

Power Quality Improvement by SCCS Using SRF and Park Transformation in PV Grid Integration Systems

Godugu Gowthami¹ Golla Koti Haritha², Ms. M. Kalpana³

¹B.Tech Student, Electrical and Electronics Engineering, Stanley College of Engineering and Technology for Women, Telangana, India

²B.Tech Student, Electrical and Electronics Engineering, Stanley College of Engineering and Technology for Women, Telangana, India

³Assistant professor, Electrical and Electronics Engineering, Stanley College of Engineering and Technology for Women, Telangana, India

Abstract - The increasing penetration of renewable energy sources, particularly photovoltaic (PV) systems, into the grid has raised concerns about power quality and reliability. This paper presents a comprehensive analysis and evaluation of power quality enhancement in PV integrated systems using a Unified Power Quality Conditioner (UPQC) with Synchronous Reference Frame (SRF) and Park transformation control strategies. The performance of UPQC with SRF and Park transformation with and without Sinusoidal current control strategies (SCCS), under various non-linear load conditions. The primary objective is to reduce harmonics, sags, swells, and voltage fluctuations, thereby enhancing power quality. The analysis utilizes MATLAB/Simulink software for simulation and comparison of Total harmonic distortion (THD). The results provide valuable insights into the effectiveness of UPQC with SRF and Park transformation for power quality improvement in PV integrated systems.

Key Words: Power Quality, UPQC, SRF, Park Transformation, SCCS, PV Integrated System and THD.

1.INTRODUCTION

The Deployment of photovoltaic (PV) systems has increased significantly globally as a result of the growing need for renewable energy. These systems are essential to the shift to sustainable energy sources because of their capacity to directly convert sunlight into power [1]. However, there are a number of difficulties in integrating PV systems into the electrical grid, especially when it comes to preserving grid stability and power quality [2]. To overcome these obstacles and improve PV system performance, a number of control solutions have been developed recently. The SRF and Park transformation techniques are two of these tactics that have become well-known because of how well they ease three-phase system control and analysis [3]. These techniques enable precise control and grid synchronization by transforming three-phase currents and voltages into a two-phase synchronous reference frame. To further improve the current and voltage parameters of PV systems, this project proposes

the combination of SRF and Park transformation methods with the Synchronous Current Control Strategy (SCCS) [5]. The SCCS method regulates the electricity that is fed into the grid, ensuring optimal power quality and stability. Additionally, the Second-Order Generalized Integrator (SOGI) based Phase-Locked Loop (PLL) is employed for precise detection of the utility voltage's phase angle, amplitude, and frequency [6]. This project aims to demonstrate the effectiveness of the proposed approach through simulation and experimental validation [7]. By integrating advanced control techniques, the project seeks to improve PV systems performance, ensuring reliable and efficient integration into the electrical grid.

1.1 UNIFIED POWER QUALITY CONDITIONER (UPQC)

A device known as a UPQC (Unified Power Quality conditioner) is used to correct for voltage distortion and imbalance in a power system. This ensures that the voltage at the load side is perfectly balanced, sinusoidal, and regulated [8]. Additionally, it corrects for load current harmonics, resulting in a source side current that is perfectly sinusoidal and free of distortions and harmonics. Shunt Active Power Filter (ShAPF) is used to compensate for load current harmonics and make the source current fully sinusoidal, free from distortions and harmonics [9]. UPQC is a combination of a Shunt Active Power Filter and a Series Active Power Filter [10]. The Shunt APF is connected in parallel to the transmission line. APF is connected in series with transmission lines [11]. Passive filters used to be employed to compensate for harmonics and voltage distortion, but they are no longer used because of their numerous drawbacks [12].

The parallel PWM converter is a controlled current source (ShAF), whereas the UPQC is a controlled voltage source (SAF) [13]. A tiny DC capacitor serves as a tiny energy-storing component, and the DC link is independent of the power source. When there is a line failure brought on by an excessive demand for reactive power or a voltage dip in the grid, the Fixed Speed Induction Generator

malfunctions and is cut off from the grid [14]. The Unified Power Quality Conditioner (UPQC) system depicted in the diagram is intended to improve power quality in electrical networks, especially when non-linear loads. Power from a source is transferred to a non-linear load via a series coupling transformer [15]. The UPQC uses both series and shunt components to reduce power quality problems. While a shunt filter and shunt converter are connected in parallel with the power line, a series low pass (LP) filter and series converter are linked in series [16]. The shunt and series converters are connected by a DC link, which permits coordinated operation. Both converters are monitored and controlled by a control system, which modifies their operation by utilizing control signal flow [17].

1.2 LITERATURE SURVEY

In order to effectively convert, regulate, and control electrical energy, power electronics are essential. Power electronics integration has become crucial for optimizing energy generation and high-power quality as renewable energy sources like solar power are increasingly used [18,19]. It emphasizes the use of photovoltaic solar technology, which turns sunlight into power using solar panels. It also covers the significance of power quality monitoring and mitigation, as well as the role that power quality plays in electrical systems [20]. The grid integration of solar photovoltaic (PV) systems presents serious power quality issues, such as flicker, harmonics, imbalance, and voltage sag. The control techniques which are used Park transformation and Synchronous Reference Frame (SRF) theory to overcome these problems [21]. By converting three-phase currents and voltages into a rotating reference frame, SRF theory makes it easier to control and analyses problems with power quality. Park transformation makes analysis and control easier by converting three-phase currents and voltages into a rotating reference frame (dq0) [22]. To enhance power quality, unified power quality conditioners (UPQC) and shunt active power filters (SAPF) have been used. These gadgets can improve power quality and lower harmonics when used with sophisticated control strategies like PI and PID controllers. These methods have the advantages of higher efficiency, lower losses, and better power quality. By developing SRF theory and Park transformation, scientists can improve grid-integrated solar PV systems' dependability and efficiency even more. Future studies should focus on creating increasingly complex control strategies and using energy storage devices to guarantee grid dependability and stability [23]. Harmonic compensation and fundamental component extraction are two areas where the SRF approach. Combining Sinusoidal Current Control strategy with SRF and Park transformation that can be effective way to manage the inverter output and lessen power quality problems. Particularly in some situations with non-linear loading,

this hybrid technique allows for precise grid synchronization and dynamic power disturbance adjustment. PV grid integration System where the inverter manages power injection and is essential to preserving grid stability [24].

2. METHODOLOGY

2.1 SYNCHRONOUS REFERENCE FRAME STRATEGY (S.R.F)

In this approach, the angle θ with regard to the α - β frame used in the p-q theory determines the reference frame d-q. For the traditional SRF approach to be employed in aviation power utilities and effectively compensate for the neutral current, only minor adjustments are needed. Because the zero-sequence component of current has not been taken into account, the zero-sequence subtract block removes the zero-sequence current from the load current. The output current then only consists of positive and negative sequence components, and following its park transformation, it only consists of instantaneous active and reactive current in the d-q frame. The dc and ac components of the active current are divided by a low-pass filter in order to compensate for the reactive and harmonic currents. By subtracting the load currents from the reference current, the active current passes through a low-pass filter and the signal from the dc voltage regulator is combined with a park counter-transformation.

1. Clarke Transformation (Stationary to Alpha-Beta Frame)

$$[v_\alpha] = \begin{bmatrix} 2 & 1 & 1 \\ 3 & 3 & 3 \end{bmatrix} [v_a]$$

$$[v_\beta] = \begin{bmatrix} 0 & 2 & -1 \\ 3 & 3 & 3 \end{bmatrix} [v_b]$$

$$[0] = \begin{bmatrix} 0 & 1 & -1 \\ 3 & 3 & 3 \end{bmatrix} [v_c]$$

- v_a, v_b, v_c are the three-phase voltages.
- v_α, v_β are the two-phase voltages in the alpha-beta frame.

2. Alpha-Beta to d-q Transformation (Synchronous Frame)

$$[v_d] = [\cos \cos(\theta) \quad \sin \sin(\theta)] [v_\alpha]$$

$$[v_q] = [-\sin \cos(\theta) \quad \cos \sin(\theta)] [v_\beta]$$

- v_d, v_q are the voltages in the synchronous d-q frame.

- θ is the angle of rotation of the synchronous frame.

3. Inverse Transformation (d-q to Alpha-Beta)

$$[v_\alpha] = [\cos \cos(\theta) \theta] [v_d]$$

$$[v_\beta] = [-\theta \theta] [v_q]$$

4. Inverse Clarke Transformation (Alpha-Beta to Three-Phase)

$$[v_a] = [1 \ 0] [v_\alpha]$$

$$[v_b] = \left[\frac{1}{2} \ \frac{\sqrt{3}}{2} \right] [v_\beta]$$

$$[v_c] = \left[\frac{1}{2} \ \frac{-\sqrt{3}}{2} \right] [v_\beta]$$

2.2 PARK TRANSFORMATION THEORY

In electrical engineering, the Park Transformation, also called the Direct-Quadrature-Zero (DQ0) transformation, is a mathematical tool that simplifies the analysis and control of three-phase systems by transforming three-phase quantities (abc) into two orthogonal components (d and q) in a rotating reference frame. This transformation reduces the complexity of control tasks such as current regulation in motor drives and inverters by making AC quantities appear as DC values. The inverse Park Transformation allows the controlled DC quantities to be converted back to three-phase AC signals for real-world applications.

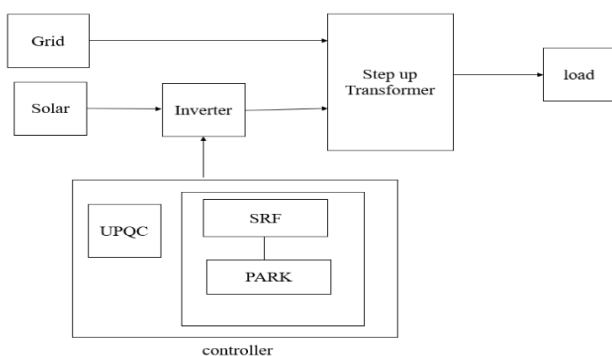


Figure 1:Block diagram of SRF and Park transformation without SCCS

In this block diagram shows the 3-phase generated in the control techniques. source block is generated with fluctuations, voltage sags, swells and harmonics in that sag generated with heavy loads to control the voltage sags by using controllers. The 3-phase VI measurement is measuring the parameters i.e., voltage and current with RLC load and diode rectifier through non-linear load. Solar having PV ray's irradiance to increment or decrement

temperature 25C by connecting the current controlled source. The PN junction integrated with silicon it will be highly generated with boost converter through MOSFET. In this pulses and gate signals generated and Solar output inverter is converted DC to AC. Solar is linked with UPQC in that having the SRF and park transformation theory to inverter through a step-up T/F to load. In that volage and current will be generated with pure sinusoidal waveform to reducing these sags, swells and harmonics and improving the power quality.

Step-by-Step Derivation of Park Transformation

1. Three-Phase System:

Consider a balanced three-phase system with the phase voltages (or currents) represented as:

$$A(t) = A_m \cos(\omega t)$$

$$B(t) = A_m \cos\left(\omega t - \frac{2\pi}{3}\right)$$

$$C(t) = A_m \cos\left(\omega t + \frac{2\pi}{3}\right)$$

- A_m is the peak value.
- ω is the angular frequency.
- t is time.

2. Transformation to Two-Axis System (d-q axes)

- The goal of the park transformation is to transform these three-phase quantities into a two-axis (d-q) reference frame.
- The transformation matrix for this is:

$$T = \frac{2}{3} \begin{pmatrix} \cos(\theta) & \sin(\theta) & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{pmatrix} \begin{pmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{2} \end{pmatrix}$$

3.Application of Transformation Matrix

The transformed d-axis (A_d) and q-axis (A_q) components can be obtained by multiplying the transformation matrix with the original three-phase quantities $A(t)$, $B(t)$ and $C(t)$.

$$\begin{pmatrix} A_d \\ A_q \\ A_0 \end{pmatrix} = T \begin{pmatrix} A(t) \\ B(t) \\ C(t) \end{pmatrix}$$

$$A_d = \frac{2}{3} \left(A \cos(\theta) + B \cos\left(\theta - \frac{2\pi}{3}\right) + C \cos\left(\theta + \frac{2\pi}{3}\right) \right)$$

$$A_q = \frac{2}{3} \left(A \sin(\theta) + B \sin\left(\theta - \frac{2\pi}{3}\right) + C \sin\left(\theta + \frac{2\pi}{3}\right) \right)$$

$$A_0 = \frac{1}{3}(A + B + C)$$

4. Simplification Using Trigonometric Identities

Using trigonometric identities, the d-axis and q-axis components can be simplified as follows:

$$A_d = \frac{2}{3} \left(A_m \cos \cos (wt) \cos \cos (\theta) + A_m \cos \cos \left(\omega t - \frac{2\pi}{3} \right) \cos \cos \left(\theta - \frac{2\pi}{3} \right) + A_m \cos \cos \left(\omega t + \frac{2\pi}{3} \right) \cos \cos \left(\theta + \frac{2\pi}{3} \right) \right)$$

$$A_q = \frac{2}{3} \left(A_m \cos \cos (wt)\theta + A_m \cos \cos \left(\omega t - \frac{2\pi}{3} \right) + A_m \cos \cos \left(\omega t + \frac{2\pi}{3} \right) \sin \sin \left(\theta + \frac{2\pi}{3} \right) \right)$$

5. Final d-q Components

Since the three-phase quantities sum to zero in a balanced system, A_0 (zero sequence component) is zero. Thus, the final d-axis and q-axis components are:

$$A_d = A_m \cos \cos (\omega t - \theta)$$

$$A_q = A_m \sin \sin (\omega t - \theta)$$

The Park transformation converts three-phase quantities $A(t)$, $B(t)$, and $C(t)$ into two orthogonal components A_d and A_q in the rotating reference frame. This transformation simplifies the analysis and control of AC machine systems, making it easier to understand their dynamic behavior.

2.3 Sinusoidal Current Control Strategy (SCCS)

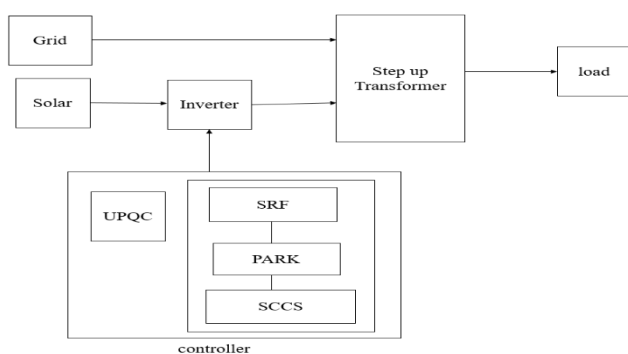


Figure 2:Block diagram of SRF and Park transformation with SCCS

The block diagram shows a system that combines solar energy with a grid system, including synchronization and power quality control methods. The system begins with a solar panel that transforms direct current (DC) into alternating current (AC) by feeding it into an inverter. Before being sent to the load and the grid, this AC power is first sent to a step-up transformer to raise the voltage

level. The system's operation is controlled by an advanced controller unit that uses methods like Park transformation, Synchronous Current Control Strategy (SCCS), and Synchronous Reference Frame (SRF). To guarantee the quality of the power sent to the grid, the controller additionally incorporates a Unified Power Quality Conditioner (UPQC). With this whole configuration, solar energy may be integrated effectively, preserving grid stability and power quality.

2.3.1 SCCS for ShAF (Shunt Active Filter)

Based on various studies on different control approach for ShAF and after observing their drawbacks, the proposed work has been carried out with a simple and old control strategy based on Instantaneous pq-theory. which representing the basic control strategy for shunt inverter control of a 3P3W system. The ShAF is very much close to the nonlinear load to draw fixed instantaneous power from the source and compensate the oscillating real power (p). The ShAF is supplied with a part of oscillating instantaneous active load current in a 3- ϕ system without neutral resulting a zero powered zero-sequence component.

$$\begin{bmatrix} v_0 & v_\alpha & v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 1 & \frac{-1}{2} & \frac{-1}{2} & 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v'_a & v'_b & v'_c \end{bmatrix}$$

Similarly, 3- ϕ line current can be converted into 2- ϕ by Clarke Transformation which helps in estimating true and complex power along with 2- ϕ voltage (v'_α ; v'_β). The illustration of the control block of AFC for sinusoidal current control technique.

$$\begin{bmatrix} i_0 & i_\alpha & i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 1 & \frac{-1}{2} & \frac{-1}{2} & 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}$$

The benefit of implementing the Clarke transformation is that it converts 3-phase system into 2-phase system and allows independent control in two phases. From the 3 instant powers, i.e., zero sequence component, active (p) and reactive (q) components, the instant phase voltages and line currents are as follows:

$$\begin{bmatrix} p & q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 & 0 & v_\alpha & v_\beta & 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_0 & i_\alpha & i_\beta \end{bmatrix}$$

From the above equation the active and reactive power

$$\begin{aligned} P &= v'_\alpha i'_\alpha + v'_\beta i'_\beta \\ q &= v'_\beta i'_\alpha - v'_\alpha i'_\beta \end{aligned}$$

The block diagram of SCCS epitomizes the entire algorithm of the controller for 3P3W ShAF which compensates the oscillating true power as well as the complex load power.

Later with the effect of LPF dynamic and PI-controller, dc voltage regulator addresses transients.

$$p_c = \tilde{P} = P - \underline{P}$$

\tilde{P} from p can be realized through selection of the power block to be compensated by a low pass filter with careful selection of cut off frequency due to implicit dynamics lead to compensate flaw in transients. The total imaginary power to be compensated is:

$$-q = -\underline{q} + \tilde{q}$$

3.3.2 SCCS for SAF

In the proposed work, instantaneous p-q theory on SAF is applied to a 3P3W system using the same control approach. SAF is meant for voltage rectification. The input for the control block meant for calculation of the instantaneous power PCC phase voltages with the compensation of line currents of the nonlinear load, i.e., a discriminated compensation characteristic for ShAF that performs as an open circuit for harmonic currents as produced by other nearby nonlinear loads.

$$\begin{bmatrix} v_{sa} & v_{sb} & v_{sc} \\ v_{ca} & v_{cb} & v_{cc} \end{bmatrix} = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}$$

Here the voltages are calculated by the dual pq - theory pretended with known currents, true and complex powers with the voltage components to be determined during the presence of series voltage compensation which is dual of compensation of shunt current) as follows:

$$\begin{bmatrix} p & q \\ v_0 & v_\alpha & v_\beta \end{bmatrix} = \begin{bmatrix} i_0 & 0 & 0 & 0 & i_\alpha & i_\beta & 0 & i_\beta & -i_\alpha \end{bmatrix}$$

The above equation leads to oscillating true power (p) and complex power (q) with zero sequence powers \underline{p}_0 and \tilde{p}_0 pretended as zero due to zero-sequence current. Along with oscillating powers, the instantaneous voltages to be injected by the SAF for load harmonic voltage compensation by using:

$$\begin{bmatrix} v'_{ca} & v'_{cb} \\ \tilde{p} & \tilde{q} \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta & i_\beta & i_\alpha \end{bmatrix}$$

A certain amount of $\Delta \underline{p}$ is added to \tilde{p} with an objective to compensate the losses. The reference voltages v'_{ca} and v'_{cb} are converted to abc reference by

$$\begin{bmatrix} v'_{ca} & v'_{cb} & v'_{cc} \\ v'_{ca} & v'_{cb} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{-1}{2} & \frac{\sqrt{3}}{2} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}$$

SAF is produced by load vibration active performance loads and generates tensions that need to be corrected by load harmonic voltage. This method guarantees a pure sinus-shaped waveform for the source-side voltage. SCC based on UPQC makes up the entire system that was inspected.

3.Results and Discussions

Two different control strategies have been simulated using MATLAB/Simulink to evaluate their performance. The simulation results clearly demonstrate that the every one of both schemes are proficient to effectively reduce the significant amount of THD in source current within limits.

A.SRF and PARK TRANSFORMATION (WITHOUT SCCS)

THD Source Current = 23.77%

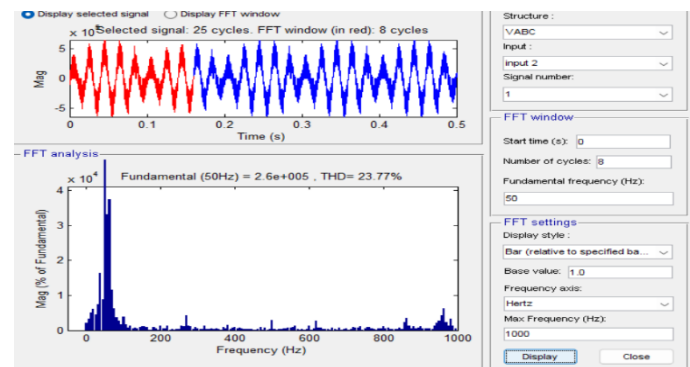


Figure 5:THD Source Current

The Total Harmonic Distortion (THD) in the source side current is 23.77%, indicating a significant presence of harmonic frequencies that can compromise power quality and system efficiency.

THD Load Current = 30.87%

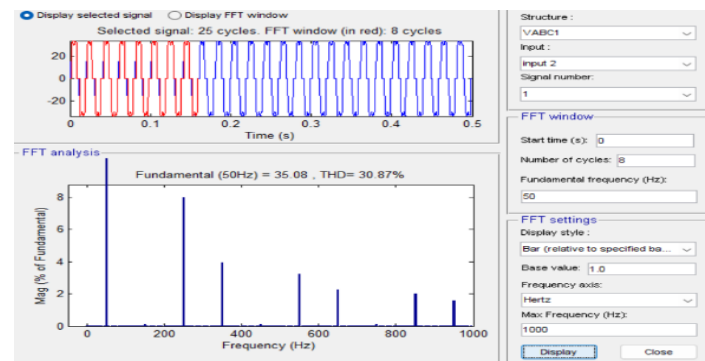


Figure 7:THD load current

The Total Harmonic Distortion (THD) in the load side current is 30.87% without the implementation of Synchronous Current Control Strategy (SCCS), indicating a significant distortion in the current waveform. This high THD value suggests that the load side current is not a clean sine wave, but rather a distorted waveform with a substantial amount of harmonic content. The absence of SCCS results in increased harmonic distortions.

B. SRF and PARK TRANSFORMATION (WITH SCCS)

THD Source Current = 23.23%

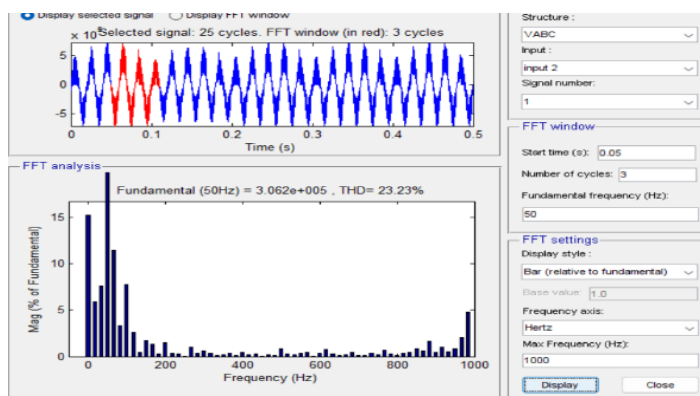


Figure 9: THD source current

The Total Harmonic Distortion (THD) in the source side current is 23.23%, indicating a significant presence of harmonic frequencies that can compromise power quality and system efficiency.

THD Load current = 0.81%

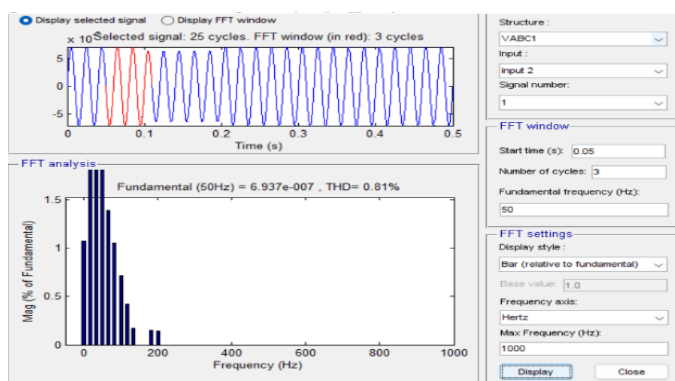


Figure 11: THD Load current

The Total Harmonic Distortion (THD) in the load side current is 0.81% with the implementation of Synchronous Current Control Strategy (SCCS), indicating a significant improvement in power quality. The SCCS has effectively reduced the harmonic distortion, resulting in a perfect sine wave, Minimal energy losses.

The implementation of SCCS has achieved a remarkable reduction in THD, from 30.87% to 0.81%, demonstrating its effectiveness in mitigating harmonic distortion and improving the overall performance of the electrical system.

Table 1: SRF and Park Transformation without SCCS

SRF and Park Transformation without SCCS	Total Harmonics Distortion (THD) %
Source Current	23.7%
Load Current	30.87%

Comparing the percentages of Total Harmonic Distortion (THD) for Source Current and Load Current under SRF and Park Transformation conditions without SCCS (Sinusoidal current control strategy) is shown in the table. At 30.87%, the THD for load current is higher than the THD for source current, which is recorded at 23.7%. Under the given circumstances, this suggests that the Load Current is subject to a higher degree of harmonic distortion than the Source Current. The absence of Sinusoidal Current Control Strategy (SCCS) can lead to increased harmonic distortion, potentially causing overheating and equipment damage, which underscores the importance of effective control strategies in maintaining optimal system performance and preventing detrimental effects on electrical equipment.

Table 2: SRF and Park Transformation with SCCS

SRF and Park Transformation with SCCS	Total Harmonics Distortion (THD) %
Source Current	23.23%
Load Current	0.81%

The table presents the Total Harmonic Distortion (THD) percentages for Source Current and Load Current with SRF (Synchronous Reference Frame) and Park Transformation with SCCS (Sinusoidal Current Control Strategy). The THD for the Source Current is 23.23%, while the THD for the Load Current is significantly lower at 0.81%. This indicates that the SCCS effectively reduces harmonics in the load current, resulting in a cleaner power supply to the load compared to the source. The control strategy effectively filters out harmonics from the source current, protecting the load from distortion and ensuring a high-quality power supply.

3. CONCLUSIONS

This project demonstrates the effectiveness of Unified Power Quality Conditioner (UPQC) in improving power quality in a 3-phase system under non-linear load conditions. This enables the development of advanced

power quality conditioning systems for renewable energy applications, facilitating smooth integration of solar energy into the grid. The comparison between the Synchronous Reference Frame (SRF) & Park transformation with and without Sinusoidal Current Control Strategy (SCCS) significantly improving power quality and reducing harmonics, sags, swells and voltage fluctuations. The analysis utilizes MATLAB/Simulink software for simulation and comparison of Total Harmonic Distortion (THD) with and without SCCS and improving power quality. This is achieved by the UPQC ability to compensate for the harmonic currents, resulting in a more sinusoidal and stable power supply. The analysis highlights the potential of UPQC with SCCS to enhance power quality in grid-tied photovoltaic (PV) systems, particularly under varying irradiance conditions

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