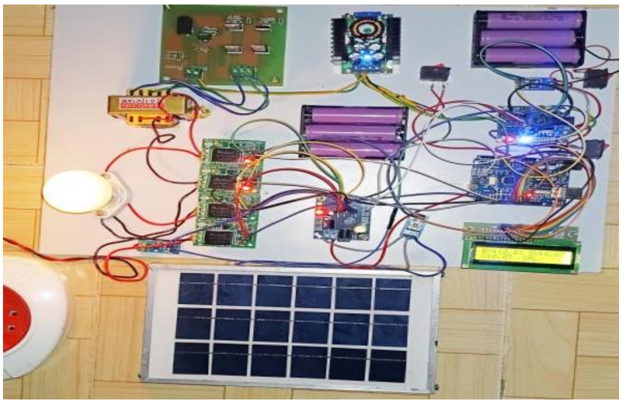
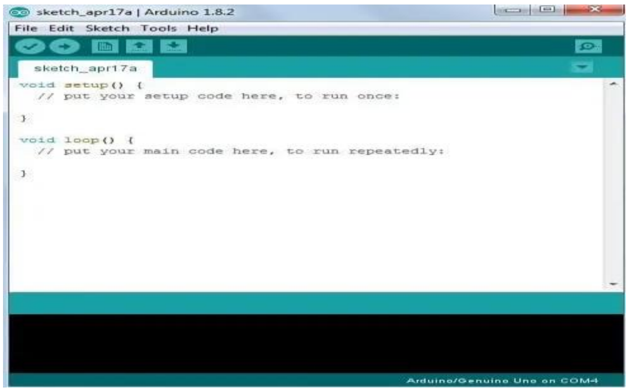


Figure 2: *Hardware View*

The Arduino-based DRL controller continuously monitors both solar PV and grid power. When solar output is low due to poor irradiation or weather, the system prioritizes the grid to ensure uninterrupted supply while maintaining stable voltage and current. If available, the battery energy storage system (BESS) helps smooth power fluctuations.

When solar PV is available and the grid is disconnected, the PV supplies the load. The DRL controller adaptively regulates voltage and power, handling changes in solar intensity or sudden shading. Overall, the system operates reliably in both grid-connected and standalone modes by dynamically adjusting to source availability.



```
void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}
```

Figure 2: *Arduino Display*

The Arduino Integrated Development Environment (IDE) is the software platform used to write and upload sketches to the board. It includes a text editor for coding, a message area for feedback, a console for displaying error messages and information, and a toolbar with commonly used Functions. Sketches are saved with the ino file extension. The IDE allows users to verify and Upload programs, create and manage sketch files, and monitor serial communication. It also displays the selected board type and serial port, making the development process simple and user-Friendly.

4.1 Discussion

The simulation and hardware results show that the proposed DRL-based LVRT controller which significantly improves performance of grid-connected PV systems in several ways:

4.1.1 Controller Response

The DRL controller reacts faster and smoother to shallow, moderate, and deep voltage sags compared to conventional PI or rule-based controllers. It dynamically adjusts active and reactive power in real-time, ensuring uninterrupted operation and intelligent fault mitigation.

4.1.2 Voltage Support and Recovery

By injecting reactive power during sags, the controller restores voltage faster with reduced oscillations. This adaptive support enhances transient stability and meets LVRT grid code requirements.

4.1.3 Reduction of Inverter Stress

Current peaks are reduced, lowering thermal stress on inverter components and improving efficiency and lifespan. Conventional controllers often cause higher overshoots and faster component degradation.

4.1.4 Robustness

The controller performs reliably under various fault severities, grid strengths, and nonlinear conditions without retuning, making it suitable for smart grids with fluctuating renewable generation.

4.1.5 Learning Stability

Training shows stable convergence of rewards, indicating effective policy learning and potential for real-time adaptive control.

5. Conclusion:

This project focused on enhancing Low Voltage Ride Through (LVRT) performance of grid-connected photovoltaic systems using a Deep Reinforcement Learning (DRL) based controller. With growing renewable penetration, stable grid operation during voltage disturbances is critical. The DRL controller addressed limitations of conventional inverter methods by adapting dynamically to grid conditions, regulating active and reactive power, and responding to fault severity and duration without relying on fixed parameters. Simulation results showed faster voltage recovery, reduced inverter stress, and smoother post-fault transitions, improving reliability, reducing thermal loading, and extending equipment lifespan. The controller also proved robust across varying grid conditions, highlighting the adaptability and resilience of learning-based strategies. This work demonstrates the potential of artificial intelligence in power system control, enabling Photovoltaic inverters to act as intelligent grid support units. While practical deployment requires further research on real-time implementation and multi-inverter applications, the study confirms that DRL is an effective approach for LVRT enhancement, supporting sustainable, reliable, and Renewable-dominated smart grids.

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