Fuzzy based Integral Terminal Sliding Mode Control for Controlling MPPT and 3-phase VSC in grid Connected PV Systems

Sai Sree Teja Amirineni, Mohammad Javad Morshed, and Afef Fekih, Senior Member, IEEE

***Abstract*—The aim of this paper is to propose Fuzzy based integral terminal sliding mode control for non-linear systems like PV grids. This paper presents a complete approach to control the PV grid by controlling the tracking error of boost converter and also controls voltage source inverter. It focuses on controlling the tracking error of maximum power point, also mitigating the voltage fluctuations due to faults raised near the grid and production of stable output by controlling the voltage source converter. Fuzzy based approach reduces complex computations by avoiding unnecessary manual tuning of gain constants. MATLAB/Simulink is used for modelling the PV grid and the results are obtained to validate the proposed approach. Different case scenarios are considered and results are compared with sliding mode control based PV grid outputs to show the effectiveness of FITSMC. FITSMC controller efficiency and ability can be said by its robustness in stability, finite time convergence and less settling time which are depicted in results.**

# **nomenclature**

PV Photovoltaic.

P & O Perturb and observe.

MPPT Maximum power point tracking.

MPP Maximum power point.

VSI Voltage source inverter.

SMC Sliding mode control.

TSMC Terminal sliding mode control.

ITSMC Integral terminal sliding mode control.

FITSMC Fuzzy based integral terminal sliding mode control.

IGBT Insulated gate bipolar transistors.

*ISC* Current generated by incident light (or) Short circuit current.

VOC Open circuit voltage.

Reverse saturation current.

*q* Electron charge = 1.602 ×  C.

*K* Boltzmann constant = 1.38 ×  J/K.

*T* Temperature of p-n junction in kelvin.

*A* Ideal diode constant.

*Ior* Nominal saturation current.

*TR* Nominal temperature.

*Eg* Band gap energy of the semiconductor.

# **INTRODUCTION**

Economically optimal size, design and cost of grid connected PV systems are of great interest to produce electricity in large-scale applications [1]**.** Drastic growth has been observed in the field of PV energy in the last decade. This progression has initiated the evolution of complex PV grid topologies to increase power, efficiency and reliability. Furthermore, grid connected PV systems (where batteries are not necessary) are well-known for their reduced cost compared to stand alone systems (where batteries are used). Although tremendous progress has been made in the field of PV systems, there are still drawbacks related to PV grids such as voltage regulation, power quality and grid faults. To facilitate all these disadvantages, a PV grid requires proper control scheme.

A typical PV grid requires control for two converters which are DC-DC converter and voltage source inverter. A DC-DC converter acts as an interface between the PV array and the inverter for enhancing the low input voltage to a high output voltage. MPPT control is required for this converter to produce maximum power at desired voltage. Switching of duty cycle for IGBT is to be controlled using the perturb and observe algorithm along with the control scheme [2]. DC-AC converters which are also known as voltage source inverters converts the DC input voltage to AC output voltage and maintains unity power factor. VSI requires a powerful control scheme to regulate the voltage and for better dynamic performance. In the context of VSI, external DC link voltage control loop has been used in conjunction with inner current control loop to produce system stability and to reduce the steady state errors [12].

Aspects to be controlled for a PV grid can be conceptualized as ensuring the stability of a system, enhancing the robustness, minimizing the tracking errors, fastness in transient response, minimizing peak and grid injected currents, reducing nonlinearities and mitigating voltage fluctuations. Various control schemes are proposed for both MPPT control and VSI control. PI controllers are well-known controllers for both control schemes [3] but those fail due to lack of robustness against constraints like irradiance and temperature and are used only under small changes. Adaptive controllers give better results but they lack accuracy and fast convergence rate.

After going through extensive literature, the studies reached common conclusions about implementing advanced design for nonlinear control strategy that is sliding mode control. Large changes in operating conditions and for more robustness SMC has been chosen [4-6]. Many combinations like adaptive SMC and higher order SMC known as TSMC are introduced. However, SMC cannot withstand entire operation range and lacks in asymptotic steadiness. Adaptive SMC cannot provide the high accuracy and precision while TSMC design leads to intrinsic singular problems due to the usage of fractional power fractions [7]. Apart from the controversies, TSMC is excellent in providing finite time convergence along with accuracy and precision.

One can provide a better control scheme to PV grid by using the advantages of TSMC and looking for a solution to the disadvantages of TSMC. In search of a solution for these TSMC drawbacks, ITSMC can provide a better alternative by reducing steady state errors to zero and minimizing intrinsic singular problems [8]. Though fuzzy logic controllers are good at handling nonlinearities and uncertainties they cannot be used all alone for entire control scheme due to tedious manual tuning which increases the complexity of the system. Using fuzzy logic only in some parts of control scheme reduces the complexity and enhances the flexibility. Much more robustness is added to the system by combining ITSMC control with fuzzy logic [17].

The main contributions of this approach are:

* Design of FITSMC approach for minimizing the tracking error produced while tracking for maximum power point.
* Design of FITSMC approach for current control in VSI which in turn control the active and reactive powers of a grid.
* Comparison of FITSMC results to SMC approach for validation of the efficiency of proposed approach.

# **PV grid structure**

A typical PV grid is shown in figure1. It consists of a PV array which generates and . The current and voltage from a PV array is given to the boost converter under which 273V DC to 500V DC conversion takes place. 500V DC output voltage is given to 3-phase voltage source inverter where the 500V DC is inverted to 260V AC. In order to filter the harmonics produced by VSI a capacitor bank is used [14]. Output from the filter bank is given to the coupling transformer from which the output is given to the utility grid [19].



Fig. 1. Grid-connected PV array block diagram

## 1. Modelling of a PV array

A PV grid uses one or more PV arrays for converting solar energy into electrical energy. The elementary unit of a PV array is a PV cell and it works on photovoltaic principle. Photovoltaic effect can be defined as conversion of light into electrical energy by means of outer electrons that break the bond in a semiconductor device when the photon energy is higher than the band gap energy [11]. A PV cell consists of semiconductor diode whose Shockley diode equation [10] is given by

(1)

The output current and reverse saturation current of a PV cell are given as

, (2)

(3)

## 2. Boost converter and MPPT

Figure-2 shows the I-V characteristics of a PV cell in which short circuit current (maximum current at zero load) and open circuit voltage (voltage is maximum at zero current) are notable. At highest voltage and current we can obtain the maximum power point which can be seen in the figure.



Fig.2. I-V characteristic curve of a PV array

Tracking of is necessary for extracting maximum power. MPP tracking can enhance the efficiency of a system and this can be done using MPPT algorithms [2]. Perturb and observe, incremental conductance, fractional circuit and fuzzy networks are some of the algorithms used for MPPT [16]. In this paper, the perturb and observe algorithm is chosen because of its simplicity in implementation and for its economic reasons. This algorithm generates reference voltage by tracking the maximum power point.



Fig.3. Flowchart for perturb and observe algorithm

Figure-3 shows the perturb and observe algorithm in which one can see that the reference voltage is changed in accordance with the power generated by the PV array. Generally, perturbation is in the same direction of the power increment and perturbation will be continued in opposite direction when there is power decrement [9]. Observation and perturbation continues till the maximum power point is achieved and this process generates a reference voltage which should be compared with the voltage generated . The error between these two voltages must be controlled since it should not affect the duty cycle given to the PWM which in turn affects the output voltage of the boost converter. Thus, controlling the duty cycle of PWM which is given to IGBT in a boost converter must be controlled in terms of the error between generated and reference voltage.

The current at the capacitor with an inductor current of a DC-DC boost converter is defined as

(4)

The voltage across the inductor with as the duty cycle and as the bulk voltage across the capacitor is given by

(5)

## 3. Voltage source inverter

A current controlled three-phase voltage inverter is used in this paper. The VSI is fed constant DC voltage from the boost converter. The output voltage of a three-phase inverter is generated by driving the gates and switches.

Let us consider the inductor currents and capacitor voltage as state variables then the state-space representation [13] of a three phase VSI connected to a grid is given by

(6)

(7)

(8)

(9)

Where , , are switching signals related to each phase of VSI. The total inductance of the grid and inverter output filter is considered as with an equivalent series resistance of .

VSI requires pulses to control the gates and these pulses are generated by PWM. These pulses are generated by VSI control and the VSI control block diagram is shown below. The three modulating signals are input for PWM. These three modulating signals are generated by output voltages and of a current controller. Thus, for simpler control design one needs to implement transformations for the state space model and this can be done by using park or dq transformation.



Fig.4. Topology of VSI control

Appling dq transformation in synchronous frame for VSI state space equations [13] can turn them as shown below

(10)

(11)

(12)

Where and , and are the direct quadrature components of grid voltage and output current of the inverter. The external DC link voltage regulator is used to generate and are maintained zeros which are used as one of the inputs in current controller later.

# **Control scheme**

Grid connected PV systems belong to a class of non-linear systems with parameters perturbation, uncertainty and external disturbances in real time applications. For this type of nonaffine nonlinear systems, ITSMC provides a better solution by holding the system error on integral terminal sliding surface and then slides the surface to zero. ITSMC design for MPPT control [15] and VSI control are discussed here.

## 1. MPPT control

Consider the following switching variable for MPPT control with as a constant

(13)

where , .

Then the sliding manifold is given as

(14)

When , the control signal is obtained. Thus,

(15)

(16)

From equation (4) we can obtain the expression of , which is substituted in (16)

(17)

Substituting (5) in (17) with *k* as a positive constant yields the control signal

(18)

*Proof:*

From the Lyapunov function we know that

=0 (19)

In order to guarantee the convergence of , the derivative of must be negative

(20)

Substituting equation (15) in equation (20) we get

(21)

(22)

Substituting the control signal *u* in the above equation produces:

(23)

Completion of proof takes place by holding the equation (23) which then guarantees the exponential convergence of to zero.

## 2. Control scheme for VSI

Rewriting the equations (10) and (11) we get

(24)

(25)

Consider the sliding surfaces and and these are given as

(26)

(27)

Where , and , . Control signals are obtained when and . When then,

(28)

Combining equations (24) and (28) yields

(29)

Similarly,

(30)

Proof:

Lyapunov function states that

=0 (31)

Convergence of is guaranteed ,when the derivative of only be negative

(32)

Consider and then by substituting equation (27) we get

(33)

From equations (24) and (28) we can rewrite the above equation as

(34)

Substituting equation (29) in the above equation gives

(35)

(36)

Similarly,

(37)

Hence, it is stable.

## 3. Fuzzy control

In general, it is difficult to tune manually the values, , , . These uncertain values can be tuned using fuzzy logic [20]. Fuzzy Logic permits different operators to merge uncertain information in a best way and incorporate experimental control in the form of if-then rules. and are the inputs given to fuzzy tuner and we get and as tuned outputs. The following table shows the control rules for fuzzy controller.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | |  | | |
| NS | Z | PS |
|  | NS | B | S | Z |
| Z | S | Z | S |
| PS | Z | S | B |

Table І

Control rules for FITSMC

The following figure shows the surface view of the rules implemented

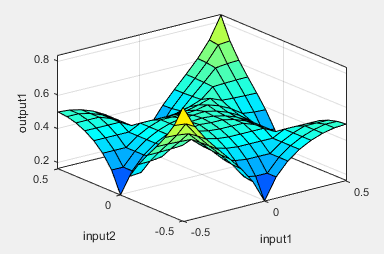


Fig.5. Surface view of if-then rules

1. **SIMULATION RESULTS**

The proposed approach is verified by performing experiments in MATLAB. Three case scenarios are considered for the illustration of benefits of this approach. Simulink model for grid connected PV array is generated, in which SPR-305E-WHT-D PV array with 66 strings and 5 series connected modules is used. Capacitor values C1, C2 and C3 values are considered as 100µF, 12mF and 12mF respectively. The inductor value is chosen to be 5mH. 10K-var capacitor bank is connected as filter bank to filter the harmonics produced by VSI. The R1 and L1 are chosen as 0.001885 and 0.00025. The switching frequency of VSI is 60 Hz. The expected output power is 100.7KW (66\*5\*305.2).

Case-1

In this scenario, results associated with FITSMC based PV grid are shown. The irradiance is considered to be 1000 W/m2 and at a temperature of 25oC. Figure.4 shows output voltage of boost converter which is regulated at reference voltage of 500V. One of the three phase voltage is given as Vab\_VSC and is shown as figure.7. Figure.8 shows output power which is around 92K. Until t=0.05 sec the boost converter and VSI are blocked and at t=0.05 both the converters are deblocked. This case shows the working of FITSMC under ideal conditions.

 Fig.4. Fig.6. Output voltage of boost converter in case-1

 Fig.5. Fig.7.Voltage in case-1

 Fig.6. Fig.8. Output power given to grid in case-1

Case-2

Irradiance and temperature varies with time in real time applications. Figures.9 and figure.10 shows the changes in irradiance and temperature respectively. From t=0.6sec to t=1.1 sec the irradiance decreases from 1000 W/m2 to 250 W/m2 and then will be stable at 250 W/m2 till t=1.2sec.



Fig.9. Irradiance given to PV array in case-2



Fig.10. Temperature given to PV array in case-2

From t=1.2sec to t=1.7 sec irradiance increases and reaches its maximum value that is 1000 W/m2. Temperature starts incresing from 25oC to 50oC when the time increases from t=1sec to t=1.5 sec and from then the temperature will be 50oC. Theses external variations should not effect the DC voltage. FITSMC based PV grid outputs are compared with outputs of SMC based PV grid [12].



Fig.11. Output voltages of FITSMC and SMC based boost converters in case-2

DC voltage outputs are shown in figure.11. Though there are external disturbances the dc voltage of FITSMC PV grid is stable and is regulated to 500V. While coming, SMC based PV grid DC voltage we could observe chattering and also the regulation cannot be done properly because of immediate external disturbances. Vab\_VSC for FITSMC is so normal and is same as the ideal case discussed in case-1. But the Vab\_VSC of SMC hasfluctuations from t=1.5 sec as shown. Power shown in the figure.13 is changed according to the change in irradiance. But it is able to reach the maximum power unlike SMC which does not show the maximum power despite of unfavorable conditions as given in figure.12.



Fig.12. Output power given to SMC based grid in case-2



Fig.13. Output power given to FITSMC based grid in case-2  Fig.14.Voltage of SMC based grid in case-2

Fig.15.Voltage of FITSMC based grid in case-2

Case-3

In this scenario a three-phase grid fault is introduce near the grid for about 0.2 sec which is from t=0.4sec to t=0.6 sec [18]. We can obseve the fluctuation in DC voltage of FITSMC based PV grid. This requies a settling time of 0.7 sec and I would consider this as minimum settling time since we can observe the SMC DC voltage is not settled till the end and also the voltage consists of chattering phenomenon.



Fig.16. Output voltages of FITSMC and SMC based boost converters in case-3

Though there are voltage fluctuations in Vab\_VSC from 0.4 sec to 0.6 sec maximum power is obtained after t=0.6sec. whereas, SMC output power shows the lack of robustness in the system and we can observe the roughness in the power graph [21]. Chattering-free performance, robustness are clearly depicted in the results of FITSMC based PV grid.

 Fig.17. Output power given to SMC based grid in case-3



Fig.18. Output power given to FITSMC based grid in case-3

Fig.19.Voltage of SMC based grid in case-3



Fig.20.Voltage of FITSMC based grid in case-3

1. **CONCLUSION**

In this paper novel approach for nonlinear systems like PV grid system is proposed. For achieving maximum power point perturb and observe algorithm is chosen and for tracking the error FITSMC is chosen. Control signal is derived by using integral terminal sliding surface. VSI dynamics are drawn and conversion using dq transformation is done for further derivation of control signal. The control signals , are derived by substituting the integral terminal sliding surface in VSI dynamics. Lyapunov theorem is proved for verifying the stability analysis of designed controller equations. The system is able to filter the components by using filter bank connected to the system. Optimal values for gains are produced by fuzzy logic which reduces the complexity. MATLAB Simulink is used to develop the PV grid model and results are obtained for three case scenarios to validate the proposed approach. Case-2 and case-3 scenarios shows the comparison results between FITSMC and normal SMC based PV grids. FITSMC results clearly depicted that the controller provides better control than SMC with less settling time, less chattering effect and minimum overshoot. Results show that FITSMC has fast tracking time or convergence and can work robustly against parametric uncertainties.

**REFERENCES**

1. A. L. Fahrenbruch and R. H. Bube, Fundamentals of Solar Cells. San Francisco, CA: Academic, 1983.
2. M. A. S. Masoum, H. Dehbonei, and E. F. Fuchs, “Theoretical and experimental analyses of photovoltaic systems with voltage and current-based maximum power-point tracking,” *IEEE Trans. Energy Convers*., vol. 17, no. 4, pp. 514–522, Dec. 2002.
3. K. J. Astrom and T. Hagglund, PID Controllers: Theory, Design, and Tuning. Research Triangle Park, NC: ISA, 1995.
4. V. Utkin, J. Guldner, J. Shi, Sliding Mode Control in ElectroMechanical Systems, CRC Press, 2009.
5. Daniel Gonz´alez Montoya, Carlos Andr´es Ramos-Paja and Roberto Giral “Improved Design of Sliding-Mode Controllers Based on the Requirements of MPPT Techniques” *IEEE transactions on power electronics*, vol. 31, no. 1, January 2016.
6. E. Bianconi, J. Calvente, R. Giral, E. Mamarelis, G. Petrone, C.A.Ramos- Paja, G. Spagnuolo, andM. Vitelli, “Perturb and observe MPPT algorithm with a current controller based on the sliding mode,” Int. J. Electr. Power Energy Syst., vol. 44, no. 1, pp. 346–356, 2013.
7. H.M. Hasanien, “An adaptive control strategy for low voltage ride through capability enhancement of grid-connected photovoltaic power plants,” *IEEE Trans. on Pow. Sys*., vol.31, no.4, pp. 3230-3237, 2016.
8. C. S. Chiu, "Derivative and integral terminal sliding mode control for a class of MIMO nonlinear systems," *Automatica*, vol. 48, no. 2, pp. 316-326, Feb. 2012.
9. X. Liu X., L.A.C. Lopez, “An improved perturbation and observation maximum power point tracking algorithm for PV arrays,”, *Proc. of IEEE Power Electronics Specialists Conf*., 2004.
10. M. G. Villalva, J. R. Gazoli, E. R. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays” *IEEE transactions on power electronics*, vol. 24, no. 5, may 2009.
11. H. S. Rauschenbach, Solar Cell Array Design Handbook. New York: Van Nostrand Reinhold, 1980.
12. S. Dhar, P.K. Dash, “Adaptive backstepping sliding mode control of a grid interactive PV-VSC system with LCL filter” Sustainable Energy, Grids and Networks 6 (2016) 109–124.
13. M.A. Mahmud, H. Pota, and M. J. Hossain, “Dynamic stability of three-phase grid connected photovoltaic system using zero dynamic design approach,” IEEE Journal of Photovoltaics, vol. 2, no. 4, pp. 564–571, 2012.
14. J.C. Das, Power System Analysis: Short-Circuit Load Flow and Harmonics, CRC Press, 2011.
15. Sai Sree Teja Amirineni, Mohammad Javad Morshed, Afef Fekih, “ [Integral terminal Sliding Mode Control for maximum power production in grid connected PV systems](http://ezproxyprod.ucs.louisiana.edu:2055/document/7588023/)” IEEE Conference on Control Applications (CCA) Part of 2016 IEEE Multi-Conference on Systems and Control September 19-22, 2016. Buenos Aires, Argentina.
16. T. Esram and P. L. Chapman, “Comparison of photovoltaic array maximum power point tracking techniques,” IEEE Trans. Energy Convers., vol. 22, no. 2, pp. 439–449, Jun. 2007.
17. [Mohammad Javad Morshed](http://ezproxyprod.ucs.louisiana.edu:2055/search/searchresult.jsp?searchWithin=%22Authors%22:.QT.Mohammad%20Javad%20Morshed.QT.&newsearch=true); [Afef Fekih](http://ezproxyprod.ucs.louisiana.edu:2055/search/searchresult.jsp?searchWithin=%22Authors%22:.QT.Afef%20Fekih.QT.&newsearch=true), “[Integral terminal sliding mode control to provide fault ride-through capability to a grid connected wind turbine driven DFIG](http://ezproxyprod.ucs.louisiana.edu:2055/document/7125237/)” [IEEE International Conference on Industrial Technology (ICIT)](http://ezproxyprod.ucs.louisiana.edu:2055/xpl/mostRecentIssue.jsp?punumber=7108493), Pages: 1059 – 1064, 2015.
18. Rolf Isermann, *Fault-Diagnosis Systems: An Introduction from Fault Detection to Fault Tolerance,* 2006.
19. [A. Kulkarni](http://ezproxyprod.ucs.louisiana.edu:2055/search/searchresult.jsp?searchWithin=%22Authors%22:.QT.A.%20Kulkarni.QT.&newsearch=true), [V. John](http://ezproxyprod.ucs.louisiana.edu:2055/search/searchresult.jsp?searchWithin=%22Authors%22:.QT.V.%20John.QT.&newsearch=true)” Mitigation of lower order harmonics in a grid- connected single phase PV inverter” IEEE transactions on power electronics, vol. 28, no. 11, pp. 5024-5037, Nov 2013.
20. Faa-Jeng Lin, IEEE, Kuang-Chin Lu, Ting-Han Ke, Bo-Hui Yang, and Yung-Ruei Chang “Reactive Power Control of Three-Phase Grid-Connected PV System During Grid Faults Using Takagi–Sugeno–Kang Probabilistic Fuzzy Neural Network Control” IEEE transactions on industrial electronics, vol. 62, no. 9, pp. 5516 - 5528 September 2015.
21. Mohammad Javad Morshed, Afef Fekih, “A Comparison Study Between two Sliding Mode Based Controls for Voltage Sag Mitigation in Grid Connected Wind Turbines” IEEE Conference on Control Applications (CCA) Part of 2015 IEEE Multi-Conference on Systems and Control September 21-23, 2015. Sydney, Australia.