Optimal Utilization of PV Solar System as DVR (PV-DVR) for a Residence or Small Industry

M. Ramasamy1* and S. Thangavel2

1Department of Electrical and Electronics Engineering, K.S.R. College of Engineering, Tiruchengode – 637215, Tamil Nadu, India
2Department of Electrical and Electronics Engineering, K.S.Rangasamy College of Technology, Tiruchengode – 637215, Tamil Nadu, India

Abstract

This paper presents a photovoltaic (PV) array fed three-phase three-wire dynamic voltage restorer (DVR) for voltage regulation in a low voltage (LV) distribution system. Besides the voltage regulation, the proposed DVR reduces the energy consumption from three-phase utility grid by utilizing the rated inverter capability after excessive or equal real power generation to load demand during daytime. The control of DVR is achieved by using minimal energy injection technique. Further, the use of low step-up DC-DC converter with fuzzy based perturb & observe (P&O) maximum power point tracking (MPPT) algorithm eliminates the drawback of the conventional PV based DVR by tracking maximum power point of the PV array. MATLAB/Simulink results are presented to validate the advantage of the proposed system.

Key Words: Dynamic Voltage Restorer (DVR), Perturb and Observe (P&O) Algorithm, Photovoltaic (PV) Array, Energy Conservation, Boost Converter

1. Introduction

The growing concern over the increasing energy consumption, environmental degradation resulting from combustion of fossil fuels and fluctuating oil prices of the nations has increased the use of renewable power generation in the power system application. PV based DVR has become favorable solutions for a home or a small industry, particularly in Tamilnadu, India rural areas have a substantial amount of insolation and have more than three hours of frequent power interruptions in a day. This may occur in the developing countries, where the generated electrical power is less than their demand. PV power generation systems have the disadvantage that the PV array looses their output capability, when the irradiation level changes. In order to attain the maximum power point of a PV array, a simple DC-DC converter associated with a function called MPPT is introduced between the PV array and battery bank. A number of different MPPT algorithms have been presented in [1,2]. The utilization efficiency of the PV system and DVR can be improved further by employing fuzzy based P&O MPPT algorithms.

The concept of utilizing PV solar system inverter as DVR, for the mitigation of voltage variations with power saver capability at the load side for single-phase is presented in [3]. The reference [4] has proposed the concept of utilizing the DVR for voltage sag and outage mitigation without PV system. The rating and design of series injection transformer of the DVR is presented in [5]. The design and control of DVR have been carried out in [6].

The main aim of this paper is to reduce the energy consumption of three-phase utility grid. A novel inverter controller and coordinating logics are proposed to operate the PV solar system as DVR, utilizing the rated inverter capacity during night time and inverter capacity remaining after excessive real power generation in the PV array during day time. The proposed DVR, if con-
nected at the terminals of a home or small industry can conserve 26.88 kWh in a sunny day. It reduces the potential tariff around 2900 $ per year by reducing the energy consumption from the grid [7,8]. This financial benefit made approximately by considering the local average annual solar irradiation and by using the panel tariff of local electricity distribution. This allows full utilization of the expensive asset of PV solar system during 8 hours period. This has additional financial benefits over the conventional DVR used in the literature. A simulation model of PV-DVR is developed in MATLAB/Simulink to validate feasibility of the proposed method.

2. System Description

The configuration of the proposed PV-DVR system is shown in Figure 1. The system is composed of a PV array, DC-DC boost converter with P&O MPPT algorithm, battery bank, voltage source three-phase inverter, series injection transformer, controlled rectifier and semiconductor switches.

The PV-DVR is designed such that when the solar energy production is greater than the load demand, the energy produced by the solar array is used to supply the home or small industries through an inverter. The excess energy stored in the battery bank is used to regulate the load voltage at night time or when the system is operated from utility grid. Figure 2 shows the power circuit and switching configuration of the proposed PV-DVR.
The control logic of the semiconductor switches $S_1$, $S_2$, $S_3$, $B_1$, $B_2$, $B_3$, $P_1$, $P_2$, and $P_3$ for different modes of operations is shown in Table 1. The control logic of the battery charge controller is shown in Table 2.

The proposed PV-DVR is operated in the following four modes of operation:

i. Compensation Mode or DVR Mode
   In this mode, the proposed PV-DVR is utilized to regulate the voltage at the load side. During this operation a series injection transformer is configured in series with the load to compensate the voltage sag/swell. The control logics of the DVR mode are shown in Table 1.

ii. Uninterruptable Power Supply (UPS) Mode
   In this mode, the series injection transformer of PV-DVR is reconfigured into parallel to provide the uninterruptable power supply to load through the battery bank on both daytime and night time.

iii. Energy Conservation Mode
   In this mode, the proposed PV-DVR disconnects the utility grid from load and it configures the series injection transformer to parallel mode to perform the inverter operation to feed the excess energy generated by the solar array to load. In this mode the excess energy generated by the PV array is stored in the battery. During low power generation by the PV, the proposed charge control algorithm reconnects the output of the controlled rectifier in parallel with the PV array to charge the batteries as presented in Table 2.

iv. Maintenance Mode or Idle Mode
   In this mode, the entire PV-DVR is disconnected through the semiconductor switches $B_1$, $B_2$ and $B_3$ by bypassing the secondary of an injecting transformer, when the DVR needs maintenance.

### 2.1 Minimal Energy Injection Technique

The proposed PV-DVR is designed to compensate the voltage sag, voltage swell and outage at the load side. Due to the limitations in energy storage capacity of the DC-link and to reduce the injection of active power from the DC-link, a new concept of restoration technique is suggested to inject minimum energy. The phasor diagram of minimal energy injection technique is shown in Figure 3.

In normal condition, the supply voltage ($V_s$) is equal to the load voltage with zero phase angle. During voltage sag/swell, the supply voltage decreases or increases to a value less than or greater than to its nominal value.

![Figure 3. Phasor diagram of minimal energy injection technique.](image-url)
DVR reacts to the sag/swell events and injects the compensating voltage $V_{dvr}$ with the supply voltage to restore the voltage at its nominal value. This method is very simple to implement and very fast, especially in calculating the DVR compensating voltage. The injected voltage of a DVR ($V_{dvr}$) can be expressed as

$$|V_{dvr}| = \sqrt{V_{\text{presag}}^2 + V_{\text{sag}}^2 - 2V_{\text{presag}}V_{\text{sag}}}$$

(1)

The required phase angle can be calculated as follows:

$$\angle V_{dvr} = \theta_{dvr}$$

(2)

$$\theta_{dvr} = \tan^{-1} \frac{V_{\text{sag}} \sin \delta}{V_{\text{presag}} - V_{\text{sag}} \cos \delta}$$

(3)

where $\delta = \phi - \cos^{-1} \left( \frac{V_L \cdot \cos(\phi)}{V_c} \right), \alpha = \frac{\pi}{2} - \phi + \delta$.

If the supply voltage parameters satisfy the following conditions then the value of $\delta$ is feasible.

$$V_L \cdot \cos(\phi) \leq V_s \quad \text{and} \quad V_L \cdot \cos(\phi) \geq V_s$$

(4)

where, $V_s$ is the supply voltage in volts, $V_L$ is the load voltage in volts, $V_{dvr}$ is injected voltage of the DVR in volts, $V_{\text{presag}}$ is the voltage of the source before the sag, $V_{\text{sag}}$ is the source voltage after sag, $I_L$ is the load current in amps, $\phi$ is the angle between $V_s$ and $I_L$, $\delta$ and $\alpha$ are the angle of $V_L$ and $V_{dvr}$, respectively.

If the above inequality (4) is satisfied then the level of voltage sag and swell is shallow. Then, the injected active power of the DVR is zero.

If the inequality (4) is not satisfied then the level of voltage sag and swell is unfathomable. Then, the injected active power of the DVR is not zero. The designed controller response to the voltage sag events of 0% to 80% and voltage swell of 120% to 150%. In the proposed work, the proposed system is designed to compensate the voltage disturbances from the range of 0% to 150% of its nominal value.

3. PV Array Modeling

PV array is a system which consists of more solar cells to convert sunlight into electricity. The developments of new efficient solar cells with MPPT algorithm have increased the use of solar panels as an alternative source of renewable energy conversion. In the proposed DVR, PV array with DC-DC boost converter associated with a function called MPPT is incorporated to function as a DC voltage source for the inverter of DVR. It is introduced between the PV and battery bank of the DC link. The electrical system powered by the PV array requires DC-DC converter due to the varying nature of the generated solar power, resulting from sudden changes in weather conditions, which changes the solar irradiation level as well as cell operating temperature. An equivalent circuit model of photovoltaic cell with DC-DC boost converter is shown in Figure 4.

The PV array is developed by the basic equations of photovoltaic cells including the effects of temperature changes and solar irradiation level [9,10]. The output voltage of the PV cell is a function of photo current that is mainly determined by load current depending on the solar irradiation level. The PV cell output voltage is expressed as

$$V_c = \frac{A_k T}{e} \ln \left( \frac{I_{ph} + I_0 - I_L}{I_0} \right) - R_s I_c$$

(5)

$$V_{pv} = V_c \times N_s$$

(6)

$$I_c = \frac{I_{pv}}{N_p}$$

(7)

where, $e$ is the charge of electron ($1.602 \times 10^{-19}$ e), $A_k$ is curve fitting factor (0.001), $V_c$ is the output voltage of PV cell in volts, $I$ is the photo current in $A$, $I_0$ is the re-
verse saturation current of diode, $k$ is Boltzmann constant ($1.38 \times 10^{-23}$ J/K), $I_L$ is the cell output current in A, $R_s$ is the cell internal resistance (0.001 Ω), $T_c$ is the operating temperature of the reference cell (25 °C), $V_{PV}$ is the output voltage of PV array, $I_{PV}$ is the output current of the PV array, $N_s$ is the number of series cell and $N_p$ is the number of parallel cells.

The design parameters $I_{ph}$, $I_o$, $R_s$, and $T_c$ are determined from the data sheet and I-V characteristics of the PV array [11]. The curve fitting factor $A$ is used to adjust I-V characteristics of the cell to actual characteristics obtained by the testing. The low step-up DC-DC converter shown in the Figure 7 is designed by using the following basic equations [12]. The voltage across the inductor ($L$) during $T_{on}$ is shown in equation (8).

$$V_L = L \frac{di}{dt} \quad (8)$$

$$V_L = V_o$$

The output voltage $V_o$ during $T_{off}$ can be expressed as

$$V_o = V_i + L_s \frac{di}{dt} \quad (9)$$

The average output voltage of the converter is depicted in equation (10).

$$V_o = \frac{V_o}{1-D} \quad (10)$$

$$D = \frac{T_{on}}{T_{on} + T_{off}} \quad (11)$$

where, $D$ is the duty cycle, $T_{on}$ is on time, $T_{off}$ is off time and $i_s$ is the current flowing through the inductor $L_s$.

4. Control Method

4.1 Maximum Power Point Tracking Method

The MPPT is an essential part of a PV solar system. This is designed to automatically find the maximum power point of the PV array. In this paper, a DC-DC converter with P&O MPPT algorithm based on fuzzy controller is incorporated to track the maximum power point of the PV array. The P&O MPPT algorithm applies a small increment or decrement of perturb voltage $\Delta V$ to the PV module operating voltage. The inputs of Fuzzy Logic Controller (FLC) are measured from the output of PV array to generate control signal ($V_{ref}$) for the PWM pulse generator. The principle of operation of the P&O MPPT is presented in [13,14].

The computation of actual state ($k$) and previous state ($k-1$) of the parameters $V$ and $I$ are considered. The actual and previous state of the power is calculated from the product of actual and previous state $V$ and $I$ as shown in Figure 5. According to the condition of error ($e$) and change in error ($\Delta e$), the increment or decrement of reference voltage ($V_{ref}$) of the PWM pulse generator is obtained. The simulink block diagram of the fuzzy con-

![Figure 5. Control structure of fuzzy based P&O MPPT algorithm.](image-url)
controller based P&O MPPT is shown in Figure 5.

The FLC used in this study has two inputs, namely error \( e \) and change in error \( \Delta e \) and one output as shown in Figure 6. The error \( e \) and change in error \( \Delta e \) are defined as

\[
\text{error}(e) = P(k) - P(k-1) \tag{12}
\]

\[
\Delta e = \text{Change in error} = e(n) - e(n-1) \tag{13}
\]

The two input variables are fuzzified and represented in fuzzy set notations by membership functions. The defined ‘if … and … then …’ rules produce the linguistic variables. These variables are defuzzified into reference signal \( V_{ref} \) for the generation firing pulse for the low step-up DC-DC converter. The membership functions of the two inputs and output are shown in Figure 7.

The inputs and output of fuzzy controller are expressed as a set of linguistics variables as follows: NB-Negative Big, NS-Negative Small, Z-Zero, PS-Positive Small and PB-Positive Big. The output of the fuzzy is chosen from a set of semantic rules that lead to track the maximum power point of PV array. The set of rules chosen are shown in Table 3.

The output of FLC is fed to relational operator to produce the gating signal for the low step-up DC-DC converter. The relational operator generates the gating pulses by comparing the \( V_{ref} \) and a carrier signal. The output of the FLC is set between 0 to 1. The magnitude of carrier signal is set, between 0 to 1 with a frequency of 25 kHz.

### 4.2 DVR Control Strategy

This compensator solves voltage problems at the load side. In the conventional controllers like P, PI and PID, the control parameters are fixed at the time of design. Hence, the conventional controllers offer good performance only for the linear system. When the operating point of the system is changed, the parameters of the conventional controllers should be designed again, and some trials and prior information of the systems are needed to design the parameters. The fuzzy controller overcomes the drawbacks of the conventional controllers [15]. The control strategy of DVR with fuzzy controller is shown in Figure 8.

In this method, the measured three-phase voltages \( V_{abc} \) and \( V_{Labc} \) are converted to rotating reference frame variables using the angle obtained from the discrete 3 Phase Locked Loop (PLL). The synchronous reference frame (SRF) is applied to extract the reference voltage for the DVR \( V_{dvra}, V_{dvrb}, V_{dvrc}, V_{dvra}, V_{dvrb}, V_{dvrc} \) from the measured \( V_{abc} \) as shown in Figure 8. The value of \( V_{ad} \) and \( V_{sq} \) are obtained as follows

\[
\begin{bmatrix}
V_{sd} \\
V_{sq}
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
V_{ad} \\
V_{sb} \\
V_{sc}
\end{bmatrix} = \begin{bmatrix}
V_{sd,dc} \\
V_{sq,dc}
\end{bmatrix} + \begin{bmatrix}
V_{sd,ac} \\
V_{sq,ac}
\end{bmatrix} \tag{14}
\]

where

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

| Table 3. Fuzzy rules for MPPT method |
|------------------|---------|---------|---------|---------|---------|
| \( e/\Delta e \) | NB | NS | Z | PS | PB |
| NB | Z | Z | PB | PB | PB |
| NS | Z | Z | PS | PS | PS |
| Z | PS | Z | Z | Z | NS |
| PS | NS | NS | NS | Z | Z |
| PB | NB | NB | NB | Z | Z |
The fundamental frequency components of $V_{abc}$ are transformed into DC quantities and the negative sequence components of $V_{abc}$ are transformed to AC components. The $V_{Lm,pu}$ can be calculated as follows

$$V_{Lm,pu} = \sqrt{V_{Ld}^2 + V_{Lq}^2}$$  \hspace{1cm} (15)

where, $V_{Ld}$ and $V_{Lq}$ are the $d$ and $q$ components of load voltage.

The difference of $V_{Lm,pu}$ and $V_{Lm,ref,pu}$ forms an error signal. The error ($e$) and change in error ($\Delta e$) signals are passed through the fuzzy controller and the output of fuzzy controller is added to the $d$ axis AC component of voltage. The input signals of the fuzzy controller are fuzzified and represented in fuzzy set notations by membership functions. The defined ‘if and then’ rules produce the linguistic variables and these variables are defuzzified into control signals to generate PWM gating pulses for VSI. There are 49 rules utilized to produce the optimum control signal. The fuzzy rules used for simulation are shown in Table 4.

The DC component of active power, $P_{dvr,dc}$ can be calculated as follows:

$$P_{dvr,dc} = V_{dvr,dc} i_d + V_{dvr,qc} i_q$$  \hspace{1cm} (16)

where, $V_{dvr,dc} = V_{Ld} - V_{sd,dc}$, $V_{dvr,qc} = V_{Lq} - V_{sq,dc}$

The $V_{sm,pu}$ can be obtained by

$$V_{sm,pu} = \sqrt{V_{sd,dc}^2 + V_{sq,dc}^2}$$  \hspace{1cm} (17)

The difference between $P_{dvr,dc,ref}$ and $P_{dvr,dc}$ passes through the PI controller and the output of the PI controller is added to the $q$ axis component to form the $V_{dvr,ref}$ for the PWM pulse generator.
5. Simulation Results and Discussion

To illustrate the capability of the proposed PV-DVR for voltage sag/swell, outage and unbalanced voltage mitigation, a three phase system is considered. A 10 kVA, 400 V (1:1) transformer is used for connecting the DVR to the system. The proposed DVR model is simulated by MATLAB Simulink to compensate voltage sag, voltage swell, outage and unbalanced voltages at the load side. The simulation system parameters are shown in Table 5.

The load has been assumed linear with power factor 0.85 lagging and its capacity is 8 kW (RL Load). To illustrate the voltage sag/swell and outage compensation by the DVR, first a voltage sag condition is generated by the three phase programmable AC source is applied, from 0.05 sec to 0.1 sec, a voltage swell condition is applied from the period 0.25 sec to 0.3 sec and an interruption is applied from 0.15 sec to 0.2 sec as presented in Figure 9(a). The voltage sag and swell applied at the source point is 50%. The injected voltage, load voltage and Total Harmonic Distortion (THD) of load voltage are shown in Figure 9(b)–(d).

To illustrate the unbalanced voltage compensation by the DVR, an unbalanced three-phase voltage is generated by the three-phase programmable ac source is applied from 0.1 sec to 0.25 sec as presented in Figure 10(a). The injected and load voltage of the DVR during unbalanced voltage compensation are shown in Figures 10(b) and (c).

The PV array consists of 54 PV cells (6 × 9), 9 cells are being connected in series to have a desired voltage output of 12 V and there are 6 parallel branches getting a total power of 200 W [16]. The number of series and parallel PV arrays are increased to 6 and 9 to get 72 V and 10800 W power output. PV array with boost converter can give greater output voltage. Figures 11(a) and (b) show the PV array output voltage without and with boost converter, respectively. Figures 11(c) and (d) shows the power obtained from the PV array and selected battery discharge characteristics.

From the Figure 11(c), it is observed that the proposed fuzzy controller based P&O MPPT controller tracked the maximum power generated by the PV array with 82% of efficiency and from the Figures 9(c) and 10(c), it is observed that the proposed DVR maintains the load voltage at a desired value with minimum distor-

Table 5. System parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>AC supply</td>
<td>Nominal line voltage</td>
<td>400 V</td>
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<tr>
<td></td>
<td>Frequency</td>
<td>50 Hz</td>
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<tr>
<td>Filter</td>
<td>Filter inductance</td>
<td>38 mH × 3</td>
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<tr>
<td></td>
<td>Filter capacitance</td>
<td>20 μF × 3</td>
</tr>
<tr>
<td>Injection transformer (1:1)</td>
<td>Power</td>
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<td></td>
<td>Voltage rating</td>
<td>400/400 V</td>
</tr>
<tr>
<td>DC bus</td>
<td>Voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Load</td>
<td>Load resistance</td>
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</tr>
<tr>
<td></td>
<td>Load inductance</td>
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<td>Battery bank</td>
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<td>400 V</td>
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<tr>
<td></td>
<td>Capacity</td>
<td>500 Ah</td>
</tr>
<tr>
<td>Low step-up DC-DC converter</td>
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<tr>
<td></td>
<td>Switching frequency</td>
<td>20 kHz</td>
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<tr>
<td></td>
<td>Input/output voltage</td>
<td>72/400 V</td>
</tr>
<tr>
<td>PV module</td>
<td>No. of solar cells</td>
<td>54 (6 × 9)</td>
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<tr>
<td></td>
<td>Nominal voltage</td>
<td>12 V</td>
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<tr>
<td></td>
<td>Maximum power</td>
<td>200 W</td>
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<tr>
<td></td>
<td>Vmp</td>
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<tr>
<td></td>
<td>Short circuit current</td>
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</table>

Figure 9. Balanced voltage variations compensation.
tion. From the discharge characteristics of the battery, it is observed that the battery can feed 50 A for 10 hours duration [17].

6. Conclusion

The simulation of PV array operated DC-DC boost converter fed DVR has been carried out for balanced and unbalanced voltage variation compensation in the distribution system. In addition to the voltage regulation the proposed DVR reduces the energy consumption and potential panel tariff around 2900 $ per year. The DVR was controlled by minimal energy injection technique with fuzzy controller. A DC-DC boost converter with fuzzy controller based P&O MPPT algorithm is implemented to track the maximum power point of the PV array. A fast convergence with small oscillation at the maximum power point can be achieved by this method. The obtained THD value of load voltage is below permissible limit of 5%. Simulation results show that the PV-DVR performance is satisfactory in mitigating the voltage variations.

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