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Interline Photovoltaic (I-PV) Power Plants For Voltage Unbalance Compensation

Ahmed Moawwad, Student Member, IEEE, Vinod Khadkikar, Member, IEEE and James L. Kirtley, Jr., Fellow, IEEE

Abstract— This paper proposes a stationary-frame control method for voltage unbalance compensation using Interline Photovoltaic (I-PV) power system. I-PV power systems are controlled to compensate voltage unbalance autonomously. The control system of I-PV plants mainly consists of active and reactive power droop controllers, voltage and current controllers and unbalance compensator. This approach is based on injecting negative sequence current from I-PV power plants to compensate for the unbalanced loads. Consequently, the Point of Common Coupling (PCC) voltage remains balanced and regulated. The results obtained from Matlab/Simulink based simulation demonstrate the effectiveness of the proposed method in compensation of voltage unbalance at PCC.

Index Terms—Flexible AC transmission system (FACTS), interline power system, active and reactive power control, voltage regulation, photovoltaic power generation and control, Distributed Generation (DG).

I. INTRODUCTION
Unbalanced voltages can result in adverse effects on equipment and power system. Under unbalanced conditions, the power system will incur more losses and be less stable. Also, voltage unbalance has some negative impacts on equipment such as induction motors, power electronic converters and adjustable speed drives (ASDs). Thus, the International Electro technical Commission (IEC) recommends the limit of 2% for voltage unbalance in electrical systems [1]. A major cause of voltage unbalance is the connection of unbalanced loads (mainly, single-phase loads connection between two phases or between one phase and the neutral). Compensation of voltage unbalance is usually done using series active power filter through injection of negative sequence voltage in series with the distribution line [2-4]. Some other works depend on shunt compensations [5-9].

On the other hand, it is well-known that the Distributed Generators (DGs) often consist of a prime mover connected through an interface converter (e.g. an inverter in the case of dc/ac conversion) to the ac power distribution system. The distribution system may be the utility grid or the local grid formed by a cluster of DGs. The main role of DG inverter is to adjust output voltage phase angle and amplitude in order to control the active and reactive power injection. In addition, compensation of power quality problems can be achieved through proper control strategies [10], [11]. In [12]-[15], some approaches are presented to use the DG for voltage unbalance compensation.

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.

A new system configuration for large-scale Photovoltaic (PV) power system with multi-line transmission/distribution networks is presented in [16]. In this approach, the PV power plant is reconfigured in a way that two adjacent power system networks/ feeders can be interconnected. The inverter modules in a PV power plant are configured such that the system is represented as a back to back inverter connected multi-line system, called as Interline-PV (I-PV) system. The I-PV system then can be controlled adequately allowing the PV solar plant to function as a flexible AC transmission system (FACTS) device, such as, interline power flow controller (IPFC). With the I-PV system both active and reactive power flow control and energy management in a multi-line system can be achieved. Additionally the system can have various applications, for example, to regulate the feeder voltages, load reactive power support, real power transfer from over power generation line to under loaded line, improve the overall system performance against dynamic disturbances (such as, power system damping) and so on.

This paper deals with a three-phase balancing method utilizing the capabilities of the I-PV power system. By the proposed method, PV converters output additional negative sequence component of current to reduce unbalanced load currents injected by the grid. As a result, the voltage unbalance that is caused by the unbalanced load can be suppressed. The proposed method is confirmed by some simulation studies carried out by Matlab/Simulink software.

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II. I-PV POWER SYSTEM CONFIGURATION

Large scale PV power plants are usually connected at one feeder. When two distribution feeders are located close to each other, the PV plant inverters can be reconfigured in such a way that the two feeders could be interconnected with each other. This configuration is addressed as Interline-PV (I-PV) system [16] and is shown in Fig. 1. The two inverters are connected back to back through switch S_{D3}. To operate the PV plant as I-PV system, switches S_{A}, S_{B1}, S_{A1}, S_{D1}, S_{A2}, S_{B}, S_{D2} and S_{D3} are closed, while switch S_{B2} is kept open. During night-time when the PV solar plant does not produce real power, switches S_{D1} and S_{D2} can be opened.

![Fig. 1 Interline-PV (I-PV) power plant system configuration.](image)

III. CONTROL SYSTEM FOR VOLTAGE UNBALANCE MITIGATION FUNCTION

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 dq frame theory. It converts the unbalanced 3-ph quantities (voltage and current) into dc positive sequence components according to the following equation:

\[
\begin{bmatrix}
  x^+_d \\
x^+_q \\
x^{+0}
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  \sin(\omega t) & \sin(\omega t + \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3}) \\
  \cos(\omega t) & \cos(\omega t + \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\
  \frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
  x_a(t) \\
x_b(t) \\
x_c(t)
\end{bmatrix} (1)
\]

Where x donates either voltage or current quantities, for example: \(V_{pcc,abc} \), \(I_{inv,abc}\) or \(I_{load,abc}\) as shown in Fig. 2.

![Fig. 2 Positive and negative sequences extraction.](image)

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 \(P'_{inv,dq+}\) from solar cells into the grid and to regulate the PCC voltage \(V'_{pcc,dq+}\) simultaneously as shown in Fig. 3.

The negative sequence controller is used to inject the negative sequence current \(I'_{load,dq-}\) 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.](image)
The following equations are used to transform the positive and negative sequence dq components into the corresponding abc components as shown in Fig. 3.

\[
\begin{bmatrix}
x_d^+(t) \\
x_q^+(t) \\
x_0^+(t)
\end{bmatrix} = \begin{bmatrix}
\sin(\omega t) & \cos(\omega t) \\
\sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) \\
\sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3})
\end{bmatrix} \begin{bmatrix}
x_d^- \\
x_q^- \\
x_0^-
\end{bmatrix}
\]  

(3)

\[
\begin{bmatrix}
x_d^-(t) \\
x_q^-(t) \\
x_0^-(t)
\end{bmatrix} = \begin{bmatrix}
\sin(\omega t) & \cos(\omega t) \\
\sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\
\sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3})
\end{bmatrix} \begin{bmatrix}
x_d^+ \\
x_q^+ \\
x_0^+
\end{bmatrix}
\]  

(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 expressed in per unit (pu), 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 System under consideration for simulation.](image)

B. Simulation Results

Fig. 5 shows the voltage and current waveforms of feeder-1 with the proposed controller to compensate for unbalanced PCC voltage. 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.

![Fig. 5 Voltage and current waveforms for feeder-1.](image)

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 I-PV 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 (Fig. 5 (b)) are similar to the PCC voltage, due to the small voltage drop on the impedance between the two buses.

When unbalanced loads are connected without any compensation applied, the unbalanced currents of the loads are supplied by the grid as shown in Fig. 5 (c). At time = 0.5 sec, it is noticed that grid currents are balanced due to compensation. Fig. 5 (d) shows the unbalanced currents injected by the PV power plant to compensate for the unbalanced load current shown in Fig. 5 (e).

![Fig. 6 PCC voltage profile of feeder-1.](image)

Fig. 6 shows the PCC voltage profile of feeder-1. The rms values of the three phases are shown in Fig. 6 (a). Before
compensation, it is noticed that the rms values are not equal (0.93 pu for phase-a, 1.00 pu for phase-b and 1.02 pu for phase-c). These values are noticed to be the same at 0.965 pu after compensation.

Fig. 6 PCC voltage profile.

Active and reactive powers of the three phases (a, b and c) supplied by the grid and I-PV power plant are shown in Figs 8 and 9. Fig. 8 (a) shows the active and reactive power supplied from the grid through phase-a. Figs 8 (b) and (c) show the powers of phases b and c respectively. It is noticed that before compensation the powers supplied by the three phases (a, b and c) of the grid are not balanced. After compensation, the active power is balanced at 2.5 pu and reactive power at 1.5 pu for the three phases as shown in Figs 8 (a), (b) and (c).

Fig. 7 Negative sequence components of feeder-1 currents.

Fig. 9 (a) shows the active and reactive power of Inv-1 (Phase-a). The phase b and c powers are shown in Figs. 9 (b) and (c) respectively. It is noticed that Inv-1 does not inject any power into the grid during the compensation process. Instead the active and reactive power generated by the Inv-1 is circulated between its phases. Phase-a supplies 0.65 pu active power as shown in Fig. 9 (a), while phases b and c absorb this amount of active power (Figs. 9 (b) and (c)). The reactive power consumed by phase-c (Fig. 9 (c)) is being generated by phases a and b as shown in Figs 9 (a) and (b).
VI. CONCLUSION

This paper represents the utilization of an I-PV power plant to compensate for unbalanced PCC voltages. The basic idea is to inject the negative sequence currents caused by unbalanced load using I-PV power plants. The proposed controller consists of positive and negative sequence loops. The positive sequence controller is used to regulate balanced PCC voltage, while the negative sequence is to mitigate the unbalanced voltage. Though both active and reactive powers are exchanged and circulated through I-PV inverter, there is no net consumption of active power by the I-PV system. A MATLAB/Simulink based simulation study has been performed to evaluate the effectiveness of proposed negative sequence controller for the PCC voltage unbalance compensation.

VI. APPENDIX I

Feeders-1 and -2 system voltage level, \( V_{s1} = V_{s2} = 11 \text{kV} \).
Line parameters: \( 0.08 + j0.04 \text{ ohm/km} \).
Line lengths: \( L_{11} = 20 \text{ km}, L_{12} = 4 \text{ km} \).

VII. REFERENCES


