Efficient PV-grid system integration with PV-voltage-source converter reactive power support

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Abstract: In this work, a complete model for the integration between the Photovoltaic Distributed Generation System (PV-DGS) and the utility grid is simulated by MATLAB/SIMULINK. The aims of this study are to provide active power of a given feeder and to improve the output power quality from the PV-DGS unit. To achieve these aims, Two PV-arrays with total power yield equal to 200 KW are modeled. The maximum power point tracking based on the perturb and observe technique is used to control the DC-DC converter. The voltage source converter is controlled to allow the system to operate in different modes. These modes are the unity output power factor and the reactive power compensation. Different control techniques have been applied including the conventional PI controller as well as the intelligent optimization tuning. A complete comparison between both techniques has been introduced and analyzed.

1 Introduction

The new techniques for increasing the production of electricity based on the renewable energy sources such as wind, solar photovoltaic (PV) and tidal energy should be encouraged. These new strategies must be able to overcome the significant and regular rise in load demand, the growing concerns about environmental pollution and the fast reduction of conventional resource challenges [1]. The goal of this paper is to reach a high-quality connection between the Photovoltaic Distributed Generation System (PV-DGS) and a given feeder. So, besides pumping the active power to the utility grid, this paper focuses on the quality of the output power from the PV-DGS. One of the drawbacks in connecting the PV-DGS to the utility grid is the voltage variation at the point of common coupling (PCC). The voltage variation results from the variation in the solar radiation and the conventional control methods for the PV inverter [1]. The voltage profile of the PV-DGS determines the maximum PV-DGS at a given feeder. Injecting reactive power has a role to play for improving the PCC-voltage profile, the grid power quality, reducing the transmission losses, and finally facing loads that have complex and unpredictable nature such as the reactive or industrial loads. More works have been made to solve the issues related to the maximum PV-DGS penetration [1].

Omran et al. [2], Sugihara et al. [3] and Liu et al. [4] have focused to present a solution for mitigating the instability voltage by setting up energy storages at either the user end or the load dispatch center. Unfortunately, this solution is not economical and practical [1]. Rueda-Media and Padilha-Feltrin [5] have focused on the ancillary activities in the DGS units such as the reactive power support to enhance the PV-DGS penetration. Wandhare and Agarwal [1] have proposed a system that combines between distribution static synchronous compensator (D-STATCOM) and the PV inverter for compensation duty. This proposed system has an auxiliary converter to overcome the transient issues that result from the inadequacy of PV-DGS output voltage and the D-STATCOM voltages. This paper presents an analysis and simulation of PV-DGS connected to the utility grid. The high quality of the system output power has been done by forcing voltage-source converter (VSC) to compensate reactive power with 20 kVAR capacitor bank. An intelligent optimisation technique has been used for improving the controller performance and the entire system efficiency.

2 PV-DGS components

This section introduces the various important parts of the PV-DGS that is illustrated in Fig. 1. The main components are the PV array, direct current (DC)–DC converter including the maximum power point tracking (MPPT) algorithm, energy storage capacitors, the VSC including the space vector modulation (SVM) as switching technique and its feedback control unit, electrically isolated transformer, and three-phases-controlled breaker. The PV arrays and the VSC models had been taken from the MATLAB library toolbox. The first array consists of 5 series modules and 66 parallel strings. The second array consists of 8 series modules and 61 parallel strings. The power electronic converters have been used to overcome the intermittent issue. They have been used to regulate voltage, frequency, and power output characteristics [6]. The DC-output voltage is regulated by the DC–DC converter to be used as the fixed input DC voltage for VSC. The MPPT algorithm calculates the optimal duty cycle (D) to continuously confirm that the PV-DGS operates at the MPP. Energy storage capacitors have been used to smooth the power that is generated from the PV array and to balance the difference between the average and instantaneous power [7]. The PV-DGS has used three-phase two-level VSC ‘metal–oxide–semiconductor field-effect transistor/diodes’ as a DC–AC converter which has been used to transform DC input voltage to asymmetric AC output voltage with the desired magnitude and frequency [7, 8]. The VSC has three control loops that can be defined as active power controller or $V_{dc}$ regulator, reactive power controller and the inner loops or the current regulators that produce the controlled voltage signal to SVM. SVM helps to match the VSC output with the utility grid. The VSC controllers use both conventional and intelligent tuning for parameter tuning process. The VSC has many details that are related to its structure, modulation technique and control unit. In the following section, the VSC will be described in more details. The PV-DGS of 200 kW has been connected to 22 kV distribution feeder via two DC–DC boost converters and a three-phase VSC. The electric grid that has been used in this paper consists of 22 kV distribution feeder and 132 kV equivalent transmission system. The block diagram of the utility grid that has been built in MATLAB environment is shown in Fig. 2.

3 GRID VSC system: control in DQ frame

In this section, the different components of the VSC will be introduced. The free-wheeling diode is necessary to give a path for
Fig. 1 Main parts of PV-DGS

Fig. 2 Block diagram of the utility grid components


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releasing the energy that is stored in the inductor when voltage drops to zero [7, 9]. The connection between the VSC and the utility grid is done by using a harmonic ‘grid’ filter [R + L]. The aim of the harmonic filter is to attenuate the output voltage harmonics of the VSC [7]. The step-up transformer has been used for the electrical isolation between PV-DGS and utility grid [10]. In the current mode control, both power components are controlled by the VSC line current with respect to the PCC voltage [9]. The VSC line current is regulated by a current-regulation loop and it can define as the inner control loop of the VSC [9].

3.1 VSC current control

Sections 4.4–4.6 in [11] presented the space phasor expressions for the instantaneous power components in terms of DQ frame variables. So, the power component expressions that transferred to the AC-utility grid at PCC are

\[ p = \frac{2}{3} u_d i_d + u_q i_q, \]  

\[ q = \frac{2}{3} \left[ u_d i_q - u_q i_d \right], \]  

where \((u_d, u_q)\) are defined as the transformed grid voltage components in terms of DQ frame and \((i_d, i_q)\) are the current components in terms of DQ frame. If the synchronous frame is aligned to voltage, the quadrature composite of the grid voltages will be equal zero. Therefore, the power equations reduce to

\[ p = \frac{2}{3} u_d i_d, \]  

\[ q = -\frac{2}{3} u_q i_q, \]  

Equations (3) and (4) proved that the independent control of the power components is done by controlling the VSC DQ current components \((i_d, i_q)\) [9]. The governing circuit equations for the current controller design will be defined in synchronously rotating reference frame. Section 8.3.2 in [9] presented the representation of space phasors in dq frame and Section 8.3.3 in [9] focused on the dynamic model of the power components’ controller. The equations of the dynamic model are

\[ \frac{d i_d}{d t} = L w(t) i_q - (R + r_{ao}) i_d + V_{sd} - \hat{V}_s \cos(w_0 + \theta_0 + p), \]  

\[ \frac{d i_q}{d t} = -L w(t) i_d - (R + r_{ao}) i_q + V_{sq} - \hat{V}_s \sin(w_0 + \theta_0 - p). \]  

where \(\hat{V}_s\) is the maximum value of the phase voltage, \(w_0\) is the utility grid frequency, \(\theta_0\) is the initial phase angle, and \(p\) is the phase shift. By assuming the steady-state condition and substituting for \(w(t) = w_0\) and \(p = w_0 + \theta_0\) \([3, 12]\), we deduce

\[ \frac{d i_d}{d t} = L w_0 i_q - (R + r_{ao}) i_d + V_{sd} - V_{sd}, \]  

\[ \frac{d i_q}{d t} = -L w_0 i_d - (R + r_{ao}) i_q + V_{sq} - V_{sq}. \]  

Equations (7) and (8) illustrate two decoupled second-order linear systems, where \(V_{sd}, V_{sq}\) are the grid voltage components in terms of dq frame; \(i_d, i_q\) are the direct and quadrature current components; and \(L\) and \(R\) are the harmonic filters. \(V_{sd}, V_{sq}\) are the input voltage signal to SVM unit [11]. \(i_d\) and \(i_q\) are state variables, \(V_{sd}\) and \(V_{sq}\) are control inputs and the grid voltage components \(V_{sd}, V_{sq}\) are feedforward compensation [1]. Taking into consideration that the voltage vector is set at the d-axis, so \(V_{sd} \equiv 0\). The VSC input voltage must be constant, so the variable DC-power source with regulation control mechanism has been used or assuming large \(C_{DC}\) has been used [1]. This assumption renders (7) and (8) as the first-order linear system and by defining new variables \(U_d\) and \(U_q\) \([10]\)

\[ U_d = L \frac{d i_d}{d t} + (R + r_{ao}) i_d, \]  

\[ U_q = L \frac{d i_q}{d t} + (R + r_{ao}) i_q. \]  

The Laplace transfer is operated on (9) and (10) and the modification form is shown below:

\[ U_d(s) = L S i_d(s) + (R + r_{ao}) i_d(s), \]  

\[ U_q(s) = L S i_q(s) + (R + r_{ao}) i_q(s). \]  

The next transfer function can be used for the VSC current loops

\[ \frac{I_d(s)}{U_d(s)} = \frac{I_q(s)}{U_q(s)} = \frac{1}{L S + (R + r_{ao})}. \]  

On the basis of (9) and (10), \(i_d\) and \(i_q\) can be controlled by \(U_d\) and \(U_q\), respectively.

3.2 VSC reactive power control

The closed-loop reactive power mechanism has been used to force the VSC to have another function related to exchange reactive power with the utility grid. It became such as a STATCOM. In a distribution system, the STATCOM has been used to regulate the voltage [13]. It changes the delivery of the reactive power to the grid. The VSC line current in polar form has been used to control the power components with respect to the voltage of the PCC [9]. We exhibit that \(V_{s hil}\) can be regulated via the closed-loop reactive power mechanism [1, 9].

4 SV modulation

The normal switching of the VSC causes disconnected positions of the voltage in the SV representation. So, the SV voltage must pursue a circular locus. The required position on this locus can be achieved by an average relationship between two next-door active vectors [14]. The zero state has been used to get a constant interval \([15]\). The choice of the states and their time duration are done by the SV transformation \([15, 16]\),

\[ V_{sb} T_s = V_{d} T_s + V_{b} T_b + V_{a} T_a. \]  

where \(T_s\) is the sampling period of the given circular locus and \(T_a, T_b\) are the time intervals corresponding to the neighbouring vectors \(V_s, V_a\) \([14, 17]\). With respect to the sector number, the equations can be written as

\[ t_a = \frac{\sqrt{3}}{T_d} V_s T_s \sin\left(\frac{a \pi}{3}\right), \]  

\[ t_b = \frac{\sqrt{3}}{T_d} V_s T_s \sin\left(\frac{(a - 1) \pi}{3}\right), \]  

\[ t_0 = T_s - t_a - t_b. \]
4.1 Implementation and advantages of SVM

SVM can be implemented through the next steps that are shown in Fig. 3 [14]:

(i) The output voltage components from the VSC’s inner control are converted to the two-phase orthogonal (αβ)-plane components.
(ii) The controlled voltage from the last step is transferred to the phasor form. The phasor form components are the amplitude ($V_s$) and the angle ($\alpha$).
(iii) The angle ($\alpha$) from the last step has been used to calculate the appropriate sector by comparing it with the angles’ range of each sector.
(iv) The amplitude ($V_s$), the angle ($\alpha$), and the appropriate sector ($n$) have been used to calculate the time interval ($T_a$, $T_b$, $T_0$) that are shown in (15)–(17).
(v) The switching sequence (01277210) has been used for symmetry reason.

5 Intelligent optimisation technique

The selection process of the proportional–integral (PI)-controller parameters to achieve the system performance specification is called the tuning process. There are various conventional methods for PI-controller tuning. Ziegler–Nichols method includes a set of rules which have been used to set the values of $K_p$ and $T_i$. Conventional methods can be improved by integrating optimisation techniques. The tuning method based on optimisation has design rules related with minimising certain performance criterion is called performance indices such as integral of square error (ISE) or integral of time multiplied by absolute error [18]. In this paper, ISE index has been used because of quickly eliminating the large errors and the smaller initial overshoot in the output response [18, 19]. ISE formula can be written as

\[ \text{ISE} = \int_0^t (e(t))^2. \]  

(18)
5.1 Genetic algorithms

Genetic algorithms (GAs) is a stochastic optimisation technique which is fabricated to mimic the natural selection and the natural biological genetics mechanism. The main concept of GA is based on the survival of the fittest [18]. The mechanism loop of GA begins by creating a primary collection of random solutions defined as population. Every individual solution in the random set is defined as a chromosome. The group of chromosomes that has been produced by the development process is called the generation. The routine repeating process has been used to produce the sequential generations which are defined as iterations process. In every repetition, the current chromosomes are estimated by using the problem fitness function. In this paper, the performance indices have been used as the fitness function. The next generations are formed by either applying the crossover operator or applying the mutation operator [12, 18]. The connection between the GA optimisation technique and the given optimisation problem is performed by using the MATLAB environment as shown in Fig. 4. The goal of

![Image](image_url)

Fig. 5 Simulation result for the system without a connected load on the low side of the transformer
a Reference and measured input DC voltage for the inverter
b Measured and reference DC component
c Measured and reference quadrature current component
d Output active power
e Output reactive power
f Output reactive power including 20 kVAR as a static compensator

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Performance indices, TISE counts, and the tuning parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Different case numbers</td>
<td>Fitness function define or the performance indices (TISE %)</td>
</tr>
<tr>
<td>Controller A</td>
<td>Controller B</td>
</tr>
<tr>
<td>Case</td>
<td>Kp</td>
</tr>
<tr>
<td>Case 1</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>50</td>
</tr>
<tr>
<td>Case 3</td>
<td>100</td>
</tr>
<tr>
<td>Case 4</td>
<td>50</td>
</tr>
<tr>
<td>Case 5</td>
<td>100</td>
</tr>
</tbody>
</table>

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this optimisation process is minimising the steady-state error by decreasing the ISE performance index [20].

6 Simulation results and discussion

6.1 Unity power factor mode with conventional tuning method

First, the simulation has been performed in the unity power factor mode, so the system can be reduced to two control loops:

(i) The outer loop or the voltage regulation loop ‘$V_{DC\text{ regulator}}$’ that produces $I_{d\text{ref}}$.
(ii) The inner loop or the current regulation that produces the controlled voltage signal or the reference voltage signal to the SVM unit and then the SVM produces the pulse gates for the inverter transistors. Fig. 4 shows the simulation result for the PV-DGS without connected load to the low side of the transformer. The PI controller that is used for controlling the DC-voltage power port is working satisfactorily. This appears in Fig. 5a where the measured DC-voltage tracks the reference DC voltage. The PI output signal is the reference current ($I_{d\text{ref}}$)

$$e(t) = V_{DC\text{mes}} - V_{DC\text{ref}}.$$

If the error $e(t)$ is positive, i.e. if $V_{DC\text{mes}}$ is greater than $V_{DC\text{ref}}$, the compensator increases $I_{d\text{ref}}$. That is shown in Figs. 5a and b. If the error $e(t)$ is negative, i.e. if $V_{DC\text{mes}}$ is less than $V_{DC\text{ref}}$, the compensator decreases $I_{d\text{ref}}$. $I_{d}$ and $I_{q}$ track their references and the optimum value at $V_{DC\text{mes}} = V_{DC\text{ref}}$. At this point, the error signal will be zero, and the average power transferred to the utility grid matches the power produced by the PV array as shown in Fig. 5d. In Fig. 5c, $I_{q}$ tracks $I_{q\text{ref}}$ and $I_{q\text{ref}}$ is zero, to maintain the unity power factor. Accordingly, at the steady state, the reactive power that is transferred to the grid equals zero as shown in Fig. 5e. The 20 kvar static reactive power compensating is connected to the high side voltage of the transformer to help the system to face loads that have complex and unpredictable nature, improve the voltage profile and reduce the transmission losses as shown in Fig. 5f [1].

Table 2 Performance of the system in different cases

<table>
<thead>
<tr>
<th>Different case numbers</th>
<th>RMS-PCC phase voltage, kV</th>
<th>Active power, kW</th>
<th>Reactive power, kVAR</th>
<th>THD, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>case 1</td>
<td>145.2 145.4 145.3</td>
<td>196.17</td>
<td>0</td>
<td>0.69</td>
</tr>
<tr>
<td>case 2</td>
<td>148.8 148.9 148.9</td>
<td>195.48</td>
<td>89.32</td>
<td>0.51</td>
</tr>
<tr>
<td>case 3</td>
<td>147.2 147.5 147.2</td>
<td>194.78</td>
<td>62.04</td>
<td>0.52</td>
</tr>
<tr>
<td>case 4</td>
<td>149.5 149.4 150</td>
<td>194</td>
<td>103.5</td>
<td>0.56</td>
</tr>
<tr>
<td>case 5</td>
<td>147.6 147.5 147.6</td>
<td>195.11</td>
<td>62.74</td>
<td>0.43</td>
</tr>
</tbody>
</table>
In this paper, the PV-DGS and the utility grid have been built and simulated using MATLAB/SIMULINK. The VSC using the SVM has been modelled and analysed successfully. The feedback control unit of the VSC had been modelled in DQ frame to supply the SVM with the accurately controlled voltage signal. The PV-DGS has been simulated in different operating modes. The PV-DGS has been simulated in the unity power factor mode and in the reactive compensation mode. Both conventional PI-controller parameters tuning and the intelligent optimisation tuning was applied to the simulation process. A complete comparison between both modes and tuning techniques has been introduced and analysed. The final acceptable results confirmed that the high-quality connection between the PV-DGS and a given feeder has been achieved when the reactive compensation mode and the intelligent optimisation tuning have been applied. The simulation results showed that besides pumping active power to face the growing loads, the output power quality has been improved. This improvement is achieved by forcing the PV-VSC to compensate reactive power besides 20 kVAR reactive capacitors bank. This reactive power mechanism works to progress the system output voltage profile, the minimal voltage variation, and the less THD in the output voltage of the PV-DGS. The simulation results show that the voltage THD is reduced from 0.69 to 0.43% and the phase voltage variation at PCC is reduced from 3.07 to 0.733%. The active power that is generated from PV-DGS is reduced by 6.2% reactive compensating mode with intelligent tuning method

The tuning parameters of the PI controllers are tuned using the intelligent optimisation method based on GA. In Table 1, the fitness function based on the performance index (ISE) is defined as

\[ \text{the objective function} = x_A \int_0^t (e(t))^2 \, dt + x_B \int_0^t \left( \frac{\text{d}e(t)}{\text{d}t} \right)^2 \, dt + x_C \int_0^t (e(t))^2 \, dt. \]  

(20)

where \(x_i\) is defined as the percentage of presence in the ISE controller \(i\) in the final form of the fitness function. In every case, the total ISE (TISE) in the whole system is estimated. The goal is getting the minimum or optimum value of the TISE. Also in Table 1, the optimum tuning parameters of each case are displayed. Table 2 presents the performance of the system in each case and the power components that travel to the utility grid. Static 20 kVAR capacitor bank has been used beside the VSC reactive power share. Also in Table 2, the root-mean-square (RMS)-phase voltage of the PCC and the voltage waveform total harmonic distortion (THD) have been shown. Start with case 1, the fitness function equals zero that means no optimisation techniques are applied to the system. The tuning parameters data are taken from Wandhare and Agarwal [1]. The controller B is out of action for reaching the unity power factor. This unity power factor case has high TISE counts, lower THD and lower tracking PCC-voltage response to its PCC references voltage. From the data in Tables 1 and 2, we can infer that case 2 and case 5 are the best because they had the lower TISE, the THD in the voltage waveform, the higher active and reactive powers travel to the utility grid and the closer PCC voltage to the reference voltage. The simulated performance of the PV system for case 2 is shown in Fig. 6. In these figures, it can be noted that the measured DC voltage quickly tracks the reference voltage (500 V). This means that the DC-voltage (or the outer) control loop are working satisfactorily. Moreover, also the RMS-PCC phase voltage faithfully tracks the reference low side transformer voltage. The VSC share reactive power with static compensator capacitive bank to the utility grid has been observed from both figures. This means that the reactive power mechanism is working satisfactorily. Moreover, also can be observed that \(d-q\) current component of VSC faithfully tracks their references. This means that the inner current (or the current regulators) control loops works properly.

7 Conclusions

In this paper, the PV-DGS and the utility grid have been built and simulated using MATLAB/SIMULINK. The VSC using the SVM has been modelled and analysed successfully. The feedback control unit of the VSC had been modelled in DQ frame to supply the SVM with the accurately controlled voltage signal. The PV-DGS has been simulated in different operating modes. The PV-DGS has been simulated in the unity power factor mode and in the reactive compensation mode. Both conventional PI-controller parameters tuning and the intelligent optimisation tuning was applied to the simulation process. A complete comparison between both modes and tuning techniques has been introduced and analysed. The final acceptable results confirmed that the high-quality connection between the PV-DGS and a given feeder has been achieved when the reactive compensation mode and the intelligent optimisation tuning have been applied. The simulation results showed that besides pumping active power to face the growing loads, the output power quality has been improved. This improvement is achieved by forcing the PV-VSC to compensate reactive power besides 20 kVAR reactive capacitors bank. This reactive power mechanism works to progress the system output voltage profile, the minimal voltage variation, and the less THD in the output voltage of the PV-DGS. The simulation results show that the voltage THD is reduced from 0.69 to 0.43% and the phase voltage variation at PCC is reduced from 3.07 to 0.733%. The active power that is generated from PV-DGS is reduced by 6.2%.

8 References


Fig. 7 Spectrum analysis of the voltage THD in case 5


