

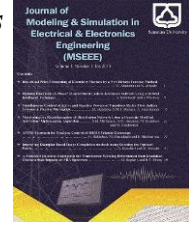


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Simulation and Experimental Implementation of a STATCOM for Power Factor Improvement in Distribution Networks

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Abstract — The increasing penetration of nonlinear loads in modern distribution networks has intensified challenges related to reactive power demand, voltage instability, and power quality degradation. This paper presents a comprehensive methodology for the design, simulation, and experimental implementation of a transformer-less Static Synchronous Compensator (STATCOM) for power factor improvement. Unlike conventional designs, the proposed STATCOM employs an undamped LCL filter, i.e., without any damping resistor, to eliminate switching harmonics. The removal of the damping resistor reduces power losses, hardware cost, and circuit complexity. However, it introduces the risk of resonance instability, which is addressed by analytically optimizing the filter parameters to achieve inherent damping. The STATCOM is simulated in MATLAB/Simulink under various loading scenarios and experimentally implemented using an STM32 microcontroller. Experimental results show a deviation of less than 5% from simulation results. The output current remains nearly sinusoidal under all tested power factor conditions, confirming the effectiveness of the undamped LCL filter. The proposed STATCOM offers a practical, low-cost, and reliable solution for reactive power compensation in real-world distribution networks.

Keywords — STATCOM, Power Factor Correction, Undamped LCL Filter, Reactive Power Compensation, Distribution Networks, Experimental Implementation.

1. INTRODUCTION

The rapid growth of nonlinear and switching-type loads — such as variable-speed drives, power electronic converters, and industrial automation systems — has significantly altered the behavior of modern distribution networks [1]. The use of STATCOMs is increasing in universities and industrial plants, and research on STATCOMs is also expanding, helping researchers to further improve their performance [2]. These loads draw substantial reactive power and inject harmonic currents into the grid, resulting in voltage distortion, increased line losses, and reduced equipment lifespan.

Power factor degradation is one of the most critical consequences of excessive reactive power demand. A low power factor increases the RMS current in transmission and distribution lines, leading to higher copper losses, transformer overheating, and reduced system efficiency. Utilities often impose penalties on consumers with poor

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power factor, highlighting the economic importance of reactive power compensation.

Traditional compensation methods, including capacitor banks and shunt reactors, offer limited controllability and slow response. Their performance deteriorates under fluctuating loads and harmonic-rich environments. With advancements in power electronics, active compensators, particularly the Static Synchronous Compensator (STATCOM), have emerged as superior alternatives. STATCOM provides fast dynamic response, precise reactive power control, and improved voltage regulation independent of system voltage magnitude [3].

A. Background and Literature Review

STATCOMs can achieve various objectives in transmission lines and distribution networks. The development of STATCOM technology began many years ago, and numerous achievements have been made in this field, the most important of which are reactive power compensation and power factor correction.

Reactive power is essential for establishing magnetic fields in inductive equipment such as motors, transformers, and reactors. Nevertheless, excessive reactive power demand causes voltage drops, increased line currents, and reduced system efficiency. Improving power factor reduces these adverse effects and enhances overall network performance. The power factor of a system must be set to a value suitable for the generation unit, transmission lines, and load consumption. There are two approaches for reactive power compensation: passive and active compensation. Both techniques are described below.

1) Passive Compensation Techniques

Passive compensators — such as capacitor banks, shunt reactors, and passive filters — have been widely used due to their simplicity and low cost. However, they suffer from several limitations:

- Inability to respond to rapid load variations
- Sensitivity to voltage fluctuations
- Resonance issues with network impedance
- Limited harmonic mitigation capability

On the other hand, although the implementation of this technique is easier than active techniques, it remains effective for its cost.

2) Active Compensation Techniques (FACTS Devices)

FACTS devices provide dynamic and precise control of reactive power. Among FACTS devices, some are more suitable for power distribution systems:

- SVC offers a moderate dynamic response
- TCSC and SSSC are suitable for transmission systems
- STATCOM provides the fastest response and highest controllability

STATCOM's ability to inject or absorb reactive power independent of grid voltage makes it ideal for distribution networks with fluctuating loads. Moreover, STATCOM can also help distribution networks absorb harmonics to improve power quality.

B. Novelty and Contributions

In comparison with previous studies [4]–[5], this paper presents the following key contributions:

- A comprehensive design methodology for a transformer-less STATCOM with an undamped LCL filter specifically intended for distribution networks.
- Experimental validation under three distinct power factor conditions (0.5 inductive, unity, and 0.5 capacitive) with detailed oscilloscope waveforms.
- A systematic comparison between simulation and hardware implementation, demonstrating a deviation of less than 5%.
- A practical, low-cost implementation using an STM32 microcontroller, making the design suitable for real-world deployment.

The remainder of this paper is organized as follows. Section II presents the STATCOM system modeling, including the dq-frame mathematical model, DC-link capacitor sizing, and LCL filter design. Section III describes the control strategy. Section IV discusses simulation studies. Section V presents the hardware implementation. Section VI provides experimental results. Finally, Section VII concludes the paper.

II. STATCOM SYSTEM MODELING

A. Overall Architecture

A STATCOM typically consists of several parts. A STATCOM is manufactured from two main units: the control unit and the power unit. In recent decades, control units have transitioned from analog to digital. In today's world, digital units are microprocessor-based, which are more flexible than analog control units and enable additional controls such as variable calculation. Overall, a STATCOM is manufactured from the following units:

- A three-phase Voltage Source Converter (VSC)
- A DC-link capacitor
- An LCL output filter
- A digital control unit

In this architecture, the STATCOM is connected directly to the grid without a transformer.

B. dq-Frame Mathematical Model

The synchronous reference frame (dq transformation) simplifies AC quantities into DC-like variables. This allows independent control of the active and reactive components of the converter current. The transformation equations are based on:

- Park transformation
- Grid synchronization via PLL
- Decoupled control of d-axis and q-axis currents

The phase lock loop (PLL) unit employs *abc* to *dq* transformation to calculate and align the converter phase with the grid phase, enabling reactive power absorption or injection. The main advantage of this transformation is

that the STATCOM can control reactive power without any active power transfer between itself and the grid [6]. This feature enables more effective reactive power control. The PLL is calculated from the following equations:

$$v_a = \sqrt{2} V \cos \varphi \quad (1)$$

$$v_b = \sqrt{2} V \cos \left(\varphi - \frac{2\pi}{3} \right) \quad (2)$$

$$v_c = \sqrt{2} V \cos \left(\varphi + \frac{2\pi}{3} \right) \quad (3)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \begin{bmatrix} \cos \theta & \cos \left(\theta - \frac{2\pi}{3} \right) & \cos \left(\theta + \frac{2\pi}{3} \right) \\ \sin \theta & \sin \left(\theta - \frac{2\pi}{3} \right) & \sin \left(\theta + \frac{2\pi}{3} \right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (4)$$

where v_a , v_b , v_c stand for the instantaneous phase voltages of the grid, V is the RMS value of the phase voltage, φ is the phase angle with respect to the system voltage and the angle θ is the angle between the axis of phase a and the d -axis. In order to convert the three-phase AC quantities into DC-like variables, the Park transformation (also known as the dq -transformation) is employed. This transformation projects the three-phase stationary frame (abc) onto a synchronously rotating reference frame (dq) that rotates at the grid angular frequency. The d -axis component represents the active power-related quantity, while the q -axis component represents the reactive power-related quantity. The transformation matrix is given by:

$$V_d = \frac{2}{3} \left[v_a \cos \theta + v_b \cos \left(\theta - \frac{2\pi}{3} \right) + v_c \cos \left(\theta + \frac{2\pi}{3} \right) \right] \quad (5)$$

$$V_q = \frac{2}{3} \left[-v_a \sin \theta - v_b \sin \left(\theta - \frac{2\pi}{3} \right) - v_c \sin \left(\theta + \frac{2\pi}{3} \right) \right] \quad (6)$$

In this transformation, the angle θ is derived from the PLL and represents the instantaneous phase of the grid voltage. The transformation effectively rotates the stationary abc reference frame to align with the grid voltage vector. As a result, under balanced and sinusoidal grid conditions, the dq components become DC quantities, which significantly simplifies the control design.

The main advantage of this transformation is that the STATCOM can control reactive power without any active power transfer between itself and the grid [7]. This feature enables more effective reactive power control. For PLL synchronization, V_q must be equal to zero. After V_q equals to zero, the PLL is synchronized with the grid voltage and then the STATCOM can be connected to the grid for reactive power exchanging.

C. DC-Link Capacitor Modeling

The DC-link capacitor stabilizes the converter voltage and provides the necessary energy buffer. To facilitate active power transfer, the DC-link capacitor stores energy in the electric field to adjust the DC-Link voltage across the capacitor at a prespecified. Sizing the DC-link capacitor depends on the following parameters:

- Voltage ripple constraints
- Transient energy requirements
- Switching frequency

The DC-link capacitor size is calculated from the following equation:

$$C = \frac{I_{DC}}{2f_{sw}\Delta V_{max}} \quad (7)$$

ΔV_{max} is the voltage ripple of the DC-link across the power electronics switches, and I_{DC} is the DC current that stores active power in the capacitor. In this equation, f_{sw} is switching frequency of power electronics switches. f_{sw} is 10 kHz in this implementation. C is value of DC-link capacitor [8]. When the STATCOM is in operation, the DC-link voltage experiences frequent fluctuations depending on the switching frequency. Therefore, the DC-link capacitor plays a critical role, affecting the output voltage, power quality, output power factor, and the STATCOM's dynamic response to reactive power variations.

D. LCL Filter Modeling

The LCL filter attenuates switching harmonics and ensures compliance with grid standards. LCL filters can include a damping resistor to reduce harmonics [9]. In this paper, the LCL filter does not have a damping resistor [4]. Its design involves:

- Selecting converter-side inductance
- Selecting grid-side inductance
- Determining filter capacitance

III. CONTROL STRATEGY

Controlling a STATCOM for power factor purposes can be achieved with various algorithms such as dq current control, PQ control, and droop control. This paper focuses on dq control.

This method regulates converter currents directly in the dq frame, enabling fast and accurate reactive power compensation. PI controllers regulate the d -axis and q -axis currents independently. A PI controller can regulate current quickly and compute reactive power within milliseconds [10]. When correctly tuned, it can also regulate voltage and current to reduce ripple and improve power quality alongside power factor [11]. This capability assists the STATCOM in effectively regulating and compensating reactive power. For this algorithm, currents must be calculated in dq form, so they are

transformed from abc to dq . Currents are calculated using the following transformation:

$$\begin{bmatrix} I_{d,s} \\ I_{q,s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} i_{a,s} \\ i_{b,s} \\ i_{c,s} \end{bmatrix} \begin{bmatrix} \cos\delta & \cos\left(\delta - \frac{2\pi}{3}\right) & \cos\left(\delta + \frac{2\pi}{3}\right) \\ \sin\delta & \sin\left(\delta - \frac{2\pi}{3}\right) & \sin\left(\delta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (8)$$

$I_{d,s}$ and $I_{q,s}$ are the dq output currents of the STATCOM measured in the rotating reference frame. In this transformation, δ is equal to θ and is calculated from the PLL section. Calculating currents with θ yields a better power factor. These transformations are also calculated for the grid current and the load current.

IV. SIMULATION STUDIES

For this study, MATLAB/Simulink is used to emulate the STATCOM's behavior under various load conditions. These scenarios demonstrate that the STATCOM can control the power factor under load variations. The tests simulated in Simulink are described below.

A. Load Variation Tests

Sudden load changes are applied to evaluate the power factor response of the STATCOM. Results show:

- Fast reactive power compensation
- Reactive power compensation time

B. Voltage Sag Tests

Voltage sag conditions are simulated to evaluate the STATCOM's voltage support capability. The STATCOM injects reactive power to restore voltage levels. In addition to reactive power compensation, the STATCOM can regulate the PCC voltage, which is important for grid stability and reactive power stabilization [12].

V. HARDWARE IMPLEMENTATION

A. Power Stage

The hardware prototype includes:

- A DC-link capacitor sized based on analytical calculations
- A three-phase IGBT inverter
- An LCL filter designed according to simulation parameters

The first step in STATCOM implementation is to validate the simulation in Simulink under load variations, test IGBT protection, and verify output currents. In this paper, after simulation and verification of results, the outputs are taken from Simulink and the STATCOM hardware is implemented.



Fig. 1. Hardware implementation of STATCOM

Fig. 1 shows the complete hardware prototype of the proposed STATCOM, including the three-phase IGBT inverter, the undamped LCL filter, the DC-link capacitor, and the STM32 microcontroller board. The power stage and control circuitry are mounted on a compact chassis, demonstrating a low-cost and practical implementation suitable for real-world distribution networks.

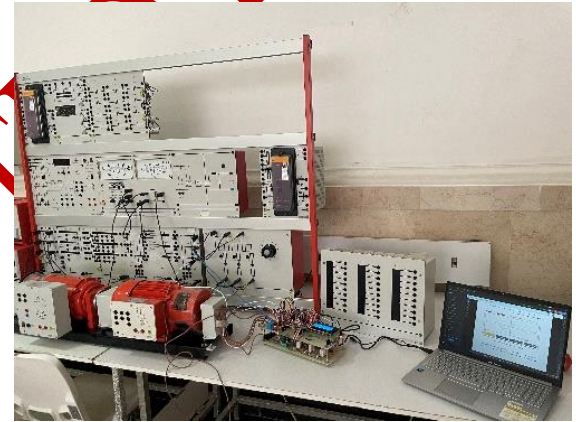


Fig. 2. STATCOM test in the laboratory

Fig. 2 presents the laboratory test setup used to validate the proposed STATCOM, consisting of programmable RLC load banks, a DC power supply, measuring instruments, and a laptop for real-time monitoring and data acquisition. The experimental results obtained from this setup confirm the effectiveness of the undamped LCL filter under various power factor conditions.

B. Control Hardware

The STM32 microcontroller is a general-purpose microcontroller used for many devices such as motor drives, cycloconverters, and others. In this paper, an STM32 microcontroller is used for:

- Real-time current and voltage sampling
- dq transformation
- PI control loops
- SPWM generation

SPWM generation is performed by the microcontroller. The main goal of SPWM generation is to control the power factor better than other compensators. With

SPWM, achieving sinusoidal voltage and current is improved, which also affects reactive power stability and enhances the connection between the grid and STATCOM [11].

The STM32 calculates the above quantities to control reactive power. In this work, the STM32 is connected to the grid and STATCOM via voltage and current sensors. The voltage sensor is ZMPT101B, and the current sensor is ACS712 20A.

VI. EXPERIMENTAL RESULTS

Hardware implementation parameters are derived from Simulink. The parameters of the STATCOM hardware are shown in Table I. Sensors and power factor values were calibrated, and deviations were less than 1.5% from real values.

TABLE I
Parameters of STATCOM Hardware

$L_1\text{-Filter } (\mu H)$	180
$C_{Filter} (nF)$	150
$L_2\text{-Filter } (\mu H)$	180
$C_{DC\text{-}Link} (\mu F)$	86
$I_{Peak,IGBT} (A)$	24.06
$R_{Snubber} (\Omega)$	150 2^W
$C_{Snubber} (nF)$	10

The hardware prototype was tested under various loading conditions. Results show:

- Output voltage waveform closely matches simulation
- Reactive power injection follows reference commands accurately
- Measured currents and voltages exhibit minimal distortion
- Experimental values deviate less than 5% from simulation results

The hardware was tested under different load consumptions. The test load is an *RBC* load. Due to *IGBT* switching limitations, the load power factor was tested between 0.5 inductive and 0.5 capacitive. Table II and Table III compare the computer simulation results with experimental implementations.

TABLE II

Comparison of Current Values Between Simulation and Experimental

Power Factor set point	Simulation			
	0.5 L	0.95 L	0.95 C	0.5 C
Grid current (A)	3.2	1.2	1.2	1.2
Load current (A)	3.2	1.2	1.2	2.6
Compensator current (A)	0	2.8	3.1	3.8
Power Factor set point	Experimental			
	0.5 L	0.95 L	0.95 C	0.5 C
Grid current (A)	3.25	1.23	1.23	1.23
Load current (A)	3.25	1.23	1.23	2.64
Compensator current (A)	0.2	2.74	3.07	3.73

Table II compares the grid, load, and compensator current values between simulation and experimental results under four power factor conditions. The grid current is significantly reduced from 3.2 A to 1.2 A in the 0.95 L and 0.95 C cases, demonstrating effective reactive current compensation. The compensator current closely follows the load demand, with a maximum deviation of less than 5% between simulation and experimental values. These results validate the accuracy of the proposed STATCOM hardware implementation and its current control strategy.

TABLE III
Comparison of Reactive power Values Between Simulation and Experimental

Power Factor set point	Simulation			
	0.5 L	0.95 L	0.95 C	0.5 C
Grid reactive power (var)	685	0	0	-262
Load reactive power (var)	685	620	685	685
Compensator reactive power (var)	0	613	685	947
Power Factor set point	Experimental			
	0.5 L	0.95 L	0.95 C	0.5 C
Grid reactive power (var)	700	0	0	-275
Load reactive power (var)	700	614	683	672
Compensator reactive power (var)	45	610	687	947

Table III is outputs of STATCOM of this paper. These findings in Table III confirm the reliability of the proposed design. Table III compares the reactive power values between simulation and experimental results under four different power factor conditions (0.5 L, 0.95 L, 0.95 C, and 0.5 C). The grid reactive power is reduced to zero for both 0.95 L and 0.95 C cases, demonstrating effective compensation. The compensator reactive power closely matches the load demand in all cases, with a maximum deviation of less than 5% between simulation and experimental values. These results confirm the accuracy of the proposed STATCOM design and the validity of the undamped LCL filter.

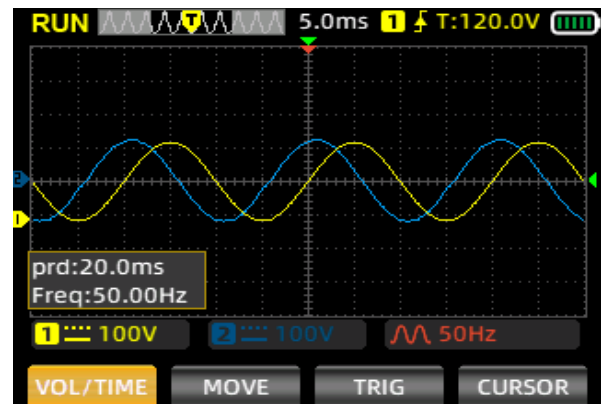


Fig. 3. Load power factor waves in oscilloscope

In Fig. 3, where the load power factor is set to 0.5 capacitive, the blue waveform represents the current and the yellow waveform represents the voltage. The nearly sinusoidal output current confirms the effectiveness of the designed *LCL* filter. The blue wave is current, and the yellow wave is voltage.

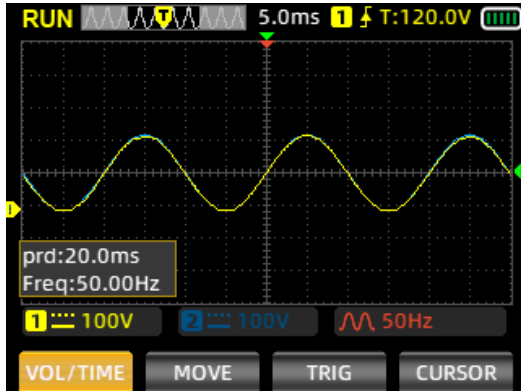


Fig. 4. Load power factor waves in oscilloscope

Fig. 4 shows the case with a unity power factor. The voltage and current waveforms are in phase, and the reactive power is nearly zero. Again, the output current remains nearly sinusoidal. The blue wave is the current, and the yellow wave is the voltage.

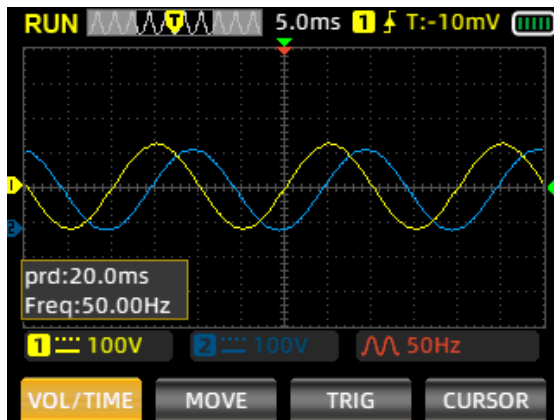


Fig. 5. Load power factor waves in oscilloscope

Fig. 5 presents the inductive case with a power factor of 0.5. The sinusoidal output current waveform further validates that the *LCL* filter parameters are suitable across different power factors. The blue wave is current, and the yellow wave is voltage.

VII. CONCLUSION

Unlike conventional STATCOM designs that rely on a damping resistor to mitigate resonance and stabilize the *LCL* filter, this paper proposes a transformer-less STATCOM with an undamped *LCL* filter (without any damping resistor) for power factor improvement in distribution networks. The elimination of the damping resistor reduces power losses, lowers hardware cost, and

simplifies the overall filter structure. However, removing the damping resistor introduces the challenge of resonance instability at the filter's natural frequency. To overcome this, the *LCL* filter parameters are analytically optimized to achieve inherent damping without any passive resistor. Experimental results confirm that the proposed undamped *LCL* filter produces a nearly sinusoidal output current with minimal harmonic distortion under all tested power factor conditions. The successful hardware implementation demonstrates that the undamped *LCL* filter is not only feasible but also advantageous for low-cost, high-efficiency STATCOM applications in modern distribution networks.

CONFLICT OF INTERESTS

Dr. Mostafa Jazaeri, the author of this paper, is the Director-in-Charge of the Journal of Modeling and Simulation in Electrical and Electronics Engineering (MSEEE). Still, he has no involvement in the peer review process to assess this work submitted to the journal. This paper was evaluated, and the Chief Editor of the MSEEE Journal managed the corresponding peer review.

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