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# Enhanced Power Quality Improvement in Distribution Networks using a Five-Level Diode-Clamped Multilevel STATCOM

**Nakka Chandu[1], Sammangi Ramyaka[2], Dr. N. Sambasiva Rao[3]**
[1]PG Scholar, Department of EEE, NRI Institute of Technology, Agiripalli, India.
[2]Assistant Professor, Department of EEE, NRI Institute of Technology, Agiripalli, India.
[3]Professor and HOD, Department of EEE, NRI Institute of Technology, Agiripalli, India.

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**ABSTRACT:**
**This paper investigates the implementation of a Five-Level Multilevel Inverter (MLI) based Static Synchronous Compensator (STATCOM) for enhancing power quality in distribution networks. The proposed STATCOM configuration employs advanced control strategies to efficiently manage reactive power flow, thereby stabilizing voltage levels and minimizing power quality issues such as voltage sags, swells, and harmonic distortions. Utilizing a MATLAB/Simulink environment, the design and operation of the five-level MLI STATCOM are modeled and simulated, highlighting its effectiveness in improving the power factor, reducing Total Harmonic Distortion (THD), and ensuring robust voltage regulation across the distribution network. The simulation results demonstrate the superior performance of the proposed STATCOM in addressing a wide range of power quality challenges, making it a viable solution for modern electrical distribution systems facing the integration of renewable energy sources and fluctuating loads. This study contributes to the advancement of STATCOM technologies for better power quality management and enhanced grid stability.**
**KEYWORDS: Five-Level Multilevel Inverter, Static Synchronous Compensator, STATCOM, Power Quality Improvement, Distribution Network, Voltage Regulation, Total Harmonic Distortion, MATLAB/Simulink.**

## 1. INTRODUCTION:

Background: Modern electrical distribution networks are the backbone of the global energy system, supporting the transmission of power from generation sources to end users [1-3]. The criticality of maintaining high power quality within these networks cannot be overstated, as poor power quality can lead to numerous problems affecting both utility providers and consumers [3-10]. Voltage sags and swells, flickers, and harmonics are among the most prevalent issues, each capable of causing equipment malfunction, increased operational costs, and reduced lifespan of electrical devices [11].

Problem Statement: Traditional power quality improvement techniques, such as passive filters, series compensators, and voltage regulators, have been instrumental in mitigating these issues. However, these solutions often fall short in dynamic response capabilities, efficiency, and the ability to handle multiple power quality problems simultaneously [12]. Static Synchronous Compensators (STATCOMs) have emerged as a viable solution, yet their effectiveness is significantly influenced by the underlying inverter technology [13].

This research aims to explore the potential of employing a five-level multilevel inverter-based STATCOM for enhanced power quality management in distribution networks [14]. The advanced inverter design promises better performance in terms of voltage regulation, harmonic reduction, and dynamic response to load changes [15].

The scope of this paper encompasses the design and simulation of a five-level multilevel inverter STATCOM, its integration into a distribution network, and a comprehensive performance evaluation [16]. A comparative analysis with traditional power quality improvement techniques will highlight the advantages of the proposed solution [17].

The paper is organized as follows: Section 2 provides a literature review on STATCOM technology and multilevel inverters. Section 3 details the system model and design of the proposed STATCOM. Methodology and simulation setup are described in Section 4, followed by the presentation and discussion of results in Section 5. The paper concludes with a summary of findings and suggestions for future work in Section 6.

## 2. LITERATURE REVIEW

STATCOM Technology: Static Synchronous Compensators (STATCOMs) represent a pivotal technology in modern power systems, designed to provide rapid and efficient voltage control and power factor correction. Utilizing voltage source converters (VSCs), STATCOMs inject or absorb reactive power into the system, directly influencing voltage levels and stability. Their application in power quality management includes mitigating voltage sags/swells, reducing flicker, and suppressing harmonics, thereby enhancing the reliability and efficiency of electrical distribution networks [18-20].

Multilevel Inverters: The evolution of multilevel inverters marks a significant advancement in power electronics, offering a sophisticated approach to generating high-quality voltage waveforms. By stacking multiple DC sources, multilevel inverters achieve higher voltage levels with reduced harmonic distortion compared to traditional two-level inverters. This feature is particularly advantageous in STATCOM applications, where the quality of the injected voltage is paramount [21]. The inherent modularity, scalability, and lower electromagnetic interference of multilevel inverters further underscore their suitability for enhancing STATCOM performance.

Previous Studies: Numerous studies have explored the integration of multilevel inverters with STATCOM for power quality improvement. Research has predominantly focused on three-level and five- level configurations, highlighting improvements in voltage stability, harmonic reduction, and dynamic response [21]. Comparative analyses with conventional power quality solutions have demonstrated the superiority of multilevel inverter-based STATCOMs in various operational scenarios [22]. However, these studies have also revealed limitations in terms of complexity, cost, and control strategies [23].

Gap Identification: Despite the promising advancements documented in previous research, a gap exists in the comprehensive analysis and practical implementation of five-level multilevel inverter STATCOMs in distribution networks. Specifically, there is a need for an in-depth exploration of the unique contributions of five-level inverter designs, including their impact on system efficiency, reliability, and scalability. This study aims to fill this gap by presenting a detailed evaluation of a five-level multilevel inverter STATCOM, addressing the limitations identified in prior works and offering innovative solutions to enhance power quality management in distribution networks.

## 3. SYSTEM MODEL AND DESIGN

Distribution Network Configuration: The study utilizes a typical medium-voltage distribution network setup, characterized by radial feeders supplying power to residential, commercial, and industrial loads. The network operates at a nominal voltage of 11 kV, with distribution transformers stepping down the voltage to the appropriate levels for end-users. The configuration includes multiple branches, each with variable load profiles, to simulate real-world conditions accurately. This setup provides a versatile platform for assessing the impact of STATCOM on power quality across different scenarios.

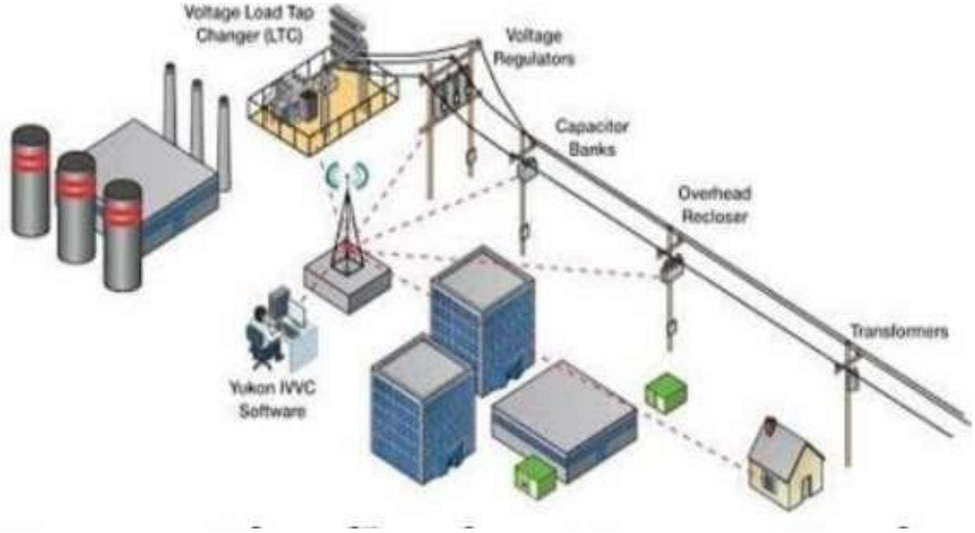


Fig 1: Distribution Network Configuration Diagram

**Five-Level Inverter Design:**

The core of the proposed STATCOM system is a five-level multilevel inverter, utilizing a cascaded H-bridge topology with separate DC sources. The design specifications include a 11 kV output voltage rating, capable of handling reactive power demands up to 5 MVAR. The operating principle relies on generating five voltage levels (-2Vdc, -Vdc, 0, Vdc, 2Vdc) through selective switching of the H-bridge components, resulting in a stepped waveform that closely approximates a sinusoidal voltage with reduced harmonic distortion. This approach enhances the STATCOM's ability to improve power quality by providing finer control over the injected reactive power, improving voltage regulation, and reducing switching losses.

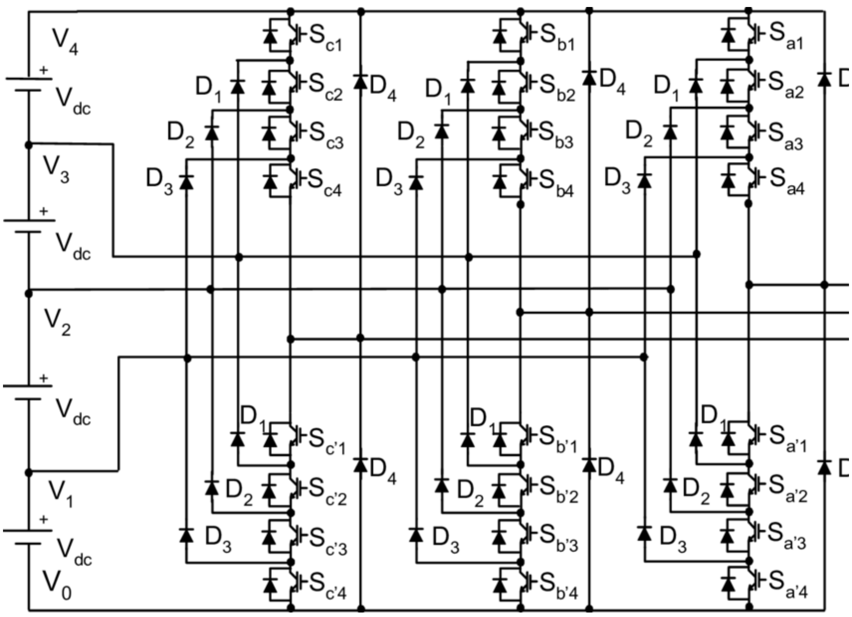

Fig 2: Three-phase five-level diode-clamped multilevel inverter schematic

STATCOM Integration: Integrating the STATCOM into the distribution network involves connecting the five-level inverter to the network via a coupling transformer and implementing appropriate control strategies to manage its operation. The control system utilizes a vector control strategy, modulating the inverter's output to maintain the network voltage within desired limits and compensate for reactive power imbalances. Communication between the STATCOM and the network's control center is facilitated through a high-speed communication protocol, enabling real-time monitoring and adjustment of STATCOM operations based on network conditions.

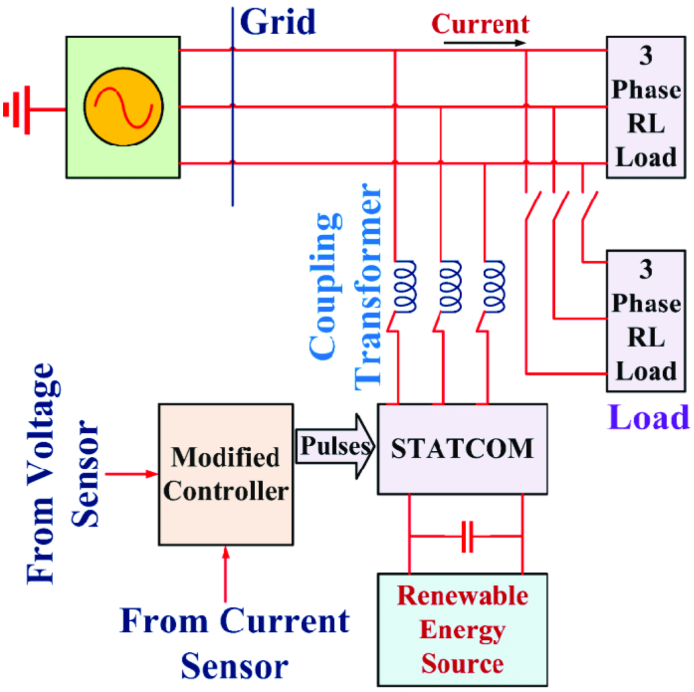


Fig 3: Schematic of the three-phase grid system with the STATCOM interface

Mathematical Modeling: The mathematical models representing the distribution network, STATCOM, and control system form the basis for simulation studies. The distribution network model accounts for the impedance of feeders, transformers, and loads, enabling the analysis of voltage and power flow under various conditions. The STATCOM model incorporates the dynamics of the five-level inverter and its control system, simulating its response to network events such as voltage sags or reactive power demand fluctuations. The control system model includes algorithms for vector control and reactive power compensation, ensuring the STATCOM's effective contribution to power quality improvement.

## 4. METHODOLOGY

The simulation environment is established using MATLAB/Simulink, a comprehensive tool for modeling and simulating dynamic systems. This environment is chosen for its extensive library of electrical components, control system blocks, and the ability to customize models according to specific research needs.

Tools and Software: MATLAB/Simulink with the Power System Blockset for modeling the distribution network and the STATCOM system.

Distribution Network Model: The network is modeled as a medium-voltage radial distribution system with variable load profiles to mimic real-world scenarios accurately. Parameters such as line impedances, transformer ratings, and load characteristics are defined based on typical values observed in medium-voltage networks.

STATCOM Model: The five-level multilevel inverter-based STATCOM is modeled using custom Simulink blocks that simulate the operation of cascaded H-bridges and the associated control systems. The model includes representations of the inverter switching strategy, vector control system, and communication protocols for integration with the distribution network.

Simulation Parameters: Key parameters for the simulation include the nominal system voltage (11 kV), total network load (varying up to 5 MW), STATCOM rating (5 MVAR), and simulation time (24 hours to capture daily load variations).

Performance Metrics

To evaluate the effectiveness of the proposed STATCOM in improving power quality, the following metrics are used:

Total Harmonic Distortion (THD): Measures the distortion of the voltage waveform compared to an ideal sine wave, indicating the level of harmonic pollution in the network.

Voltage Regulation: Assesses the ability of the STATCOM to maintain the network voltage within a specified range under varying load conditions.

Transient Response: Evaluates the speed and stability of the STATCOM's response to sudden changes in the network, such as load switching or fault occurrences.

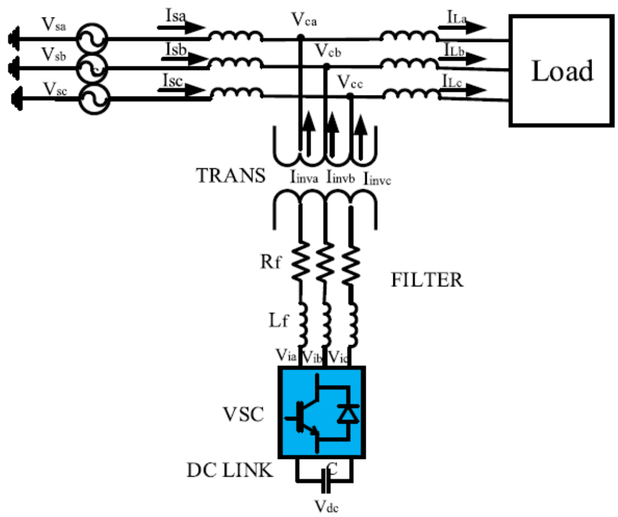


Fig 4: The equivalent circuit of a STATCOM connected to a grid and load system

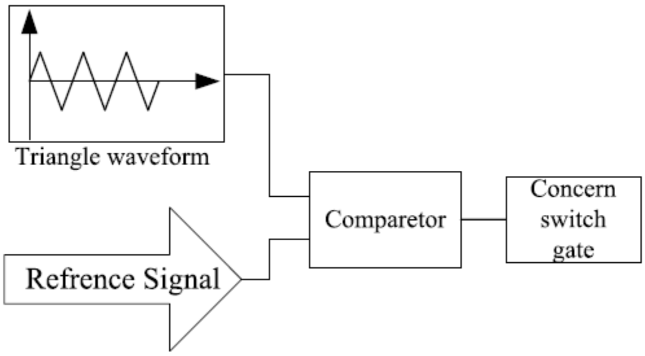


Fig 5: Structure and operation of PWM switching method

**5. SIMULATION ANALYSIS**

In this section, various case studies are reviewed to demonstrate the effect of the proposed control. It must be noted that the proposed structure in various practical applications such as three phase active filters [19] as well as three phase STATCOM [20] has been implemented and validated previously. The novelty of this paper is to propose an improved one-cycle control algorithm that is implemented on the former tested structures. In order to evaluate the effectiveness of the proposed control algorithm, simulations have been carried out on the available structures. The network understudy and three-level STATCOM are shown in Fig. 8, in which one load is connected to a source via a transmission line, and STATCOM is connected in parallel. The system parameters are presented in Table 1. This paper uses the proposed approach in two case studies for STATCOM. The proposed approach is tested in 4 modes for the first study, and the simulation results are presented. In the case of the second study, to better demonstrate the benefits of the proposed controller, the simulation results of the proposed control and the SPWM method are compared when a fault occurs in the system.

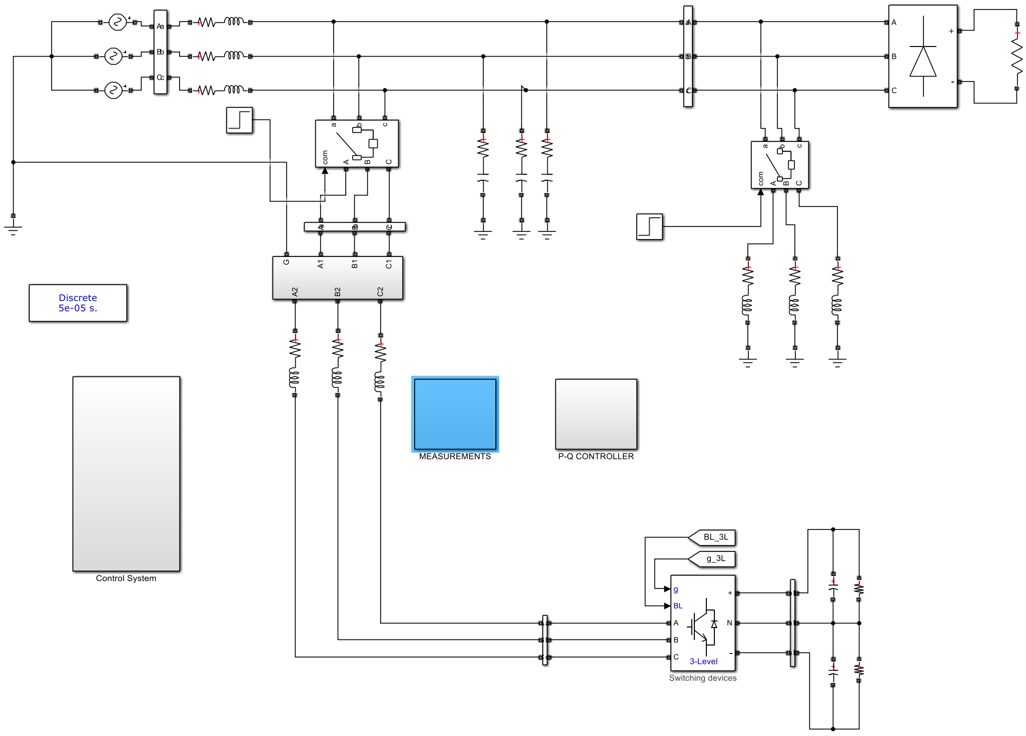


Fig 6: Simulation diagram of the system

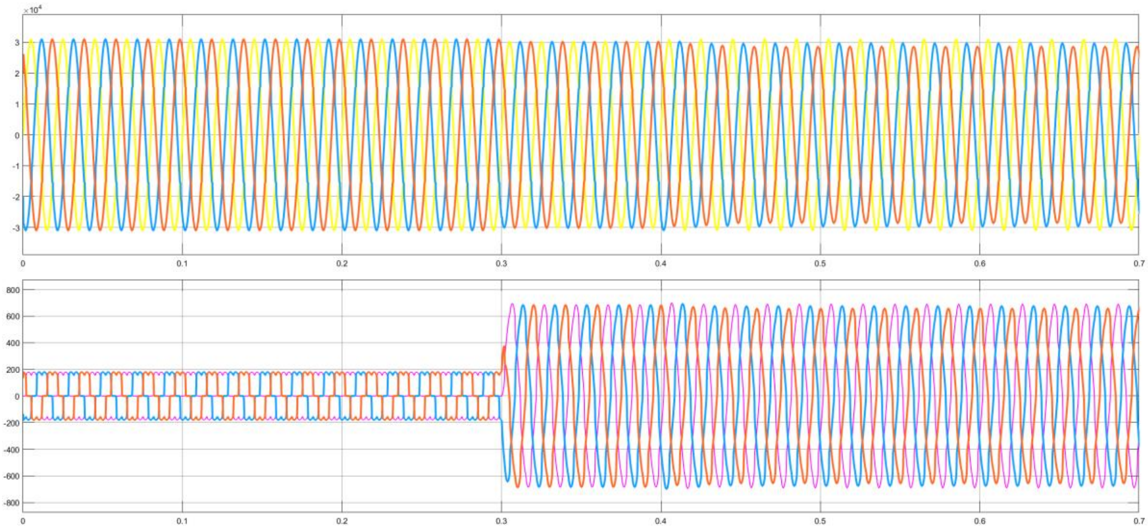

Fig: Load Voltage and current

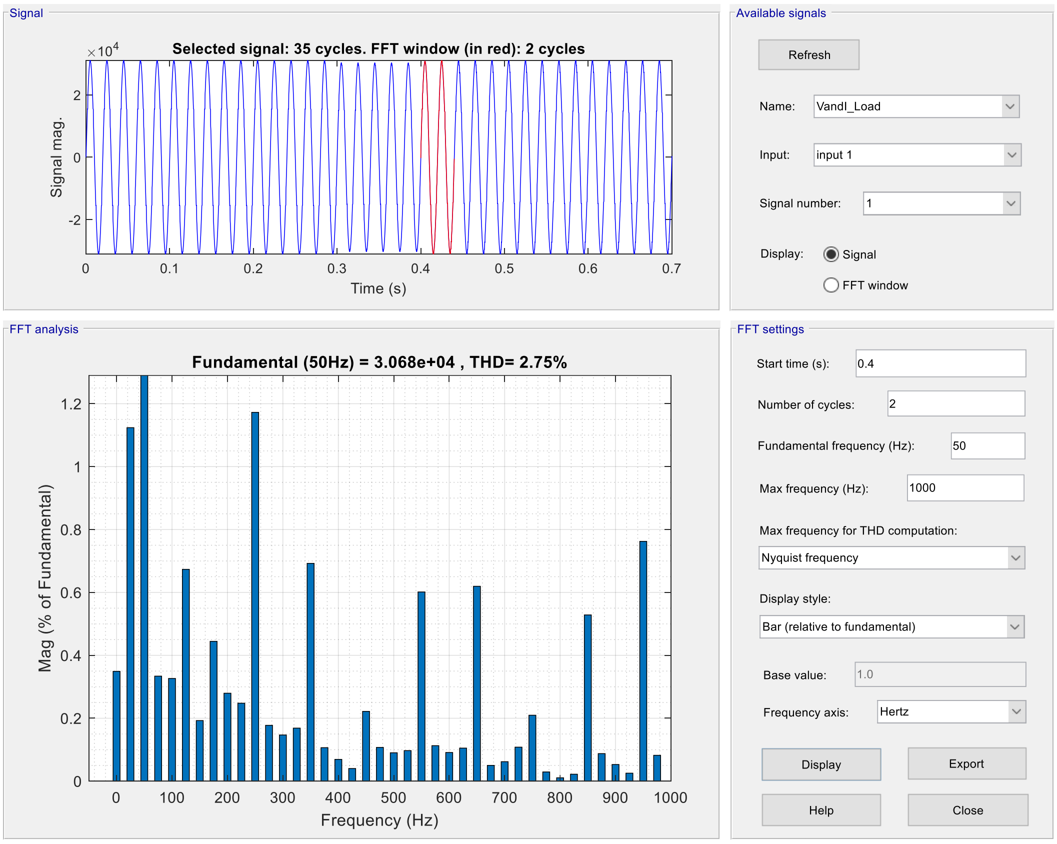


Fig: THD of load voltage (2.75%)

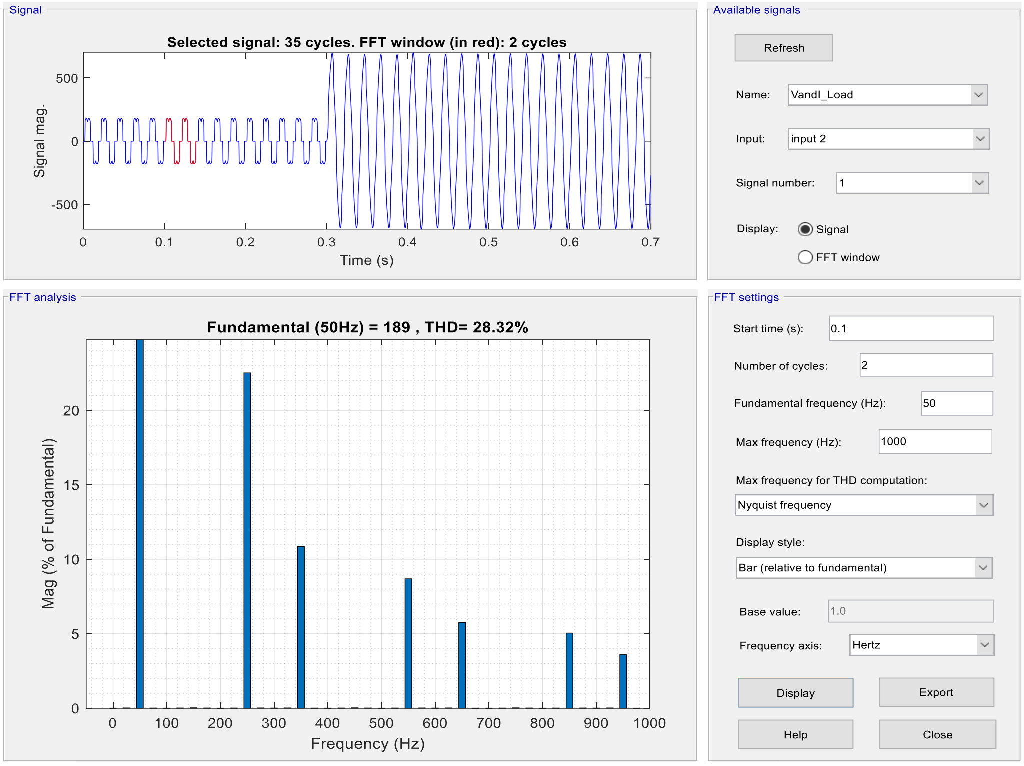


Fig: THD of load current without STATCOM (28.32%)

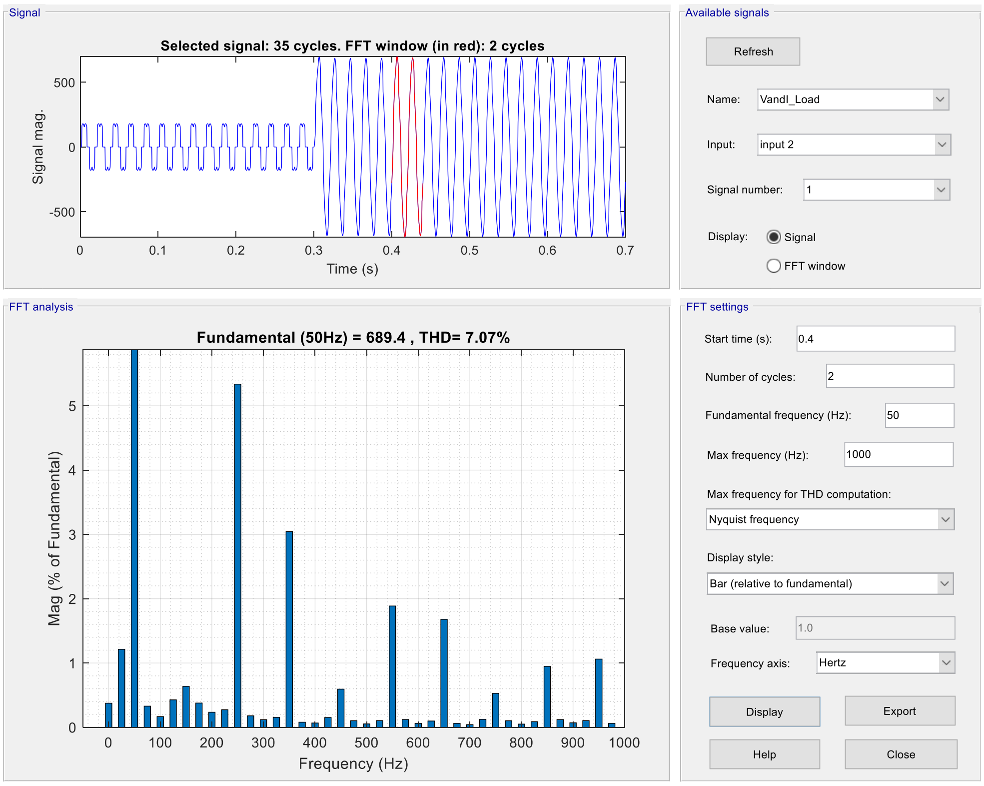


Fig: THD of load current with STATCOM (7.07%)

**Five-Level Inverter Design:**

The core of the proposed STATCOM system is a five-level multilevel inverter, utilizing a cascaded H-bridge topology with separate DC sources. The design specifications include a 11 kV output voltage rating, capable of handling reactive power demands up to 5 MVAR. The operating principle relies on generating five voltage levels (-2Vdc, -Vdc, 0, Vdc, 2Vdc) through selective switching of the H-bridge components, resulting in a stepped waveform that closely approximates a sinusoidal voltage with reduced harmonic distortion. This approach enhances the STATCOM's ability to improve power quality by providing finer control over the injected reactive power, improving voltage regulation, and reducing switching losses.

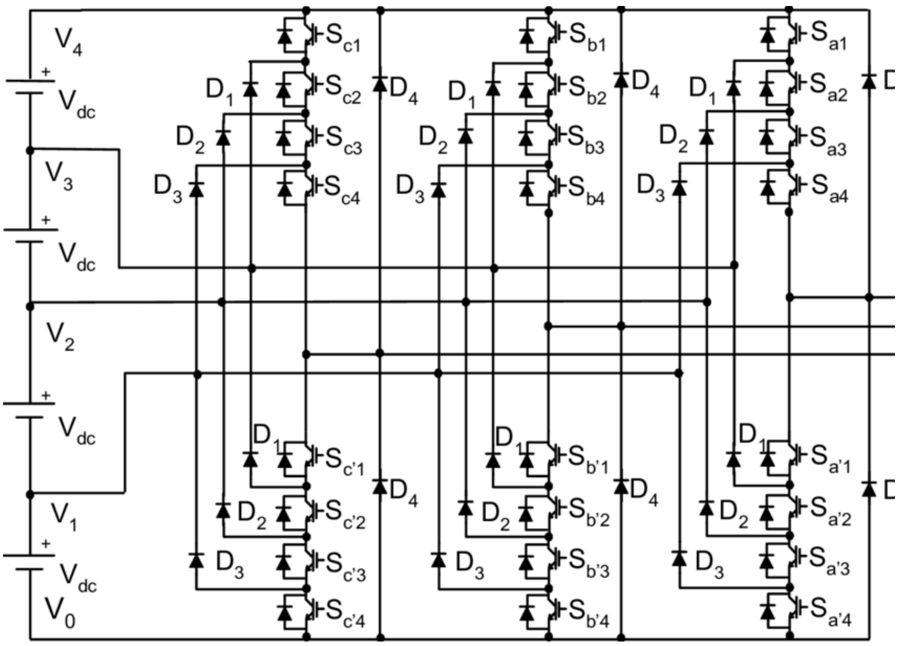


Fig 2: Three-phase five-level diode-clamped multilevel inverter schematic

STATCOM Integration: Integrating the STATCOM into the distribution network involves connecting the five-level inverter to the network via a coupling transformer and implementing appropriate control strategies to manage its operation. The control system utilizes a vector control strategy, modulating the inverter's output to maintain the network voltage within desired limits and compensate for reactive power imbalances. Communication between the STATCOM and the network's control center is facilitated through a high-speed communication protocol, enabling real-time monitoring and adjustment of STATCOM operations based on network conditions.

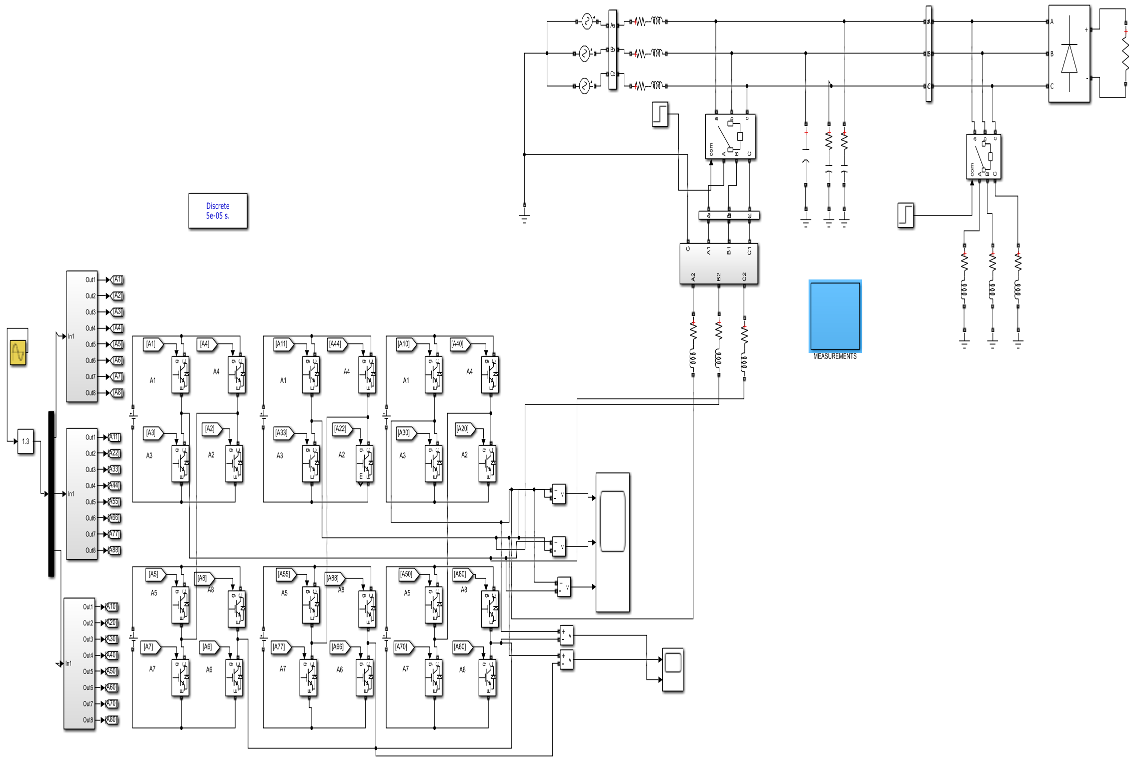

Fig: Simulation diagram of 5 level inverter

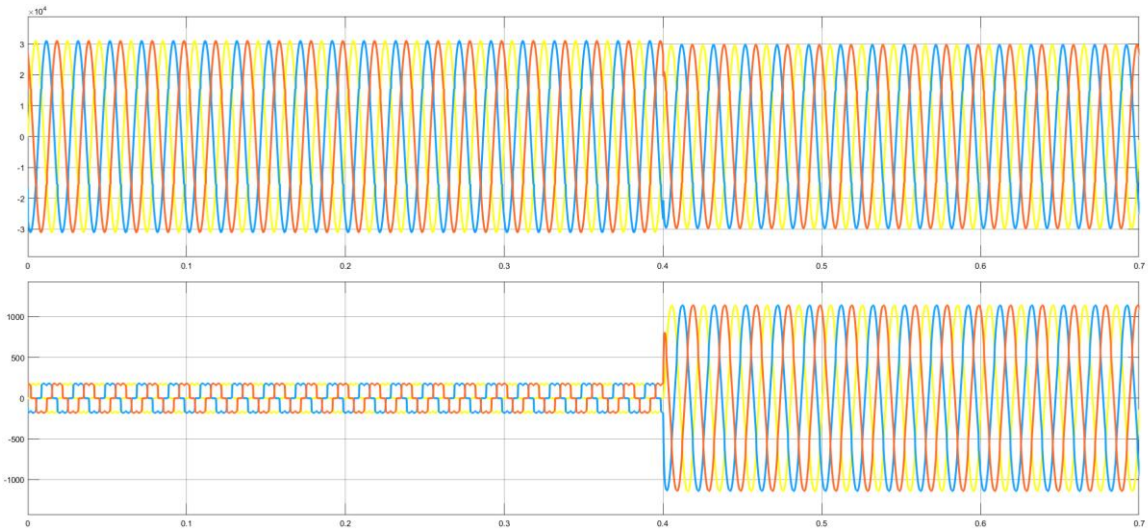

Fig: Load Voltage and current with 5 level inverter

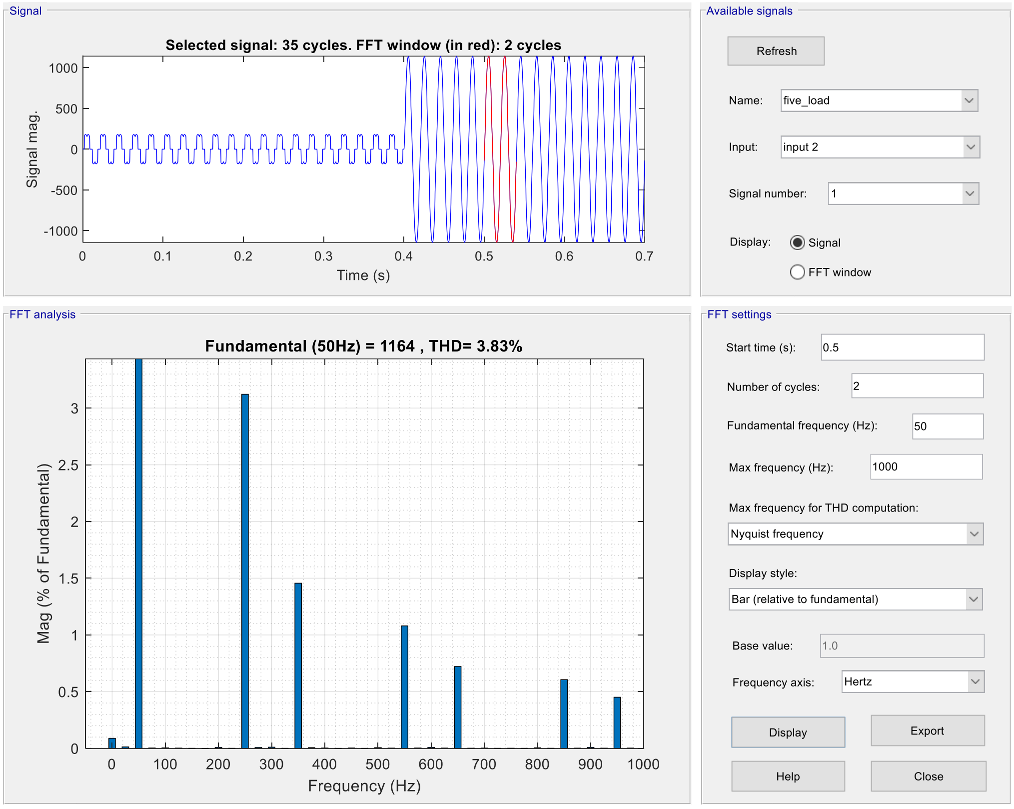


Fig: THD of load current with STATCOM (3.83%)

## 6. CONCLUSIONS

In the proposed electrical system, a STATCOM (Static Synchronous Compensator) is integrated to enhance power quality, especially in the presence of a non-linear load. Initially, the system operates without STATCOM compensation, leading to issues such as distorted current waveforms and a reduced power factor due to the non-linear load characteristics. At a specific moment, marked at 0.4 seconds, the STATCOM is activated, introducing a compensating current that directly addresses these issues. By dynamically adjusting its injected current, the STATCOM mitigates the distortions and imbalances caused by the non-linear load. As a result, the overall current waveform is significantly improved, aligning closer to the ideal sinusoidal shape. Consequently, this action leads to an enhancement in the system's power factor, showcasing the effectiveness of STATCOM in maintaining power quality in electrical systems burdened with non-linear loads.

### Future Scope

The future scope for a Five-Level Multilevel Inverter STATCOM-based Distribution Network for Power Quality Improvement encompasses advancements in semiconductor technology, control strategies, and grid integration to enhance efficiency, reliability, and scalability. Emerging semiconductor materials such as silicon carbide (SiC) and gallium nitride (GaN) promise to reduce the size, cost, and power losses of multilevel inverters, making them more suitable for widespread applications. Additionally, the development of advanced control algorithms, including artificial intelligence and machine learning techniques, is expected to improve the STATCOM's performance in dynamic grid conditions, enabling more precise compensation for power quality issues such as voltage sags, swells, and harmonics. Integration with renewable energy sources and smart grid technologies is also a critical area, facilitating the transition towards more sustainable and resilient power systems. Moreover, advancements in modular design will likely ease the scalability and maintenance of these systems, allowing for customized solutions tailored to specific grid requirements. Overall, the continuous innovation in these areas is set to significantly enhance the capability of multilevel inverter STATCOMs in power quality improvement, marking a pivotal step towards more efficient and reliable electrical distribution networks.

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