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Control Strategies for Enhancing Power Quality with Unified Power Quality Conditioner in a Solar-PV Integrated Utility System

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Abstract: The electrical utility systems are well-liked as local energy systems because of their capacity to incorporate renewable energy, enhance energy effectiveness and strengthen the resilience of the power system. These benefits do, however, come with specific complications regarding control and power quality (PQ). PQ within a utility system is paramount to ensure the appropriate operation of connected devices and the well-being of the overall system. As a result, both voltage quality & current quality are significant. Control strategies in conjunction with cutting-edge power electronics devices (PED) offer a solid framework to handle PQ challenges. Hence, this paper's proposed work discusses the application of a Solar-Photovoltaic (PV) fed Unified Power Quality Conditioner (UPQC) for power quality enhancement towards the supply grid network. The Solar-PV fed UPQC enhances PQ and maximizes solar energy utilisation, leading to an eco-friendly and cost-effective solution while injecting clean, renewable energy into the grid. In this paper, the control strategies for UPQC are based primarily on the Adaptive Leaky Least Mean Square (AL_LMS) algorithm as compared with the Synchronous Reference Frame (SRF) based theory for switching of series and shunt active converters of UPQC. This AL_LMS approach extracts reference signals to switch UPQC's shunt and series voltage source converters (VSCs) by iteratively updating the weights. Thus, the control strategy applied to Solar-PV fed UPQC mitigates voltage problems like voltage sag and swell, current harmonic distortions and other PQ issues. The work is done in MATLAB/ Simulation software and simulation outcomes show the effectiveness of Solar-PV fed UPQC in improving power quality by maintaining within the IEEE-519 Standards.

Introduction

Supplying consumers with electricity in the custom of sinusoidal voltages and currents with adequate magnitudes and frequencies near the point of common coupling (PCC) is one of the Utility system's main responsibilities. System and user equipment are designed and inspected based on sinusoidal voltages and currents with standardized/rated amplitudes and frequencies (Sabin et al., 2022). Power Quality (PQ) has always been a regular issue, and with the increase in the number of electrical appliances, these issues have increased significantly over the years. PQ problems, like voltage sag, voltage swell, harmonics, and flicker, can lead to disruptions, damage to sensitive equipment, and reduced efficiency in power supply systems. In this context, the application of Power Quality Enhancement (PQE) techniques has gained significant attention to mitigate power disturbances and voltage fluctuations (Bollen, 2000). To improve the functionality and stability of electric power systems and resolve issues with power quality, numerous devices and technologies have been proposed and put into practice. Flexible AC Transmission Systems (FACTS) devices are cutting-edge technological solutions for enhancing voltage regulation, besides stable and immediate apparent controlling of active and reactive powers at the fundamental frequency. Supplementary

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methods rely on distinctive power apparatuses that provide a range of alternatives, such as both shunt and series compensation of active along with reactive power to enhance power quality, voltage control associated with performance at fundamental and harmonic frequencies w.r.t. steady-state and dynamic situations (Fuchs et al., 2023; Hingorani and Gyugyi, 2000; Watanabe et al., 2018). UPQC is regarded as a customized power device that has emerged as a promising solution in alleviating both Voltage and Current PQ issues to electrical supply systems and it can be installed at the PCC in the distribution network (Agarwal et al., 2021). Its primary objective is ensuring continuous power quality improvement by regulating voltage and mitigating various PQ issues, such as voltage sags, swells, and harmonics. It consists of two components: an active power filter in series (SeAPF) and in the shunt (ShAPF) with a common DC link. The SeAPF is responsible for compensating voltage-related conflicts, such as sags and swells, while ShAPF mitigates current-related issues, such as harmonics and reactive power demand and makes regulations of DC-link voltage (Heenkenda et al., 2021; Satish et al., 2023).

Currently, a major area of research in industry and academia is the network interaction of renewable energy sources (RES) for improved system performance (Alam et al., 2021; Bajaj and Singh, 2020; Mlilo et al., 2021). The increasing integration of RES, particularly Solar-Photovoltaic (PV) systems, into the power grid has brought numerous benefits in terms of sustainability and reduced carbon emissions. Several advantages can be realized by integrating solar-PV system with UPQC. Firstly, Solar-PV system can serve as a clean RES, reducing the inevitability of traditional fossil fuel-based electricity generation and contributing to a more sustainable electricity supply. Secondly, the PV system can provide dynamic support to the active power, enabling the UPQC to regulate voltage under different load conditions and maintain a stable power grid (Jha et al., 2023; Suresh et al., 2018). To switch the series compensator and the shunt compensator, respectively, a reference load voltage signal and source current signals must be generated via the proper control structure for UPQC. Conventional time-domain techniques like Instantaneous Symmetric Component Theory (ISCT), Synchronous-Reference-Frame (SRF or d-q-0) technique, Instantaneous-Reactive-Power (IRPT or p-q) Theory have been utilized in several studies (Diab et al., 2021; Venkata and Reddy, 2023). The performance of these classical algorithms formed on p-q and d-q-0 theories is unsatisfactory when the load is unbalanced due to the low pass filters' insignificant performance. Several frequency domain methods are realized by means of Wavelet Transform and the Fast Fourier method, but these approaches consume more memory, elasticities, slower response, and require additional computational efficacy (Chawda et al., 2020; Martinez et al., 2022). A modified generalized second-order integrator-based control system is used to remove DC Offset current from the load (Chandrakala Devi et al., 2020). Soft Computing Techniques based control schemes (e.g., Neural Networks) are likewise used to distinguish and categorize power quality issues (Khetarpal et al., 2020; Sudheer et al., 2022; Venkata and Reddy, 2023).

In order to regulate a 3-Φ DSTATCOM providing harmonic and reactive power compensation for linear and nonlinear loads, research (Patel et al., 2019) affords an optimum step size Least Mean Square (LMS) algorithm. This algorithm adaptively calculates the step factor conditioned to calculate the active and reactive weights, establishes reference currents, and sets the VSC trigger pulses. In (Devena et al., 2023) study, a Variable Leaky Least Mean Square (VLLMS) control is used with an adaptive shunt active filter. By using the suggested method, a non-linear load's harmonic content, power quality, power losses, and power factor can all be improved. To lower THD in the Solar-PV system, study (Alhafadhi et al., 2022) suggests a strategy focusing on the Leaky LMS adaptive filter algorithm. The suggested filter significantly lowers the input’s signal harmonic content and delivers to the load.

This paper is structured as follows: The main system architecture is discussed in Section-II. The procedure of the control mechanism is elucidated in Section-III. Section-IV suggests controlling examination and explanations of MATLAB/Simulink results for non-linear load conditions and Section-V states the conclusions of the paper.

Proposed System Model

Figure 1 depicts the schematic representation of a proposed system model comprising of Solar-PV fed UPQC in a grid-connected mode. A coupled inductor (L_{se}) and a 3-Φ series injection transformer (T_{se}) are used to link the series VSC component of UPQC in series with the distribution grid. The Shunt VSC component has joined in parallel to the load point over the interface inductor (L_{sh}) and a capacitor (C_{dc}) links amongst the two compensators. To cut out the high-frequency constituent of voltage as a result of switching of VSCs, Ripple filters (L_r & C_r) are used. A reverse blocking diode across the DC-link capacitor links a Solar-PV module.

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A Non-Linear (R-L) load is connected to the circuit using the 3-Φ diode bridge rectifier.

Clarke's transformant. Again, these are changed from "α-β-0 coordinates" to rotating "d-q-0 coordinates"

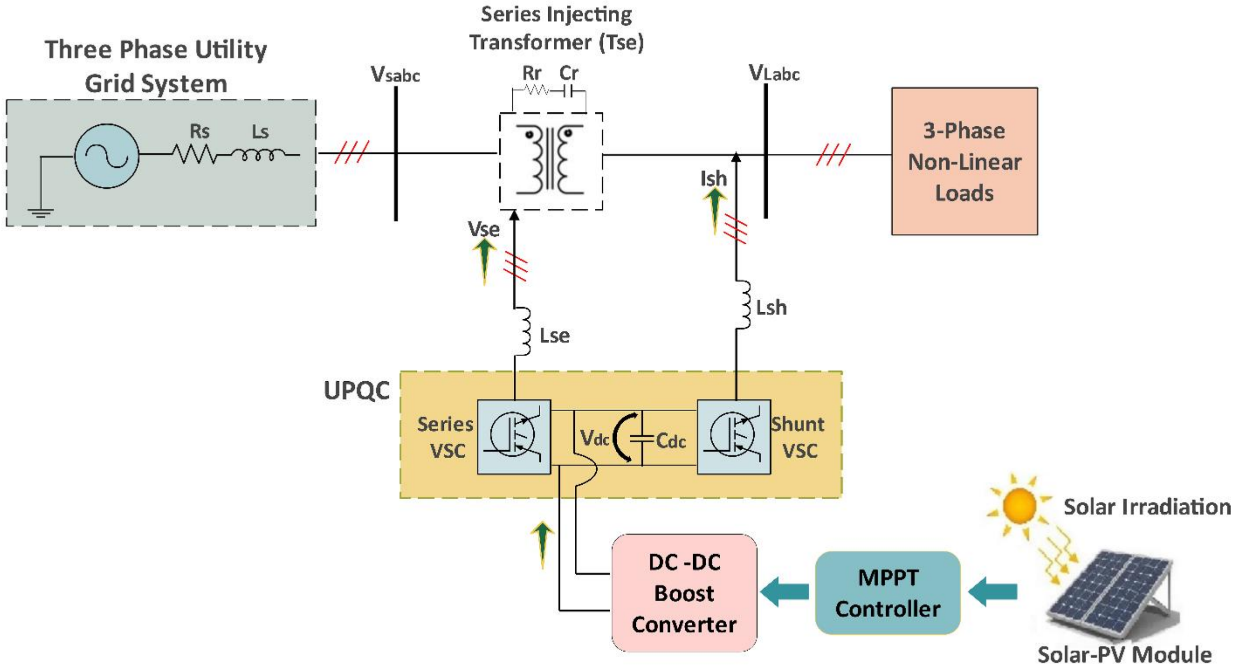

Figure 1. Illustration of a proposed Solar-PV fed UPQC system model

UPQC Control Methodologies

In the proposed Solar-PV fed UPQC integrated into the grid system, the main objective is meant to address the PQ challenges brought on by the 3-Φ non-linear load. Here, Shunt VSC is ensured by reducing the harmonics in the network source current and retaining DC-link voltage significantly. Additionally, it helps PCC meet its demand for reactive power. The load voltage's harmonics, Voltage sag and swell are all reduced through the series VSC. In this paper, in order to conjecture the reference signals meant to directive together shunt and series VSCs of UPQC, controlled approaches based on the SRF theory and the proposed AL_LMS algorithm are discussed to estimate the reference voltage and current for operating both series and shunt compensators. The proposed method gives a superior condition than the conventional SRF theory as the adaptive leakage parameter feature of the AL_LMS method offers higher performance in both steady-state and dynamic circumstances without the drift of weighted parameters exceeding the limits. So, the Solar-PV fed UPQC's performance is enhanced by fast and more precise estimate of the reference signals used for switching the VSCs.

Conventional SRF technique

The Synchronous Reference Frame (SRF) technique is often referred to as direct-quadrature-zero (or d-q-0) axis theory (Ahmad et al., 2020). This transformation results in the combination of Clarke's and Park's transformations. At first, voltages and currents in "a-b-c coordinates" are transfigured into "α-β-0 coordinates" by through Clarke's transformant. Again, these are changed from "α-β-0 coordinates" to rotating "d-q-0 coordinates" through Park's transform in the process. In this case, 'θ = ωt' denotes the angle through which d-q-0 frame rotates. The source voltage is considered when calculating this 'θ = ωt' and Phase Locked Loop (PLL) method (Hoon et al., 2019) is employed to this aspect.

SRF Control Scheme for Shunt VSC

The Figure 2 shows the d-q-0 Control Strategy for shunt VSC and reference signals to estimate are described as below. Firstly, Source's Currents (I_{sa}, I_{sb}, I_{sc}) & Voltages (V_{sa}, V_{sb}, V_{sc}), Load Currents (I_{La}, I_{Lb}, I_{Lc}) and DC-link voltage (V_{dc}) are detected. The load currents being then transfigured from "a-b-c coordinates" to "d-q-0 frame" using the below equation 1.

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & -\sin\left(\theta - \frac{2\Pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & \frac{1}{2} \end{bmatrix}\begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \ldots\ldots (1)$$

The components 'Id and Iq' are processed via a filter to obtain constant DC-components. The current signal Iddc is paired with the loss component produced by the tuned dc link error signal to obtain the direct axis reference current (Idref) as given in equations 2 and 3.

$$I_{l(t+1)} = I_{lt} + k_{pd}(V_{dc(t+1)} - V_{dc(t)}) + k_{id}V_{dc(t)} \ldots\ldots (2)$$

and

$$I_d^* = I_l + I_{ddc} \ldots\ldots (3)$$

Similarly, the current Iqdc is paired to tune supply voltage error signal for getting quadrature reference current (I_{qref}) as given by equation 4.

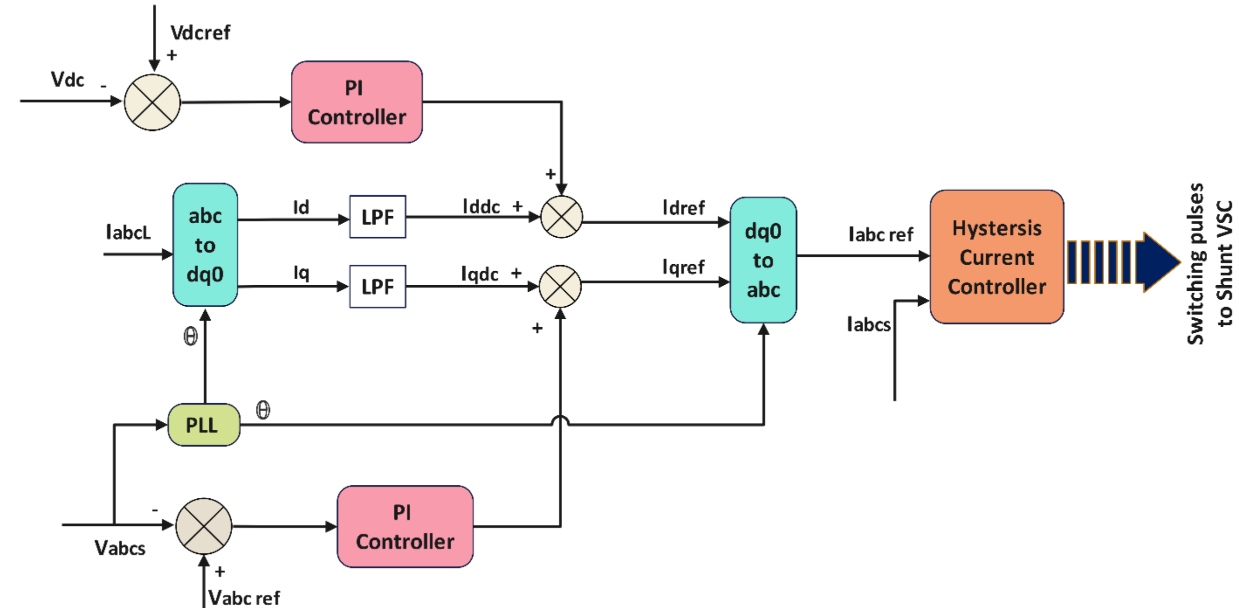

Figure 2. d-q-0 Control Strategy for shunt VSC

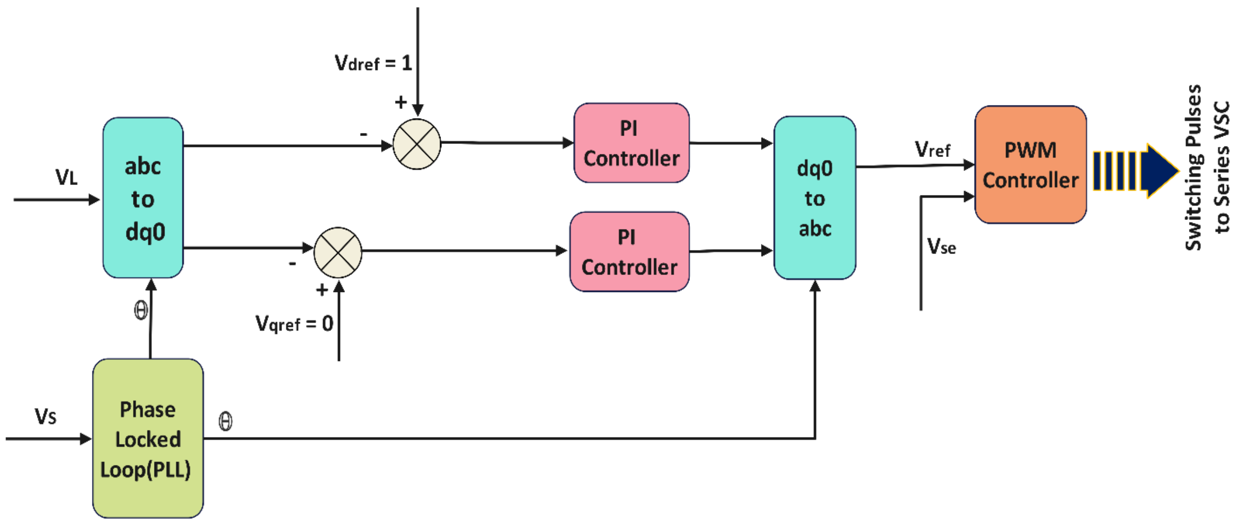

Figure 3. d-q-0 Control Strategy for Series VSC

$$I_{qr(t+1)} = I_{qr(t)} + k_{pq}(V_{t(t+1)} - V_{t(t)}) + k_{id}V_{t(t)} \text{.........}(4)$$

These reference currents (I_{dref} and I_{qref}) are transfigured back to "a-b-c reference" coordinates using the Inverse Park's transformant, through which the final reference currents can be obtained and as given by equation 5.

$$i_q^* = i_{qr} + i_{qdc} \text{ ....}(5)$$

By means of Hysteresis Current Controller (HCC) controller (Pengaluru Suresh et al., 2019), Switching Gate pulses are formed using the variance among the reference currents and actual source currents. With these Gate pulses, at PCC point, the ShAPF inoculates the currents for suppressing the harmonics within the current in addition to paying off the reactive power demand.

Control Scheme for Series VSC

The Figure 3 illustrate the "d-q-0" control strategy for Series VSC and reference signals to estimate are described as below. At first, source voltages are transformed into synchronous "d-q-0 reference" frame with the equation 6.

$$V_s^{dq0} = \frac{2}{3}\begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & -\sin\left(\theta - \frac{2\Pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & \frac{1}{2} \end{bmatrix} * V_s^{abc}$$

$$= V_{sp} + V_{sn} + V_{s0} + V_{sh} \text{ .... }(6)$$

Where V_{sp}, V_{sn}, V_{s0}, and V_{sh} are positive, negative, zero sequences and harmonic components respectively.

The primary aim is in obtaining sinusoidal voltages, accordingly "d-q-0 reference" frame of load voltage is given by the equation 7 below.

$$V_L^{dq0} = V_s^{*abc} =$$

$$\begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\Pi}{3}\right) & -\sin\left(\theta - \frac{2\Pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\Pi}{3}\right) & \sin\left(\theta - \frac{2\Pi}{3}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} U_m \\ 0 \\ 0 \end{bmatrix} \text{..................}(7)$$

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The compensating "d-q-0 reference" coordinates voltage is given by equation 8 and this voltage is transformed again back to "a-b-c reference" frame.

$$V_{dq0}^{ref} = V_s^{dq0} - V_L^{dq0} \quad \text{.................................} \quad (8)$$

Using the Sinusoidal PWM technique (Pal et al., 2020), the switching gate pulses are produced to compensate for the load voltage disturbances.

Proposed Adaptive Leaky LMS (AL_LMS) Technique

In a customized filtering application, a modified conventional LMS method called as the Adaptive Leaky LMS (AL_LMS) algorithm is employed. In this context of adaptive filtering, the determination is to find an optimal set of filter coefficients (weights) that minimizes the eeriness amongst the desired output and the filter's output. Here, in the applied AL_LMS algorithm, a leakage factor is introduced to regulate the rate at which the filter coefficients are updated, thus achieving a trade-off between tracking speed and stability. The mathematical equation correlated to AL_LMS and its estimator (Ray et al., 2022; Bag, A. et al., 2020) are described by below equations 9 and 10.

$$W(t+1) = [1 - \mu\,\lambda(t)] * W(t) + \mu E(t) * X(t) \ldots. \quad (9)$$

$$\text{and } Y(t) = W^T(t) * X(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Where

X(t): Input vector at time step 't'

W(t): Weight vector of filter coefficients at the time step 't'

μ: Step-size or learning rate, controlling the adaption rate

λ(t): The leakage factor, which can vary at each time step 't' based on system conditions

E(t): The instantaneous error signal at time step 't', defined as desired output 'D(t)' minus predicted output 'Y(t)' i.e.

$$E(t) = D(t) - Y(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The cost function $F_c(t)$ is specified by

$$F_c(t) = E^2(t) + [\lambda(t) * W^T(t) * W(t)] \quad \ldots\ldots\ldots. (12)$$

And updating of weights are accomplished such that it attains a minimal value. The weight update expressions are obtained thru the equations 13 – 16.

$$W(t+1) = W(t)[\,1 - 2\mu(t) * \lambda(t)] + [2\mu(t) * E(t) * X(t)] (13)$$

$$\lambda(t+1) = \lambda(t) - [2\mu(t) * \rho * E(t) * X^T(t) * W(t-1)] \ldots (14)$$

$$\mu(t+1) = [\alpha * \mu(t)] + [\lambda(t) * R^2(t)] \ldots\ldots\ldots\ldots\ldots. (15)$$

$$R(t) = [\beta * R(t-1)] + [(1-\beta) * E(t) * E(t-1)] \, . (16)$$

Here, **R(t):** Autocorrelation between E(t) & E(t-1)

β : Exponential weighing parameter used to control averaged estimated time so that 0 < β < 1

α and ρ : Time convergence control constraints such that 0 < α < 1 and ρ > 0.

Here, in this research of Solar-PV fed UPQC, The UPQC can be controlled adaptively by using the AL_LMS algorithm to produce appropriate reference signals for operating the device. The main objective is to ensure that UPQC effectively compensates for power quality issues by adaptively adjusting the control signals based on the real-time measurement of the electrical parameters. This algorithm computes the variance amongst the desired (ideal) values and the measured values of these parameters such that the difference indicates the power quality error and is used to adaptively adjust the reference signals provided to the UPQC to minimize the error. The algorithm updates the reference signals based on the error signal and a learning rate (μ), which determines the adaptation rate. The adapted reference signals generated by the algorithm are used to control the UPQC's operations. This comprises generating appropriate compensation signals to correct the power quality problems. The process continues in a feedback loop, with the UPQC continuously adjusting its control signals based on the changing electrical conditions in the system.

Proposed Control for Shunt VSC

The proposed controller representation of shunt VSC is illustrated in Figure 4. The strategy aims to produce a balanced sinusoidal source current while controlling DC-link voltage. The first step is to sense the instantaneous phase voltages (v_{sa}, v_{sb} and v_{sc}) at PCC for all the phases. Following that, the phase voltages are applied to compute the PCC voltage's phase amplitude (Vsp) as follows:

$$V_{sp} = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

The source voltage's in-phase unit templates are defined with the formula as

$$v_{pa} = \frac{v_{sa}}{V_{sp}}; \quad v_{pb} = \frac{v_{sb}}{V_{sp}}; \quad v_{pc} = \frac{v_{sc}}{V_{sp}} \ldots\ldots\ldots\ldots\ldots (18)$$

By means of in-phase unit templates, the voltage quadrature unit templates are calculated as follows:

$$v_{qa} = \frac{-v_{pb}+v_{pc}}{\sqrt{3}}; \; v_{qb} = \frac{\sqrt{3}}{2}v_{pa} + \frac{1}{2\sqrt{3}}(v_{pb} - v_{pc});$$

$$v_{qc} = -\frac{\sqrt{3}}{2}v_{pa} + \frac{1}{2\sqrt{3}}(v_{pb} - v_{pc}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

W.r.t the control technique, the grid, and the PV array supply the load active power requirement. The grid also affords the UPQC's internal losses by keeping the constant voltage over DC-link. The predicted DC-link voltage (V_{dcref}) given by MPPT of Solar-PV output is correlated to the measured DC-link capacitor voltage (V_{dc}), and then an error signal (E_{dc}) is attained, which is given for PI controller so as to minimize the error. Thus, the required loss component (W_{loss}) is obtained and expressed by equations (20) and (21).

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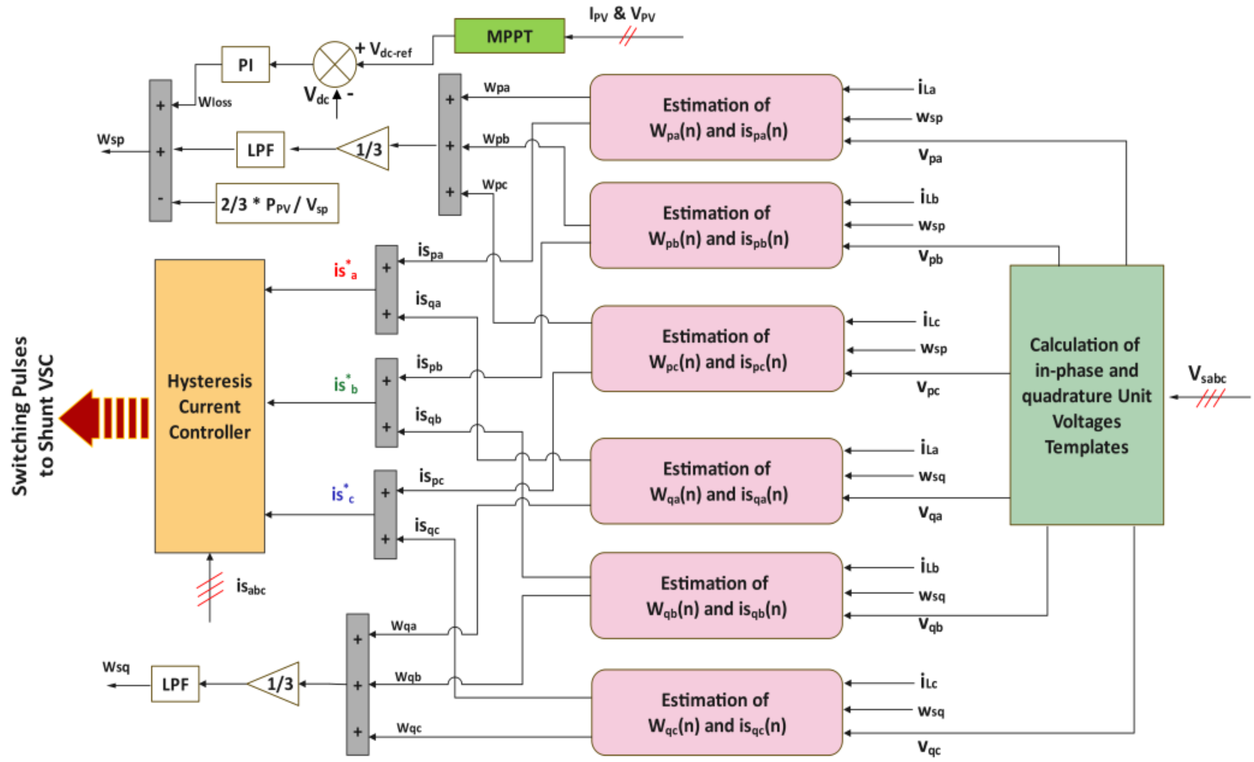

Figure 4. Proposed schematic control diagram of shunt VSC

$E_{dc}(t) = V_{dcref}(t) + V_{dc}(t)$ ………………………. (20)

$W_{loss}(t+1) = W_{loss}(t) + K_p * [E_{dc}(t+1) - E_{dc}(t)] + K_i * E_{dc}(t+1)$……………………………………. (21)

The fraction of active current supplied by Solar-PV array (W_{PV}) is specified by:

$W_{pv} = \frac{2}{3} * \frac{P_{PV}}{V_{sp}}$ …………………………………... (22)

Now, the fundamental constituent of phase 'a' active load current can be determined with help of basic weight update expressions given in (13), (14), (15) and (16) as follows:

$W_{pa}(t+1) = W_{pa}(t)[1 - 2\mu_{pa}(t) * \lambda_{pa}(t)] + [2\mu_{pa}(t) * E_{pa}(t) * v_{pa}(t)]$……………………….... (23)

$\lambda_{pa}(t+1) = \lambda_{pa}(t) - [2\mu_{pa}(t) * \rho * E_{pa}(t) * v_{pa}(t) * W_{pa}(t-1)]$……………………………………... (24)

$\mu_{pa}(t+1) = [\alpha * \mu_{pa}(t)] + [\lambda_{pa}(t) * R^2_{pa}(t)]$ .... (25)

$R_{pa}(t) = [\beta * R_{pa}(t-1)] + [(1-\beta) * E_{pa}(t) * E_{pa}(t-1)]$ ………………………………………. (26)

And the predicted error will be now as

$E_{pa}(t) = i_{La}(t) - v_{pa}(t) * W_{pa}(t)$………………. (27)

Where i_{La} is load current of phase 'a'. In a similar way, at any time instant, weights of active components (W_{pb} and W_{pc}), leakage factors (λ_{pb} and λ_{pc}), step size (μ_{pb} and μ_{pc}), error autocorrelation (R_{pb}, R_{pc}) and predicted error (E_{pb}, E_{pc}) can be updated similarly to the phases 'b' and 'c' for the shunt VSC. Hence, weighted average of the fundamental active component (W_{pave}) is specified as:

$W_{pave} = \frac{W_{pa}(t) + W_{pb}(t) + W_{pc}(t)}{3}$……………………… (28)

From (22), (23) and (28), the reference grid current's total weight of active component (W_{sp}) and active components of reference grid current (i_{spa}, i_{spb} and i_{spc}) are computed as

$W_{sp} = W_{pave} + W_{loss} - W_{PV}$…………………....…. (29)

$i_{spa} = W_{sp} * v_{pa}$; $i_{spb} = W_{sp} * v_{pb}$; $i_{spc} = W_{sp} * v_{pc}$ ……………………………………….……... (30)

In the same way, load current's reactive components are obtained by having quadrature unit vector voltage templates and corresponding updated weights related towards reactive current components and are expressed as

$i_{sqa} = W_{sq} * v_{qa}$; $i_{sqb} = W_{sq} * v_{qb}$; $i_{sqc} = W_{sq} * v_{qc}$ ……………………………………......………. (31)

Here, weight average of fundamental reactive components are equal to the weight of total reactive components (W_{sq}). Thus, the extracted resulting reference source currents are attained by summing up the components in (30) and (31) obtained above.

$i^*_{sa} = i_{spa} + i_{sqa}$; $i^*_{sb} = i_{spb} + i_{sqb}$; $i^*_{sc} = i_{spc} + i_{sqc}$ ……………………………………......………. (32)

Henceforth, comparing the resultant reference (i^*_{sa}, i^*_{sb} and i^*_{sc}) and measured (i_{sa}, i_{sb} and i_{sc}) network source currents and also the attained erroneous signals are enumerated toward the Hysteresis Current Controller (HCC) in engendering the estimated switched signals meant for shunt VSC.

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Proposed Control for Series VSC

The representation of schematic control for series compensator is shown in Figure 5. The control objective is in obtaining the nominal magnitude and pure sinusoidal load voltages. The reference load voltages are evaluated using the proposed AL_LMS algorithm as described below. The 3-Φ load currents (i_{La}, i_{Lb} and i_{Lc}) are sensed for calculating the magnitude (I_{Lp}) and the load current unit templates are given by equations 33 and 34 respectively.

$$I_{Lp} = \sqrt{\frac{2}{3}(i_{La}^2 + i_{Lb}^2 + i_{Lc}^2)} \quad (33)$$

$$u_{pa} = \frac{i_{La}}{I_{Lp}};\ u_{pb} = \frac{i_{Lb}}{I_{Lp}};\ u_{pc} = \frac{i_{Lc}}{I_{Lp}} \quad (34)$$

These in-phase unit templates are used in computing the quadrature current unit templates and are given as

$$u_{qa} = \frac{-u_{pb}+u_{pc}}{\sqrt{3}};\ u_{qb} = \frac{\sqrt{3}*u_{pa}}{2} + \frac{1}{2\sqrt{3}}(u_{pb} - u_{pc});$$

$$u_{qc} = -\frac{\sqrt{3}*u_{pa}}{2} + \frac{1}{2\sqrt{3}}(u_{pb} - u_{pc}) \quad (35)$$

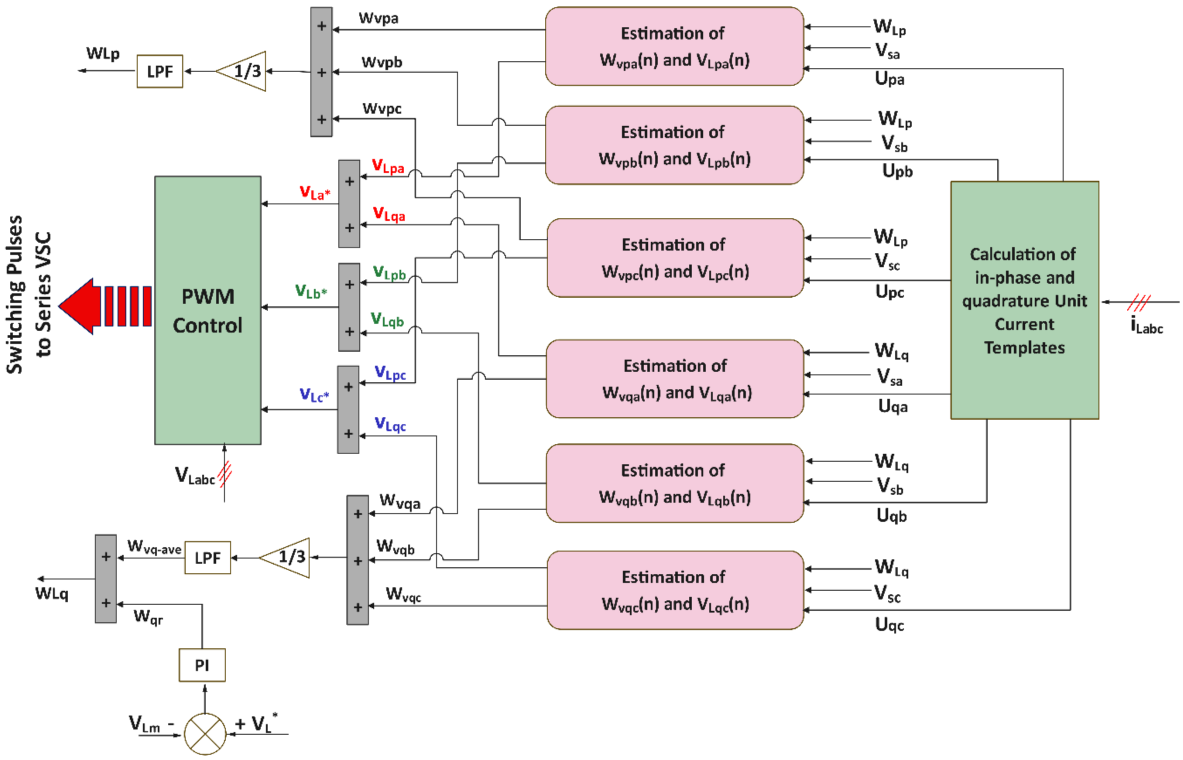

Figure 5. Schematic control representation for Series VSC

Now, load voltage weighted in-phase component (W_{vpa}) of phase 'a' is computed by means of basic weighted updated expressions given in (13), (14), (15) and (16) as follows

$$W_{vpa}(t+1) = W_{vpa}(t)\left[1 - 2\mu_{vpa}(t) * \lambda_{vpa}(t)\right] + [2\mu_{vpa}(t) * E_{vpa}(t) * u_{pa}(t)] \quad (36)$$

$$\lambda_{vpa}(t+1) = \lambda_{vpa}(t) - \left[2\mu_{vpa}(t) * \rho * E_{vpa}(t)\right] * [u_{pa}(t) * W_{vpa}(t-1)] \quad (37)$$

$$\mu_{vpa}(t+1) = [\alpha * \mu_{vpa}(t)] + [\lambda_{vpa}(t) * R_{vpa}^2(t) \quad (38)$$

$$R_{vpa}(t) = [\beta * R_{vpa}(t-1)] + [(1-\beta) * E_{vpa}(t) * E_{vpa}(t-1) \quad (39)$$

And error predicted will be obtained as

$$E_{vpa}(t) = V_{sa}(t) - u_{pa}(t) * W_{vqa}(t) \quad (40)$$

where, V_{sa} is the source voltage of phase 'a'. Likewise, at any instantaneous, in-phase weights component (W_{vpb} and W_{vpc}), leakage factors (λ_{vpb} and λ_{vpc}), step size (μ_{vpb} and μ_{vpc}), error auto correlation (R_{vpb} and R_{vpc}) and error prediction (E_{vpb} and E_{vpc}) can be similarly updated in the phases 'b' and 'c' of series VSC. The in-phase component weighted average (W_{vpave}) is calculated as:

$$W_{vpave} = \frac{W_{vpa}(t) + W_{vpb}(t) + W_{vpc}(t)}{3} = W_{Lp} \quad (41)$$

The components of in-phase reference load voltage are measured as:

$$V_{Lpa} = W_{Lp} * u_{pa};\ V_{Lpb} = W_{Lp} * u_{pb};\ V_{Lpc} = W_{Lp} * u_{pc} \quad (42)$$

In the same way, the load voltage's quadrature component weights (W_{vqa}, W_{vqb} and W_{vqc}) using proposed AL_LMS algorithm are attained. Then, the reactive component weighted average is given by

$$W_{vqave} = \frac{W_{vqa}(t) + W_{vqb}(t) + W_{vqc}(t)}{3} \quad (43)$$

Now, a loss component (W_{qr}) is taken here into account for the regulation of the load voltage and stated as

$$W_{qr}(t+1) = W_{qr}(t) + K_{pq} * [E_{ac}(t+1) - E_{ac}(t)] + K_{iq} * E_{dc}(t+1) \quad (44)$$

By comparison of the magnitudes of measured load voltages (V_{La}, V_{Lb} and V_{Lc}) and rated load voltage (V^*_L), produces an error signal and it is been fed to a PI controller for keeping load voltage's magnitude at desired value as given by the below equations

$$V_{Lm} = \sqrt{\frac{2}{3}(V_{La}^2 + V_{Lb}^2 + V_{Lc}^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(45)}$$

And $\quad E_{ac}(n) = V_L^*(n) - V_{Lm}(n) \quad \ldots\ldots\ldots\ldots\ldots \text{(46)}$

The over-all quadrature component weight (W_{Lq}) of reference load's voltage is expressed as

$$W_{Lq} = W_{vqave} + W_{qr} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(47)}$$

The over-all quadrature component of reference load's voltage is specified by the equation below

$$V_{Lqa} = W_{Lq} * u_{qa};\ V_{Lqb} = W_{Lq} * u_{qb};\ \ V_{Lqc} = W_{Lq} * u_{qc} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(48)}$$

Thus, the considerable reference load voltages for all the three phases are given as

$$V_{La}^* = V_{Lpa} + V_{Lqa};V_{Lb}^* = V_{Lpb} + V_{Lqb};\ V_{Lc}^* = V_{Lpc} + V_{Lqc} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(49)}$$

At last, by comparing the reference and measured load voltages, the variance is fed to a PWM generator to produce switching pulses to the series VSC. Hence, the operation of UPQC is done for the PQ enhancement.

Simulation Results and Discussions

The suggested Solar-PV fed UPQC configuration is modelled in the MATLAB/Simulink platform as shown in below Figure 6, and is then simulated for examining the performance analysis of Non-linear load condition, Voltage Sag and Swell situations using the conventional SRF theory and proposed AL_LMS algorithm. The parameters of the described system are tabulated below.

Table 1. Parameters used for Simulating the Proposed System

Parameters	Value
Supply Voltage (V_s)	415 V (L-L)
Coupling inductors (L_{se} and L_{sh})	1.5mH
DC-link capacitor (C_{dc})	8000 μF
DC-link Voltage (V_{dc})	700 V
Gains of Shunt VSC (Kp and Ki)	2 and 0.1
Gains of Series VSC (Kp and Ki)	4 and 800
Solar-PV voltage and current at MPP	700V, 60A
Non-linear load	15 KW, 7.2 KVA

Series VSC's Performance Analysis for Voltage Sag and Swell Conditions

Using Conventional SRF theory

The performance of the series component of UPQC using conventional SRF theory for voltage sag and swell conditions is shown Figure 7 below. At t=0.1Sec, a 0.5 P.U. voltage sag and on t=0.3Sec, a 1.2 P.U voltage swell has created and has been mitigated by series VSC of UPQC, resulting in rated load voltage.

From the Figure 7, it is shown that the voltage sag and swell are mitigated by UPQC using the conventional SRF theory. The %THD of load voltage using conventional SRF theory applied to UPQC is obtained as 4.8% as depicted in Figure 8. Further, it is investigated with proposed method for better enhancement of power quality as described below.

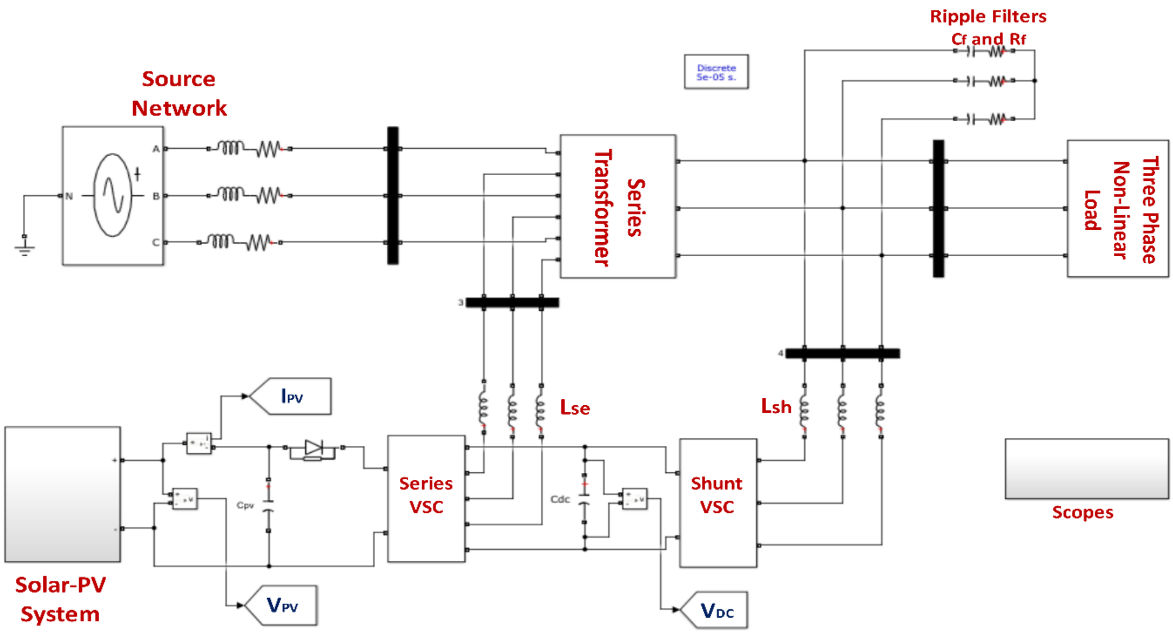

Figure 6. Simulation diagram of proposed Solar-PV fed UPQC system

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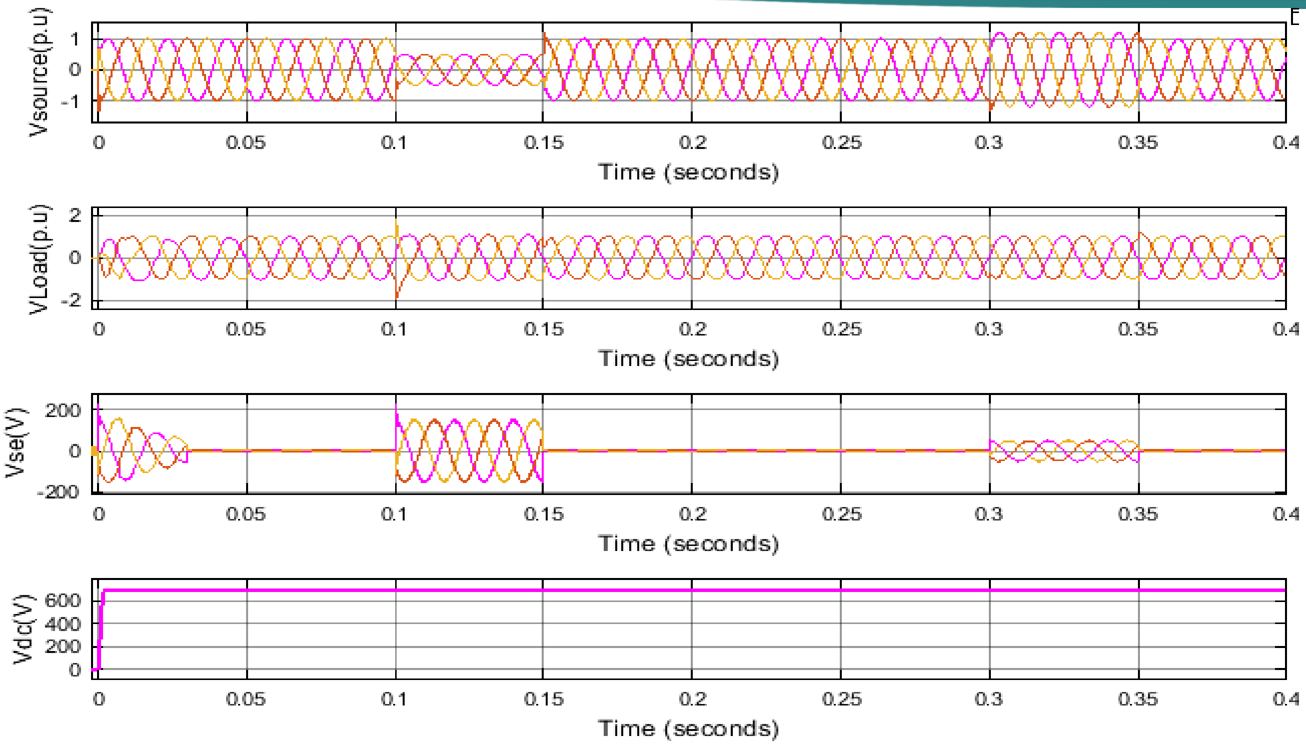

Figure 7. Compensation of Voltage Sag and Swell conditions by UPQC-SRF theory

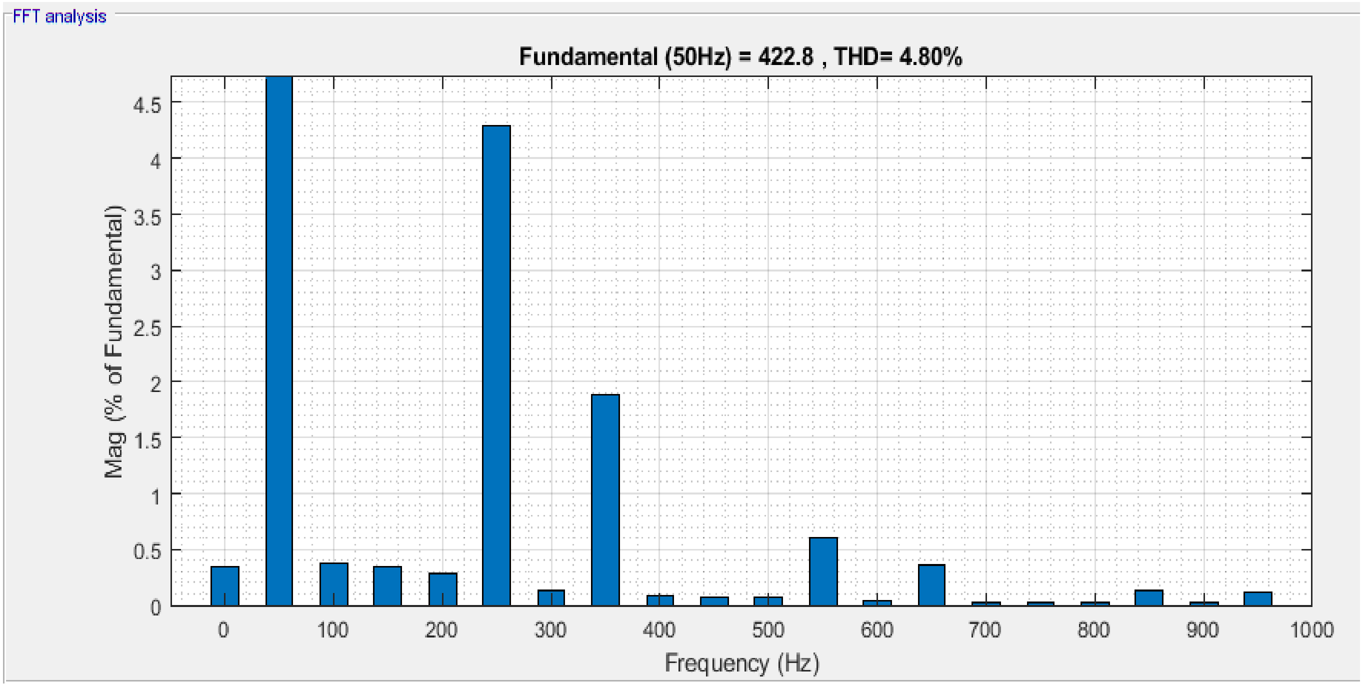

Figure 8. %THD of Load voltage by conventional SRF theory

Using proposed AL_LMS Algorithm

The performance of the series component of UPQC using the proposed AL_LMS algorithm for voltage sag and swell conditions is depicted in the graph below. At t=0.1Sec, a 0.5 P.U. sag and at t=0.3Sec, a 1.2 P.U swell has created which can be mitigated by series VSC of UPQC and results rated load voltage.

Figure 9 shows that the proposed AL_LMS algorithm better compensates voltage sag and swells with improved performance of %THD. The obtained %THD of the load voltage is 2.41% as compared to the conventional SRF theory of 4.80% as depicted in Figure 10.

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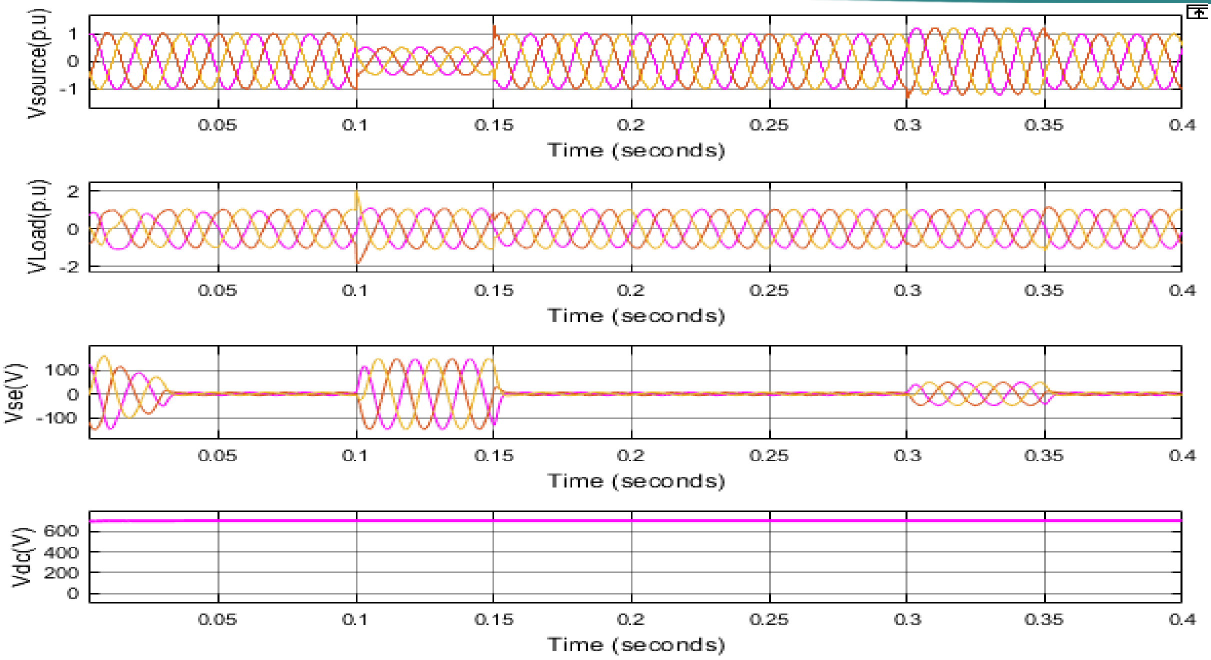

Figure 9. Compensation of Voltage Sag and Swell by proposed AL_LMS algorithm

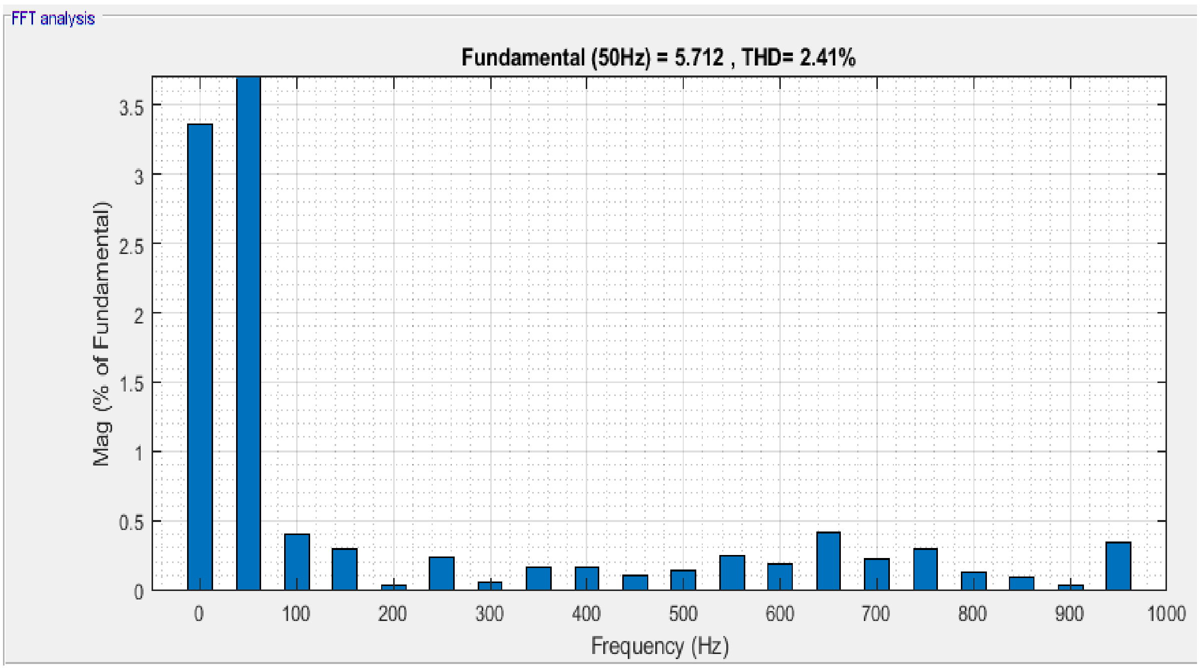

Figure 10. THD of Load Voltage with proposed AL_LMS algorithm.

Performance Analysis of Shunt VSC for Non-linear load condition

Using Conventional SRF theory

From the Figure 11, it can be observed that before t=0.04Sec, the harmonics due to non-linear load are reflected into the network source current. At t=0.04Sec, UPQC has been associated to the network. The shunt VSC of UPQC compensates the non-linearities injected into the network source current, resulting in a sinusoidal grid current.

The performance of shunt VSC for non-linear load conditions is depicted in the Figure 11 and 12 below. Using conventional SRF theory, the shunt VSC of UPQC compensates the non-linearities present in the network source current and is made sinusoidal, as depicted in a Figure 11. The Figure 12 shows %THD of source current obtained is 4.82% using conventional SRF theory. Also, W.r.t the control technique, the grid, and the PV array supply the load active power requirement and keep the DC-link voltage at a significant level.

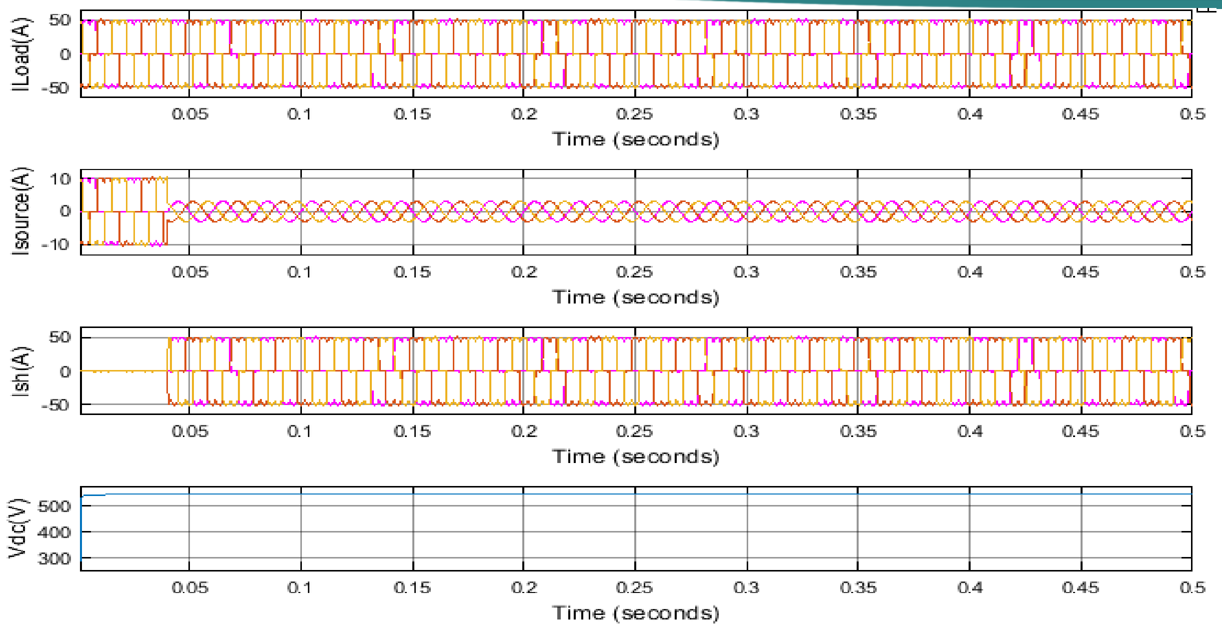

Figure 11. Performance of Shunt VSC with Non-linear load by conventional SRF theory

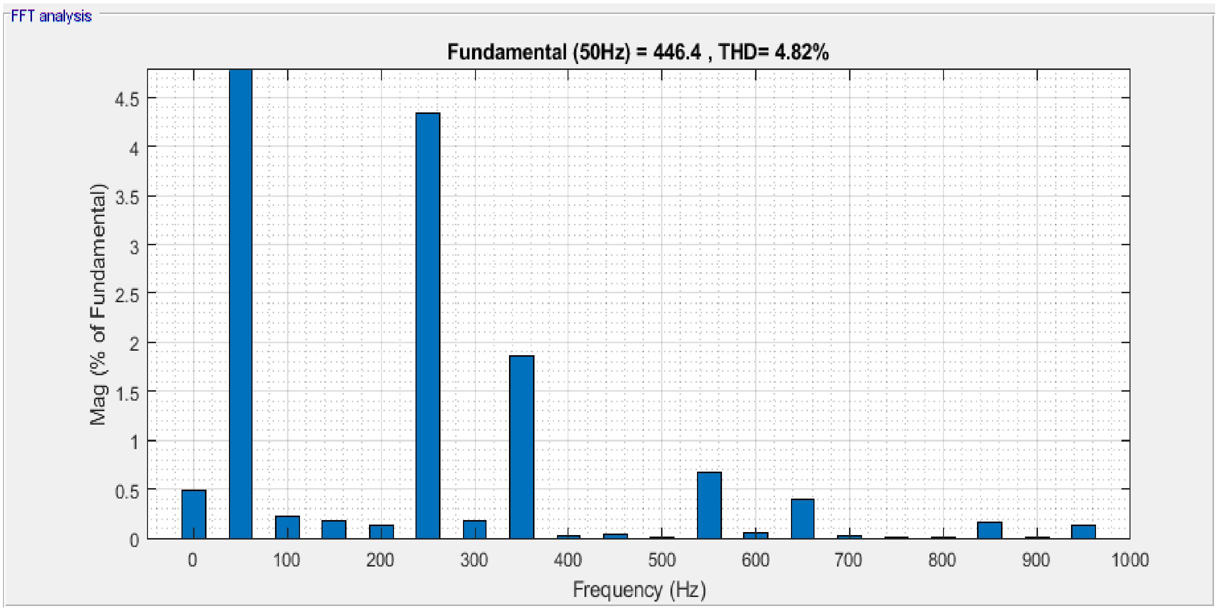

Figure 12. %THD for source current with conventional SRF theory

Using proposed AL_LMS Algorithm

Furthermore, the system is investigated for non-linear load conditions with proposed algorithm. At t=0.04Sec, the shunt VSC of UPQC compensates the non-linearities injected into the network source current, resulting in sinusoidal grid current while maintaining the constant DC-link voltage, as depicted in Figure 13.

The non-linearities in the source current and load current are further reduced by using proposed AL_LMS algorithm compared to SRF theory and %THD obtained in the source network current is 3.49% as of 4.82% in the conventional SRF theory as illustrated in Figure 13 and 14 below. Thus, it can be proved that the enhancement of power quality is superior by using the proposed AL_LMS algorithm. The outputs of control strategies of the system are featured in Table 2 below.

Table 2. %THD comparison of UPQC Control Strategies

S.No.	Parameter	Conventional SRF Theory	Proposed AL_LMS Algorithm
1	Load Voltage (Sag and Swell)	4.80%	2.41%
2	Source Current (Non-linearities)	4.82%	3.49%

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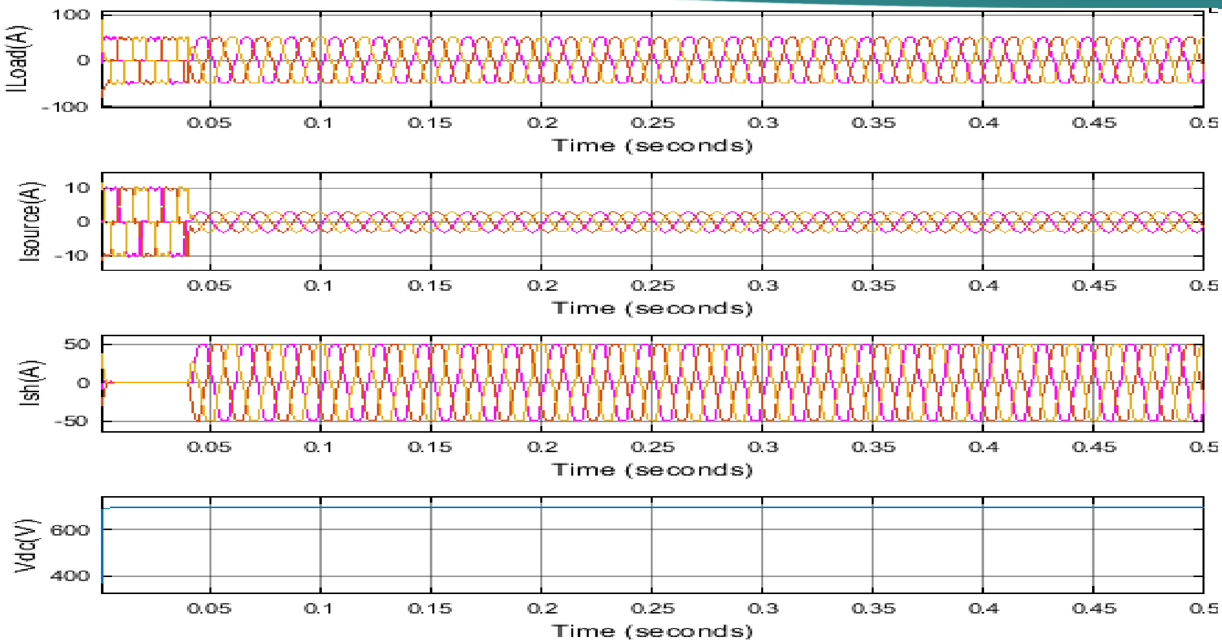

Figure 13. Performance of Shunt VSC with Non-linear load by proposed algorithm

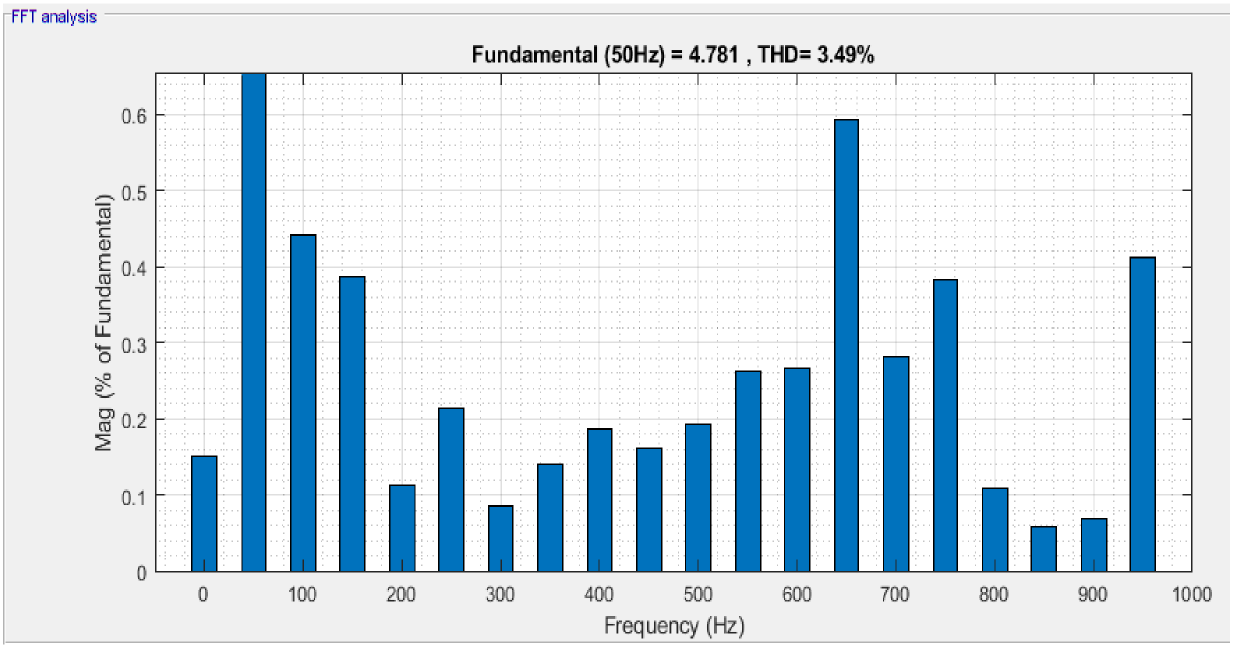

Figure 14. %THD for source current with proposed AL_LMS algorithm

Conclusion

A new control strategy based on the AL_LMS algorithm for the enrichment of the power quality with Solar-PV fed UPQC in the distributed network has been proposed in this paper. The proposed algorithm assesses the system's performance compared to the conventional SRF theory with %THD of non-linear load condition, voltage sag and swell conditions. The proposed AL_LMS algorithm has achieved better results in these conditions by generating proper reference currents to both the shunt and series VSCs of UPQC. Even in instances of voltage sag and swell situations, the load voltage is satisfactorily kept at its nominally rated voltage of 1 P.U. at a decrease in %THD of 2.41% and also source current %THD had been reduced significantly to 3.49% and made sinusoidal for non-linear load currents condition as compared to conventional SRF theory. Furthermore, the suggested strategy assists in meeting the active power requirement for loads by capturing solar-PV energy and, consequently, reducing the load burden upon the network grid.

Conflict of Interest

The authors declare no conflict of interest.

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