Backstepping control for distributed power supplies of telecommunication equipment

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***Abstract*—In the theory of Control Systems, a technique named Backstepping Control was introduced by Petar V. Kokotovic in 1990. Stabilizing controls are being designednfor a particular set of nonlinear systems which are dynamical in nature. These systems derived from subsystems are given out from a subsystem which is irreducible in nature and which are possible to be stabilized using even other methods. There will be a known stable system and Backstepping Control has a recursive structure because of which design process can be started by the designer at this system which is stable and 'back out" controllers which are new and the outer subsystems are being stabilized by these controllers in stages. The process runs until it obtains the external control which is final. The Maximum power obtained from the MPPT tracking in a PV based system is tracked using a new control method which is nonlinear, Backstepping Control. The DC-AC converter controls the inverter input voltage and supples a telecommunication load and injects or absorbs UPF ac current from the grid which is sinusoidal in nature. The Backstepping Control is completely Lyapunov function based which ensurea the system's stability and robustness. Better results will be obtained since a recursive methodology is being applied in this control to model direct dynamics. The system comprises of PV generator, Buck Boost Converter and DC AC inverter interfaced to grid network. The duty ratio of Buck Boost Converter is being controlled to control the system and thus the input voltage of Buck Boost Converter is being set to a voltage which gives maximum power output. Numerical simulations in Matlab/Simulink are used to analyze the performance of the system.**

Keywords—component Backstepping; buck–boost converter; dc/ac converter; MPPT; self-consumption; smart grids

I. INTRODUCTION

Increased electrical energy demand has been a result of population growth and industrial development and progress. The growing importance of environmental protection and increase in energy consumption dramatically over the last few decades has made most of the countries to decide to strongly develop and promote sustainable and clean power generation sources [5]. For development solar energy is a most potential and important green energies. PV energy helps to give power to isolated autonomous devices and houses and where grid can’t reach and supply power. Renewable sources of energy can supply power even directly to the utility grid and this has been becoming very popular as the cost is reduced because a battery subsystem may be absent. Solar energy is being converted to electrical energy by PV modules which then transfers to the electrical network. Environmental conditions like temperature and amount of irradiance plays a vital role in determining the quantity of DC power generated. A solar array or module has solar cells that are being connected in a series manner and then being paralleled. Each PV module is having an operating point where it gives maximum Power under particular conditions.

The grid coupled PV system has an array of PV modules, a Buck Boost Converter, a DC-AC converter and the new nonlinear controller. PV system can be either be interfaced or coupled to the electrical network with the help of a DC-AC converter to inject a current which is sinusoidal in nature and the voltage of electrical network has to be in phase with the injected current to get UPF or can be even connected to a load. There are two modes for PV application, that is the stand alone PV system (To store energy battery banks are required) and PV system connected to grid (in distributed generation systems to supply power to utility grid). PV modules combined in series and the paralleled create solar panel which can assist in the reduction of power consumed of ac smart grids during peak hours. Under the self energy consumption concept of electrical power it should be made possible for each consumer to have connected a PV system and available surplus has to be injected into the electrical grid. PV systems are capable of supplying or storing the extra or excess power during the hours of peak power consumption.

The telecommunication apparatus power consumption is almost constant. So the self consumption concept is suited for these applications well. Here, we connect a telecommunication load between Buck Boost Converter of distributed PV panel and DC–AC converter (fig 1)[1]. The nominal value of voltage is 48 V generally, and can vary in an interval between 36 and 75 V. So the explained system is suitable for LV telecommunication apparatus.

The system is connected to the power grid with the help of DC–AC converters. Community storages of energy can be integrated with distributed resources of energy. There are two operating modes for a microgrid where one being isolated mode or by controlling the consumption and generation) the power electronics interfaces between the buses of dc and ac should be controlled according to that. System. The system uses and controls a single-phase DC–AC converter to inject current which is sinusoidal in nature (to reduce harmonic distortion) which is in phase with the LV–ac grid.

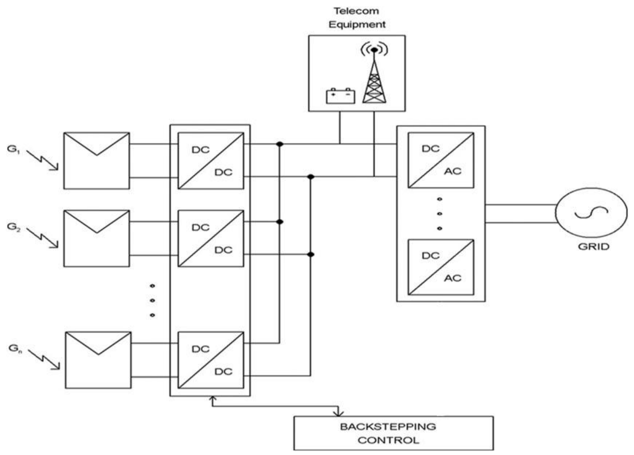

Figure 1. Telecom Load Connected PV Self Consumption

Under the concept of self energy consumption, there should be inversion and rectification or as a UPF rectifier depending on the power requirement of telecom load, depending on the power being generated by PV panel and on the load requirements of battery/telecom.

When more power is needed by the telecommunication application than the power that can be generated by the PV system there is a rectifier coming into play when the PV panel is unable to generate power that is required due to low levels of irradiance. At midday hours due to high irradiance levels, PV panels produce excess power which can be injected to electrical network after the recharge of battery. Then the DC–AC converter works as inverter. Moreover, if the grid is faulty, voltage sag that might be caused will not be allowed to affect the system as the system will be energized by battery and PV panel[1].

There are many tracking control strategies which had been proposed such as Perturb and Observe (P and O) method[1], Incremental conductance, Ripple correlation control, Sliding mode control, or artificial neuronal networks based MPP trackers, or fuzzy logic [1]. The oscillatory behavior shown by P and O it has a tendency to give local maximum inspite of global maximum and the required processing time, different accuracy and complexity of other MPPT algorithms that is advanced ones, a non linear control method has been introduced to reach MPP i.e. Backstepping Control. The maximum power point at different temperature and irradiance can be tracked as well as maintaining the grid current with the grid voltage and tight regulation of DC bus. It also reduces the harmonic content of the network current thus assuring high accuracy output characteristic and good robustness with system perturbation.

II. System Modeling

A. PV Array Modelling

The system may have many PV panels which can convert extra power than needed by load during midday hours. Photovoltaic system model has model of the solar cell, DC DC power converter modeling and the inverter model. Here the solar cell modeling is done.

Solar cell consists of a current source I_1(in A) which shows the current generated by the photons, which is constant if temperature and irradiance are constants too. It also consists of an antiparallel diode D1, a shunt electrical resistance R_{sh} in Ω which represents the current leakage and a series resistance R_s in Ω, which models the ohmic losses[2].

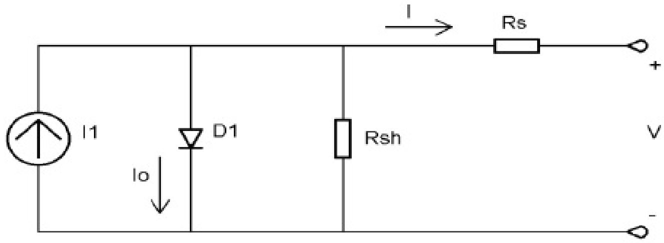

Figure 2. PV Equivalent Circuit

The equation for a solar cell that relates its current with voltage is given below

$$I = I_l - I_0(\exp^{q\frac{V+R_S I}{nKT_K}} - 1) - \frac{V + R_s I}{R_{sh}} \qquad (1)$$

Where I_l is the light generation current in A, I_o is the cell reverse saturation current in A, n is the ideal factor (dimensionless), q is the charge of an electron in C, K is the Boltzmann's constant in J/K and T_K is the working temperature of the cell in K [2].

If the temperature and irradiance of the whole PV array is homogenous, the system power curve will have only one maximum. Under partial shading conditions the PV curve has several local maximum but one global maximum. The proposed control will help to achieve a global maximum.

At a particular temperature T in ^{0}C and solar radiation G in w/m^2 there is only one operating point with a maximum output power for a PV array.

Table 1. Electrical Parameters of Solar Module at $1000W/m^2$ and 25^0C

Parameter	Values
$Maximum\ Power\ (P_{max})\ (W)$	54
$Maximum\ Power\ Voltage\ (V_{MPP})\ (V)$	18.2
$Maximum\ Power\ Current\ (I_{MPP})\ (A)$	3
$Open\ Circuit\ Voltage\ (V_{OC})\ (V)$	21.7
$Short\ Circuit\ Current\ (I_{SC})\ (A)$	3.31
$Equivalent\ Series\ Resistance\ (R_s)\ (\Omega)$	0.2
$Equivalent\ Shunt\ Resistance(R_{sh})\ (\Omega)$	200

B. Buck Boost Converter Modelling

The function of the control in closed loop is to regulate the voltage of the solar modules controlling the duty cycle, D so as to achieve MPP. The system has a filtering capacitor connected to the output of PV panel and is controlled to ensure the voltage v_{PV} across this capacitor equals maximum power point voltage v_{MPP} and thus transferring the maximum power from the solar array[3].

In the Fig.3 the switch ON/OFF commutation, controlled by means of Pulse Width Modulation (PWM) principle, permits the energy charge and discharge of the storage elements, getting an output voltage higher or lower than the input voltage. The transistor T1 and diode D2 implicits a nonlinear behaviour of the converter. The output voltage of the converter is of opposite polarity compared to the input voltage[3]. The duty cycle of the converter is $D=t_{on}/t_{c.}$ where t_{on} is the time when switch is ON and t_c being switching period (0<D<1)[1].

The output voltage to input voltage ratio is

$$\frac{v_0}{v_{PV}} = \frac{D}{1-D} \tag{2}$$

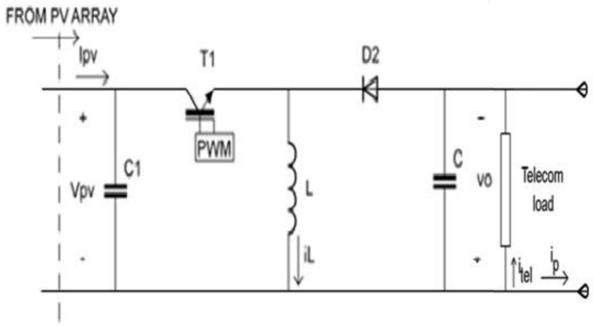

Figure 3. Buck Boost Equivalent Circuit

When the switch is ON, inductor is supplied energy from the PV array and the diode is inversely polarized. Then the charge is insulated from the source. The supplied energy is stored in the inductor that way. The diode conducts and the stored energy in the inductor is transferred to the charge when the switch is OFF[2].

The converter usually works in two modes, Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM), depending on the current of the inductor in the period of operation. In continuous conduction mode, the current through the inductor is never zero, but it fluctuates between maximum and minimum values based on the time when the switch is ON. In discontinuous conduction mode, when the switch is OFF the current of the inductor is zero for a particular time. When the time for which the switch is OFF greater than the time the inductor transfers energy the inductor will be completely discharged. The DC-DC converter will work in CCM here[2].

In fig. 3 we assume ideal semiconductors and continuous-conduction mode (CCM) operation. v_p is the buck–boost converter output voltage in V, i_{PV} is the PV panel output current in A, $i_L(1-u)$ the output current in A, i_L the inductor current in A, i_{tel} the telecom load current which is considered to be a disturbance and i_P the inverter dc current.

The buck–boost converter dynamics using state-switching period averaged values are as follows [1]

$$\frac{dv_{PV}}{dt} = \frac{i_{PV}}{C_1} - \frac{ui_L}{C_1} \tag{3}$$

$$\frac{di_L}{dt} = \frac{uv_{PV}}{L} - (1-u)\frac{v_P}{L} \tag{4}$$

$$\frac{dv_P}{dt} = (1-u)i_L - i_p - i_{tel} \tag{5}$$

C. DC AC Converter Modelling

Buck boost converter output voltage v_{P} is the DC AC converter input voltage which is being supplied to the telecom load. So this is to be maintained almost constant. DC AC converter interfaces the system with either the load or the grid. Strict feedback form DC AC converter dynamics is given in the equations (6) and (7) below[1].

$$\frac{dv_P^2}{dt}C_2 = i_p v_p - i_{L2} v_R \tag{6}$$

$$\frac{di_{L2}}{dt}L_2 = \beta v_p - v_R \tag{7}$$

Considering the system to be conservative and at unity power factor energy transfer through the DC AC converter is shown in equation(6). In equation (7), β is the sinusoidal modulation waveform that converts the DC AC converter switched voltage v_{PWM} to the fundamental sinusoidal voltage. These equations define the slow and fast dynamics of the DC AC converter.

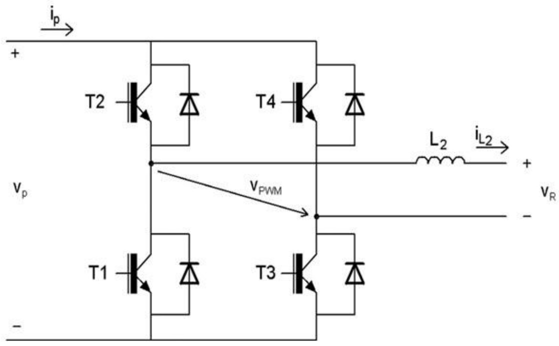

Figure 4. DC AC Converter Circuit

When there is excess power from the PV array that is during midday hours, excess power may increase the v_p voltage. Then the dc–ac converter has to inject the excess power into the electrical network. It is connected using a step-down transformer to the network. Otherwise, if the power delivered by the array is not sufficient, then the PWM rectifier sinks power from the electrical network.

The DC AC converter must inject a nearly sinusoidal current in phase with the network voltage when injecting excess power to the network (to prevent harmonic distortion). While sinking power from the electrical network the ac current will have opposite phase relative to the network voltage[1].

III. Control in the System

A. *Buck Boost Converter Control*

The controlled output of a mechanism and the controlling input is automatically being compared with each other. This defining attribute of this control. The error signal is the difference between the settings or positions of the output and the input, which makes to bring the output to its desired value.The backstepping technique stabilizes a nonlinear dynamical system. Any nonlinear dynamical system can be stabilized only with Lyapunov function approach. So backstepping technique is invariably adopted. The stabilizing function is designed at every step of dynamics starting from the output towards input in case of backstepping approach. In the strict-feedback form, this recursive method is for stabilizing the origin of a system. The controller will have the terms of system state variables, reference input and its derivatives, and corresponding error terms. The error and its derivatives have to be settled down to zero which is the basic aim of the controller. Strong closed loop stability is ensured by designing the controller based on Lyapunov based function. In the theory of control systems, Lyapunov functions are scalar functions and these functions may be used to prove the stability of equilibrium of a control system.

The control laws for the DC DC converter and the DC AC converter are obtained by a nonlinear backstepping approach. In this method the fictitious or virtual control input i_L is calculated first to stabilize the lower order subsystem equation (3) at the origin, and then to enforce the dynamics in system equation (4) it finds a way to calculate u which is necessary to track the iL value required to stabilize system (3). The ultimate control u is obtained by the algorithm stepping backward from (4) until the control is obtained. Since backstepping applies a recursive methodology it gives better results compared to linear controllers. It also guarantees robustness and system stability. Usually the output voltage v_p is maintained constant by controlling the buck boost converter. But here in this system buckboost backstepping controller obtains the converter duty cycle so that its input voltage is controlled by the converter to enforce the PV panel operation at the maximum power point. To accomplish this, The inductor current i_L is defined to be controlled by the backstepping input v_{PV} voltage outer loop. The needed duty cycle to track i_{Lref} is defined by a recursively obtained inner current loop[1]. To apply Backstepping Control and have zero error that stabilizes the system to the origin, the buck boost input voltage should track the PV array maximum power point voltage given as reference $v_{PV\ ref}$ thus error e_{PV} is defined first (zero tracking error).

$$e_{PV} = v_{PV} - v_{PVref} \qquad (8)$$

Time derivative of e_{PV} in equation (8) using model (3) it gives

$$\frac{de_{PV}}{dt} = \frac{i_{PV}}{C} - \frac{ui_L}{C} - \frac{dv_{PVref}}{dt} \qquad (9)$$

In the equation (9) i_L, being the stabilising control input and current reference for inner loop, can be determined. Now a Lyapunov function is to be selected which is radially unbounded and globally negative definite for all e_{PV}.

$$V_v = \frac{e_{PV}^2}{2} \qquad (10)$$

The time derivative of the Lyapunov function $\frac{dV_v}{dt}$ must be globally negative definite for all e_{PV} for the solution to be globally asymptotically stable. Hence $e_{PV}\frac{de_{PV}}{dt} < 0$

$$\frac{de_{PV}}{dt} = -k_{PV}e_{PV} \qquad (11)$$

$\frac{dV_v}{dt} < 0$ is verified if k_{PV} in equation (11) is positive and constant. Assuming zero tracking error $i_L = i_{Lref}$ and $0 < u < 1$

$$i_{Lref} = (Ck_{PV}e_{PV} + i_{PV} - C\frac{dv_{PVref}}{dt})/u \qquad (12)$$

The reference current i_{Lref} is a function of u. To define u second feedback loop $i_L = i_{Lref}$ is needed. To have zero tracking error defined as $e_{iL} = i_L - i_{Lref}$ the inductor current i_L should be equal to i_{Lref}.

$$\frac{de_{i_L}}{dt} = \frac{di_L}{dt} - \frac{di_{Lref}}{dt} \qquad (13)$$

$$\frac{di_{Lref}}{dt} = -k_{PV}e_{i_L} - \frac{Ck_{PV}^2}{u}e_{PV} + \frac{1}{u}\frac{di_{PV}}{dt} \qquad (14)$$
$$-\frac{C}{u}\frac{d^2v_{PVref}}{dt^2} - i_{Lref}\frac{du}{dt}/u$$

The time derivative of e_{iL} is written as, from previous equations

$$\frac{de_{i_L}}{dt} = -\frac{v_p}{L} + \frac{v_{PV}+v_p}{L}u + k_{PV}e_{i_L} \qquad (15)$$
$$+\frac{Ck_{PV}^2}{u}e_{PV} - (\frac{1}{u}\frac{di_{PV}}{dt} - \frac{C}{u}\frac{d^2v_{PVref}}{dt^2} - i_{Lref}\frac{du}{dt}/u)$$

A recursively obtained Lyapunov function is considered for inductor current, considering the input Lyapunov function (10)

$$V_i = e_{PV}^2/2 + e^2i_L/2 \qquad (16)$$

Lyapunov function time derivative is given considering equations (11), (13) and (15).

$$\frac{dV_i}{dt} = -k_{PV}e_{PV}^2 + e_{i_L}[\frac{-v_p}{L} + \frac{v_{PV}+v_p}{L}u + e_{PV}(\frac{Ck_{PV}^2}{u} - \frac{u}{C}) \quad (17)$$

$$-k_{PV}e_{i_L} + \frac{C}{u}\frac{d^2 v_{PVref}}{dt^2} - \frac{1}{u}\frac{di_{PV}}{dt} + i_{Lref}\frac{du}{dt}/u]$$

Here the constant k_{iL} must be positive for the above function to be negative. From the above equations controller $\frac{du}{dt}$

$$\frac{du}{dt} = \frac{1}{i_{Lref}}[\frac{v_p}{L} - \frac{v_{PV}+v_p}{L}u^2 - e_{PV}(\frac{Ck_{PV}^2}{-}\frac{u^2}{C}) \quad (18)$$

$$-(k_{PV} - k_{i_L})ue_{i_L} - C\frac{d^2 v_{PVref}}{dt^2} + \frac{di_{PV}}{dt}]$$

A virtual control du/dt is obtained and the control input u is obtained by passing through an integrator [1].

B. DC AC Converter Control

The DC AC converter should inject unity power factor nearly sinusoidal current to the electrical network. The inverter helps in interfacing the system with the load or the grid with the help of a transformer. A dc telecom load is supplied at the output of the buck boost converter. When there is excess power the system has a tendency to increase the voltage v_p at the input of the inverter. This is the voltage across the telecom load and it is to be maintained constant. Hence when v_p is more than the required voltage of the load the excess power is supplied to the grid. When the voltage is less than that is required by the load the inverter section is switched off and the rectifier section comes into play. Thus the required power is supplied by the electrical network. When the current is being injected to the network it is in phase with the network and when the network supplies current to the system the current is out of phase with the system.

IV. Results and Discussions

The proposed backstepping control has been validated under different conditions. At an irradiance of 1000W the simulator gives a power of nearly 54W. A transformer is connected between DC AC converter and the grid.

The measured input current is 2.95 A and voltage is 18.2 V at the input of the dcdc converter when the irradiance level is 1000 W/m^2. PV panel outputs a maximum power of 54.6 W. Tracking of v_{MPP} is shown in Fig. 8, the buck boost input voltage v_{PV} is tracking the reference voltage $v_{PV\ ref}$ at 18.2 V. The controller will have the terms of system state variables, reference input and its derivatives, and corresponding error terms. The error and its derivatives have to be settled down to zero which is the basic aim of the controller. Strong closed loop stability is ensured by designing the controller based on Lyapunov function. Error in voltage graph is shown in fig. 5. Error in inductor current is shown in fig. 6. The control signal for the buck boost converter from backstepping control is shown in fig. 7.

Table 2. Simulation Parameters

Parameter	Values
C_1	1000μF
C	5700μF
L	20mH
L_2	13.1mH
k_{PV}	5
k_{i_L}	75

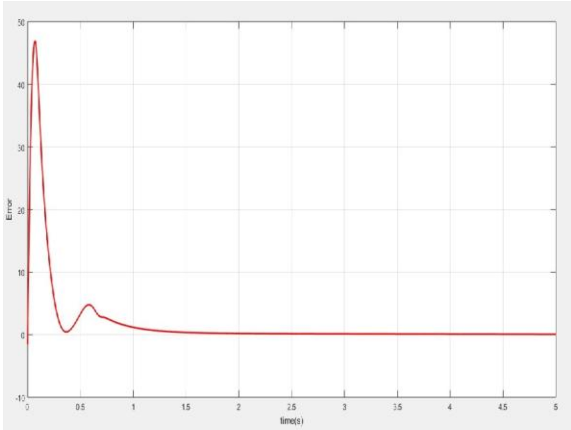

Figure 5. Error in PV output voltage

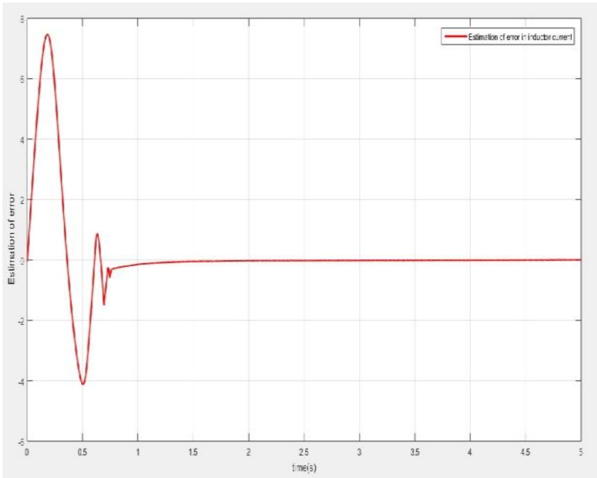

Figure 6. Error in buck-boost inductor current

The telecom load has a voltage within the range of 36 to 75 V and the ac output voltage is adapted to the grid voltage by the transformer. The telecom load voltage and current at 1000W/m^2 and 500W/m^2 are shown in fig. 11 and Fig. 14 shows the voltage at the grid side.When there is an irradiance that is sufficient to supply the load and if there is surplus

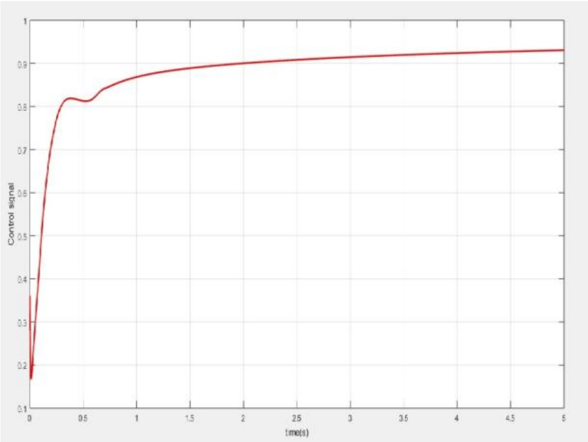

Figure 7. Control signal to buck-boost converter

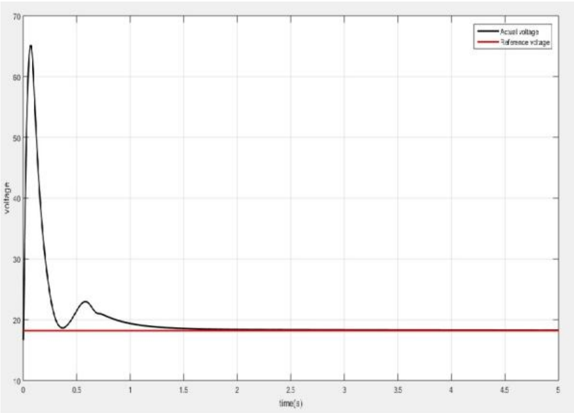

Figure 8. PV panel output voltage tracking

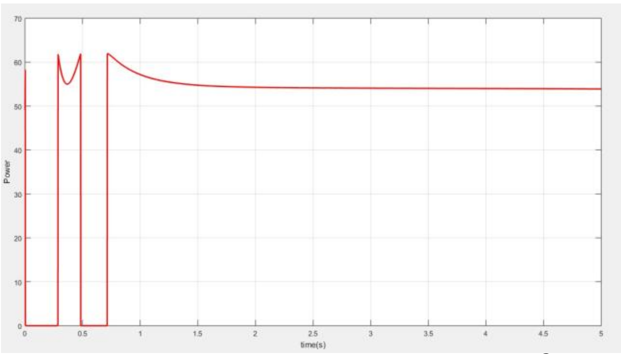

Figure 9. Power waveform at 1000W/m^2

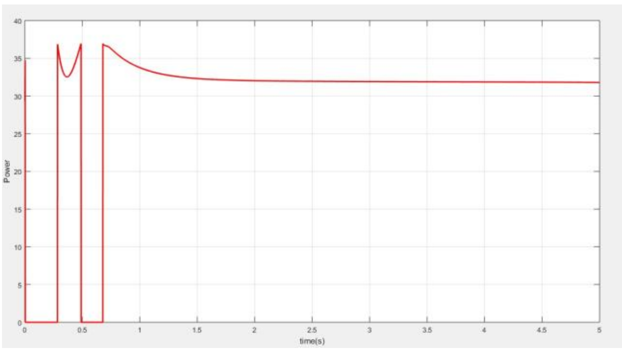

Figure 10. Power waveform at 600W/m^2

Fig. 12 shows the output voltage of inverter when the irradiance changes from 1000 to 500W/m^2. That is when there is 1000W/m^2 irradiance there is enough power to supply to the grid but when the irradiance changes from 500W/m^2 there is not enough power so the supply to the grid eventually stops. Fig.13 shows the grid voltage, rectifier output voltage and current.

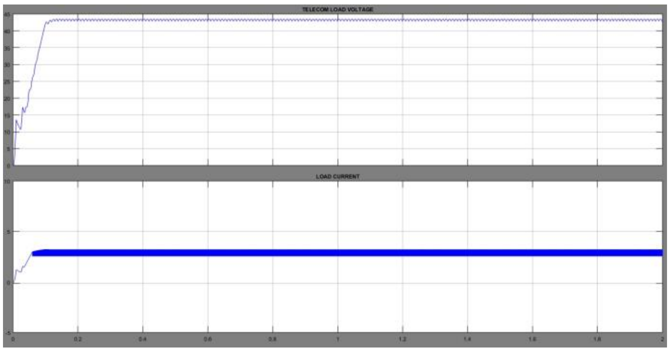

Figure 11. Telecom load voltage and current when irradiance is 1000W/m^2

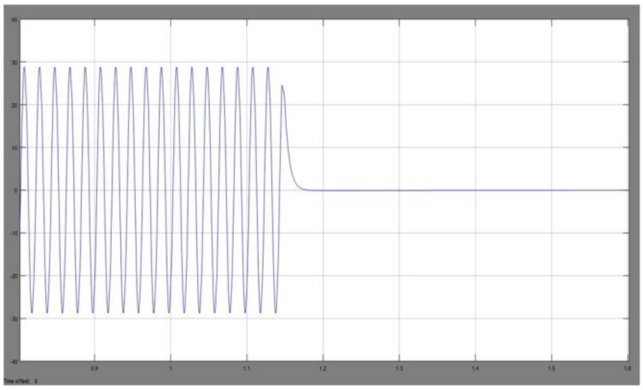

Figure 12. Inverter output voltage when irradiance changes from 1000W/m^2 to 500W/m^2

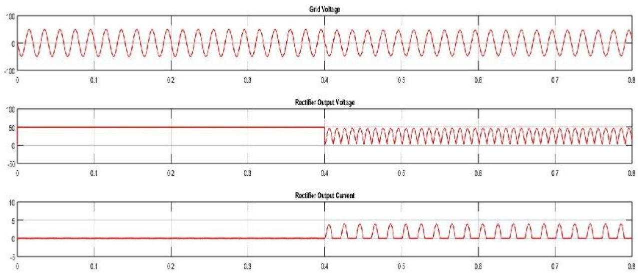

Figure 13. (a)Grid voltage (b)Rectifier Output Voltage (c)Rectifier Output Current when irradiance changes from 1000W/m^2 to 500W/m^2

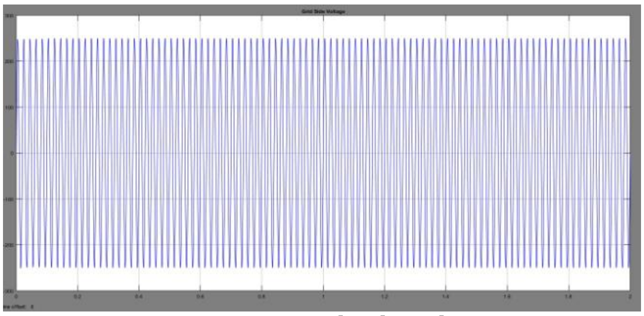

Figure 14. Grid Side Voltage

A. *Comparison between Backstepping Control and Perturb and Observe Method*

Compared to Perturb and Observe method here backstepping control gives more stable and robust output and the oscillatory behaviour of this algorithm is compensated. Fig.15 shows the power tracked using Perturb and observe method and fig.16 shows the power tracking using backstepping control.

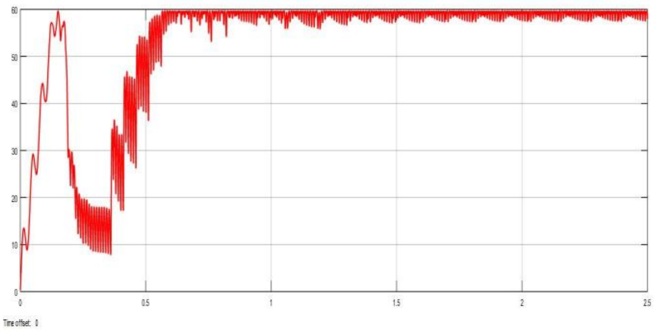

Figure 15. Power tracking at 1000 W/m2 using P and O method

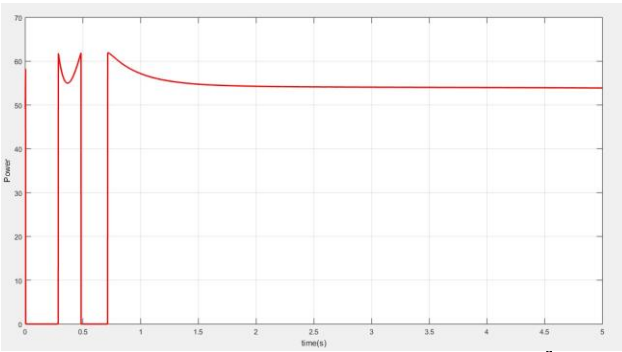

Figure 16. Power tracking at 1000 W/m^2 using Backstepping control method

V. CONCLUSIONS

Here in this work a backstepping controller for a PV panel connected to a buck boost converter, interfaced to a telecom load is being presented. A single-phase dcac converter connected to a grid which injects nearly sinusoidal grid currents at near unity power facto when there is excess power and the rectifier absorbs power during sunless hours. This contributes to the peak power shaving strategy of smart grid. New nonlinear backstepping control law help in achieving MPP operation by controlling input voltage of the buck boost converter. The DC-AC converter should inject sinusoidal current which is of unity power factor to the electrical network. The inverter helps in interfacing the system with the load or the grid with the help of a transformer. A dc telecommunication load is supplied at the output of the Buck Boost Converter.

When there is excess power the system has a tendency to increase the voltage v_p at the input of the inverter. This is the voltage across the telecommunication load and it is to be maintained constant. Hence when v_p is more than the required voltage of the load the excess power is supplied to the grid. When the voltage is less than that is required by the load the inverter section is switched off and the rectifier section comes into play. Thus the required power is supplied by the electrical network. When the current is being injected in to the network it is to be ensured that it is in phase with the network and when the network supplies current to the system the current will be out of phase with the system.

Compared to Perturb and Observe method here Backstepping Control gives more stable and robust output and the oscillatory behaviour of this algorithm is compensated.

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