Application of Reaching Law Approach to Design of Sliding Mode Voltage Controller for PV System

Mehmet İlyas Bayındır
Department of Electronics and Automation
Fırat University
Elazığ, Turkey
mbayindir@firat.edu.tr

Koray Şener Parlak
Department of Electronics and Automation
Fırat University
Elazığ, Turkey
ksparlak@gmail.com

Abstract—Photovoltaics are one of the most important renewable energy sources. Since they are quite affected from environmental conditions, efficiently operation of PV system is valuable issue. In order to ensure this aim, the PV system must be precisely operated at maximum power point without ripples. In this study, sliding mode controller based on reaching law approach is proposed as a voltage controller providing fast and accurate tracking maximum power voltage reference. Simulation results reveal good control performance under different operation conditions.

Keywords—photovoltaic systems; maximum power point; sliding mode control; reaching law approach

I. INTRODUCTION

There is an increasing interest in alternative energy sources due to the increased need for energy in recent years throughout the world. The adverse environmental effects of conventional energy sources, and doubts over their sustainability. Although different types of energy sources exist, wind and solar powered systems are currently the most popular. It is widely known that, solar energy systems include photovoltaic (PV) panels that convert solar energy into electricity. There has been a recent increase in the number of studies on modeling of PV panels, their control, and improving their efficiency through new methods.

When there is a change in the irradiation that falls on the PV array, the local maximum power point (MPP) of the array also changes, and this point must be redefined to harvest the maximum power. Thus, MPP tracker (MPPT) devices are used between the PV array and the load to track the MPP and ensure that the array works at this point. The MPPT relies on the principle of providing the PV system to track MPP by adjusting the duty cycle according to a certain algorithm.

Various MPPT algorithms are given in the literature. Best known MPPT methods are Perturbation and Observation (P&O) [1-2] and Incremental Conductance (IC) [3]. In the P&O method, the MPP is located by constantly changing the operating point of the system and comparing the power and voltage information of the panel to previous values. The IC method is based on the principle of locating the MPP according to the derivative of power to voltage. There are a lot of papers in literature which are based on P&O and IC methods. Some MPPT approaches reveal power chattering around the MPP [11-13]. Chattering at the voltage output causes power loss in PV system. Hence, in order to improve system efficiency, voltage regulation should be empowered. Two-loop MPPT control schemes are used to obtain easy implementation and assured stability [11-15]. The first loop determines the MPV reference of the PV array, and the second loop is to regulate the PV array voltage to the reference voltage. In order to reach the maximum power, first loop produces the MPV reference; second loop tracks the voltage reference by controlling DC-DC converter. Tracking performance depends on performance of the tracking controller in the second loop. Disturbances and uncertainties are frequently seen in the PV systems and they badly affect control performance. The advantage of two-loop method is that some traditional MPPT algorithms, for example, incremental conductance method, perturb and observe method, etc., can be realized with guaranteed convergence stability. However, the tracking performance is highly dependent to the performance of the tracking controller in the second loop.

Sliding mode control (SMC) is a very effective nonlinear robust control method. A powerful controller can be designed for control of uncertain systems by this method. The controlled system with sliding mode exhibits robustness properties with respect to both internal parameter uncertainties and external disturbances [16]. Robust controllers have fixed structure. They include a nominal part and additional terms aimed at compensating for uncertainty. In a robust control system, satisfactory performance is guaranteed for a defined uncertainty range [17]. To design a general sliding mode robust control system, switching function is firstly chosen. Switching functions are defined in the state space and they form a switching surface for system trajectories in phase plane. Then, a discontinuous control function or a switching logic is specified associated with the discontinuity surfaces. A SMC controller has two modes: reaching and sliding modes. In reaching mode, state trajectory of the system is driven from an initial condition to the sliding surface. In sliding mode, the control signal is only produced in order to maintain on the surface by keeping the switching function close to zero.
The design of the SMC is conventionally based on the Lyapunov stability criteria. There is a new design approach called Reaching Law Control (RLC) is also used to design both reaching and sliding modes [18, 19]. In this method, the convergence rate of reaching mode can be adjusted, while it provides asymptotically stable and finite convergence time [18-20]. There are many research studies about application of SMC method to PV system control in literature. These studies are commonly based on classical equivalent control approach. But, RLC approach is not seen for PV system control in literature.

In this paper, a sliding mode controller is applied as a tracking controller to obtain maximum power from photovoltaic system via RLC approach. The advantages of this controller are high precision, good stability, simplicity, invariance, robustness against uncertainties. This allows it to be particularly suitable for systems with imprecise model.

The organization of paper as follows, firstly PV panel model is given. The controller design is given in Section III, then simulation results presented in Section IV.

II. MODEL OF THE PV PANEL

In this study to simulate the PV panel single diode and five parameters PV model is used. As very well known a PV panel consists of PV cells which are connected in series-parallel. The equivalent circuit of the single diode PV cell is shown in Fig.1.

The output current-voltage characteristic of an ideal PV cell in a single diode model is given in Equation (1).

\[ I = I_{pv} - I_0 \left[ \exp \left( \frac{V + R_s I}{V_A} \right) - 1 \right] - \frac{V + R_s I}{R_p} \] (1)

In order to obtain the single diode model mentioned above, five parameters must be determined. In the Equation (1), the \( R_c \) and the \( R_p \) values are series and parallel resistors in the equivalent circuit, respectively.

The photoelectrical current \( (I_{pv}) \) depends on irradiation and the temperature and the change in the diode saturation current \( (I_0) \) is dependent only on the temperature. As a result, the model is completed with Equations (2) and (3) below.

\[ I_{pv} = \frac{G}{G_n} \left( I_{scn} + K(T - T_n) \right) \] (2)
\[ I_0 = \frac{I_{scn} + K_n(T - T_n)}{e^{\frac{V_{pv} - K(T - T_n)}{N \nu A_T}}} \] (3)

Here, \( I_{scn} \) is the short circuit current at standard test conditions \((G_s=1000W/m^2, \ T_s=25^\circ C \text{ and air mass (AM=1.5).} \) \( T \) and \( T_n \) represent the real and nominal temperatures of the cell, respectively; and \( G \) and \( G_n \) are the real and nominal radiation levels, respectively. \( K_n \) is the thermal coefficient of the short circuit current, and \( K \) is that of the open circuit voltage. \( V_r \) given in Equation (1), is the thermal junction constant and is equal to the \( kT/q \) value. Here, \( k \) is the Boltzmann constant \((1.38*10^{-23} \text{ J/K})\), and \( q \) is the electron load \((1.602*10^{-19} \text{ C})\).

The last parameter used in the model is the diode ideality constant \((A)\), whose value varies between 1 and 2 depending on the type of the PV panel [21].

III. SLIDING MODE CONTROLLER DESIGN

Schematic diagram of the proposed method is shown in Fig.2. The system consists of PV array, boost type dc-dc converter and sliding mode controller.

In order to design a SM controller state-space model of the plant is needed. Well known model of the boost controller is expressed as follows.

\[ \begin{align*}
  i_L &= \frac{V_{pv}}{L} - \frac{V_0}{L} + \frac{V_0}{L}\cdot \delta \\
  V_0 &= i_L - \frac{V_0}{L} + \frac{i_L}{C} \cdot \delta
\end{align*} \] (4)

where \( C \) is the capacitor, \( L \) is the inductance, \( R_L \) is the resistive load and \( \delta \in [0, 1] \) is the duty ratio, which is also the control signal. \( V_0 \) is the output voltage and \( i_L \) is the inductor current. Note the resistance of the inductor and wiring resistance are neglected in the case, so \( i_L \) is assumed to be equal to the PV current \((I_{pv})\). Eq. (4) can be written in general form of time invariant system [22].

\[ X = [i_L \quad V_0]^T \cdot \dot{X} = f(X) + g(X) \cdot \delta \] (5)

\( V_{pv}^* \) is defined as the voltage reference for output of PV panel and for input of boost converter at same time. It should be converted to for voltage output \((V_o)\) of boost converter as state variable of the system. Note that, \( V_{pv} \) is not a state variable of the system model in Eq.(4). Therefore, it should not be used to produce control signal. Reference and error values treated as follows:
\[ e = V_0^* - V_0 = V_{PV}^* - \frac{1}{1 - \delta} - V_0 \] (6)

In this study, \( V_{PV} \) and \( V_0 \) are related by \( 1/(1-\delta) \) ratio under the assumption that the boost converter operates in continuous conduction mode (CCM). That is, voltage reference is primarily determined for \( V_{PV} \) and then converted to state variable \( V_0 \) by the ratio. Simulations use this conversion by taking into account instantaneous value of \( \delta \). Note that, this conversion is used only for voltage reference value, it is not used for between instantaneous \( V_{PV} \) and \( V_0 \) values. If this conversion is not used, the DC-DC converter can’t be controlled properly.

The switching function of the sliding mode controller can be defined as follows [23, 24].

\[ s = \lambda_1 \cdot e + \lambda_2 \cdot \int e \cdot dt \] (7)

An integral term is introduced into the switching function as an additional controlled state variable to reduce steady-state error. This is commonly known as integral SM control, and its application in power converters has studied in literature [25–27]. Coefficients of the switching functions (\( \lambda_1, \lambda_2 \)) are the most critical design parameters that dominantly determine the control performance of the system. The switching function must be stable and converge to zero. When the switching function is equal to zero, the system trajectory is said to be on the sliding surface and the system operates in the sliding mode. In the RLC approach, a reaching law which is a differential or difference equation specifying the dynamics of the switching function is first chosen [18,19]. Derivative of switching function must rely on the reaching law.

\[ \dot{s} = -q \cdot s - \varepsilon \cdot \text{sgn}(s) = -\lambda_1 \cdot V_0 + \lambda_2 \cdot e \] (8)

Where \( q \) and \( \varepsilon \) are the parameters which determine the dynamic behavior of the switching function. Value of \( q \) dominantly affects reaching mode, and value of \( \varepsilon \) dominantly affects sliding mode behavior. The control input is then synthesized from the reaching law in conjunction with a known model of the plant including nominal parameters. Using equations (4-8) the control signal is derived as follows.

\[ \delta = 1 - \frac{V_0}{R_L \cdot i_L} - \frac{C}{\lambda_1 \cdot i_L} \left( q \cdot s + \varepsilon \cdot \text{sgn}(s) + \lambda_2 \cdot e \right) \] (9)

IV. SIMULATION RESULTS

The simulations are established on serially connected three PV panels. To prove of effectiveness of SMC method for tracking reference voltage, simulations are realized different partial shade conditions and load variations. In the first simulation, different irradiances are applied to PV panels and different MPP’ are obtained each condition. In the second simulation load of converter is changed while controller has fixed reference voltage. Third and fourth simulations are done to investigate effects of RLC parameters on controller performance.

The parameters of the boost converter have been chosen such that it operated in CCM mode. These are as follows:

- \( L=10\text{mH} \), \( C=80\mu\text{F} \), \( f_s=10\text{kHz} \), \( R_L=30\Omega \).
- The PV panel parameters are \( I_{sc}=3.75\text{A} \), \( V_{oc}=22\text{V} \), \( P_{max}=45\text{W} \).
- SMC parameters are \( \lambda_1=1 \), \( \lambda_2=1500 \), \( q=350 \), \( \varepsilon=100 \) (for Simulation 1 and 2).

A. Simulation-1

In this simulation, the reference voltage values of the system is changed as regarding variation of irradiance level of PV panels due to partial shade conditions. The MPP occur at different voltage as partial shade varies. Three examined conditions for PV array and P-V curves are given in Fig.3 for each condition. Irradiance levels of PV panels are also remarked in the figure. It can be seen from the figure voltage values of MPP are 51V, 35V, and 17V so these values are given as reference voltages to SM controller.

![Fig. 3. PV curves of serial connected panels under three different irradiation conditions due to partial shading.](image)

Fig. 3. PV curves of serial connected panels under three different irradiation conditions due to partial shading.

Fig. 4 shows output voltage variation of PV array for three operating points. It is clear in the figure that the controller can accurately track to the reference voltages.

![Fig. 4. Voltage tracking performance of system for partial shading conditions, while R_L=30Ω and reference voltages are 35V, 51V and 17V respectively.](image)

Fig. 4. Voltage tracking performance of system for partial shading conditions, while R_L=30Ω and reference voltages are 35V, 51V and 17V respectively.
It can be seen from the figure the ripples are quite low and thanks to this power efficiency of PV array will be high.

Fig. 5 shows duty ratio variation produced by controller. It is seen from the figure that duty ratio variate within reasonable scale.

Fig. 5. Duty ratio variations of DC-DC converter, for voltage tracking while $R_L=30\Omega$ and reference voltages are 35V, 51V and 17V respectively.

B. Simulation-2

This simulation is performed for two loads under partial shade conditions defined above. Firstly, the load is assigned as 15$\Omega$ while controller has fixed nominal parameters. The voltage variation is depicted in Fig.6 and it can track reference voltage against parameter uncertainty. The most attracted property of SMC, robustness, is proven by this figure.

Fig. 6. Voltage tracking performance of system for $R_L=15\Omega$ and reference voltages are 35V, 51V and 17V respectively.

Later, the simulation is repeated for $R_L=45\Omega$. Result of this simulation is shown in Fig.7.

Fig. 7. Voltage tracking performance of system for $R_L=45\Omega$ and reference voltages are 35V, 51V and 17V respectively.

C. Simulation-3

Performance of the control system can be adjusted by $(\lambda_1, \lambda_2)$, $q$ and $\varepsilon$ parameters. These critical design parameters determine the control performance of the system hierarchically. $\lambda_2$ is the most effective parameter of the controller, due to defining the switching function. Value of $q$ dominantly affects reaching mode, and value of $\varepsilon$ dominantly affects sliding mode behavior.

Fig. 8. Voltage tracking performance for $\lambda_2=500$ and 1500 values while $R_L=45\Omega$, $q=350$, $\varepsilon=100$.

Effect of variation of the $\lambda_2$ parameter on the system performance is depicted in Fig.8. When the controller parameters are chosen by trial and error method, it is seen that the $\lambda_2$ parameter must be high enough.

Later, the simulation is executed for $q=150$ and 500 values while $\lambda_2=1000$. Voltage tracking performance is depicted in Fig.9. Effects of the $q$ parameters are seen from the figure.

Fig. 9. Voltage tracking performance for $q=150$ and 500 values, while $R_L=45\Omega$, $\lambda_1=1$, $\lambda_2=1000$, $\varepsilon=100$. 
Variation of q parameter affects especially reaching mode dynamics of the voltage. There must be an optimum value for (q) between maximum and minimum values as regarding Fig.9. Because, low q value causes slow dynamic performance, but large value causes overshoot.

In reaching law approach, ε parameter is designed to manage sliding mode behavior of system. It is proven that low ε value causes steady state error, on the other hand large value triggers chattering problem [19]. But in this study, it has no important effects on the performance. It can be explained as effect of additional integral term in the switching function, in order to reduce steady-state error.

V. CONCLUSION

In this study, sliding mode voltage controller based on reaching law approach (RLC) aimed to voltage control of PV system is proposed. As a robust controller with fixed structure, maximum power point voltage references are accurately tracked under different operation conditions caused by partial shading and load variations. Additionally the controller has good transient performance and low voltage ripple in steady state. RLC approach is an alternative SMC design method to equivalent control method. Effects of parameters of RLC on system behavior at reaching and sliding modes are examined. It is seen from the simulation results, controller parameters, especially λ2 and q, should be optimized between maximum and minimum values.

REFERENCES