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Grid Integration of Solar PV Using UPQC with Differential Inverter Control

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ABSTRACT

Ensuring voltage stability in integrated photovoltaic (PV) distribution systems is essential for the reliable operation of all connected devices within the network. One of the primary challenges in PV system integration is maintaining a stable voltage profile. This study focuses on stabilizing the voltage profile for a sensitive load of 22 kVA. A single-phase distribution system with PV integration serves as the basis for this analysis. The innovation lies in the use of differential inverters functioning as both a dynamic voltage restorer and a distribution static synchronous compensator within a unified power quality conditioner (UPQC). A key benefit of employing differential inverters is their capability for active power decoupling. The main goal of this research is to connect a 10-kW solar PV system to the distribution network using the proposed UPQC configuration. The study identifies and evaluates the most effective control strategy for the UPQC integrated with a battery energy storage system. A 20 kVA UPQC is designed specifically for enhancing voltage stability and supporting PV integration in the distribution network, with assumptions of constant frequency, voltage, and reactance-to-resistance (X/R) ratio.

Keywords: *UPQC, PV system , Power Quality.*

1. INTRODUCTION

A growing adoption of electric vehicle (EV) burden in the sharing grid has posed challenges in maintaining a pure sin voltage&current. Conventional EV charging stations frequently depend on fossil fuel-based energy sources, which diminish their environmental benefits. However, EVs can become a more sustainable option when charged using Renewable Energy Sources. The incorporation of RES into power utilities enhances system efficiency, flexibility, and reduces power losses and environmental impact. Among various RES, solar photovoltaic (PV) systems are particularly advantageous due to their cost-effectiveness, minimal maintenance requirements, and ease of installation, as they lack moving components [1].

Solar PV panels have been proposed for use in parking lots and office buildings, functioning both as energy sources and as thermal shields for surrounding structures. A PV-based EV charging system not only mitigates grid congestion but also offers an economically viable solution for charging infrastructure. Bidirectional charging strategies utilizing voltage source converters (VSCs) have gained popularity, particularly in systems where solar PV is connected to a DC bus. Previous research has explored different grid supporting of solar PV-based charging methods, such as hybrid boost converters and unified power management systems. However, these techniques often struggle to provide distortion-free charging, especially in grid-to-vehicle (G2V) mode during nighttime or periods of low solar irradiance [2-3].

Several studies have investigated power quality issues in EV charging. Sliding mode control (SMC) has been employed to regulate DC link voltage under varying irradiance conditions, but it does not prevent grid pollution in G2V mode. Other approaches have used static compensators to integrate AC and DC buses, reducing current harmonics are vehicle-to-grid (V-G) mode, though they fail to ensure harmonics are charging free in G2V mode.This study introduces a control technique designed to achieve harmonic-free charging for EVs, ensuring clean grid currents even during nighttime or low irradiance conditions. Unlike conventional methods that connect the PV array source directly to a DC bus, the proposed system integrates the PV array source at an AC grid side. This configuration allows the grid to charge EV batteries without causing current distortions [4].

2. DISTRIBUTION SYSTEM INCORPORATING PV AND UPQC

Electric utilities are required to deliver electricity at specified voltage and frequency levels while conforming to established power quality (PQ) standards. Present-day PQ issues include excessive reactive power demand due to low power factor loads, harmonic distortions introduced by non-linear equipment such as converters, computers, and arc furnaces, and voltage imbalances resulting from single-phase load connections. Solar photovoltaic (PV) systems, as clean and renewable energy sources, contribute to lowering both energy consumption and distribution losses. Nonetheless, a major limitation of many PV systems is their inability to provide adequate reactive power support [5-6].

An advanced technology that addresses these concerns is the Unified Power Quality Conditioner (UPQC), which integrates two Voltage Source Inverters (VSIs): a Distribution Static Synchronous Compensator (D-STATCOM) and a Dynamic Voltage Restorer (DVR). The D-STATCOM is responsible for reactive power compensation and harmonic filtering, whereas the DVR handles voltage fluctuations such as sags and swells. When operated in differential mode, these components significantly enhance power quality. Although the frequency within the Indian power grid remains relatively stable, maintaining consistent voltage levels remains a challenge. Even a 1% variation in voltage can lead to approximately 2% change in power for impedance-type loads. According to IEEE Standard 1159 (1995), power quality guidelines permit voltage dips between 10% and 90%, with durations ranging from 0.01 to 0.06 seconds [7-8].

Conventional reactive power solutions like capacitor banks and reactors are limited in their dynamic response. In contrast, the D-STATCOM can inject reactive power in real time and, when combined with a Battery Energy Storage System (BESS), also supply active power. Integrating a solar PV system with UPQC not only improves voltage regulation and reactive power control but also facilitates the seamless incorporation of renewable energy sources, addressing key challenges in modern power distribution networks [9].

3. CIRCUIT TOPOLOGY OF UPQC

Figure.1 illustrates the circuit layout of a single-phase Unified Power Quality Conditioner (UPQC) utilizing differential inverters. The power source is modeled as a 230 V single-phase supply, representing the R-phase of a three-phase, four-wire distribution network with a neutral connection. The DC link is maintained at 360 V, and a Battery Energy Storage System (BESS) of the same voltage is incorporated into this link [10-11]. The primary function of the shunt-connected D-STATCOM controller is to supply reactive power to the grid at the point of common coupling (PCC). By ensuring that the source only provides real power along with system losses, unity power factor operation can be attained. To achieve this, the reference current must be accurately generated. The series-connected DVR is responsible for addressing voltage disturbances such as sags and swells within the distribution network [12].

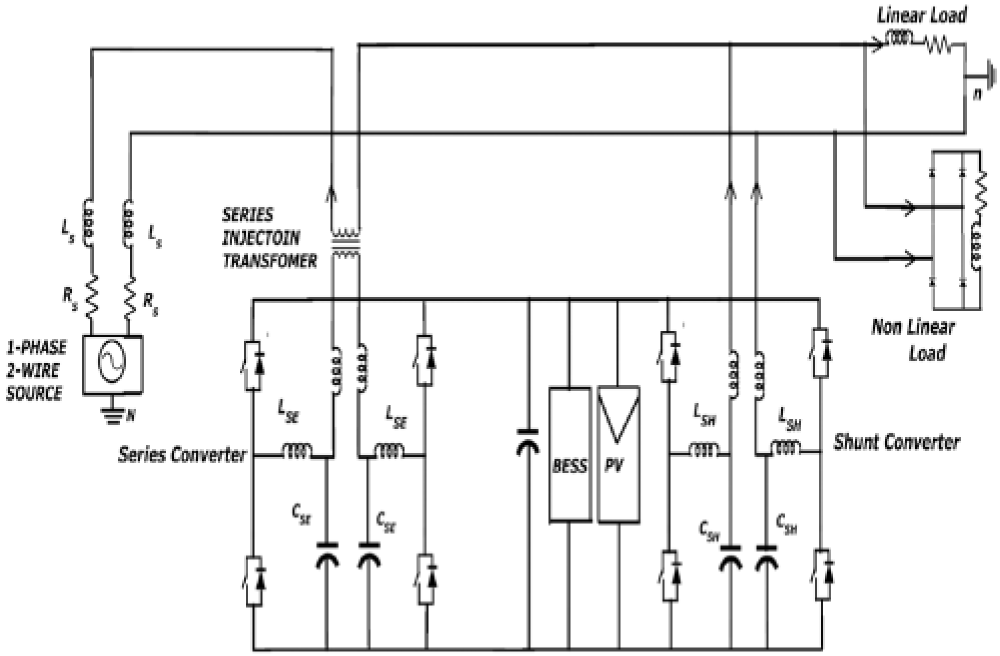

Fig.1. Circuit diagram of 1-phase UPQC using differential inverters

4. SIMULATION RESULTS AND DISCUSSION

By using MATLAB/Simulink to simulate the proposed UPQC system as shown in fig.2.

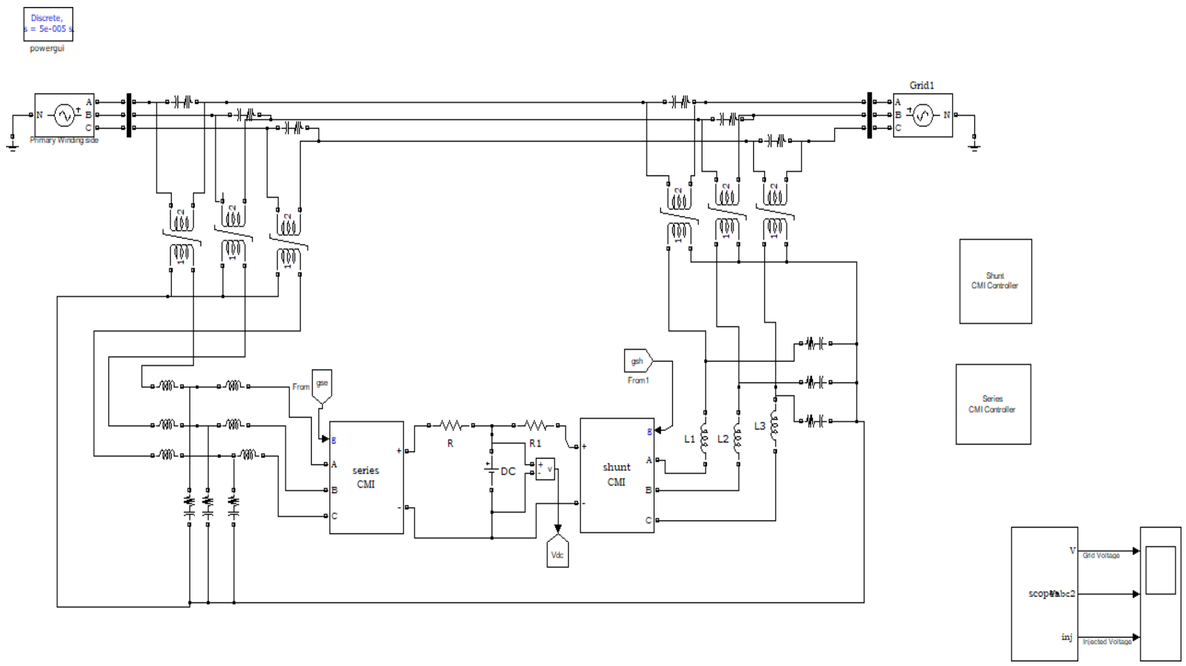

Fig.2. simulation diagram of proposed UPQC with PV system

The diagram below illustrates the simulation setup and its control mechanism.The PV system simulation is carried out using a solar-integrated MATLAB function. The system operates with an open-circuit voltage of 360 V and powers a 10 kW load over a duration of 10 hours, resulting in a total battery storage requirement of 100 kWh. Each battery cell is rated at 12 V. To achieve the necessary DC bus voltage of 360 V, 30 cells must be connected in series. With each cell offering a capacity of 100 Ah, achieving the desired total capacity of 278 Ah requires configuring three parallel strings of 30 series-connected cells.

In this case, the photovoltaic (PV) system operates at its maximum capacity of 28 kW. Half of this power (14 kW) is allocated to the electric vehicle (EV) load, maintaining a steady voltage of 760 V at the voltage source converter (VSC), while the remaining 14 kW is fed into the grid. When the battery's state of charge (SOC) drops to a critical level, the MSCC control initiates a mode transition, enabling the EV to supply power back to the grid in vehicle-to-grid (V2G) mode. During this stage, the total power delivered to the grid, combining contributions from both the EV and PV system, reaches 41.5 kW.

Figure.3a presents the source voltage waveform when the UPQC is active, displaying voltage values comparable to those in Figure2. Figure3b illustrates the load voltage waveform with the UPQC in operation, showing a peak value of 320 V. The corresponding source current waveform is depicted in Figure 3c, reflecting the same transient and steady-state loading conditions. The source current remains stable between 0.1 and 0.4 seconds, reaching a peak of 60 A, following the expression is=60sin(ωt)i_s = 60 \sin(\omega t)is=60sin(ωt). This current represents the demand for 10 kW of active power along with system losses. Importantly, the source current maintains a unity power factor throughout voltage sags and swells when the UPQC is in service. Figure 3d displays the load current waveform.

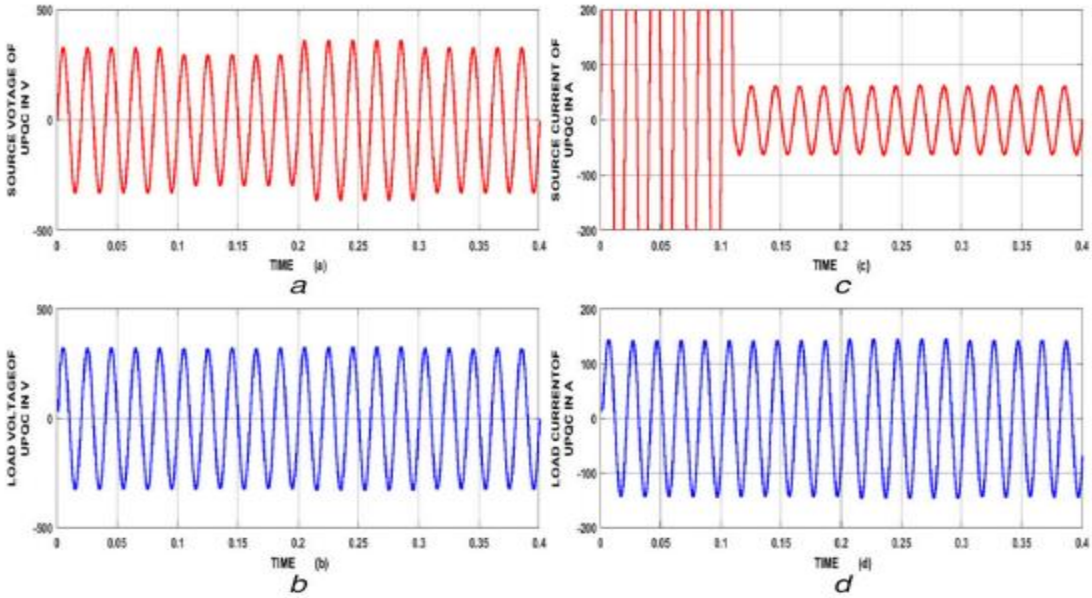

Fig.3.(a) Source voltage, (b) Load voltage, (c) Source current during transient loading, sag, swell and normal conditions, (d) Load current with UPQC

Figure 4a displays the source voltage waveform with the UPQC in operation under transient loading conditions on the PV side. Figure 4b illustrates the corresponding load voltage waveform, where the peak voltage is observed to be 320 V

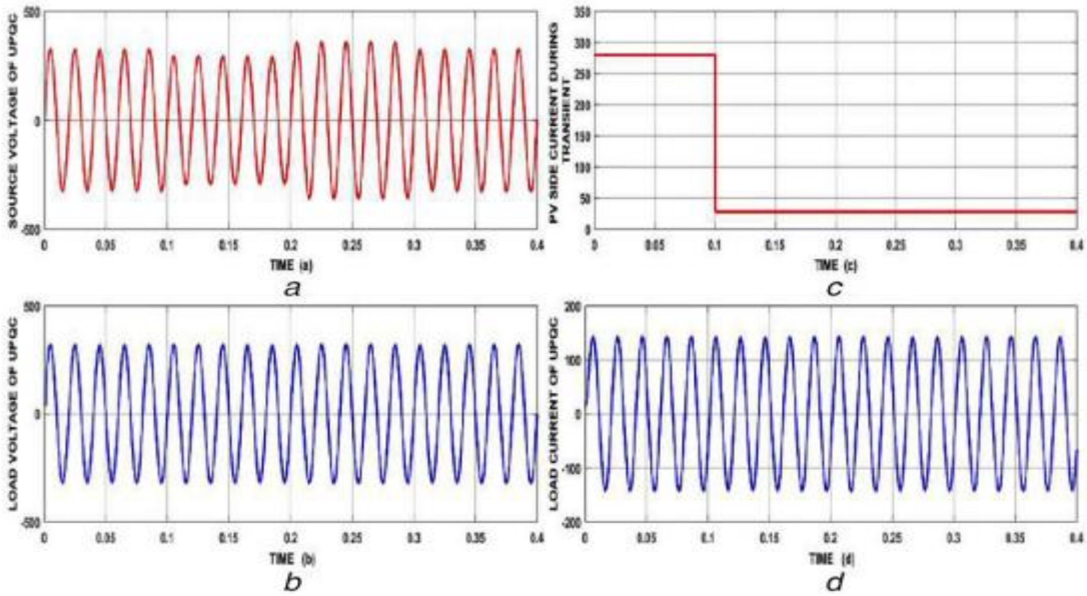

Fig.4.(a) Source voltage, (b) Load voltage, (c) PV side current during transient, (d) Load current with UPQC

In Figure 4c, the PV side current is shown under a transient loading condition, where a 280 A DC load is applied between 0 and 0.1 seconds. This condition is created using a switching mechanism and a delay timer. The transient load is designed to be ten times greater than the standard PV integration current of 28 A, which corresponds to a 10 kW load. After 0.1 seconds, the current returns to the normal value of 28 A up to 0.4 seconds. Figure 4d presents the load current waveform for a load voltage of 320sin(ωt)320 \sin(\omega t)320sin(ωt), showing a peak current of 140 A. Despite the presence of a transient disturbance on the PV side, the UPQC effectively sustains both load voltage and current, demonstrating its robustness.

5. CONCLUSION

The research presents a simulation of a 20 kVA single-phase Unified Power Quality Conditioner (UPQC) within a PV-integrated distribution system, using a reduced DC link voltage of 360 V. The simulation is performed in MATLAB R2016a with the ode23tb solver. The total system load is 22 kVA, and the voltage is effectively maintained at 226 V. Despite voltage sags and swells, the system consistently delivers a load voltage of 200 V, demonstrating its cost-effective and reliable performance. This configuration is especially suitable for PV-based distribution networks and power producers aiming to meet power quality standards. Future work includes developing a 100 kVA, three-phase, four-wire UPQC, tailored for critical applications such as hospitals.

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