# A Novel Approach on Interline Photovoltaic Power Systems for Voltage Droop Control

**Seshankar.N.B, Parthasarathy.S, Vidya.B**

***Abstract*— This paper proposes an interline power flow control method using photovoltaic (PV) plant for both transmission and distribution networks in order to regulate the feeder voltages. In the proposed approach the interline power flow between two or more feeders will be achieved by appropriately reconfiguring the PV plant. The reconfiguration is made in such a way that the PV plant acts as a flexible ac transmission system (FACTS) device to regulate the point-of-common coupling (PCC) voltage on either feeder. The control system of I-PV plants mainly consists of active and reactive power droop controllers, voltage and current controllers and unbalance compensator. The negative sequence current is injected from the I-PV power plant to compensate for the unbalanced loads. In addition to voltage regulation, active and reactive power flow control and energy management in a multi-line system can be achieved using the proposed method. The simulation of the proposed model was carried out using MATLAB/Simulink and the effective performance was analyzed.**

***Index Terms*—Active and Reactive power control, FACTS, Interline power system, Voltage regulation.**

## I. Introduction

Recent technological developments have made it possible to generate power, in order of tens of mega-watts (MW) to hundreds of MWs, using renewable energy resources, such as, photovoltaic (PV) solar and wind turbines systems. However, as the penetration levels of these distributed generators (DG) continue to grow to the extent that it is affecting the normal operation of a power system [1-4].

The large-scale real power injection by DG systems at certain locations on power transmission/distribution networks can violate the power system constraints, such as, excessive feeder voltage rise [4]. Apart from this, the issues related with poor power quality, harmonics, proper active and reactive power management, etc. are becoming more prevalent [1-3]. The adequacy of generating capacity in a power system can be improved by interconnecting two or more power systems. Better performance of power system can be achieved by controlling the flow of power in interconnected system.
Alternately, flexible AC transmission system (FACTS) devices have been utilized to increase the power transfer capability of transmission systems and regulate the power flow over transmission lines. Some of the important FACTS devices can be listed as, thyristor controlled reactor (TCR), thyristor controlled series compensator (TCSC), static synchronous compensator (STATCOM), static synchronous series compensator (SSSC), unified power flow controller (UPFC), interline power flow controller (IPFC) and others [5-8].

The control method presented in [12] and [13] is based on using a two-inverter structure one connected in shunt and the other in series with the grid, like a series-parallel active power filter. The main role of the shunt inverter is to control active and reactive power flow, while the series inverter balances the line currents and the voltages at sensitive load terminals, in spite of unbalanced grid voltage. This is done by injecting negative sequence voltage

Recently, PV solar plant inverters have been called on to perform additional tasks, such as current harmonic compensation, load reactive power support and voltage regulation [9-14]. This paper proposes a new system configuration that can be considered as a FACTS device, realized using existing inverters in a PV solar power plant. Generally, a large-scale PV solar power plant is constructed by connecting several smaller inverter – solar array units (order of few hundred kW up to 500 kW or more) in parallel.

The idea here is to reconfigure these several units such that two or more transmission (or even distribution) lines can be interconnected using the PV solar plant inverters. The system configuration thus achieved is termed as Interline PV (I-PV) system. This configuration is similar in construction to the IPFC. However, in the I-PV system two or more transmission/distribution lines are connected though shunt connected back to back converters contrary to IPFC where they are connected in series with the lines.

The proposed I-PV system can be used to control the flow of active and reactive power in multi-line transmission networks, support leading or lagging reactive powers to different lines independently to regulate the line voltage, and so on. The I-PV system configuration could be an attractive solution especially during the period when PV solar power plant remains inactive, namely, late evening hours, throughout night hours and early morning hours.

Furthermore, the concept of I-PV system can be extended during daytime hours providing further flexibility over control and regulation of real power generated by PV solar power station. In this paper the concept of interline PV system is introduced. A MATLAB/SIMULINK based study is carried to illustrate one of many capabilities of proposed I-PV system.

## II. I-PV Power Plant System Configuration

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Fig. 1 shows a two-feeder distribution system in which feeder-1 and feeder-2 are considered to be located close to each other. A large-scale PV solar power plant is connected at feeder-1. The PV plant inverters are reconfigured in such a way that the two feeders could be interconnected with each other. This configuration is referred to as an 'Interline-PV' (I-PV) system [15]

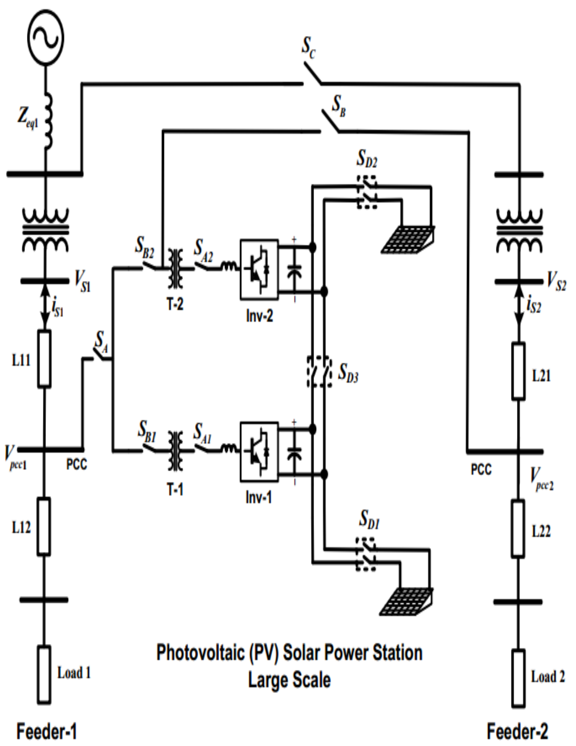


Fig. 1 Interline-PV (I-PV) power plant system configuration

Table I shows the flexibility of I-PV power plants to inject the solar energy into feeder-1 only or feeder-2 only or to share it with both feeders. These operations can be achieved by opening and closing different switches, as illustrated in Table I. Switch is used for islanded/non islanded operation of feeder-2. Based on the load demand on feeder-1 and feeder-2, the active power generated by the PV system can be delivered to one of the feeders fully or to both of the feeders partially. For example, when the switches $S_A$, $S_c$, $S_{A1}$, $S_{A2}$, $S_{B1}$, $S_{B2}$, $S_{D1}$, and $S_{D2}$ are closed and switches $S_B$ and $S_{D3}$ are open, the PV generated active power is delivered to feeder-1 only, whereas when $S_B$, $S_c$, $S_{A1}$, $S_{A2}$, $S_{B1}$, $S_{B2}$, $S_{D1}$ and $S_{D2}$ are closed and $S_A$ and $S_{D3}$ open, the active power is delivered to feeder-2 only. During the night, when there is no power generation from the PV system, configuring the switches $S_A$, $S_B$, $S_c$, $S_{A1}$, $S_{A2}$, $S_{B1}$, and $S_{D3}$ as close $S_{B2}$, $S_{D1}$, $S_{D2}$ are open, the active power exchange between feeder-1 and feeder-2 can be accomplished. Note that during all of the different operating modes (given in Table I), based on the system requirement, the respective feeder inverter(s) can inject or absorb reactive power as well.

TABLE I

DIFFERENT MODES OF PV POWER INJECTION

| Power injected to | Switch status | |
|---|---|---|
| | Closed | Open |
| feeder-1 only, day time | $S_A$, $S_C$, $S_{A1}$, $S_{A2}$, $S_{B1}$, $S_{B2}$, $S_{D1}$, $S_{D2}$ | $S_B$, $S_{D3}$ |
| feeder-2 only, day time | $S_B$, $S_C$, $S_{A1}$, $S_{A2}$, $S_{B1}$, $S_{B2}$, $S_{D1}$, $S_{D2}$ | $S_A$, $S_{D3}$ |
| feeders-1 and -2, day time | $S_A$, $S_B$, $S_C$, $S_{A1}$, $S_{A2}$, $S_{B1}$, $S_{D1}$, $S_{D2}$ | $S_{B2}$, $S_{D3}$ |
| feeders-1 and -2, night time | $S_A$, $S_B$, $S_C$, $S_{A1}$, $S_{A2}$, $S_{B1}$, $S_{D3}$ | $S_{B2}$, $S_{D1}$, $S_{D2}$ |

## III. CONTROL SYSTEM FOR VOLTAGE REGULATION

In this section, the control algorithm for PCC voltage unbalance compensation is discussed. The idea of this controller is to split the main controller of the PV converters into positive sequence and negative sequence controllers.

A. Positive and negative sequence extractions:

Fig. 2 shows the structure used to extract the positive and negative sequence components. The positive sequence extraction is established on the d-q frame theory. It converts the unbalanced 3-ph quantities (voltage and current) into dc positive sequence components according to the following equation

$$\begin{bmatrix} x_d^+ \\ x_q^+ \\ x_o^+ \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} \quad (1)$$

Where x donates either voltage or current quantities.

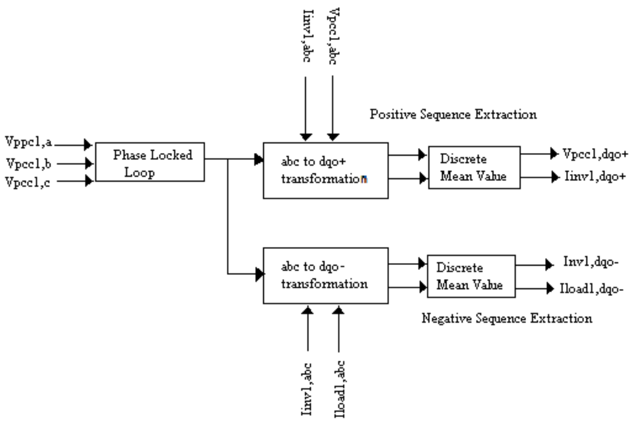


Fig. 2 Positive and negative sequences extraction.

The negative sequence is a balanced set of three phases quantities that rotates in the opposite direction of the positive sequence component. Thus, when the positive sequence component rotates in abc direction, the negative sequence component rotates in acb direction. Hence, the negative sequence component of the voltage or current is extracted according to the following equation:

$$\begin{bmatrix} x_d^- \\ x_q^- \\ x_o^- \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin(\omega t) & \sin(\omega t + \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{bmatrix} \quad (2)$$

B. Positive and negative sequence controllers

Fig. 3 shows the positive and negative sequence controllers for I-PV power plants. The positive sequence controller is used to inject the reference active power $P^*_{inv1,dqo}+$ from solar cells into the grid and to regulate the PCC voltage from solar cells into the grid and to regulate the PCC voltage $V^*_{pcc1,dqo}+$ simultaneously as shown in Fig. 3.

The negative sequence controller is used to inject the negative sequence current $I_{load1,dqo}-$ required by the unbalanced load using PV converters. Thus, cancelling the negative sequence current absorbed from the grid and maintaining the PCC voltage balanced.

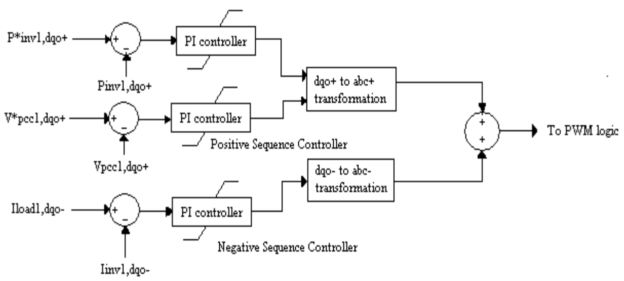


Fig. 3 Positive and negative sequence controllers.

The following equations are used to transform the positive and negative sequence dq components into the corresponding abc components as shown in Fig. 3

$$\begin{bmatrix} x_a^+(t) \\ x_b^+(t) \\ x_c^+(t) \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} x_d^+ \\ x_q^+ \\ x_o^+ \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} x_a^-(t) \\ x_b^-(t) \\ x_c^-(t) \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} x_d^- \\ x_q^- \\ x_o^- \end{bmatrix} \quad (4)$$

## IV. SIMULATION STUDY

In this section, a simulation study based on the given I-PV power system and its control to compensate the unbalanced PCC voltage is discussed.

### *A. System under consideration*

Fig. 4 shows the power distribution network that is used for the simulation study. The system consists of two feeders, while the study is performed on just one feeder (i.e. feeder-1). The voltages of the two feeders are considered as 11 kV. The loads on the feeders are normalized as PQ loads, located at the ends of each feeder. The loads have different values on each feeder and are programmed to emulate balanced and unbalanced conditions.

The simulation results are taken with base voltage of 11 kV and base MVA of 1. Appendix-I contains the detailed data for the system under simulation for balanced and unbalanced conditions. Fig.4 shows System under consideration for simulation.

### *B. Simulation Results*

Fig.6 shows the voltage, current, real power and reactive power waveforms of feeder-1 without PV plant. Fig.7 shows the voltage, current, real power and reactive power waveforms of feeder-1 with PV plant. Fig.8 shows the voltage, current, real power and reactive power waveforms of feeder-1 and feeder-2 with PV plant. Following are the important simulation timelines:

Time - 1 = 0.45 sec: unbalanced loads are connected to the feeder without any compensation.
Time - 2 = 0.50 sec: Inv-1 starts to compensate for the unbalanced loads

The PCC three phase voltage waveforms are shown in Fig. 5(a). It is noticed that the waveforms of the voltages are unbalanced in magnitude (without compensation). When the IPV system Inv-1 is controlled to compensate, this unbalance in the PCC voltages is mitigated achieving a balance set of PCC voltages. The load voltage waveforms are similar to the PCC voltage, due to the small voltage drop on the impedance between the two buses. Load three phase voltage waveforms are shown in Fig 5(b).

Fig.9 shows simulated output voltage waveform in which the feeder voltage is regulated at the point of common coupling (PCC) at the time period of 0.5 sec

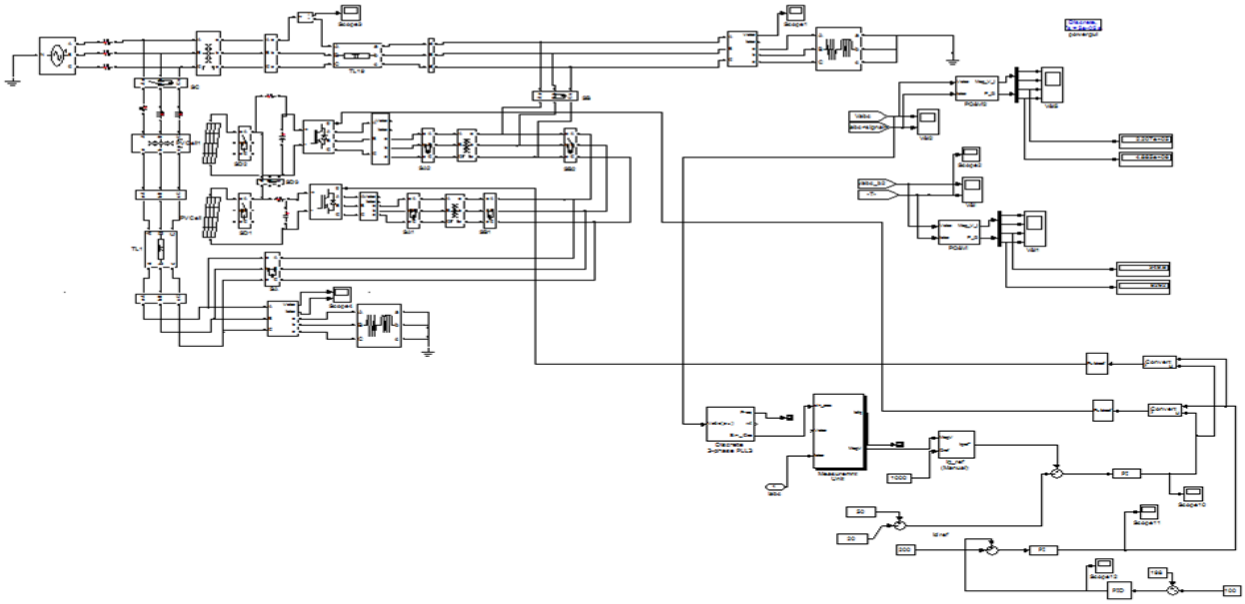

Fig. 4 System Simulation

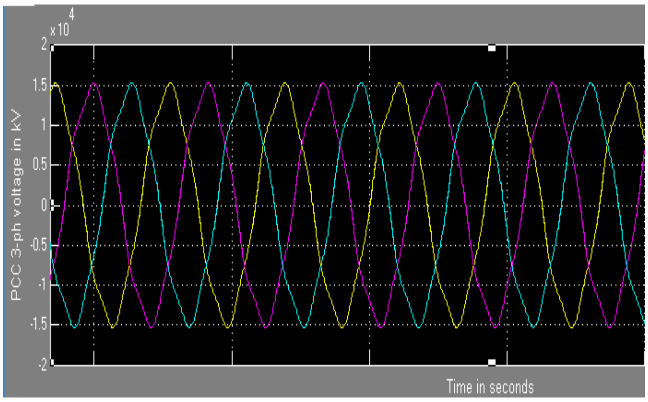


Fig. 5.a Simulated output for PCC 3-ph voltage waveform

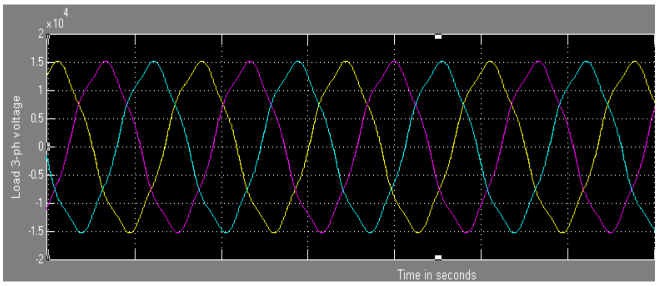


Fig. 5.b Simulated output for Load 3-ph voltage waveform

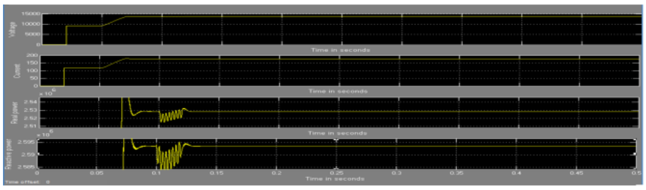

Fig. 6.Simulated output waveform for V, I, P and Q without PV plant.

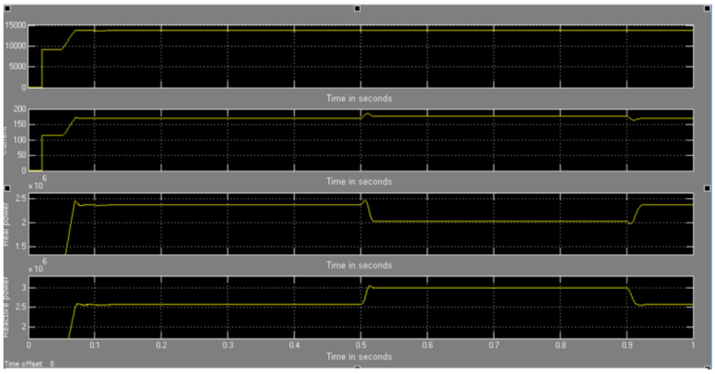


Fig. 7 Simulated output waveform for V, I, P and Q with PV plant in feeder 1.

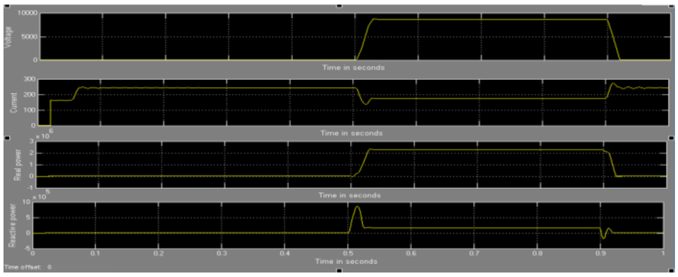

Fig. 8 Simulated output waveform for V, I, P and Q with PV plant in feeder 1 and 2.

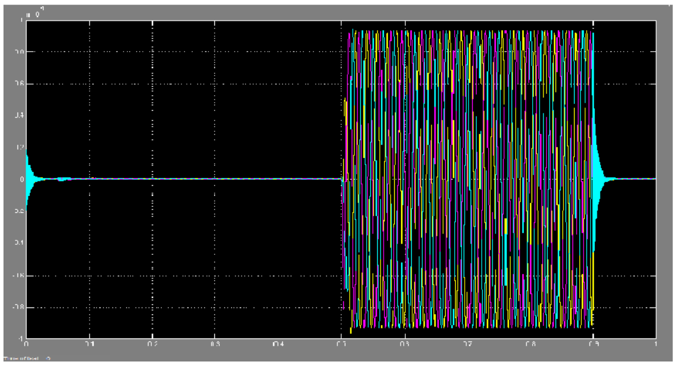

Fig. 9 Simulated output voltage waveform at PCC.

## V. CONCLUSION

A new concept of using a PV solar power plant as interline PV system is introduced in this paper. As the name suggests, the interline PV system interconnects two (possibly more) transmission/distribution lines by reconfiguring existing PV solar plant inverters. This newly developed system thus can act as a FACTS device providing a flexible control over both active and reactive powers on multiple lines simultaneously. The interline PV system can be implemented during night hours when PV solar plant produces no real power. The configuration can possibly be realized during daytime hours too. The interline PV system can be used to regulate the transmission/distribution line voltages, to support inductive load VAR requirements, to improve the system performance during dynamic disturbances, manage real power flow between two or more interconnected lines and so on.

A MATLAB/SIMULINK based case study is discussed in the paper to demonstrate the control concept of interline PV system. A detailed study however is essential and authors expect to conduct a thorough analysis and in-depth study in the near future.

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