

A Mathematical Framework for Simultaneous Voltage and Frequency Regulation in Distributed Generator (DG) Grid-Interfaced Systems

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Abstract:

Recent advancements in distributed generation (DG) systems interfaced with microgrids necessitate robust regulatory mechanisms to manage inherent power fluctuations, particularly from renewable sources like photovoltaics. These fluctuations can significantly impact the stability and efficiency of microgrids. This paper introduces a novel mathematical framework for simultaneous voltage and frequency regulation, aimed at addressing power quality and stability challenges in DG-grid interfaced systems. Utilizing a combination of algebraic topology and dynamical systems theory, we develop a model that incorporates an adaptive virtual frequency-impedance control loop. This mathematical approach allows for the analytical examination of the stability properties of the system and the design of control strategies that guarantee optimal operational thresholds. We extend the conventional droop control mechanisms with a rigorously defined Simultaneous Voltage and Frequency Correction Scheme (SVFCS), providing a theoretical underpinning that supports experimental observations. The efficacy of the proposed model is validated through numerical simulations that demonstrate adherence to the IEEE 519 standard, ensuring reduced harmonic distortion and enhanced system reliability. Our results highlight the potential for these mathematical methods to provide foundational insights into the control and optimization of microgrid operations.

Keywords: Mathematical Modeling, Distributed Generation, Microgrid Stability, Voltage Regulation, Frequency Control, Dynamical Systems, Algebraic Topology.

NOMENCLATURE

MG	Micro-grid
T	Clark's transformation matrix
PV	Photovoltaic
DG	Distributed Generator
VSI	Voltage Source Inverter
CSI	Current Source Inverter (Current fed)
SVFCS	Simultaneous Voltage and Frequency Correction Scheme
SPWM	Sinusoidal Pulse Width Modulation
FACTS	Flexible Alternating current transmission system
HAPF	Hybrid Active Power Filter
SVM	Space vector modulation

1. Introduction

A microgrid can be conceptualized as a localized grid system capable of disconnecting from the main grid and operating autonomously. This configuration not only enhances reliability in face of main grid instability but also facilitates localized control over power generation and distribution, often incorporating distributed generators (DG). The structural advantage of a microgrid lies in its ability to mitigate systemic risks during grid maintenance and provide resilience against external disruptions such as severe weather conditions or power outages.

The operational independence of microgrids is mathematically intriguing due to the complex interplay of power generation, load management, and stability controls, which are often governed by renewable and conventional energy sources. The point of common coupling (PCC) serves as a critical node for maintaining the voltage and frequency alignment with the central power grid, requiring sophisticated control strategies to manage these parameters effectively.

For islanding operations, droop control mechanisms are implemented to facilitate decentralized power sharing, leading to the development of the renowned Q-U (reactive power-voltage) and P- ω (active power-frequency) control models [3]-[5]. These models describe the relationship between line parameters and operational controls and are vital for theoretical analysis. Virtual parameters are also used to decouple converter control from direct line interactions, enhancing load sharing capabilities without compromising system stability [6]-[7].

The implementation of maximum power point tracking (MPPT) algorithms optimizes the efficiency of photovoltaic DG units [8]-[11]. Advances in semiconductor technology and the shift towards transformer-less topologies have significantly reduced system costs and improved reliability but have introduced complexities in control mechanisms. The mathematical formulation of these technologies is critical for understanding their impact on system dynamics and stability.

Power quality improvement, another key aspect of microgrid operations, involves devices like passive filters, shunt and hybrid filters, and STATCOMs. The control strategies, including sinusoidal pulse width modulation (SPWM) and space vector modulation (SVM), are mathematically modeled to mitigate harmonics in accordance with the IEEE-519 standard. These models are essential for designing filters and compensators that address issues of load imbalance, harmonics, and poor power factor in a cost-effective manner.

Further mathematical exploration is seen in the development of dynamic voltage restorers (DVR), static VAR compensators (SVC), and DSTATCOMs, which are designed to compensate for power quality issues through cooperative control mechanisms [41-47]. These controls are often modeled as hierarchical systems that require precise timing and coordination, challenging to implement due to the intermittent nature of power fluctuations. The Simultaneous Voltage and Frequency Correction Scheme (SVFCS) introduced in this paper leverages a virtual impedance loop to address these challenges, offering a novel mathematical approach to microgrid control without the need for extensive communication infrastructures.

In conclusion, the mathematical models and control strategies discussed here form the theoretical backbone for enhancing microgrid performance and reliability. The ongoing development of these models reflects a significant area of research in the mathematical analysis of power systems,

emphasizing the need for robust, scalable solutions to ensure sustainable and efficient energy distribution.

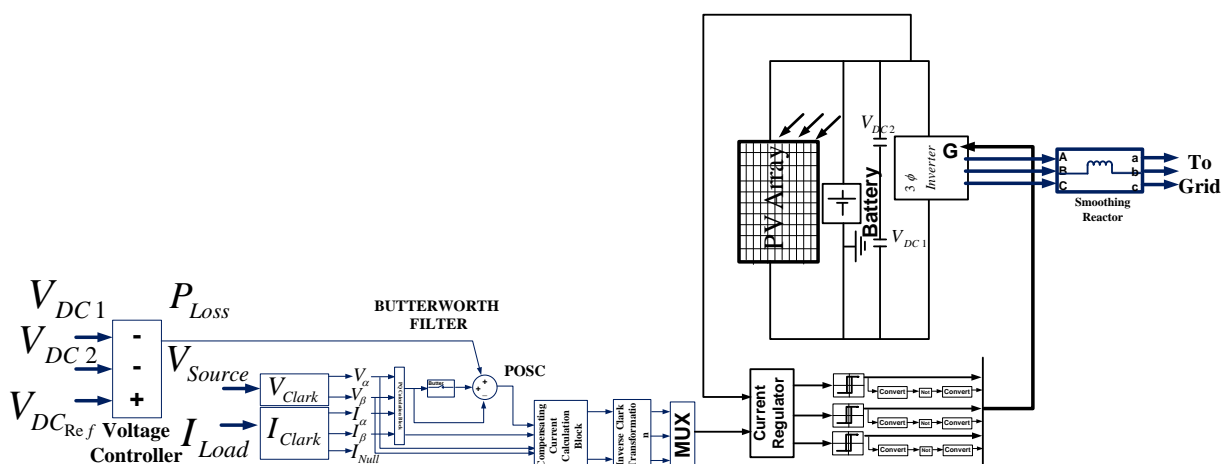
That's why the said SVFCS topology is very practical regarding DG grid interfaced system where the system is prone to rapid power fluctuation. The exploration of microgrid dynamics extends to the analysis of transient behaviors and steady-state responses within these decentralized networks. Advanced mathematical tools such as nonlinear dynamical systems theory and algebraic topology are applied to examine how microgrids react to changes in load and generation capacity. These tools facilitate a deeper understanding of stability margins and the bifurcation behavior of microgrids under different operational conditions. Particularly, the implementation of sophisticated algorithms like MPPT and the design of control strategies based on SPWM and SVM can be rigorously analyzed using perturbation methods and Lyapunov functions. These mathematical approaches are crucial for proving the stability and optimizing the performance of microgrids, ensuring that they not only meet current standards such as IEEE-519 and IEC 61000-3-2 but also adapt effectively to evolving grid conditions and renewable integration challenges. Such comprehensive mathematical analyses serve as the cornerstone for the next generation of microgrid technology, paving the way for smarter, more resilient energy systems [40-47].

The manuscript focused on following points: Droop control mechanism for PV based DG with VSI shown in section II. Simultaneous voltage and frequency corrector suggested overwhelming frequency and voltage imbalance generated by DG – Grid interface discussed in section III. Microgrid implementation based on DG Discussed in section IV & V followed by results and verification over proposed control mechanism. Brief conclusion listed in section VI.

2. Modeling of CCVSI in Grid tied DG System

A. Grid tied DG System subjected to Droop control mechanism:

The Controlling parameters like voltage current etc. can be sensed by the respective CTs and PTs from point of common coupling.



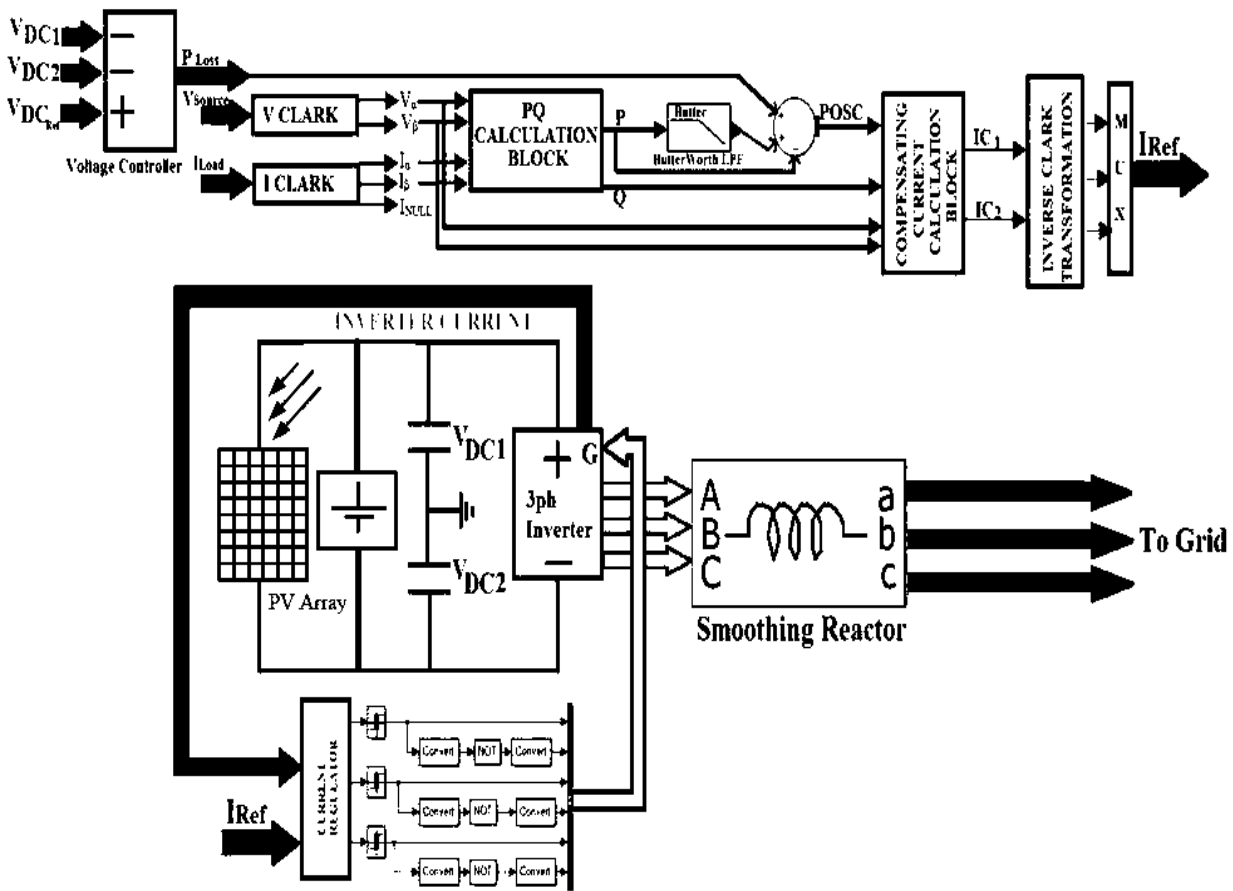


Fig. 1. Pictorial representation on Grid tied DG with Battery

The above figure depicts the suggested strategy for DG GRID interface with Battery energy storage. The interconnected DGs fed power to the PCC and they are generally coupled with droop control mechanism in islanded mode. The equivalent circuit depicted in figure 2 represents 2 interconnected inverters in parallel shared by a common burden.

The terms $E_x(x=1,2), U_x(x=1,2)$ reveals DG inverter voltage output and Bus voltages. Similarly $\phi_x(x=1,2)$ $Z_x(x=1,2)$ reveals DG inverter phase angle of voltage and impedance and θ , reveals the phase angle.

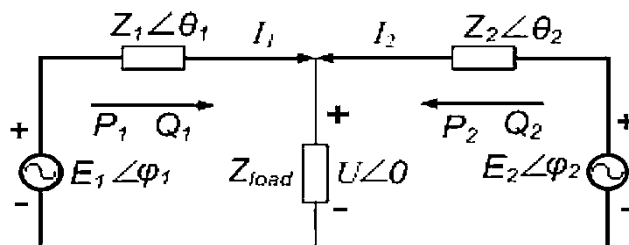


Fig. 2. Interconnected DG CCVSI Equivalent circuit

Active power, Reactive power for the inverter of 1st DG will

$$P_1 = \frac{E_1 U}{Z_1} \cos(\theta_1 - \phi_1) - \frac{U^2}{Z_1} \cos\theta_1 \quad (1)$$

$$Q_1 = \frac{E_1 U}{Z_1} \sin(\theta_1 - \phi_1) - \frac{U^2}{Z_1} \sin \theta_1 \dots\dots\dots (2)$$

The output voltage and branch impedance can affect the CCVSI voltage. Mostly, the impedance may be subdivided as a sum of feeder impedance and Z_{output} . The impedance can be of a virtual type and may be treated as fully resistive or inductive type.

$$Z = Z_{out} + Z_{feeder} \dots\dots\dots (3)$$

If the Z_{Feeder} is small enough then the effective impedance can be equivalent as the Z .

For reactive loads the system impedance (Z_{out}) may be written as:

$$P_1 = \frac{E_1 U}{X_1} \sin \phi_1 \dots\dots\dots (4)$$

$$Q_1 = \frac{E_1 U \cos \phi_1 - U^2}{X_1} \dots\dots\dots (5)$$

X_1 can be the inductive reactance of voltage output. If ϕ_1 is lesser compared to other parameters ($\sin \phi_1 \approx \phi_1, \cos \phi_1 \approx 1$), then $P_1 = E_1$

Similarly $P-\omega$ and $Q-U$ droop mechanism can be expressed as follows with m_p and m_q are agreeing droop gains; mathematically

$$\omega^* = \omega_n - m_p P \dots\dots\dots (6)$$

$$U^* = U_n - m_q Q \dots\dots\dots (7)$$

The control mechanism of above droop control scheme is as follows. The figure 3 shows a droop controller:

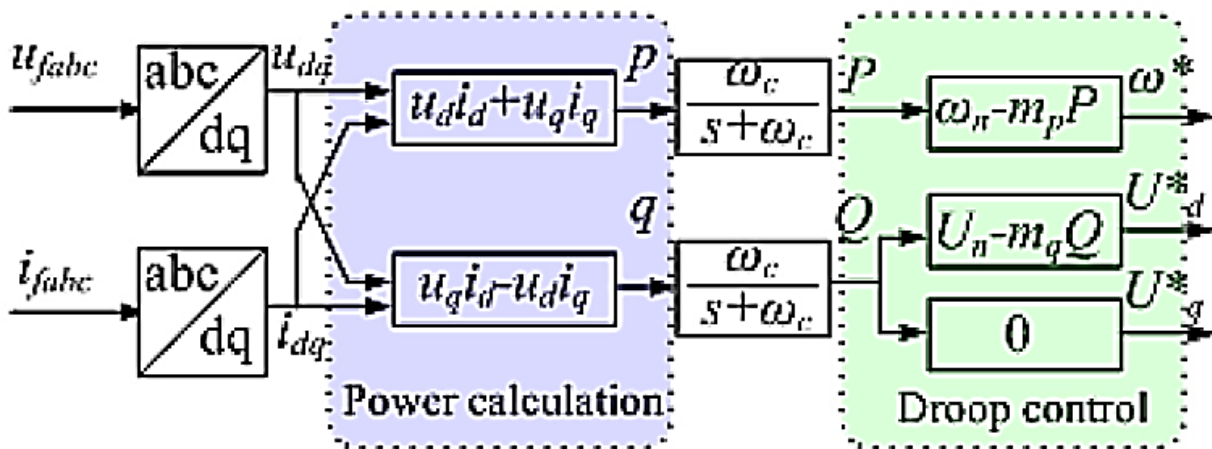


Fig. 3 Droop control mechanism.

The Droop gain may effect on stable operation and dynamic stability. Therefore on the basis of the droop gain the system stabilizes and may results to have decent power sharing. But it may lead to deviation on system voltage and frequency [33] [9]. Therefore, it is recommended to talk on accuracy in Voltage and frequency relation and should take care while adjusting droop gains. It can be treated as a compromise between V/f. In this present work m_p (droop gain) can be a fraction of ω_{\max} (maximum frequency) and P_{\max} (Variation in active power). Mathematically:

$$m_{p\max} = \frac{\Delta\omega_{\max}}{\Delta P_{\max}} \quad (8)$$

The variation in voltage obstructed by drop in voltage through System impedance (Z) at output and U_{\max}, Q_{\max} droop control. That's way droop gain

$$m_{q\max} = \frac{\Delta U_{\max} - I_{0\max} Z}{\Delta Q_{\max}} \quad (9)$$

In some circumstances the system impedance may be foremost, $m_{q\max}$ may be approximated as follows [9]:

$$m_{q\max} \approx \frac{\Delta U_{\max} - I_{0\max} Z_{\text{virtual}}}{\Delta Q_{\max}} \quad (10)$$

3. Modelling of Photo Voltaic based Micro-grid in islanded mode:

Output Voltage modeling:

It is known that Micro-grid in islanded mode consists of DG with CCVSI. The DG is a Photovoltaic based distributed generator with P/O MPPT. For easier calculation point of view the CCVSI assumed to have same capacity. The output voltage of CCVSI be governed by:

$$U_{d^*} = U_n - \frac{1}{n} m_q (Q_L - Q_{pv}) \quad (11)$$

$$U_{q^*} = 0 \quad (12)$$

$$\omega^* = \omega_n - \frac{1}{n} m_p (P_L - P_{pv}) \quad (13)$$

where:

$U_{d^*} \rightarrow$ "d" axis voltage

$U_{q^*} \rightarrow$ "q" axis voltage

$\omega^* \rightarrow$ Reference angular frequency

U_n & $\omega_n \rightarrow$ minimal values over that frequency and voltage.

m_p & $m_q \rightarrow$ droop gain (active and reactive)

P_L & $Q_L \rightarrow$ True & Reactive Power of the load

$P_{PV} \rightarrow$ DG True power

Q_{PV} Is the DG reactive power

The droop controller have several disadvantages like, it will affect Bus frequency and voltage in line for the presence of CCVSI. In equation (11), (12) and (13) it is seen that parameters related to droop control and yield power results voltage over CCVSI. It results voltage and frequency variation from the nominal value and cause power quality issue. This fluctuation in power may lead to variation in either DG power or load power and the PV based DG is certainly an unpredictable means of Energy. Therefore it is essential to have a limit on the above-mentioned effects for maintaining AC bus voltage and frequency. This paper focuses on above aspects.

The CCVSI Controller is revealed in Figure 4. Where $L_f, C_f, R_{vir}, L_{vir}, \omega_0$ can be the filter inductance, capacitance, virtual Impedance and angular frequency respectively. Voltage transfer function is $G_v(s)$ and $G_i(s)$ can be the current transfer function of respective PI controllers. (U_{od}, U_{oq}) can be the direct axis and quadrature axis feedback signals. Similarly I_{od} and I_{oq} can be the direct axis and quadrature axis feedback inverter signals currents. Other currents like $I_{Ld}, I_{Lq}, I_{od}, I_{oq}$ are introduced for improvement of power handling capability. Similarly other voltages like U_{od}, U_{oq} are introduced for improvement of power handling capability and regulation.

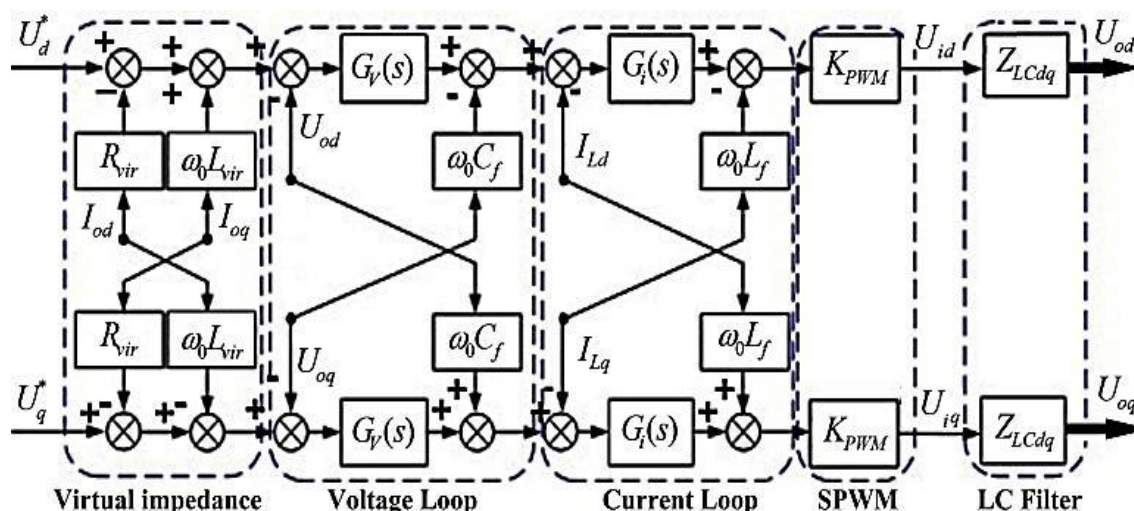


Fig. 4. CCVSI Controller.

Now we can write the droop control equation as follows:

$G(S)$ and $Z(S)$ can be the voltage gain and output matrix impedance.

$$\begin{bmatrix} U_{od}(s) \\ U_{oq}(s) \\ 0 \end{bmatrix} = G(s) \cdot \begin{bmatrix} U_n - \frac{1}{n} m_q (Q_L - Q_{PV}) \\ 0 \end{bmatrix} - [Z(s)] \begin{bmatrix} I_{od}(s) \\ I_{oq}(s) \end{bmatrix} \quad (14)$$

$$G(s) = \frac{G_{vi}(s) K_{PWM}}{L_f C_f S^2 + C_f G_i(s) K_{PWM} s + G_{vi}(s) K_{PWM} + 1} \quad (15)$$

$$[Z(s)] = G(s) \cdot G(s) \cdot \begin{bmatrix} R_{vir} + R_g - \omega_0 L_{vir} & \\ \omega_0 L_{vir} & L_{vir} + R_g \end{bmatrix} \quad (16)$$

Everywhere $R_g = \frac{G_i(s) K_{PWM} + s L_f}{G_v(s) G_i(s) K_{PWM}}$, $G_{vi}(s) = G_v(s) G_i(s)$

and $\omega^* = \omega_n - \frac{1}{n} m_p (P_L - P_{pv})$ the angular frequency of CCVSI is interrelated with m_p, P_{pv} and n

Such other factors like $Q_{pv}, m_q, G(s), [Z(s)], I_{od}, I_{oq}$ also affect the system performance. The listed drawback can be overwhelmed by adaptive regulation of CCVSI. The m_p (droop gain) should set as small as possible as it affect the deviation in system frequency and latter it affect the system active power demand. This can be mitigated by very small adjustment of droop gain m_p . Similarly by adjusting droop gain m_q reactive power variation can be compensated. This tuning may lead low reactive power distribution. It can be noted that U-Q droop control mechanism realization is very difficult in micro-grid [6], [9], [10]. In this literature focuses on adaptive impedance topology for restoration of voltage and simultaneously it takes care for the droop gain m_q .

4. Simultaneous Voltage and Frequency Corrector for Grid Tied Dg System

A. Adaptive impedance compensation topology

In this topology another virtual loop is used for generation of adaptive virtual impedance. Basically it is operated in 2 modes. Firstly making ready the offline CCVSI that to be connected to the PCC and secondly online CCVSI for compensation purposes for the power quality issue of the grid.

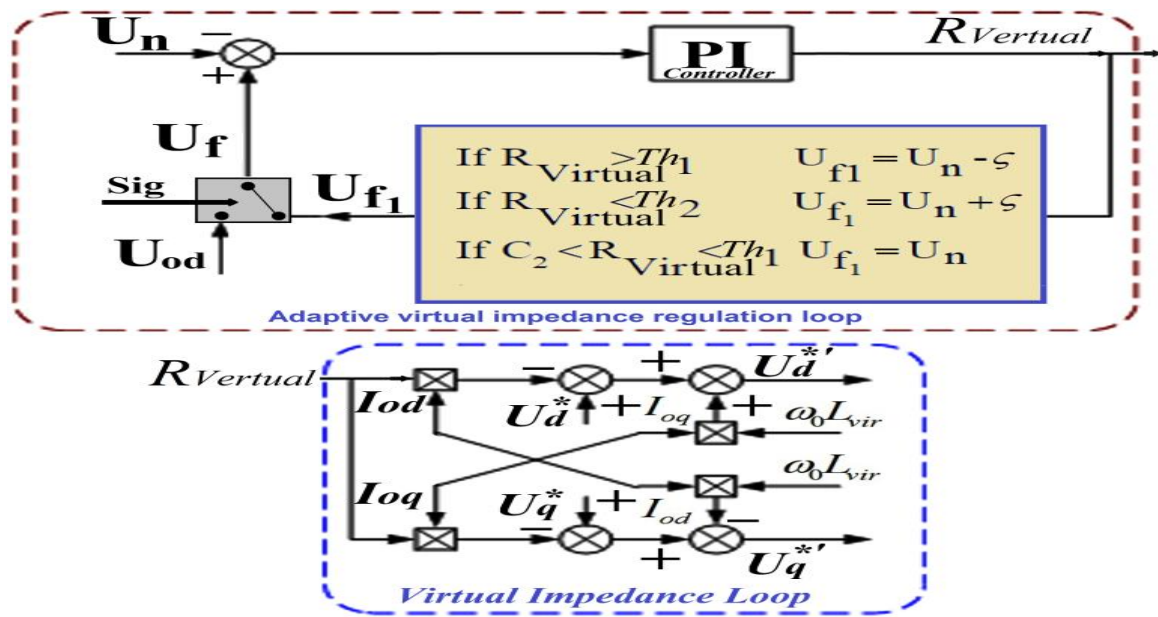


Fig.5. Proposed controller model.

Mode 1: in this mode of operation PI Controller output should be adjusted with in a hysteresis bound to overcome -ve effect at the time of closing the switch at PCC. It is shown in figure 5.

In this circumstance $sig = 0$. The voltage across CCVSI is the nominal voltage. Obviously initial values of PI controller are some random values

$$\begin{aligned} \text{If } R_{Virtual} > Th_1 & \quad U_{f1} = U_n - \zeta \\ \text{If } R_{Virtual} < Th_2 & \quad U_{f1} = U_n + \zeta \\ \text{If } C_2 < R_{Virtual} < Th_1 & \quad U_{f1} = U_n \end{aligned}$$

$\therefore \zeta$ is a constant value and varies between $.1U_n \approx .5U_n$. Hence $R_{Virtual}$ varies between Th_1 and Th_2 (Upper and Lower threshold value).

Mode 2: in this mode of operation CCVSI has to be coupled with microgrid Alone. By means of droop control terminology deviation in output voltage may lead to variation in output power and results a fluctuation in DG power. In this circumstance $sig = 1$. Then U_f (feedback voltage) = U_{od} (CCVSI voltage output). Hence the real-time regulations of virtual impedance occur by voltage deviation and can be depicted as follows:

$$R_{virtual} = K_p(U_{od} - U_n) + \frac{1}{K_i} \int (U_{od} - U_n) dt \quad (17)$$

Where K_p the proportional gain and K_i is the integral gains for the CCVSI. The CCVSI reference is

$$U_d^{*'} = U_d^* - (k_p(U_{od} - U_n)) + \frac{1}{K_i} \int (U_{od} - U_n) dt \cdot i_{od} + \omega_0 L_{vir} \cdot i_{od} \quad (18)$$

$$U_q^* = 0 - (k_p(U_{od} - U_n)) + \frac{1}{K_i} \int (U_{od} - U_n) dt + \omega_0 L_{vir} i_{od} \quad (19)$$

Where U_d^* is the direct axis reference voltage and U_q^* is the quadrature axis voltages reference with AVI (Adaptive Virtual Impedance) topology.

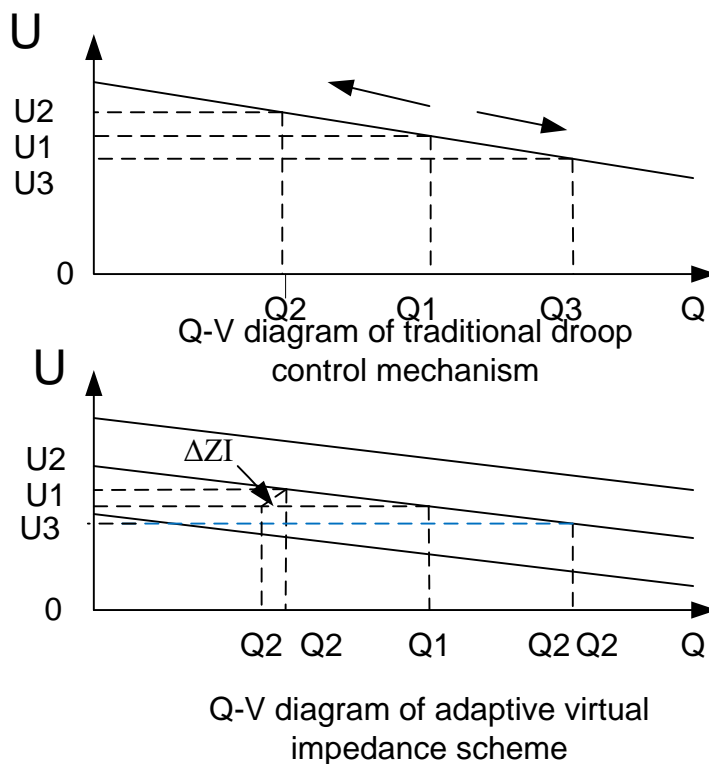


Fig. 6. The Q-V diagram of traditional droop control and AVI control mechanism.

Control Mechanism	Using Traditional droop controller	Using AVI controller
Q-U	from Q_1, U_1 to Q_2, U_2 or Q_3, U_3	deviation eliminated Q_2, U_2 to Q_2', U_1 or Q_3, U_3 to Q_3', U_1

The innermost droop control ring must be fast enough than the outer AVI mechanism for the assurance of voltage stability and adoptive power sharing.

Otherwise speaking droop control play a major role for power sharing and for restoration of voltage AVI scheme can be implemented for restoration of voltage

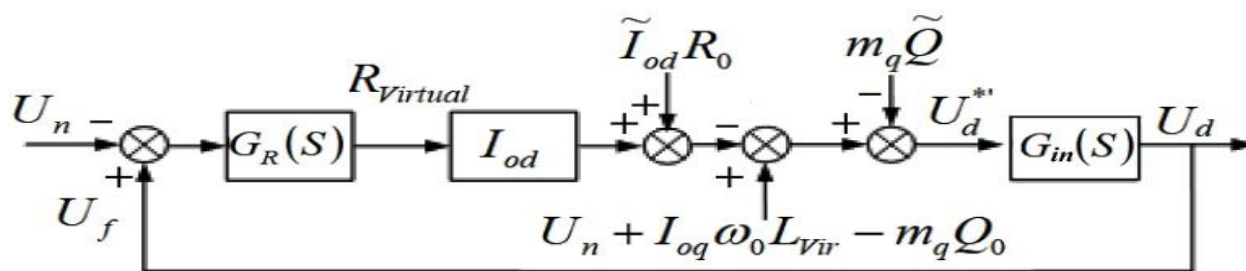


Fig. 7. The Control Voltage blocks.

In the above figure

$G_R(s) \rightarrow$ is the AVI controller

$G_m(s) \rightarrow$ Inner voltage control ring

$I_{od} \rightarrow$ Constant part of current at output

$\tilde{I}_{od} \rightarrow$ Variable part of current at output

$Q_0 \rightarrow$ Reactive power Constant part

$\tilde{Q} \rightarrow$ Disturbances that impact the voltage.

The disturbance caused by \tilde{Q} and \tilde{I}_{od} in voltages can be mitigated by tuning the AVI loop

$$U_{od} = \frac{G(s)m_q}{1 + G_R(s)G(s)I_{od}} \tilde{Q} \quad (20)$$

Where $G_R(s)$ can be a task of AVI compensator and $G(s)$ can be voltage transfer gain.

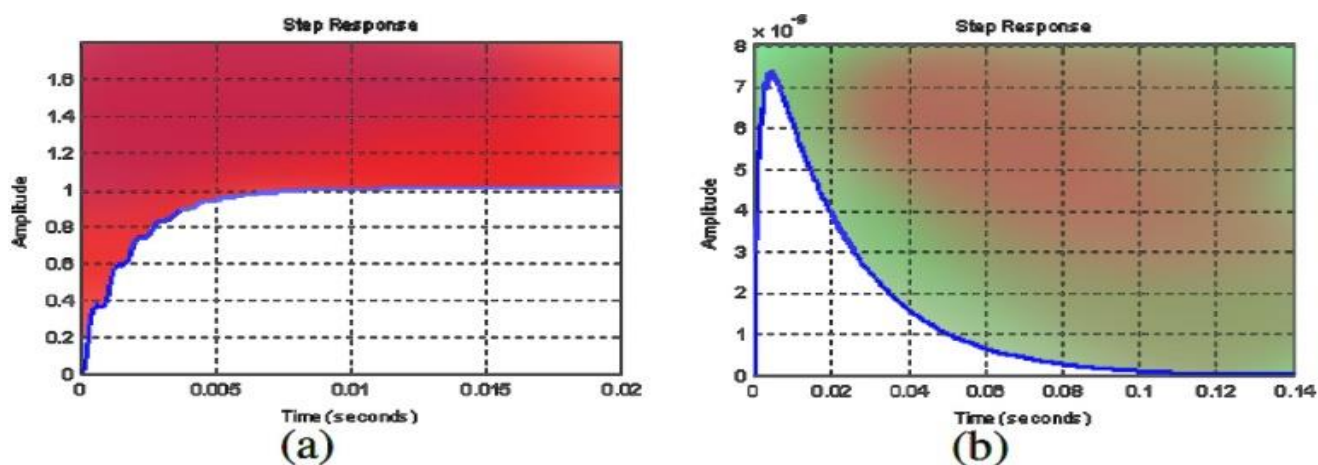


Figure 8 Step response for Inner Ring (a) outer voltage modification loop (b).

The figure above depicts the step response of Outer voltage correction ring and inner control ring. Care should be taken while designing the control loops. The f_c (Crossover frequency) set to $.10f_s$ to $.20f_s$.in that equation f_s can be actuating frequency. Generally f_c (frequency crossover) for the voltage which is quite lesser with respect to f_c . To mitigate disturbance, the outer control ring is used. It is to be noted that for stable operation it is recommended that output loop step reaction time should 10 times greater than the inner loop step reaction time. From this we can determine K_p and K_i .

5. Extensive Simulation & Experimental Verification

The usefulness of this Simultaneous Voltage and Frequency Correction Scheme addressed through the manuscript is verified on MATLAB/SIMULINK platform with both islanded mode and grid connected mode. DG with CCVSI employed for maintaining the voltage on AC bus. Table 1 shows the list of different parameters. Several supported tests done for checking the performance of this adaptive technique for mitigation of power quality issues

TABLE I. Organization of the System

SOLAR PHOTOVOLTAIC BASED DG AND INVERTER RATINGS	
Required DC Voltage	625 V
Peak Voltage DC	810 V
Filter Inductance and Resistance	200 μ H and 1.5 m Ω ,
Peak Power DC	1250 KW
Related DC Voltage	1250 V
Rated Power	1MW
Coupling Inductor	2.5mh
DC link Capacitor 2 NOs	4200 μ F
Transformer	50 Hz ,160 VA
Sampling Frquency	4.5KhZ
GRID SPECIFICATION	
Source Voltage	450 V
Ls,	45mH,
Source Frequency	50Hz
Xs/Rs	7.5
LOAD SPECIFICATION	
Load(Linear)	Active Power = 15.5 Kw
	Positive VAR= 15.5 Kvar
	Negative VAR= 7.5Kvar
1 Non Linear Load	120 ohm
3Phase Diode Load with resistor and inductor	300 mili Henery
2 Non Linear Load	P Active =15kW
Controlled Rectifier With RLC Value	+ve VAR = 320

Resistor and Inductor Unbalanced Load

-ve VAR = 160
 phase A resistance, reactance = 80Ω , 245mH
 phase B resistance, reactance = 85ohm, 235mH
 phase C resistance, reactance = 35ohm, 170mH

Switching on and switching off of DG

The PV based DG coupled with CCVSI as shown in figure 1. At the time of switching on and switching off power flow variation occur and it drives to power swing.

Figure 9 and 10 shows the amplitude and frequency of bus voltage. It is seen that it without compensator there is sufficient deviation from nominal at the instant of closing the switch.

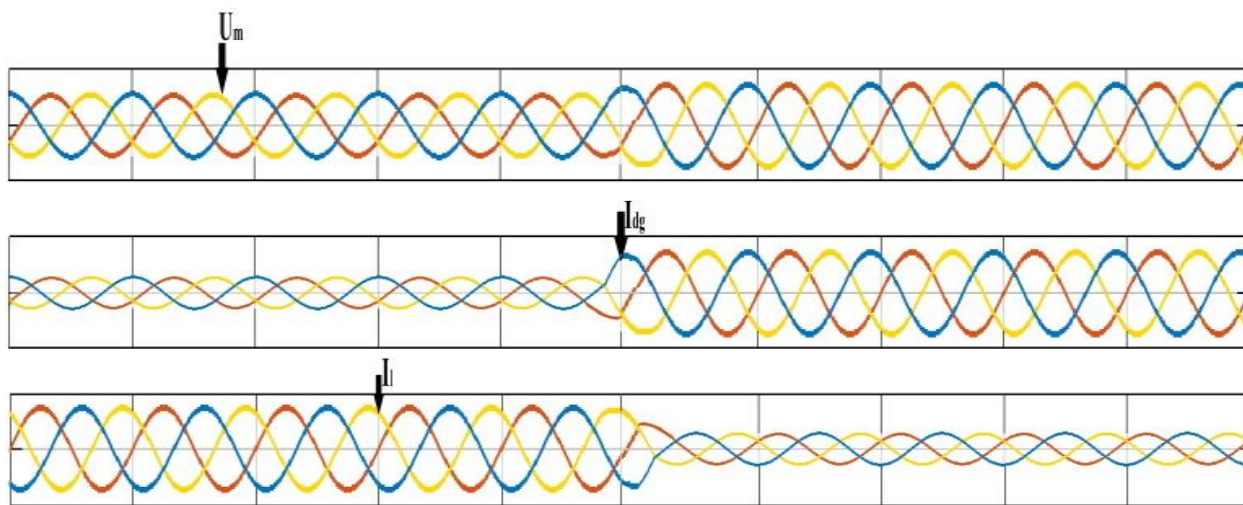


Fig. 9. AC bus voltage and current wave shape without Simultaneous Voltage and Frequency Correction.

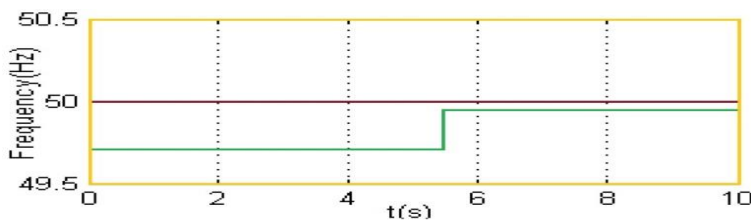


Fig. 10 AC bus frequency without Simultaneous Voltage and Frequency Correction.

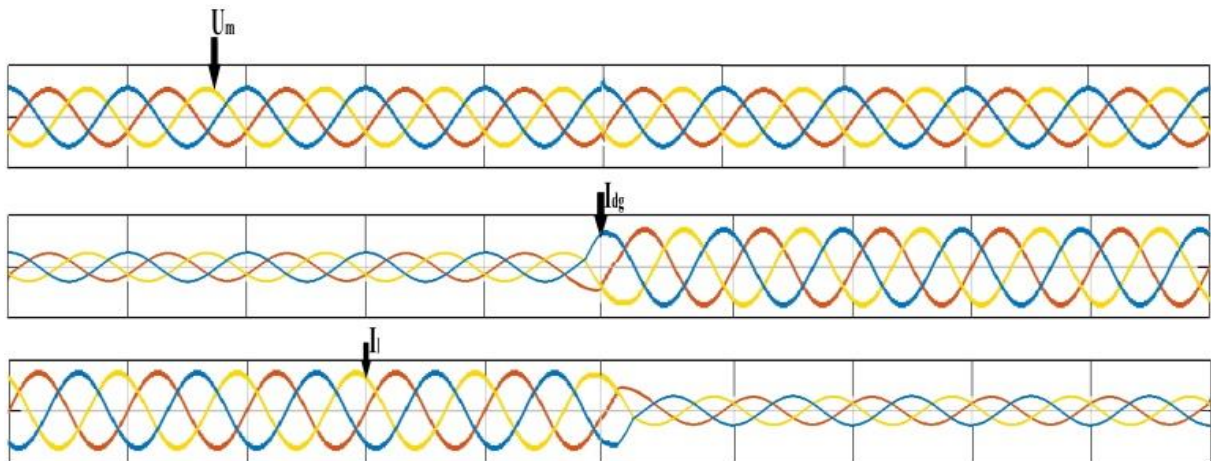


Fig.11 AC bus voltage and current wave shape with Simultaneous Voltage and Frequency Correction.

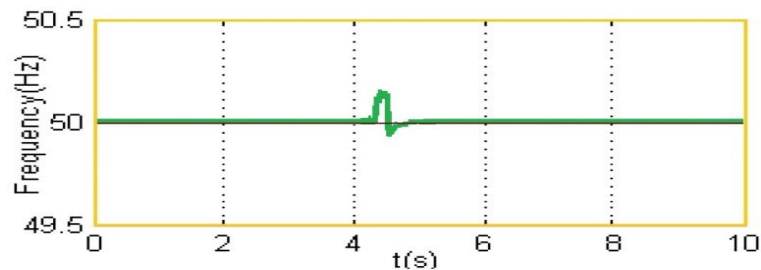


Fig.12 AC bus frequency with Simultaneous Voltage and Frequency Correction.

The wave shape depicted in figure 11 and 12 shows the amplitude and frequency of bus voltage. It is seen that it with compensator there is very less deviation from nominal value. There is a small transient period to for the stabilization of the voltage. It can also be seen in frequency waveform with a small settling time. The compensator satisfactorily ensures its job after closing the switch. It can be noted that by the use of Simultaneous Voltage and Frequency Corrector, the frequency and voltage variation touch almost 10 V and 0.35 Hz once the power deviation takes place. but it taken less time and returns to their nominal values. If we detach the DG from the grid the frequency and voltage retouches almost 15 V, 0.45 Hz respectively.

2) *Power fluctuation resulting from load variation.*

The Variation in load parameter also affects the system performance. The CCVSI controller should so adjusted that power output i.e., both active, reactive power should there in permissible limit. This compensators automatically manage the load change and will fine tune the PI controller to achieve similarity between wave shapes before and after load switching. It is seen that there is voltage sag for a small period (in micro second range). Soon after the transient period dies out it drives to normal steady state operation.

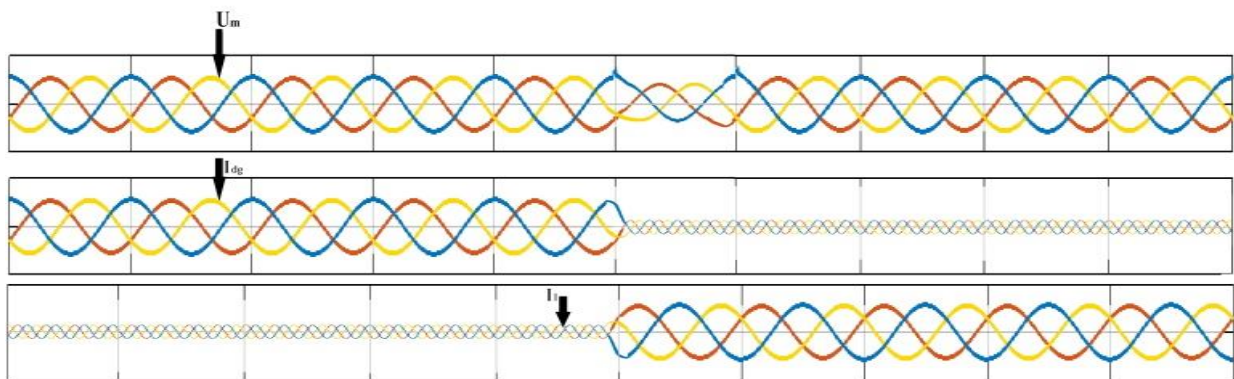


Fig.13 Simulink result with DG detached Grid with Simultaneous Voltage and Frequency Correction showing source voltage dg current and load current waveforms.

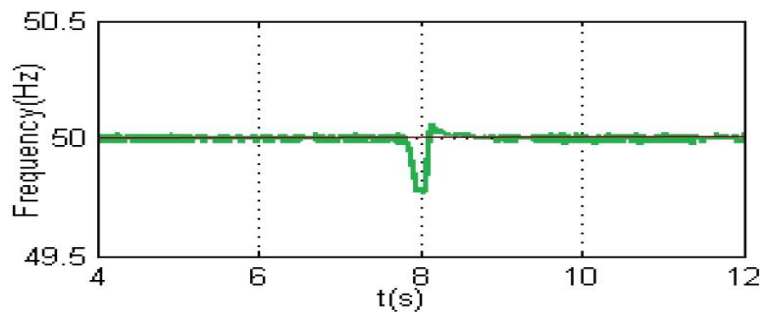


Fig.14 Simulink result with DG detached Grid with Simultaneous Voltage and Frequency Corrector showing Frequency waveform.

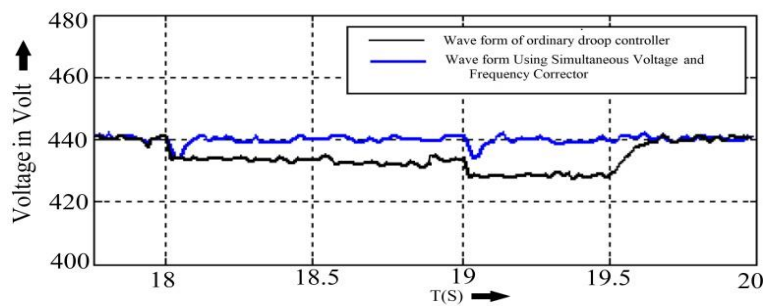


Fig. 15 Voltage deviation with Conventional droop controller and Simultaneous voltage and frequency corrector.

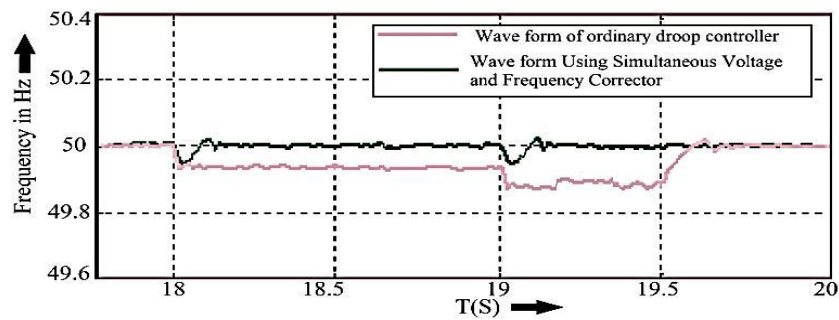


Fig. 16 Frequency deviation with Conventional controller with respect to droop and Simultaneous voltage and frequency corrector.

The table shown below is an experimental verification of different nonlinear loads connected to the grid. The load here can be a controlled rectifier type load. The alteration over firing angle of for rectifiers may result power quality issue. For the improvement of the power quality of any type of load change can be compensated precisely and results system stability which improves to a great extent.

TABLE II: RESULT AT DIFFERENT FIRING ANGLES

Typical Firing Angel of Non Linear Loads	Without DG VTHD	Without DG ITHD	With DG VTHD	With DG ITHD
60 ⁰	0.355%	92.676%	0.188%	1.322%
30 ⁰	0.477%	83.588%	0.300%	1.544%
45 ⁰	0.411%	85.544%	0.244%	1.477%

6. CONCLUSION

Presently various appliances and equipment are more delicate related to the old appliances and equipment. Therefore increase in harmonic content for electronic equipment is detrimental in all respect and impose new problems and leads poor performance. Therefore it is essential to design a sophisticated Power quality conditioner topology for improvement of power quality in DG Grid interfaced system. In this present work the said scheme efficiently compensate the power Quality Issue for 3 Φ system with typical linear, nonlinear, unbalanced burdens (20% - 80% of load ability). Reference current and voltage for both source and load can be taken care by Clark's transformation for the reduction of computational burden.

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