*International Journal for Modern Trends in Science and Technology*, 8(06): 177-184, 2022

ISSN: 2455-3778 online
DOI: https://doi.org/10.46501/IJMTST0806027
Available online at: http://www.ijmtst.com/vol8issue06.html

# Mitigation of Voltage Sag, Swells and Harmonics in a PV Connected Distribution System using Unified Power Quality Conditioner(UPQC)

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**To Cite this Article**
Sowmyashree N, Dr M S Shashikala, Dr K T Veeramanju and Mouna Machamma P M. Mitigation of Voltage Sag, Swells and Harmonics in a PV Connected Distribution System using Unified Power Quality Conditioner(UPQC). International Journal for Modern Trends in Science and Technology 2022, 8(06), pp. 177-184. https://doi.org/10.46501/IJMTST0806027

**Article Info**
Received: 09 May 2022; Accepted: 02 June 2022; Published: 07 June 2022.

## ABSTRACT

***With the rapid increase in energy demand, conventional method is not enough to satisfy the requirement necessity and due to this, renewable sector have gained more popularity. Out of several renewable sources, solar power is more widely used, but integrating it into the power system raises several power quality issues that might lead to the failure of the entire system. In this paper, a Photovoltaic system connected to an IEEE 15 bus network is considered and a custom power device such as Unified Power Quality Conditioner is used to mitigate the Power Quality issues such as voltage sag, swell and harmonics.***

**KEYWORDS:** *Photovoltaic System, Power Quality, Voltage Sag and Swell, Harmonics, UPQC*

## 1. INTRODUCTION

In recent years, with the increase in population and various developments in technical field, the demand for power is increasing at a high rate. And with the increasing energy crisis, conventional methods like fossil fuels are not able to meet the energy demand as they are on the verge of depletion. Due to these crises and their impact on the environment, renewable sources are used to assess the power and solar energy has become one of the most popular renewable energy sources in recent years [1][2].

A 11KV IEEE 15 bus system is integrated with a 140KW photovoltaic system but various power quality issues are subjected to the grid with the increase in single phase non-linear loads and sensitive power electronic devices. Having a better power quality in an electrical system is very essential as it is the capability of an electrical gadget to consume the energy being rendered to it and it is one of the major concerns while integrating Photovoltaic systems to the feeders. Out of several power quality problems, the mitigation of voltage sag, voltage swell and current harmonics is significant because they are the most frequently occurring issues. Several researches have been taken up regarding the mitigation of these power quality issues using Custom Power Devices such as STATCOM (Static Compensator), DVR (Dynamic Voltage Restorer) and UPQC (Unified Power Quality Conditioner) [3]. Unified Power Quality Conditioner (UPQC) is mainly considered to extenuate both voltage and current related issues as it is easy and efficient when compared to other devices [4].

In this paper Unified Power Quality Conditioner with Phase-Locked Loop (PLL) and Hysteresis controller are used for voltage and current compensation respectively in a PV connected distribution system.

## 2. PROPOSED METHODOLOGY

A 11KV IEEE 15 bus system is developed and integrated with a 140KW Photovoltaic system at a common point of coupling (PCC). Here the 13th bus is taken as the common point of coupling. The Photovoltaic system used consists of MPPT for maximum efficiency which uses P&O algorithm. A Unified Power Quality Conditioner is proposed with control techniques such as Phase-Locked Loop (PLL) to mitigate voltage sag and swell and a Hysteresis controller to mitigate the current harmonics that occur in the system

### *A. Photovoltaic System Connected To Grid*

***PV system***

Figure 1 shows the basic block diagram of the PV system used. It consists of a PV array, DC/DC converter, an inverter connected a feeder.

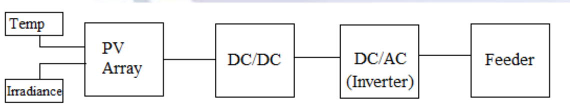


**Figure 1. Block diagram of a simple 140KW PV system**

*i. PV Array*

Photovoltaic cells are semiconductor diodes which consists of a p-n junction that is exposed to light and when illuminated by sunlight, it generates electric power [5], [6]. A single PV cell cannot produce the sufficient power and thus by inter-connecting many single PV cells in series (for high voltage) and in parallel (for high current) desired power isobtained. The interconnection of PV modules in series or parallel is called a photovoltaic array [7].

The output current of the cell is:

$I = I_{ph} - I_D - I_{sh}$ (2.1)

The photo current changes with temperature and irradiance.

$$I = Iph - Is[\exp\frac{(V + IRs)q}{akTNs} - 1] - \frac{V + IRs}{Rsh} \quad (2.2)$$

$$I_{ph} = I_r \frac{I_{sc}}{I_{r0}} \quad (2.3)$$

$$I_s = I_{sc} / [\exp(\frac{V_{oc}}{aV_t}) - 1] \quad (2.4)$$

$$I_d = I_s[\exp(\frac{V + IR_s}{aV_t}) - 1] \quad (2.5)$$

$$I_{sh} = (V + IR_S)/R_{sh} \quad (2.6)$$

$$V_t = \frac{kTN_s}{q} \quad (2.7)$$

The above equations display the relationship between voltage and current in a photovoltaic module. The expression (2.2) is said to be nonlinear and for the sake of mathematical analysis, Sun Power SPR-315EWHT-D PV array has been chosen. The PV array data is as shown in Table 1.

**Table 1: The key specifications of PV array**

| | |
|---|---|
| Cell type | Polycrystalline silicon |
| Maximum Power[W] | 315.075 |
| Open circuit voltage $V_{oc}$[V] | 64.6 |
| Short circuit current $I_{sc}$[A] | 6.14 |
| Voltage, maximum power $V_{mpp}$[V] | 54.7 |
| Current, maximum power $I_{mpp}$[A] | 5.76 |
| Temperature co-efficient of $V_{oc}$ KV [V/K] | -0.27269 |
| Temperature co-efficient of $I_{sc}$ KI[A/K] | 0.061694 |
| a | 0.9507 |
| $R_{sh}$[Ω] | 430.0559 |
| $R_s$[Ω] | 0.43042 |
| Ns | 5 |

*ii. Maximum Power Point Tracking*

Maximum power point tracker (MPPT) excerpts maximum power from the photovoltaic module and then shifts that power to the load. It is preferable to control the module at the peak power point since the module efficiency is low. This maximum power from the solar PV module is transferred from DC/DC converter to the load as an interfacing machine. By switching the duty cycle, the load impedance can be changed and corresponded at the point of peak power. There exists a single maxima of power, i.e. a peak power corresponding with specific voltage and current in the power versus voltage curve of a PV module and the maximal power can be distributed to the load under diversified temperature and irradiation conditions. This amplified power aids to enhance the utilization of the solar PV module. Perturb and observe algorithm is used for tracing the peak power point of the solar photovoltaic module automatically i.e., when a small perturbation is inserted in the system, the power of the module is altered because of it. If the power increases because of the perturbation then it is proceeded in that direction. As power attains its peak point, the next instant power decreases and thus the perturbation reverses. The perturbation size is kept very small to keep the power variation small. Based on the value of the previous power sample, the algorithm continuously increments or decrements the reference voltage.[8]

Figure 2 shows the V-I characteristics at 25 and 45 degree Celsius at a constant irradiation of 1000W/m$^2$.

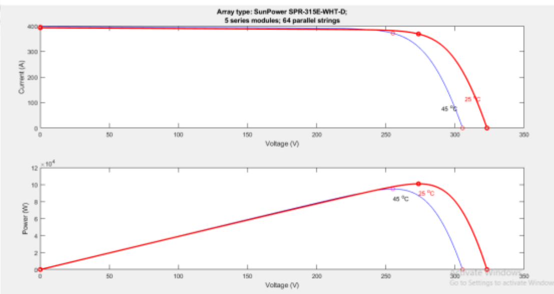

**Figure 2. Array at 1000W/m$^2$ at 25 and 45 degree Celsius**

When the temperature of the module raises, the voltage reduces and the supplied current will remain practically invariant. In the matter of produced electric power, it is a depletion in the behavior of the PV panels [9].

The same figure represents the V-P characteristics of the photo-voltaic panel for a level of irradiation 1000 W/m$^2$ at different temperatures.

*iii. DC/DC Converter*

It is used in regulating the solar input voltage to the MPP and rendering impedance corresponding to the maximum power transfer to the load. The output of MPPT block, which is either duty cycle or a voltage parameter, is used as input to DC-DC converter. A DC-DC converter is a main part of any MPP circuit system. In this paper, to step up the operating voltage at the maximum power point Boost converter is used. The MPPT gives the gating signal to Boost converter which keeps the operating voltage at the maximum operating point irrespective of temperature and solar irradiance. The circuit comprises of an inductor, a diode, a capacitor, a load and a switching device like BJT, MOSFET etc., as shown in figure 3.

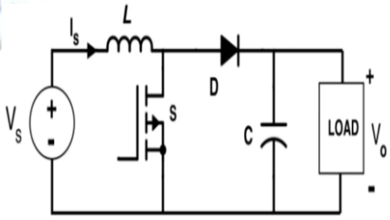


**Figure 3. Boost Converter Schematics**

It manipulates the duty cycle of the switching device that causes the voltage change in Boost converter. Boost converter has two working modes based on "ON" and "OFF" states of the switching device (MOSFET)

*iv. Power Inverter*

In this work, a voltage source inverter is used. A Voltage Source Inverter converts the DC voltage from the energy storage unit to a controllable three phase AC voltage [10]. It consists of switching devices which can yield a sinusoidal voltage at any requisite magnitude, frequency and phase angle. This voltage is boosted through the injection transformer to the main system in order to maintain the balanced load voltage. The inverter control are normally fired using a sinusoidal Pulse Width Modulation (PWM) strategy. The PWM renders sinusoidal signals by scrutinizing a sinusoidal wave with a saw tooth wave and sends appropriate signal to the inverter switches. IGBT is preferable since it is more reliable when compared to other switching devices. The output voltage of VSI should be balanced and pure sinusoidal and it should be in phase with the supply voltage. Figure 4 shows the circuit diagram of a Voltage Source Inverter.

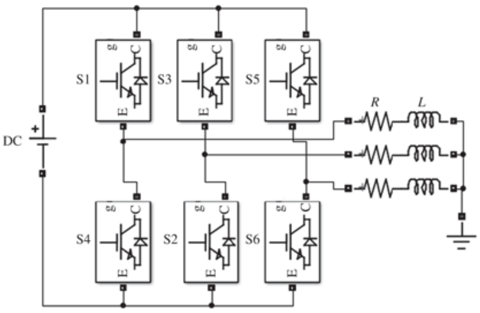


**Figure 4. Voltage Source Inverter.**

Considering all the above mentioned characteristics, a PV module is built and simulated using Matlab/Simulink. The simulation model of the modeled PV system is as shown in figure 5.

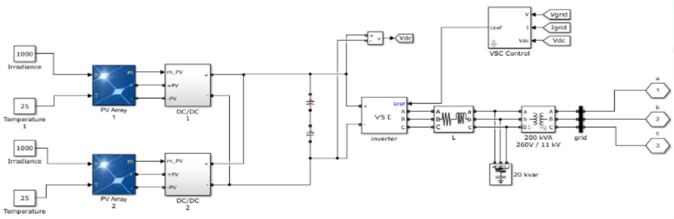

**Figure 5. Simulation Model of a PV system**

## *B.* IEEE 15 Bus system

The performance of the proposed PV system is evaluated on an IEEE 15-bus radial distribution network. The test system is modified by connecting a solar PV unit at a common coupling point i.e., bus 13. Figure 6 shows a PV Integrated IEEE 15 bus radial distribution system.

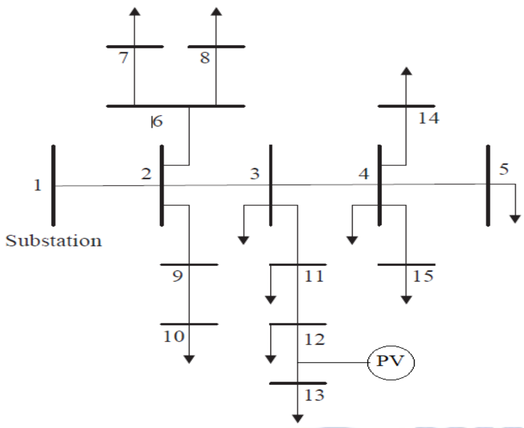


**Figure 6. PV Integrated IEEE 15 bus radial distribution system**

## III. POWER QUALITY ISSUES AND CONTROL TECHNIQUES.

As mitigation of voltage sag, voltage swell and current harmonics is the primary objective of the work, Unified Power Quality Conditioner (UPQC) is chosen to be the most suitable device to compensate all three issues.

### *A. Unified Power Quality Conditioner (UPQC)*

At the distribution level, Unified Power Quality Conditioner (UPQC) is one of the most appealing answers to counterbalance several major power quality problems [12-17]. It fundamentally comprises of two voltage source inverters, which are linked up back to back using a mutual DC bus capacitor. The general block diagram of UPQC is as shown in Figure 7[13].

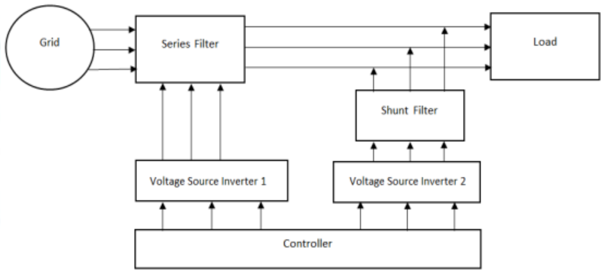


**Figure 7. Block diagram of UPQC**

The shunt APF would render VAR backup to the load and provides harmonic currents to keep it from getting into the power system. When the supply voltage would experience sag, series APF interjects desirable voltage with supply and compensates all voltage associated issues like harmonics, swell, flicker etc.[15]

The simulation model of a UPQC system that is connected to the 11KV IEEE15 bus system at the PCC 13th bus is as shown in Figure 8.

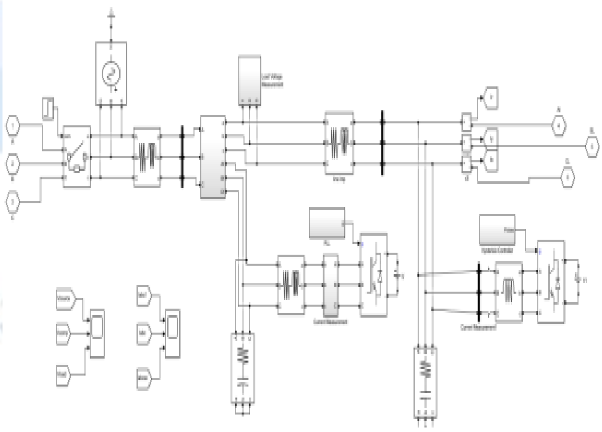

**Figure 8. Simulation Model of UPQC**

*B. Control Techniques*

Control techniques play the most important role in Unified Power Quality Conditioners.

In this work, Phase-Locked Loop (PLL) control technique and Hysteresis current control technique are used in UPQC to extenuate the voltage sag, voltage swell and current harmonics respectively that occurs in three phase system.

*i. Phase Locked Loop Controller*

Phase-locked loop controller is used for voltage compensation. This is a feedback controller used to control the output of the inverter in UPQC to generate compensation voltage for voltage sag and swell condition. AC is a three phase current with 120 degree phase shift and it varies sinusoidally and thus sinusoidal signal has to be generated. The unit vector generated due to the phase are

$U_a = \sin(u)$

$U_b = \sin(u-2pi/3)$ ; $U_b = \sin(u-120)$

$U_c = \sin(u+2pi/3)$ ; $U_c = \sin(u+120)$.

By multiplying the peak amplitude of fundamental input voltage with the above shown unit vector templates, the reference load voltage can be obtained.

$V^*_{abc} = U_{abc}$

This is the reference signal[18-19]. A reference signal is very necessary in the operation of a PLL controller. This is compared with the voltage(load signal) $V_{abcse}$ , that has been sensed by the sensor. If there is a difference, a pulse will be generated by the Pulse Width Modulation (PWM) voltage controller. Six pulses will be generated because the three phase bridge generator type is used. The gate pulse is thus generated and it is injected through an injecting transformer. Figure 9 shows the simulation model of PLL controller.

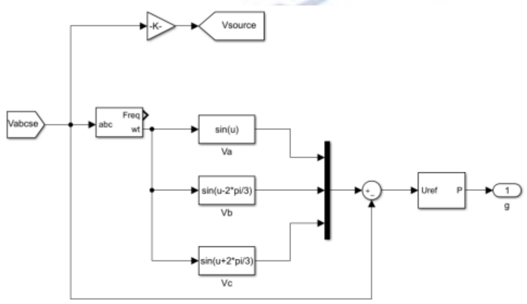


**Figure 9. Phase Locked Loop Controller**

In the present work, a conventional Phase Locked Loop control technique is used which is of nonlinear voltage control type. Based on voltage error the switching occurs and when the output voltage surpasses the upper limit the output voltage would decrease [20-21].

*ii. Hysteresis Controller*

Hysteresis controller is used in generating switching signals to restraint SAPF switches in forcing the desired current into the system. Figure 10 shows the simulation model of Hysteresis controller. The compensating currents of active filter are to be calculated by sensing the peak voltage, load currents and current of AC source [22]

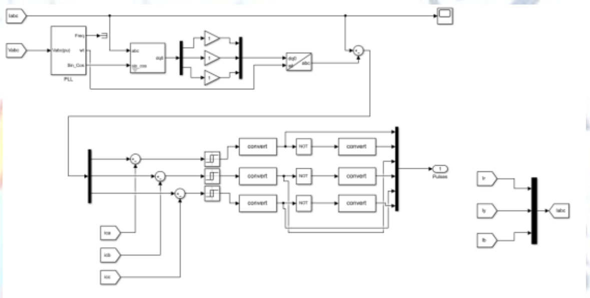

**Figure 10. Hysteresis Controller**

The switching signals supported on hysteresis mechanism are normally acquired in two stages. By deducting the real load currents ($i_{ca}$, $i_{cb}$ and $i_{cc}$) from the reference current template ($i^*_{sa}$, $i^*_{sb}$, $i^*_{sc}$) to get the instantaneous reference current of the APF ($i^*_{fa}$, $i^*_{fb}$, $i^*_{fc}$)[22].

By deducting ($i^*_{fa}$, $i^*_{fb}$, $i^*_{fc}$) from the current generated by the SAPF (real harmonic current) to obtain the switching pulses for voltage source inverter (active power filter).

The reference current required is generated by PLL. Its sine and cos angle taken and using dq it is converted into abc transform. In the case of positive input current if the current error surpasses the upper limit of the hysteresis band; and inverter output has to be set as zero, thus the current error would be forced to the other direction without crossing the negative limit. If this zero state does not render the opposite of current error, it will continue forwarding through inner limit to the opposite outer hysteresis limit. At this point of time, a reverse polarity of inverter output will be controlled and therefore current direction will be reversed. The switching frequency of hysteresis current control strategy described and presented above depends mainly on how fast is the current modified from the upper limit to the lower limit of hysteresis band and inversely. Thus, the switching frequency alters along with the current waveform and does not stay invariant throughout the switching operation.

## 4. SIMULATION RESULTS

### *A. Results of 11kV Grid Connected System Simulink Model*

Simulink model of 11KVgrid connected system without PV array is developed to show the performance of the system during normal healthy operation without any kind of fault in the system.

Figure 11 shows the voltage and current profile of the load side bus for a simulation duration of 0.2s. It is found in healthy state as observed from the simulation results.

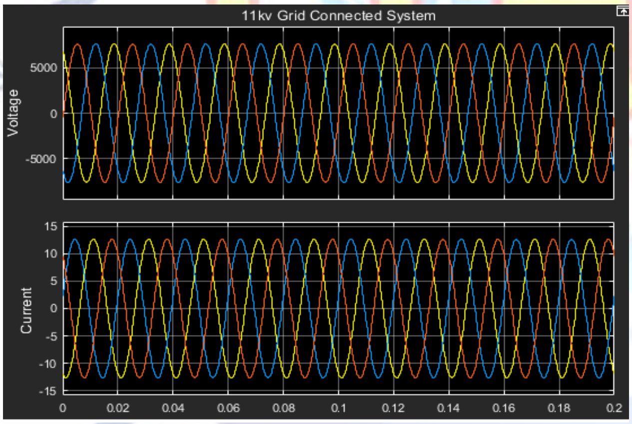


**Figure 11. Simulation result of 11kV grid connected system**

### *B. Results of Simulink Model of 140KW PV Array Grid Connected System*

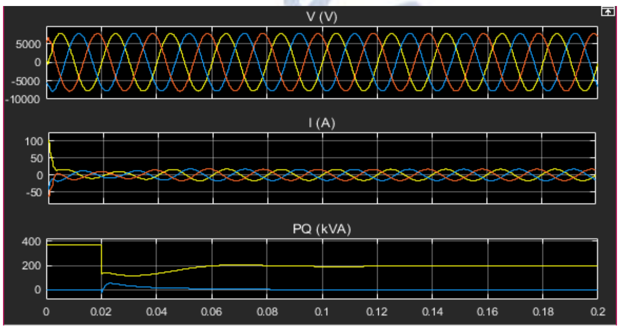


**Figure 12. V, I, PQ characteristics of PV**

Figure 12 represents the voltage, current and Power characteristics of a PV system. The active and the reactive power generated by the PV system is also clearly shown.

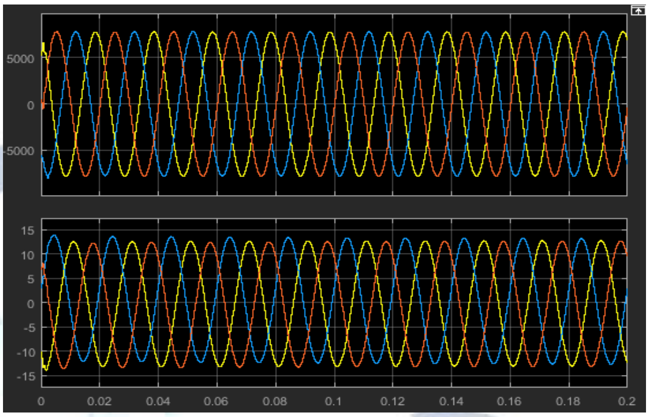

**Figure 13. V and I characteristics of PV system connected to grid**

Figure 13 represents the voltage and current characteristics of the PV system when it is connected to the common point of coupling (Pcc) ($13^{th}$bus), in an IEEE15 bus system.

### *C. Results of Simulink Model of 140KW PV Array system connected to the Grid along with UPQC to Substantiate Voltage Sag, Swell and Harmonics*

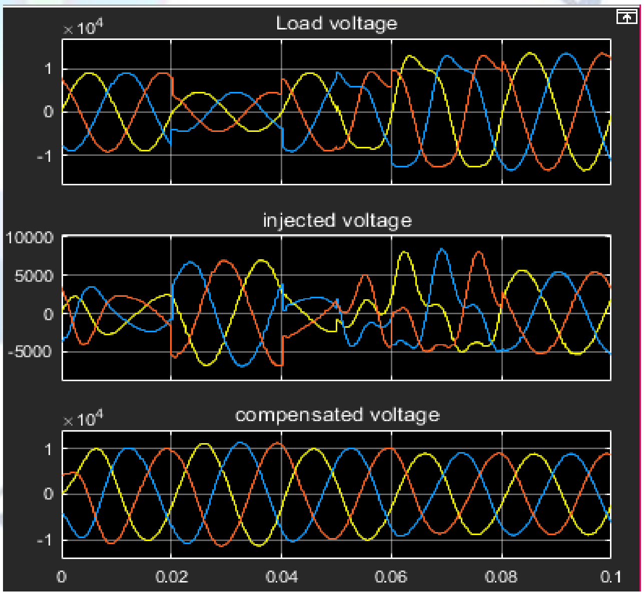


**Figure 14. Voltage characteristics after implementing UPQC**

Figure 14 represents the voltage compensation. The first portion represents voltage sag/ swell at the amplitude of [1, 0.5, 1, 1.5, 1.0] during the time period [0, 0.02, 0.04, 0.06, 0.1]sec and harmonics from 0.05 to 0.08 sec. The second section denotes the voltage injected to compensate the load voltage with the help of UPQC and its control techniques. And the third portion shows us the compensated voltage, after mitigation of sag, swell and harmonics

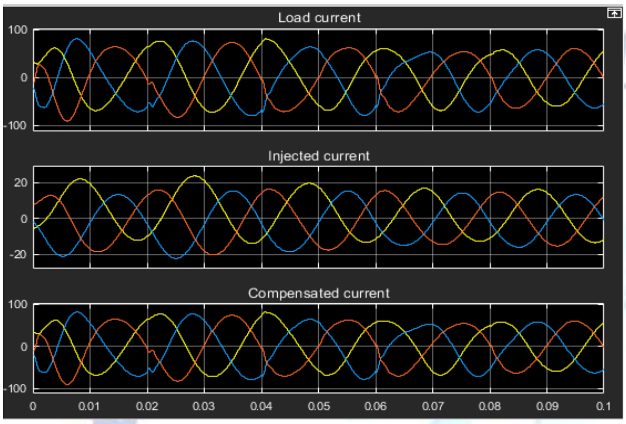


**Figure 15 Current characteristics after implementing UPQC**

Figure 15 represents the current characteristics after the implementation of UPQC. The first portion represents the load current, the second portion represents the current injected to the system and the third portion represents the compensated current.

## 5. CONCLUSION

This work focus on the enhancement of power quality by mitigating voltage sag, voltage swell and current harmonics in the PV integrated distribution network. Due to its reliability, UPQC is chosen to be the best solution for both voltage and current compensation. In this paper a 140KW Photovoltaic system is designed and integrated with 11KV IEEE 15 bus system. From the simulation results, it is observed that UPQC employed with PLL and Hysteresis control techniques works effectively in mitigating voltage sag, voltage swell and current harmonics by injecting sufficient voltage and current and thereby enhancing the overall power quality of the distribution system. Total Harmonic Distortion of 4% is observed. The extensive simulation study is carried out using MATLAB/SIMULINK.

### Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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