Multilevel Voltage Source Converter for HVDC Transmission System

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Abstract: This paper introduces a novel multilevel Voltage Source Converter (VSC) for High Voltage Direct Current (HVDC) systems, featuring an integrated Uninterruptible Power Quality Conditioner (UPQC) to improve power quality and performance. Unlike traditional Modular Multilevel Converters (MMC), which are complex and costly, the proposed VSC uses series full-bridge submodules and an AC side unfolder to minimize component requirements and reduce switching losses. The advanced control strategy regulates active/reactive power and maintains capacitor voltage balance, enhancing stability and efficiency. Simulations confirm this design's superior performance, highlighting its potential as an efficient, resilient solution for modern HVDC applications.

1 INTRODUCTION

High Voltage Direct Current (HVDC) systems are essential for modern energy infrastructure due to their efficiency in transmitting large power loads over long distances. This efficiency makes HVDC technology highly suitable for integrating renewable energy sources, such as wind and solar, into power grids, thereby supporting sustainable energy solutions. By minimizing transmission losses and stabilizing grids, HVDC plays a crucial role in enhancing the reliability and reach of energy networks. A common HVDC technology is the Modular Multilevel Converter (MMC), which offers scalability and flexibility in power transmission. MMCs use numerous submodules to manage high voltage levels, making them suitable for scaling with power demands.

However, the high component count in MMC systems leads to increased costs and complex control requirements. Balancing voltage across submodules is particularly challenging under variable loads, while the large number of components contributes to switching losses, affecting system efficiency and reliability. These factors add to the operational complexity and costs of MMC-based HVDC systems.

The proposed solution introduces a novel multilevel Voltage Source Converter (VSC) that integrates full-bridge submodules and an AC side unfolder, significantly reducing component count compared to traditional MMC designs. This reduced component structure simplifies the control system, lowering costs and enhancing efficiency. Additionally, by operating most switches in a soft-switching mode, the design minimizes switching losses and thermal stress, which improves the converter’s reliability and longevity. This streamlined design supports an HVDC system that is both cost-effective and more efficient than conventional MMC approaches.

The proposed VSC incorporates an Uninterruptible Power Quality Conditioner (UPQC), which enables effective management of power quality disturbances such as voltage sags, swells, and harmonics. This feature ensures a stable, high-quality power supply, an increasingly important aspect of modern grids. An advanced control strategy further optimizes the VSC by balancing active and reactive power, maintaining capacitor voltage, and adjusting to dynamic load conditions. This approach offers a

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sustainable and resilient HVDC solution, crucial as renewable energy sources continue to expand within global power networks.

2 COMPONENTS

A Unified Power Quality Conditioner (UPQC) system. Input power is processed through a Voltage Source Converter (VSC) and regulated by the UPQC to improve power quality for the load. A PIC controller with a buffer manages the control signals, supported by a 5V DC power supply.

A driver circuit, powered by 12V DC, interfaces the controller with the VSC. The system ensures reliable and clean power delivery to the load.

2.1 Voltage Source Converter (VSC)

The Voltage Source Converter (VSC) utilizes a topology of series full-bridge submodules, which enhances efficiency while reducing the number of components compared to Modular Multilevel Converters (MMC). It employs power semiconductor switches, such as IGBTs or MOSFETs, arranged in full-bridge configurations to facilitate soft-switching, thereby minimizing switching losses. The VSC is designed to achieve a DC-link voltage 3.33 times greater than the AC-side RMS voltage, ensuring balanced stress across both the converter and transformer components.

2.2 Uninterruptible Power Quality Conditioner (UPQC)

Uninterruptible Power Quality Conditioner (UPQC) integrates with the VSC to effectively mitigate power quality disturbances, improving voltage regulation and reactive power supply as needed. This system includes both series and shunt converters, along with voltage and current sensors and control circuitry, which work together to ensure smooth operation under varying load conditions, thereby enhancing overall system performance and reliability.

2.3 Load

The load in the system can be either resistive or inductive, representing the actual load conditions in simulations. For this setup, it is specified at 12V DC, simulating typical operational conditions that the VSC and UPQC are designed to handle. This load configuration is essential for evaluating the performance and effectiveness of the overall system under realistic scenarios.

2.4 Driver Circuit

The driver circuit's primary purpose is to convert control signals from the PIC controller into gate drive signals that activate the VSC switches. Operating on a 5V DC supply, the driver circuit ensures compatibility with the outputs of the microcontroller. This circuit plays a crucial role in facilitating reliable switching operations of the VSC, thereby maintaining the overall efficiency and effectiveness of the system.

2.5 PIC Controller with Buffer

The PIC controller serves as the main control unit for the system, executing an advanced control strategy to regulate both active and reactive power. To enhance stability and reliability, a buffer circuit isolates the PIC controller from the high-power switching elements of the VSC.

This isolation ensures that the controller can effectively manage system operations without being adversely affected by high voltage or current fluctuations during switching events.

3 SIMULATION PROCEDURE

A The simulation showcases a high-voltage direct current (HVDC) transmission system designed for efficient long-distance power transfer. It connects two 230 kV, 50 Hz, 2000 MVA AC systems.

Station 1 (Rectifier): Converts AC to DC for transmission using a Voltage Source Converter (VSC).

HVDC Cable: A 75 km cable transmits DC power with reduced losses.

Station 2 (Inverter): Converts the DC back to AC for integration into the second AC system.

Both stations incorporate VSC pole control for precise operation and data acquisition systems for signal recording and system monitoring. A simulated three-phase fault near Station 2 evaluates the system's stability, fault tolerance, and response under disturbance. This system highlights efficient power transfer and robust fault management.

A high-voltage direct current (HVDC) transmission system, an advanced and highly efficient technology for long-distance power transmission. HVDC systems are widely used to transfer bulk power over long distances with minimal losses, making them a preferred choice for interconnecting distant AC grids or for projects that involve submarine or underground cables. The simulation focuses on the key operational aspects, fault-handling capabilities, and the stability of an HVDC system.

This system connects two large AC grids, each operating at 230 kV, 50 Hz, and with a power rating of 2000 MVA. The first AC grid supplies power to Station 1, which functions as a rectifier, converting the AC power into direct current (DC) for transmission. The rectification process is controlled using Voltage Source Converter (VSC) technology, which allows precise regulation of the DC voltage and current, ensuring smooth power transfer. VSC technology also enables fast response to changes in load or grid conditions, making the system more stable and adaptive to fluctuations.

Once converted to DC, the power is transmitted over a 75 km HVDC cable. The use of DC for long-distance transmission offers several advantages over AC systems, including reduced energy losses and the elimination of reactive power issues. HVDC cables are also more efficient for submarine and underground installations, as they require fewer conductors and have a lower footprint. This feature makes HVDC systems particularly suitable for applications such as cross-border power exchanges or linking offshore wind farms to the main grid.

At the receiving end, Station 2 acts as an inverter, converting the DC power back into AC for integration into the second AC grid. Like the rectifier, the inverter station also uses VSC technology to ensure proper synchronization with the receiving grid. This includes maintaining a stable voltage and frequency while accommodating variations in load or power demand. The combination of rectifier and inverter stations ensures bidirectional power flow, which is crucial for modern interconnected power systems that require flexibility.

To monitor the performance of the system, both stations are equipped with data acquisition systems. These systems collect real-time operational data, allowing engineers to analyze power flow, voltage levels, and system stability. The data is critical for identifying potential issues, ensuring reliable operation, and optimizing the performance of the HVDC system. Additionally, the simulation incorporates a three-phase fault near Station 2 to test the system’s fault-handling capabilities. This feature is essential for evaluating how the system responds to disturbances, such as short circuits or grid instability. The fault simulation helps in designing robust protection mechanisms, ensuring that the system can recover quickly without compromising power delivery.

The simulation provides a comprehensive overview of an HVDC transmission system's operation and reliability. It highlights the advantages of HVDC technology, including its efficiency, adaptability, and ability to handle faults. By using advanced control systems such as VSCs and incorporating fault analysis, the simulation demonstrates the suitability of HVDC systems for modern power transmission challenges, making them an integral part of future energy infrastructure. This setup is particularly relevant for projects that demand high capacity, long-distance transmission, and interconnection of renewable energy sources to the grid.

3.1 Parameter Labels and Signals

The system includes key parameters such as the DC pole-to-neutral voltage (Vdc PN), which ranges from -10 to 10 volts for monitoring or setting purposes, and measured.

DC voltage and power in per-unit (pu) terms (<Udc_meas> and <Pdc_meas>, respectively). This per-unit system standardizes values across the HVDC setup, facilitating easier interpretation and management of voltage and power dynamics during operation.

3.2 Graphical Scales and Simulation Status

Each parameter in the simulation has corresponding graphical scales to visualize fluctuations, such as voltage and power changes, dynamically. The simulation indicates that it is currently "Running," with a sample time of 0.438 seconds, which affects the model's responsiveness and accuracy during real-time execution. For the BUS B1 STATION_1 component, the simulation tracks voltage, active power, and reactive power measurements, which are critical for maintaining power quality and system balance.

3.3 Control Signals Station

The control_signals station focuses on managing the direct (d-axis) and quadrature (q-axis) components of current and voltage, essential for maintaining power quality in the HVDC system.

Key parameters include the d-axis current reference (lv_d Iref_d) and the q-axis reference (Iv_q Iref_q), both displayed in per-unit terms, with a range from -10 to 10. The modulation index (<Mod index>) adjusts the converter's output voltage, while the reference voltage for three phases (Vref_abc) ensures stable power delivery. This section also shows a simulation status of "Running" with a sample time of 2.002 seconds, reflecting the need for less frequent updates due to the stability of the managed parameters

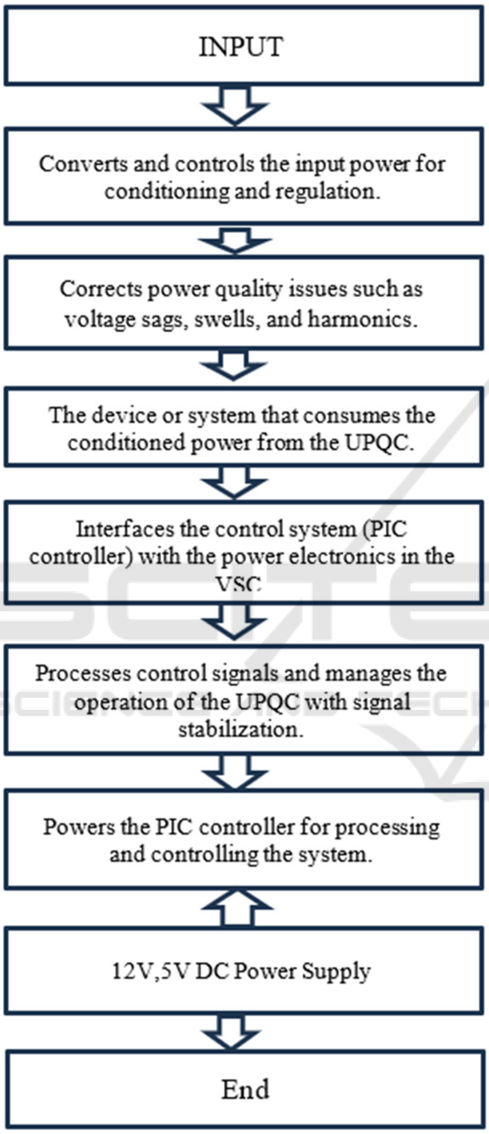

Figure 1. Working Procedure.

3.4 Filter Bus Station 2

The filter_bus station_2 block is designed for filtering and measuring voltage and current parameters, which are vital for stabilizing power transmission and minimizing harmonic content. It includes filtered voltage measurements (<Uf_meas>) and three-phase voltage outputs (Uf_abc), as well as filtered three-phase current (Iv_abc) and unfiltered voltage (Uv_abc) for comparison. The simulation status indicates it is "Running" with a sample time of 2.284 seconds, suggesting that the filtering process requires less frequent updates, which aligns with its role in ensuring clean and stable signals for the HVDC.

3.5 Simulation Outcome

The system begins with AC System 1, which serves as the power source at the sending end of the HVDC link. This AC system operates at 230 kV and 50 Hz, with a capacity of 2000 MVA. The electrical power generated by AC System 1 is delivered to Station 1, which functions as a rectifier. The primary role of Station 1 is to convert the alternating current from AC System 1 into direct current (DC). This conversion is accomplished using advanced power electronics, such as thyristors or insulated-gate bipolar transistors (IGBTs), which are controlled by a Voltage Source Converter (VSC) system. The VSC control system ensures efficient and stable conversion while managing power quality and minimizing losses. Additionally, Station 1 includes data acquisition systems that monitor and control the conversion process in real-time. Once the power is converted to DC at Station 1, it is transmitted through a 75 km cable to Station 2. This transmission cable is a critical component of the HVDC system, designed to handle high voltage and current with minimal losses. Depending on geographical and environmental factors, HVDC cables can be overhead lines, underground cables, or submarine cables.

The 75 km distance highlights the system's capability to transmit power over significant distances with high efficiency. Upon reaching Station 2, the DC power is converted back into AC power suitable for use in AC System 2, which operates at the same voltage and frequency as AC System 1. Station 2 functions as an inverter, utilizing VSC technology similar to Station 1 to ensure efficient and precise conversion from DC to AC. Like Station 1, Station 2 is equipped with data acquisition systems for continuous monitoring and control.

The AC power is then delivered to AC System 2 at the receiving end of the HVDC link. AC System 2 also operates at 230 kV and 50 Hz, with a 2000 MVA capacity, and receives the transmitted power for distribution. The schematic also includes various protection and control mechanisms to ensure safe and reliable operation. Notably, a three-phase fault is indicated on the AC System 2 side, which is used to test the system's stability and response to faults.

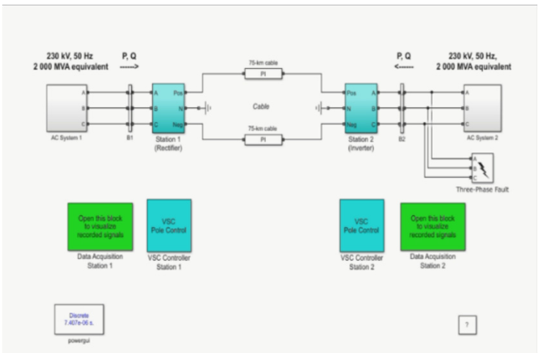

Figure 2: Simulation

These tests ensure that the HVDC system can handle unexpected disruptions and maintain stable operation. Overall, this HVDC transmission system exemplifies advanced electrical engineering techniques used to achieve efficient long-distance power transmission.

4 CONCLUSIONS

In conclusion, the proposed multilevel Voltage Source Converter (VSC) for High Voltage Direct Current (HVDC) systems with an integrated Uninterruptible Power Quality Conditioner (UPQC) presents a significant advancement in power transmission technology. By utilizing series full-bridge submodules and reducing component count, this VSC design offers enhanced efficiency, reliability, and improved power quality for HVDC systems. The innovative control strategies implemented ensure stable operation by dynamically managing both active and reactive power, while maintaining voltage balance across the capacitors.

The incorporation of UPQC further strengthens the system's ability to mitigate voltage sags, swells, and harmonics, ensuring high-quality power delivery. Additionally, the reduced DC-link voltage stress and soft-switching operations contribute to the overall efficiency and longevity of the system. The design has been validated through simulations and experiments, demonstrating its effectiveness in real-world scenarios. Ultimately, this VSC design contributes to the ongoing efforts to enhance HVDC transmission technology, making it more adaptable to modern energy demands, particularly in the context of integrating renewable energy sources. Its scalability, reliability, and cost-effectiveness offer a viable solution for future power grid applications.

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