Voltage variation due to solar photovoltaic in distribution network

H. I. Azad¹, V. K. Ramachandaramurthy¹, Hesamaldin Maleki¹
¹Power Quality Research Group, Department of Electrical Power Engineering, Universiti Tenaga Nasional, 43000, Kajang, Selangor, Malaysia
E-mail: h.maleki@ieee.org

Abstract. Grid integration of solar photovoltaic (PV) plant offers reduction in greenhouse emissions and independence from fossil fuels for power generation. The integration of such forms of power generation also brings with it a variety of policy and technical issues. One of the technical issues is the variation in grid voltages in the presence of solar photovoltaic (PV) plant, resulting in degradation of power quality. In this paper, the application of a dq current controller to limit the voltage variation at the point of common coupling (PCC) due to a 2 MW solar photovoltaic (PV) plant will be discussed. The controller’s goal is to ensure that the voltage variation meets the momentary voltage change limits specified in TNB’s Technical Guidebook for the connection of distributed generation. The proposed dq current controller is shown to be able to limit the voltage variation.

1. Introduction
Direct generation of electricity from fossil fuels has various negative impacts on the environment as the CO₂ emissions released contribute towards the greenhouse effect, deteriorate air quality, and cause other harms to various ecosystems. With increased awareness and electricity demands, renewable sources of power generations (RE) are attracting the attention of policy makers, utilities and businesses around the world. As of 2010, installed capacity for solar PV is estimated to be around 40 GW [1], accounting for only 0.78% of the overall global installed capacity of 4,742 GW.

Though solar PV only represents a small percentage, its rapid growth is demonstrated by over 17.5 GW of solar PV installations in 2010, as compared to 7.5 GW of installations in 2009 [2]. The rapid growth can be accredited to policy measures such as Feed in Tariffs (FIT), tax incentives and other incentives encouraging innovation, resulting in reduced costs for PV panels and other relevant equipment. The integration of RE in the electricity network however presents various challenges ranging from power quality (PQ), power flow control, voltage and frequency stability, new requirements for simulation tools, and the revision of Grid Codes and Standards. The integration of solar PV is addressed in the grid codes from developed countries, such as the German utility, BDEW, which lists the requirements for solar PV integration and operation in the medium voltage (MV) network [3], while PV integration is not included in codes / guidelines from developing countries, such as the Malaysian TNB guidelines [4]. Solar PV plants are connected to the grid via inverters utilizing pulse width modulation (PWM). The switching nature can result in degradation of power quality in the interconnection network, potentially resulting in grid code violations. As such, control
systems need to be designed to take into account the network parameters, grid code regulations, and the state of the PV plant.

For application of the above mentioned, the Putrajaya’s medium voltage (MV) network is modeled in PSCAD. A 2 MW PV plant is introduced and the effects on the voltage change, i.e. steady state and momentary, are observed. The simulations are performed with the controller integrated, and the results compared.

2. PV System Modelling and Controller Design

An overview of a grid connected PV plant is shown in Figure 1.

![Figure 1. Overview of Grid connection PV plant [6]](image)

The DC output voltage of a PV panel must be regulated at \( V_{MPP} \) in order to extract maximum power from the array. The MPPT block “finds” the \( V_{MPP} \) by using Maximum Power Point Tracking (MPPT) algorithms. The \( V_{MPP} \) is then used as a reference voltage, \( (u_{dref}) \) in Figure 1, for the voltage controller, which controls the switching of the IGBTs in the buck / boost converters to regulate the capacitor voltage, also known as the DC link voltage. For independent control of real and reactive power, dq0 transformation of the PV plant and grid parameters is used.

2.1. dq0 representation of Inverter

The DC link voltage is governed by the principle of power balance [7]:

\[
\mathcal{E}_c \left( \frac{dV_{dc}}{dt} \right)^2 = P_{PV} - P_{DC}
\]

where \( P_{PV} \) is the power generated by the PV array, and \( P_{DC} \) is the power drawn by the DC side of the inverter. Assuming no losses in the inverter, \( P_{DC} \) can be equated to the power output of the inverter:

\[
P_{DC} = P_{inv} = \left( \frac{1}{2} \right) \Re \{ V_d I_d \} + \left( \frac{3}{2} \right) \Re \{ V_q I_q \} = P_p + P_l
\]

Substituting (2) into (1):

\[
\mathcal{E}_c \left( \frac{dV_{dc}}{dt} \right)^2 = P_{PV} - \left( \frac{1}{2} \right) \Re \{ V_d I_d \} + \left( \frac{3}{2} \right) \Re \{ V_q I_q \}
\]

Equation (3) establishes the relationship between the real power output and the DC link voltage. Equation (2) can be transformed to the dq0 reference frame as:

\[
P_{inv} = \left( \frac{1}{2} \right) \left( V_{td} I_d + V_{iq} I_q \right)
\]

The inverter AC side current equations are transformed to the dq0 reference frame as:

\[
L I_d' = L \omega I_q + m_d \frac{V_{dc}}{2} - V_{td}
\]

\[
L I_q' = -L \omega I_d + m_q \frac{V_{dc}}{2} - V_{iq}
\]

From equations (5) and (6), it can be seen that control of the ‘d’ and ‘q’ axis currents can be achieved via control of the modulation index ‘m’.
2.1.1. DC link control and reference current generator
The relationship between the DC voltage and real power output with the integration of the PLL is shown in Equation 7.

\[
\frac{1}{2} \left( \frac{dV_{dc}}{dt} \right)^2 = P_{pv} - \left( \frac{3}{2} \right) \{V_t d \ i_d \}
\]

(7)

The DC link controller is shown in Figure 2.

![Figure 2. DC link control and reference current generator](image)

2.1.2. Current controller
The current controllers for the ‘d’ and ‘q’ axis are shown in Figure 3 and Figure 4.

![Figure 3. ‘d’ axis current controller](image)  ![Figure 4. ‘q’ axis current controller](image)

The performance of the controllers is presented in the sections to follow.

3. Simulation in PSCAD
Simulations were performed in PSCAD for a 2 MW PV plant connected to the Putrajaya MV network and the steady state voltage rise were assessed, for the plant without/with the controller.

3.1. Steady State Voltage Change
For steady state voltage rise, the solar radiation was held constant at 800 W/m², as shown in Figure 5.

![Figure 5. Constant radiation of 800 W/m²](image)  ![Figure 6. PV plant output power](image)  ![Figure 7. PCC voltage](image)

The plant output, 1.6 MW, shown in Figure 6 is expected at 800 W/m². In Figure 7, it can be shown that upon connection of the PV plant, the grid steady voltage rises slightly more than 1% of the nominal voltage. While this is not a violation of the grid code [4], it may limit PV penetration in the
network. The PV plant was simulated with the controller integrated and the results are as shown in Figure 8 to Figure 11.

From Figure 8, the DC link controller can be seen to track the \( V_{\text{MPP}} \) output by the MPPT controller, effectively. The real power output, Figure 9 remains unchanged as compared to the case without the controller, Figure 6. The current controller is designed to regulate the power factor at near unity, to prevent the flow of excessive reactive power which results in the increase of PCC voltages. As seen from Figure 10, the reactive power output is almost zero. At the PCC, the steady state voltage change is reduced to 0.4%, as compared to 1% without the controller. It can be concluded that with the controller integrated, the PV penetration can be increased without violating the steady state voltage guidelines by the utility.

4. Conclusion
Solar PV penetration contributes to deteriorated power quality, amongst other negative impacts. Grid codes / guidelines must be modified accordingly to allow for ease of integration while ensuring system reliability and quality of supply. A 2 MW solar PV plant connected to the Putrajaya MV network was simulated and the impact on the steady state voltage and momentary voltage change was observed. Operation of the plant did not result in any violations of TNB’s technical guidelines but posed limits on increased PV penetration. Integration of the controller resulted in reduced variations in the steady state and momentary voltage changes.

References
[1] Renewable Energy Policy Network for the 21\textsuperscript{st} Century, 2011, REN21.
[2] Mehta, S. (2011, April), State of the Solar Union: Present and Future, IEEE Power and Energy Magazine, pp. 93-96.
[3] Generating Plants Connected to the Medium-Voltage Network, June 2008, BDEW, Berlin.
[4] Technical Guidebook for the Connection of Generation to the Distribution Network, First Edition, March 2005, TNB Research Sdn. Bhd.