Improvemed Power Quality Using Photovoltaic Unified Static Compensation Techniques

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Abstract - This paper describes the design and simulation of custom power controller photovoltaic based power electronic device used for mitigations in voltage sag, swells and reactive power compensation and also controlled current harmonics. This system increases efficiency when compared to the conventional power distribution system. A new PWM based control scheme is performed by using digital simulator PSCAD/EMTDC.4.2 and the simulation was carried out. The simulation results prove the capability of the photovoltaic based system in mitigating voltage sag, flicker reduction and voltage unbalanced mitigation in a power distribution system.

Keywords - Voltage sag, custom power, PVUC, PSCAD/EMDC, photovoltaic cells.

I. Introduction

In recent years power quality issues have become more and more important both in practice and in research. Power quality can be considered to be the proper characteristics of supply voltage and also a reliable and effective process for delivering electrical energy to consumers. Binding standards and regulations impose on suppliers and consumers, the obligation to keep required power quality parameters at the point of common coupling (PCC).

Interest in power quality issues results not only from the legal regulations but also from growing consumer demands. Owing to increased sensitivity of applied receivers and process controls, many customers may experience severe technical and economical consequences of poor power quality. Disturbances such as voltage fluctuations, flicker, or imbalance can prevent appliances from operating properly and make some industrial processes shut down. On the other hand, such phenomena now appear more frequently in the power system because of systematic growth in the number and power of nonlinear and frequently time variable loads. When good power quality is necessary for technical and economical reasons, some kind of disturbance compensation is needed and that is why applications of power quality equipment have been increasing.

II. Operation of Photovoltaic Unified Ompensation (PVUC)

The general structure of the Photovoltaic Unified Compensation (PVUC) contains two "back to back" voltage source converters using Insulated-Gate-Bipolar Transistor (IGBT) with a common DC link in Fig.1. Shunt converter is connected as parallel and another converter is series with distribution system.

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The shunt converter is used to provide active power demanded by the series converter through a common DC link. The series converter provides the main function of the PVUC by injecting an AC voltage with controllable magnitude and phase angle. To the Distribution system through series converter and it exchanges the active and reactive power with the AC system. Since the converters are connected to a common DC link, they exchange only active power and there is no reactive power between them. It means that reactive power can be controlled independently at both converters. The Fig.1 enables voltage control by the shunt inverter and the series inverter controls active and reactive power.

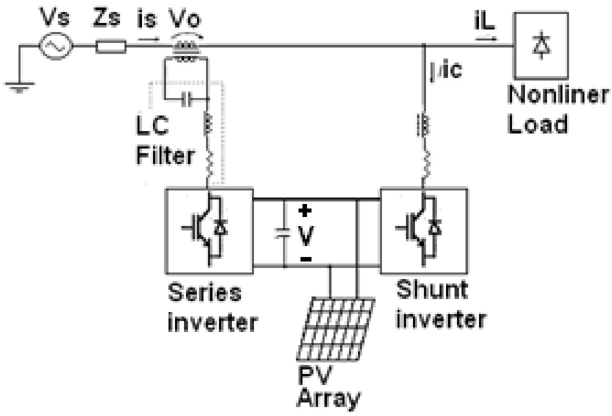


Fig.1: Diagram of the photovoltaic unified compensator.

In the shunt branch of PVUC the controlled by the phase angle of the converter and output voltage. In the series branch of PVUC the active and reactive power in the transmission line are influenced by the amplitude as well as phase angle of the injected voltage. Therefore the active power controller indicated with the reactive power and vice versa. In order to improve the interaction between the active and reactive power control, by decoupled control algorithm based on d-q axis theory was used [8,9]. Photovoltaic models have been presented by several authors [8, 6]. The PVUC model consists of a controllable voltage source connected in series with the Distribution system and two current sources added in shunt. The present model is connected in series and shunt with Distribution system.

III. Control Strategy of PVUC

The control system of PVUC has two parts and is described in the following subsections.

A. *Control system of shunt Inverter*

The controlling magnitude and phase of line voltage and power flow can be controlled. By the PV array supplies the voltage and inverter injected voltage to the distribution system shown Fig 2. The design of controllers for shunt and series inverter as follows.

The inverter output voltage represented by in three phase system as follows.

$$v_{kn} = v_{kN} - v_{nN} \qquad \text{k= a, b, c} \tag{1}$$

$$v_{an} = v_{aN} - v_{nN} \quad \text{similarly b and c phases.}$$

Each phase voltage can be written as:

$$v_{kn} = v_{Sk} - L_c \frac{di_{Ck}}{dt} \tag{2}$$

In a three phase, three wire system voltage represent with respect neutral:

$$v_{nN} = \frac{1}{3}\left(v_{aN} + v_{bN} + v_{cN}\right) \tag{3}$$

Substituting V_{nN} in equation (1)

$$v_{1n} = \frac{2}{3}v_{aN} - \frac{1}{3}v_{bN} - \frac{1}{3}v_{cN} \tag{4}$$

Similar equation can be written for phase b and c.
The phase voltage can be also written as:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = [V] \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \tag{5}$$

The variables T_k represent the states of inverter switches operation. T_k is '0' for open the Switches and '1' for closed the Switches. Defining the d_k switching state function.

$$\begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix} \tag{6}$$

Converter devices voltage represents.

$$\frac{dv}{dt} = \frac{i_{dc}}{C} = \frac{1}{C}\left(T_a i_{Ca} + T_b i_{Cb} + T_c i_{Cc}\right) \tag{7}$$

The system model is complete in the 'abc' reference equation (8) in Fig 3.

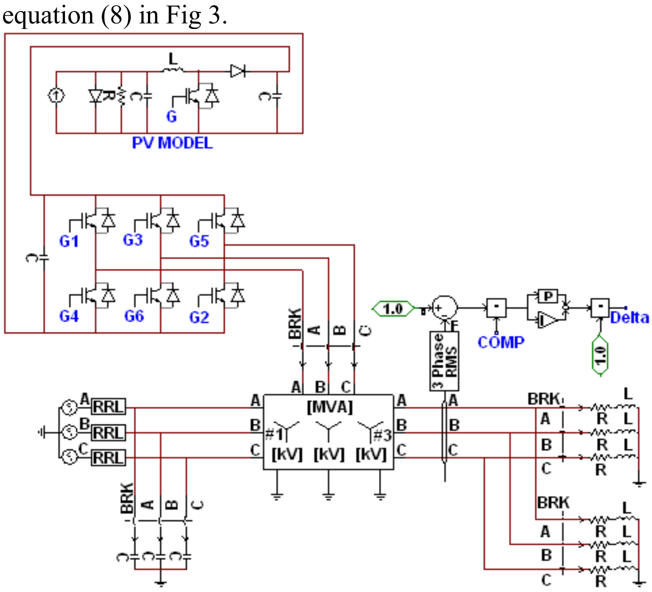


Fig. 2: Shunt Inverter PSCAD/EMTDC simulation circuit.

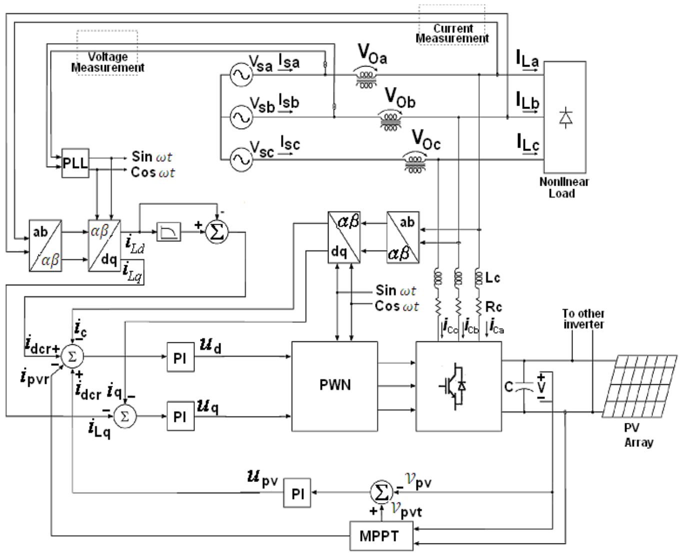


Fig. 3: Control block diagram of shunt Inverter.

$$\frac{d}{dt}\begin{bmatrix} i_{Ca} \\ i_{Cb} \\ V \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{d_a}{L_C} \\ 0 & 0 & -\frac{d_a}{L_C} \\ \frac{2d_a + d_b}{C} & \frac{d_a + 2d_b}{C} & 0 \end{bmatrix} \begin{bmatrix} i_{Ca} \\ i_{Cb} \\ V \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} V_{S1} \\ V_{S2} \\ 0 \end{bmatrix} \tag{8}$$

where:

i_{Ca}, i_{Cb}, i_{Cc} - three phase converter1 current,
Lc - inductance of the transformer,
da,db,dc - three phase switching state functions,
C - Capacitance of DC link,
Vsa,Vsb,Vsc- three phase supply voltages.

In eq(8), the steady state fundamental components are sinusoidal to reduce control complexity and 'dq' frame in eq (9) rotating at the supply frequency can be used. With this frame, the positive sequence components at fundamental frequency become constant.

$$\begin{bmatrix} i_{cd} \\ i_{cq} \\ i_{co} \end{bmatrix} = \left[\sqrt{\frac{2}{3}}\right] \begin{bmatrix} \cos wt & \cos(wt - 2\pi/3) & \cos(wt + 2\pi/3) \\ -\sin wt & -\sin(wt - 2\pi/3) & -\sin(wt + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} \tag{9}$$

where:
icd, icq -d-axis q-axis converter currents,
ico - Zero sequence converter current,
w - Supply angular frequency,

Taking into account the absence of the zero-sequence components in the currents in a three wire system, the simplified transformation matrix can be used.

$$\begin{bmatrix} i_{Cd} \\ i_{Cq} \end{bmatrix} = \sqrt{2}\begin{bmatrix} \cos(wt - \pi/6) & \sin wt \\ -\sin\cos(wt - \pi/6) & \cos wt \end{bmatrix} \cdot \begin{bmatrix} i_{Ca} \\ i_{Cb} \end{bmatrix} \tag{10}$$

The model of d-q frame equation (11) is:

$$\frac{d}{dt}\begin{bmatrix} i_{Cd} \\ i_{Cq} \\ V \end{bmatrix} = \begin{bmatrix} 0 & w & -\frac{d_d}{L_C} \\ -w & 0 & -\frac{d_q}{L_C} \\ \frac{d_d}{C} & \frac{d_q}{C} & 0 \end{bmatrix} \begin{bmatrix} i_{Cd} \\ i_{Cq} \\ V \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} V_{Sd} \\ V_{Sq} \\ 0 \end{bmatrix} \tag{11}$$

where:
d_d,d_q –d-axis and q-axis switching state functions,

V_{sd},V_{sq}-d-axis an dq-axis supply voltages.
The equation (11) changes in to the current equation models.

$$L_C \frac{di_{cd}}{dt} = L_C.w.i_{Cq} - V.d_d + V_{Sd} \quad (12)$$

$$L_C \frac{di_{cq}}{dt} = -L_C.w.i_{Cd} - V.d_q + V_{Sq} \quad (13)$$

Define

$$u_d = L_C.w.i_{Cq} - V.d_d + V_{Sd} \quad (14)$$

$$u_q = -L_C.w.i_{Cd} - V.d_q + V_{Sq} \quad (15)$$

and considering that the current control is realized by using PI controller, the equations (16) and (17) using in Fig. 3.

$$d_d = \frac{v_{Sd} - L_C.w.i_{Cq} - u_d}{V} \quad (16)$$

$$dq = \frac{v_{Sq} - L_C.w.i_{Cd} - u_q}{V} \quad (17)$$

The voltage equation in the model (13) can be written as:

$$C\frac{dv}{dt} = d_d.i_{Cd} + d_q i_{Cq} \quad (18)$$

$$u_{pv} = d_d.i_{Cd} + d_q.i_{Cq} \quad (19)$$

And considering that voltage control is realized by using a PI controller, the equation (20) using in Fig. 3 is:

$$i_{dcr} = \sqrt{\frac{2}{3}}\frac{V}{V\sup}u_{pv} \quad (20)$$

B. Control system of series inverter

The voltage compensator is a system based on power electronics inverter injected voltage and compensate the voltage sags, and keeping the load voltage around its rated value Fig 4. Under balanced condition the series inverter output voltage The variables T_{k2} represent the states of series inverter operation of switches. T_{k2} is '0' for open the Switches and '1' for the closing the Switches.

Defining the d_k as switches state function.

$$\begin{bmatrix} d_{a2} \\ d_{b2} \\ d_{c2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} T_{a2} \\ T_{b2} \\ T_{c2} \end{bmatrix} \quad (21)$$

The filter output voltage is

$$\frac{dv_{ko}}{dt} = -\frac{1}{C_f}\left(i_{fk} - i_{Lk}\right) \quad (22)$$

The dq complete model of the system as shown Fig. 4.

$$\frac{d}{dt}\begin{bmatrix} i_{fd} \\ i_{fq} \\ v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & w & \frac{1}{L_f} & 0 \\ -w & 0 & 0 & \frac{1}{L_f} \\ -\frac{1}{C_f} & 0 & 0 & w \\ 0 & -\frac{1}{C_f} & -w & 0 \end{bmatrix}\begin{bmatrix} i_{fd} \\ i_{fq} \\ v_{od} \\ v_{oq} \end{bmatrix} + \begin{bmatrix} -\frac{d_{d2}}{L_f}V \\ -\frac{d_{q2}}{L_f}V \\ \frac{1}{C_f}i_{ld} \\ \frac{1}{C_f}i_{Lq} \end{bmatrix} \quad (23)$$

where: i_{Ca}, i_{Cb}, i_{Cc} three phase converter currents

Lc - inductance of the transformer,
d_a, d_b, d_c - three phase switching state functions,
C - Capacitance of DC link,
V_{sa},V_{sb},V_{sc}- three phase supply voltages.
The steady state fundamental component is sinusoidal to reduce control complexity in the dq frame when rotating at the supply frequency can be used. With this fame the positive sequence components at fundamental frequency becomes constant.
The current equation in the models can be written as:

$$u_{d2} = L_f\omega i_{fq} + v_{0d} - Vd_{d2} \quad (24)$$

$$u_{q2} = -L_f\omega i_{fd} + v_{0q} - Vd_{q2} \quad (25)$$

Considering that the current control is realized by using PI compensators the equations (26) and (27) using in Fig. 5.

$$d_{d2} = \frac{v_{od} + L_f\omega i_{fq} - u_{d2}}{V} \quad (26)$$

$$d_{q2} = \frac{v_{oq} + L_f\omega i_{fd} - u_{q2}}{V} \quad (27)$$

The voltage equation in the model (23) can be written as:

$$C\frac{dv}{dt} = d_d.i_{Cd} + d_q i_{Cq} \quad (28)$$

$$u_{pv} = d_d.i_{Cd} + d_q.i_{Cq} \quad (29)$$

and considering that voltage control is realized by using a PI compensator, the equations (26) and (27).

$$i_{dcr} = \sqrt{\frac{2}{3}}\frac{V}{V\sup}u_{pv} \quad (30)$$

Figs 3 and 5 shows the gate pulse generator circuit of the series and shunt inverters based on SPWM technique. In the presented SPWM technique, the error signal is applied to a PI controller and the output signal of PI controller is the reference signal of the SPWM technique. Voltage sag compensate equation is

$$\%Sag = \frac{V_{per\text{-}sag} - V_{per(pu)}}{V_{per\text{-}sag\,(p\,u)}} * 100 \quad (31)$$

IV. SIMULATION RESULTS

The schematics diagrams Figs. 2 and 4 are simulated by using PSCAD/ EMTDC, The PVUC is placed in a 11 kV distribution system with static load of 2.7 MVA. The simulations are carried out and illustrate the effectiveness of the PVUC as a unified compensator for voltage regulation, voltage sag compensation, voltage flicker reduction, and voltage unbalance mitigation.

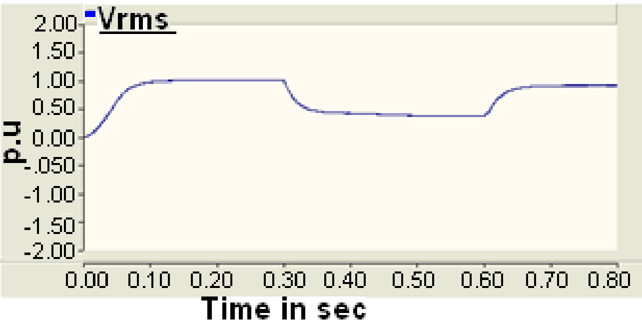
Load is increased from 0.5 to 1.0 per unit as shown in Fig 6. The load voltage decreases and returns to its rated voltage due to the voltage sag compensation capability of PVUC system.

Fig 7 (a).shows the line voltage sag without PVUC and the Fig 7 (b) shows that line voltage sag compensation with PVUC.

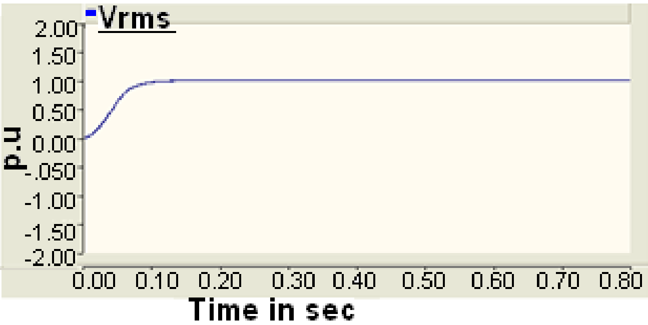
- The simulation period 300ms-600ms, the load is increased by closing switch C. In this case, the voltage drops by almost 34% with respect to the reference value.

- At 600ms. The switch C is opened and remains so throughout the rest of the simulation the load voltage is very close to the reference value.
- In this same interval A is closed and the PVUC starts operating to mitigate the voltage sag and restore the voltage back to the reference value.

The simulation also carried initially an unbalanced voltage due to two phase to ground faults that are phase A and phase C at time t = 300ms to t = 600ms. As shown in Fig 8.

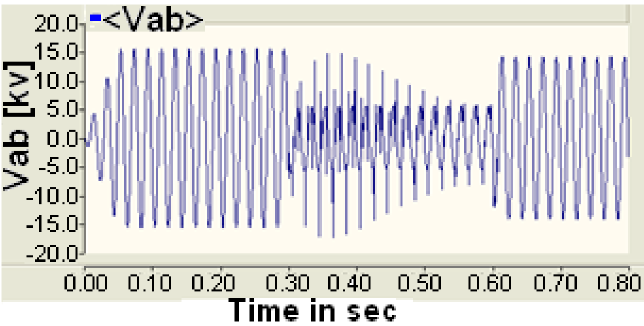


a) Without PVUC.

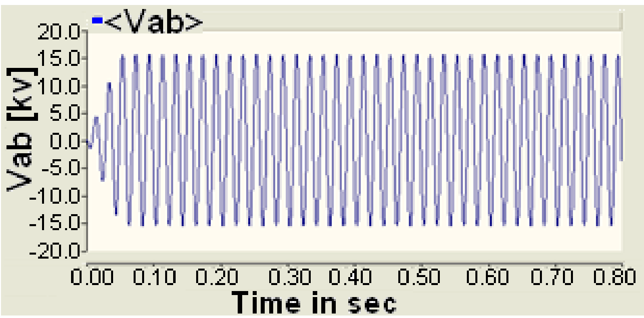


b) With PVUC.

Fig.6: Per unit Voltage V_{rms} at the load point.

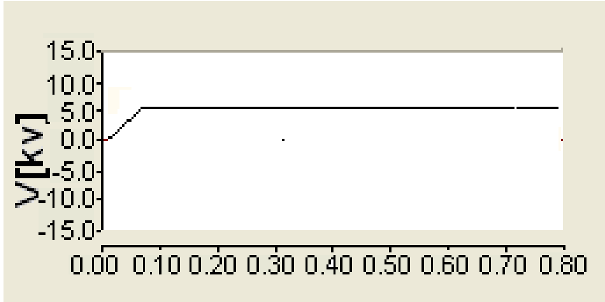


a) Without PVUC.

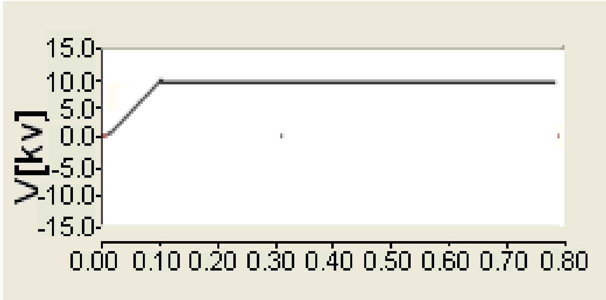


b) With PVUC.

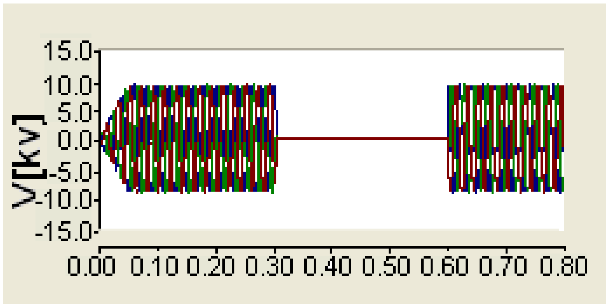
Fig 7: Line Voltage V_{ab} at the load point.



a) PV voltage without boost converter

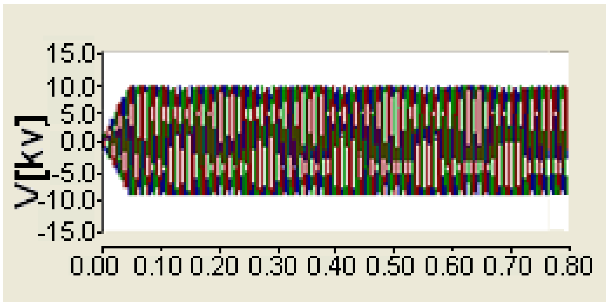


b) PV voltage with boost converter



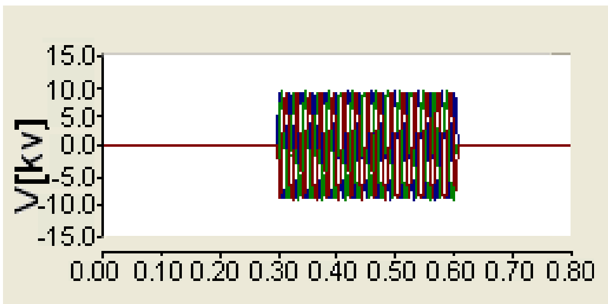
Time in sec

a) Without PVUC



Time in sec

b) With PVUC



Time in sec

c) With supply voltage of PVUC

Fig. 8: Phase faults

V. CONCLUSION

The use of computer programs in simulation of custom power controllers including photo voltaic is extremely important for the development and understanding of the power electronics based technology. The result is achieved through digital simulation which clearly shows the capability of the PVUC to mitigate the voltage sags providing a continuously variable level of shunt compensation of voltage sages and regulates the voltage a new PVUC design which incorporates PV module as a DC voltage source to mitigate voltage sags in a distribution system has been presented. The PVUC is modeled with a new feedback controller scheme to control the IGBT switches of the inverter. The output is filtered in order to mitigate the harmonics generated from switching. The PV is connected to a boost converter so as to achieve a higher output voltage for charging the capacitor efficiently. Simulation results prove that the PV is a useful alternative DC source for the PVUC.

VI. REFERENCES

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