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Three Phase Grid Connected Photovolaicsystem Using Effective Linear Stabilization System

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ABSTRACT

This paper presents a robust linear stabilization scheme for a three-phase grid-connected solar system to control the output current of solar cell connected to the grid and dc-link voltage to extract maximum output power from solar units. The scheme is mainly based on the design of a robust controller using a feedback linearization approach, where the robustness of the proposed scheme is ensured by undertaking nonlinearities within the solar system model. In this paper, the nonlinearities are modeled as designed nonlinearities are based on the matching of satisfactory conditions. The performance of the proposed linearization scheme is evaluated on a three-phase grid-connected solar system in terms of delivering maximum power under undesirable conditions.

Index Terms—Grid-connected solar system, matching conditions, nonlinear controller, partial feedback linearizing scheme, structured nonlinearity.

I. INTRODUCTION

The utilization of grid-connected solar systems is increasingly being pursued as a supplement and an alternative to the conventional fossil fuel generation in order to meet increasing energy demands and to limit the pollution of the environment. The major concerns of integrating PV into the grid are stochastic behaviors of solar irradiations and interfacing of inverters with the grid. Because of high initial investment, changes in solar irradiation, and reduced life-time of PV systems, as compared with the traditional energy sources, it is beneficial to extract maximum power from PV systems. Maximum power point tracking (MPPT) techniques are widely used to extract maximum power from the PV system that is delivered to the grid through the inverter. Recent improvements on MPPT can be seen in [5] and [6]. Interconnections among PV modules within a shaded PV field can affect the extraction of maximum power [7]. A study of all possible shading scenarios and interconnection schemes for a given PV field, to maximize the output power of PV array, is proposed in [7]. Inverters interfacing PV modules with the grid perform two major tasks—one is to ensure that PV modules are operated at maximum power point (MPP), and the other is to inject a sinusoidal current into the grid. In order to evaluate these tasks effectively, we need one efficient control schemes are essential .In a grid-connected PV system, control objectives are met by a strategy using a pulse width modulation (PWM) scheme.

Feedback linearization has been increasingly used for nonlinear controller design. It transforms the nonlinear system into a fully or partly linear equivalent by canceling nonlinearities. A feedback linearizing technique was first proposed in [16] for PV applications where a superfluous complex model of the

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inverter is considered to design the controller. To overcome the complexity, a simple and consistent inverter model is used in [17], and a feedback linearization technique is employed to operate the PV system at MPP. In [16] and [17], a feedback linearizing controller is designed by considering the dc-link voltage and quadrature-axis grid current as output functions. Power-balance relationships are considered to express the dynamics of the voltage across the dc-link capacitor. However, this relationship cannot capture nonlinear switching functions between inverter input and output; to accurately represent a grid-connected PV system but it is essential to consider these switching actions. The current relationship between the input and output of the inverter can be written in terms of switching functions rather than the power balance equation. Therefore, the voltage dynamics of the dc-link capacitor include nonlinearities due to the switching actions of the inverter. However, the main difficulties of the robustness algorithm, as presented in [21]–[23], are the consideration of linearized PV system models that are unable to maintain the stability of the PV system over a wide changes in atmospheric conditions.

Although there are some advances in the robust control of grid-connected PV systems, research into the robustness.

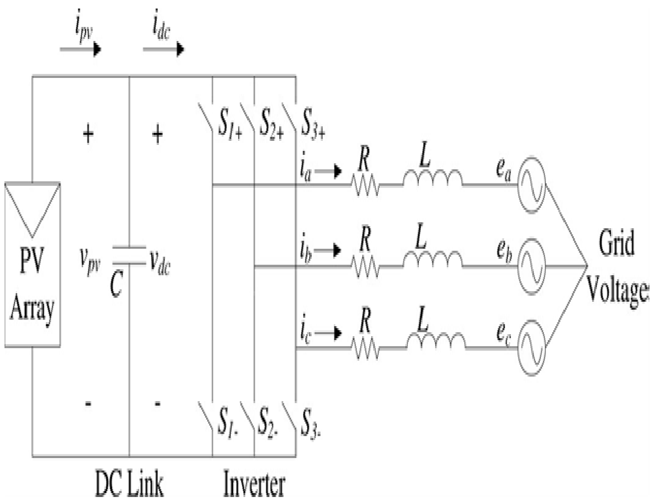

Fig. 1. Three-phase grid-connected PV system.

Analysis and the controller design of nonlinear uncertain PV systems remains an important and challenging area. Since the feedback linearization technique is widely used in the design of nonlinear controllers for power systems, this paper proposed the extension of the partial feedback linearizing scheme, as presented in [18], by considering uncertainties within the PV system model. In this paper, matching conditions are used to model the uncertainties in PV systems for given upper bounds on the modeling error, which include parametric and state-dependent uncertainties. These uncertainties are bounded in such a way that the proposed controller can guarantee the stability and enhance the performance for all possible perturbations within the given upper bounds of the modeling errors of nonlinear PV systems. The effectiveness of the proposed controller is tested and compared with that of a partial feedback linearizing controller without uncertainties, following changes in atmospheric conditions.

II. PHOTOVOLTAIC SYSTEM MODEL

The schematic diagram of a three-phase grid-connected PV system, which is the main focus of this paper, is shown in Fig. 1. The considered PV system consists of a PV array, a dc-link capacitor *C*, a three-phase inverter, a filter inductor *L*, and grid voltages *ea* , *eb* , *ec* . In this paper, the main aim is to control the voltage *v*dc (which is also the output voltage of PV array *v*pv) across the capacitor *C* and to make the input current in phase with grid voltage for unity power factor by means of appropriate control signals through the switches of the inverter.

A. Photovoltaic Cell and Array Model

A PV cell is a simple p-n junction diode that converts the irradiation into electricity. Fig. 2 shows an equivalent circuit diagram of a PV cell that consists of a light generated current source *IL* , a parallel diode, a shunt resistance *R*sh , and a series resistance *Rs*. In Fig. 2, *I*ON is the diode current that can be written as

$$ION = Is\,[\exp\,[\alpha\,(vpv + Rs\;ipv\,)] - 1]\;(1)$$

where $\alpha = \frac{q}{AkTC}$, $k = 1.3807 \times 10^{-23}$ JK^{-1} is the Boltzmann's constant, $q = 1.6022 \times 10^{-19}$ C is the charge of electron, *TC* is the cell's absolute working temperature in Kelvin, *A* is the p-n junction ideality factor whose value is between 1 and 5, *Is* is the saturation current, and *v*pv is the output voltage of the

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PV array which is also the voltage across *C*, i.e., *v*dc. Now,

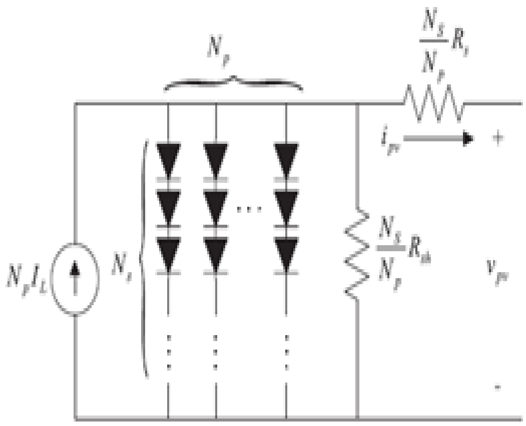

Fig 3. Equivalent circuit diagram of the PV array.

by applying Kirchhoff's current law (KCL) in Fig. 2, the output current (*i*pv) generated by a PV cell can be written as

$$i_{\mathrm{pv}} = N_p I_L - N_p I_s \left[\exp\left[\alpha\left(\frac{v_{\mathrm{pv}}}{N_s} + \frac{R_s i_{\mathrm{pv}}}{N_p}\right)\right] - 1\right] - \frac{N_p}{R_{\mathrm{sh}}}\left(\frac{v_{\mathrm{pv}}}{N_s} + \frac{R_s i_{\mathrm{pv}}}{N_p}\right). \quad (5)$$

B. Three-Phase Grid-Connected Photovoltaic System Model

In the state-space form, Fig. 1 can be represented through the
following equations [17], [18]:

$$\dot{i}_a = -\frac{R}{L}i_a - \frac{1}{L}e_a + \frac{v_{\mathrm{pv}}}{3L}(2K_a - K_b - K_c)$$
$$\dot{i}_b = -\frac{R}{L}i_b - \frac{1}{L}e_b + \frac{v_{\mathrm{pv}}}{3L}(-K_a + 2K_b - K_c)$$
$$\dot{i}_c = -\frac{R}{L}i_c - \frac{1}{L}e_c + \frac{v_{\mathrm{pv}}}{3L}(-K_a - K_b + 2K_c) \quad (6)$$

Where *Ka*, *Kb* , and *Kc* are the input switching signals. Now, by applying KCL at the node where the dc link is connected, we obtain

$v^{\cdot}$pv =1/*C* (*i*pv − *i*dc). (7)

However, the input current of the inverter *i*dc can be written as [19]

*i*dc = *iaKa* + *ibKb* + *icKc* (8)

which yields

$v^{\cdot}$pv =1/*C* *i*pv −1/*C* (*iaKa* + *ibKb* + *icKc*) (9)

III.OVERVIEW OF PARTIAL FEEDBACK LINEARIZING STABILIZATION SCHEME

As the three-phase grid-connected PV system as represented by (10) has two control inputs (*Kd* and *Kq)* and two control outputs (*Iq* and *v*pv), the mathematical model can be represented by the following form of a nonlinear multi input multi output (MIMO) system:

$x^{\cdot} = f(x) + g1\,(x)u1 + g2\,(x)u2$

$y1 = h1\,(x)$

The partial feedback linearizing scheme transforms the nonlinear grid-connected PV system into a partially linearized PV system, and any linear controller design technique can be employed to obtain the linear control lawfor the partially linearized system. However, by the partial feedback linearizing scheme before obtaining a control law , it is essential to ensure the partial feedback linearizability and internal dynamics stability of the PV system. The details of partial feedback linearizability and internal dynamics stability of the considered PV system are presented in [18] from where it can be seen that the PV system is partially linearized and that the internal dynamic of the PV systems is stable. The partially linearized PV system can be written as

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*z*1 = −*ωId* –*R/LIq* –*Eq/L*+ *v*pv/*LKq* = *v*1
·

_

*z*2 =1/*Ci*pv −1/*CIdKd* −1/*CIqKq* = *v*2 (14)

where

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z represents the transformed states, and *v* represents the linear control inputs that are obtained through the PI design approach [18]. The nonlinear control law can be written as Equation (15) is the final control law that is obtained through a partial feedback linearizing scheme, and the controller ensures the stability of the PV system for the considered nominal model and exact parameters of the system need to be known. However, in practice, it is very difficult to determine the exact parameters of the system. Thus, the considered partial feedback linearizing scheme is unable to maintain the stability of the PV system with changes in system conditions and the consideration of uncertainties

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within the PV system is necessary, which is shown in the following section.

IV. UNCERTAINTY MODELING

In a practical PV system, atmospheric conditions change continuously for which there exists a variation in cell working temperature, as well as in solar irradiance. Because of changes in atmospheric conditions, the output voltage, current, and power of the PV unit changes significantly.as the values of the parameters used in the PV model are not exactly known, there are also parametric uncertainties. The PV system model as shown by (10) cannot capture these uncertainties. Therefore, it is essential to consider these uncertainties within the PV system model. In the presence of uncertainties, the nonlinear mathematical model of the three-phase grid-connected PV system, as shown in (13), can be represented by the following equation:

$\dot{x} = [f(x) + \Delta f(x)] + [g1(x) + \Delta g1(x)]u1 + [g2(x) + \Delta g2(x)]u2$, $y1 = h1(x)$ $y2 = h2(x)$

which are uncertainties in $f(x)$ and $g(x)$, respectively. The uncertainties need to be modeled in such a way that the controller will robustly stabilize the original system despite the uncertainties The relative degree of the uncertainty Δf can be calculated from the following equation:

$L\Delta f\ L1-1, f\ h1(x) = \Delta f1,\ L\Delta f\ L1-1, f\ h2(x) = \Delta f3$. (19)

If the relative degree of Δf corresponding to the outputs $h1$ and $h2$ is 1, then the total relative degree of Δf will be 2, which will happen if $\Delta f1$ and $\Delta f3$ are not equal to zero. To match the uncertainty Δg, the relative degree of Δg should be equal to or greater than the relative degree of the nominal system and will be 2 if the following conditions hold:

$L\Delta gL1-1, f\ h1(x) = \Delta g11 \_= 0,\ L\Delta gL1-1, f\ h2(x) = \Delta g31 + \Delta g32 \_= 0$ (20)

where $\Delta g11$ must not be zero and either $\Delta g31$ or $\Delta g32$ can be zero, to match the uncertainty with the structure of the PV system. Since the proposed uncertainty modeling scheme considers the upper bound of the uncertainties, it is important to set these bounds, and the controller needs to be designed based on these bounds. If the maximum allowable changes in the system parameters is 30% and the variations in solar irradiation and environmental temperature are considered up to 80% of their nominal values, the upper bound of uncertainties Δf and Δg can be obtained as.

$$\Delta f(x) = \begin{bmatrix} -0.025\frac{R}{L}I_d + 0.6\omega I_q - 0.23\frac{E_d}{L} \\ -0.36\omega I_d - 0.042\frac{R}{L}I_q - 0.23\frac{E_q}{L} \\ 0.16\frac{1}{C}i_{pv} \end{bmatrix}$$

and

$$\Delta g(x) = \begin{bmatrix} 0.18\frac{v_{pv}}{L} & 0 \\ 0 & 0.18\frac{v_{pv}}{L} \\ -0.08\frac{I_d}{C} & -0.14\frac{I_q}{C} \end{bmatrix}.$$

The partial feedback linearizing scheme as presented in [18] cannot stabilize the PV system appropriate if the aforementioned uncertainties are considered within the PV system model as the controller is designed to stabilize only the nominal system. However, in the robust partial feedback linearizing scheme, the aforementioned uncertainties need to be included to achieve the robust stabilization of the grid-connected PV system.

V. ROBUST CONTROLLER DESIGN

This section aims the derivation of the robust control law that robustly stabilizes a grid-connected PV system with uncertainties whose structures are already discussed in the previous section. The following steps are followed to design the robust controller for a three-phase grid-connected PV system.

1) Step 1 (Partial feedback linearization of grid-connected PV systems): In this case, the feedback linearization for the system with uncertainties, as shown by (16), can be obtained as

$\dot{\bar{z}}1 = Lf\ h1(x) + L\Delta f\ h1(x) + [Lg1\ h1(x) + L\Delta g1\ h1(x)]u1 + [Lg2\ h1(x) + L\Delta g2\ h1(x)]u2$

$z2 = Lf\, h2\,(x) + L\Delta f\, h2\,(x) + [Lg1\, h2\,(x) + L\Delta g1\, h2\,(x)]u1 + [Lg2\, h2\,(x) + L\Delta g2\, h1\,(x)]u2$.

For the PV system, the partially linearized system can written as

$$\dot{\tilde{z}}_1 = -1.36\omega I_d - 1.042\frac{R}{L}I_q - 1.23\frac{E_q}{L} + 1.18\frac{v_{\mathrm{pv}}}{L}K_q$$
$$\dot{\tilde{z}}_2 = \frac{1.16}{C}i_{\mathrm{pv}} - \frac{1.08}{C}I_dK_d - \frac{1.14}{C}I_qK_q. \qquad (21)$$

If $v1$ and $v2$ are linear control inputs for the aforementioned partially feedback linearized system, (21) can be written as

$$v_1 = -1.36\omega I_d - 1.042\frac{R}{L}I_q - 1.23\frac{E_q}{L} + 1.18\frac{v_{\mathrm{pv}}}{L}K_q$$
$$v_2 = \frac{1.16}{C}i_{\mathrm{pv}} - \frac{1.08}{C}I_dK_d - \frac{1.14}{C}I_qK_q \qquad (22)$$

which can be obtained using any linear control technique, and in this paper, here we are using two PI controllers

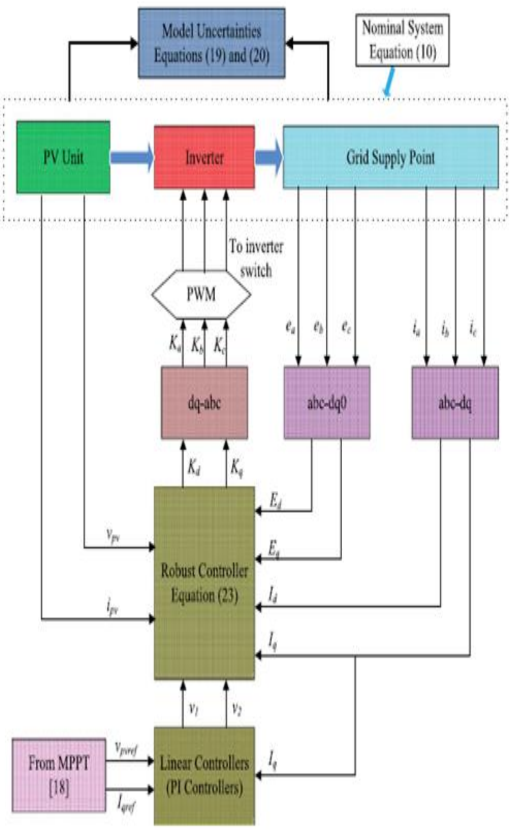

Fig. 4. Construction of block diagram.

before designing and implementing the controller based on partial feedback linearizing scheme, it is essential to check the stability of the internal dynamics that is similar to that described in

2) Step 2 (Derivation of robust control law):

From (22), the robust control law can be obtained as follows:

$$K_d = 0.85\frac{L}{v_{\mathrm{pv}}}\left(v_1 + 1.36\omega I_d + 1.042\frac{R}{L}I_q + 1.23\frac{E_q}{L}\right)$$
$$K_q = -0.88\frac{C}{I_q}\left[v_2 + 1.16\frac{i_{\mathrm{pv}}}{C} - 1.08\frac{I_d}{C}K_d\right]. \qquad (23)$$

Equation (23) is the final robust control law for a three grid connected PV system, and the modeled uncertainties are involved in control law. The main difference between the designed robust control law (23) and the control law (15) is the inclusion of uncertainties within the PV system model. The performance of the designed robust stabilization scheme is evaluated and compared in the following section with our previously published partial feedback linearizing scheme with no uncertainties [18]. The performance of the controller is evaluated in the following section.

VI. CONTROLLER PERFORMANCE EVALUATION

Since partial feedback linearizing controllers of system parameters are very sensitive , it is essential to have an exact system model in order to achieve good performance. However, for real life grid-connected PV systems, there often exist inevitable uncertainties within the constructed models. In addition, there exist uncertain parameters that are not exactly known or are difficult to estimate. Therefore, to evaluate the performance of the designed robust control scheme, it is essential to consider these uncertainties.The implementation block diagram of the proposed scheme is shown Fig. 4, in which the modeled uncertainties have been included with the nominal PV system model. From Fig. 4, it can also be seen that the three-phase grid voltages and currents are transformed into direct and quadrature axis components through $abc - dq$ transformation that is done to match with the proposed modeling presented in Section II. The

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designed scheme is the combination of linear PI controllers and the partial feedback linearizing scheme. Finally, the control inputs are again transformed into three-phase components using $dq - abc$ transformation to implement them through the inverter switches. To make the input signals suitable for switches, a PWM technique is used. The designed stabilization scheme is validated through the simulation and experimental results in the following sections.

A. Simulation Results

To evaluate the performance of the three-phase grid connected PV system with the designed robust controller, a PV array with 20 strings each characterized by a rated current of 2.8735 A is simulated using PSCAD. Each string is subdivided into 20 modules characterized by a rated voltage of 43.5 A and connected in series. The total output voltage of the PV array

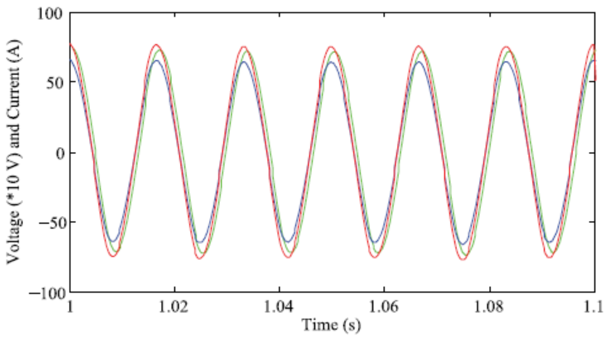

Fig. 5. Performance under standard atmospheric conditions (Blue line—grid voltage, red line—grid current with the RPFBLSS, and green line—grid current with the PFBLS).

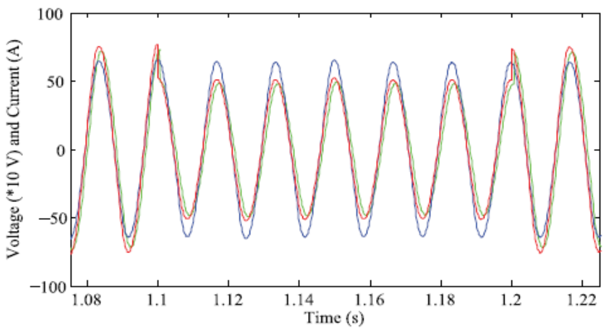

Fig. 6. Performance under changing atmospheric conditions (Blue line—grid voltage, red line-grid current with the RPFBLSS, and green line—grid current with the PFBLS).

1) Case 1 (Performance evaluation under standard atmospheric conditions):

In this case study, the standard values of the solar(PV) irradiation (1 kW−2) and environmental temperature (298 K) are considered. Since the main control objective is to inject maximum power (50 kW) into the grid, the designed robust control scheme must be able to deliver this power into the grid by considering some uncertainties into the parameters and states of the system. To achieve this, the grid current and voltages are in phase, which is already discussed in our previous work in [18]. However, with uncertainties, the voltage and current will not be in phase as the uncertainties are not considered with the technique proposed in [18]. In such situation, the designed robust controller ensures the operation of the three-phase grid-connected PV system at unity power factor that is shown in Fig.. (5) it can be seen the partial feedback linearizing scheme (PFBLS) is unable to transfer maximum power into the grid (green line) when 25% variations in the system parameters and 70% uncertainties in the solar irradiation and cell temperature are considered within the PV system

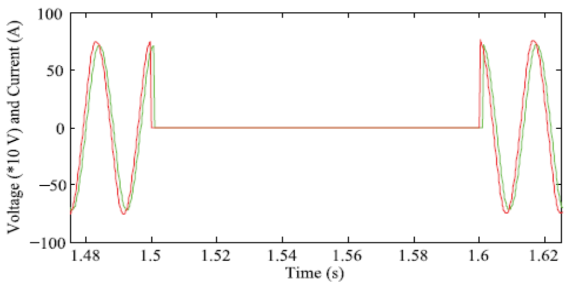

Fig. 7. Performance under a three-phase short-circuit fault (Red line—grid current with the RPFBLSS, and green line—grid current with the PFBLS).

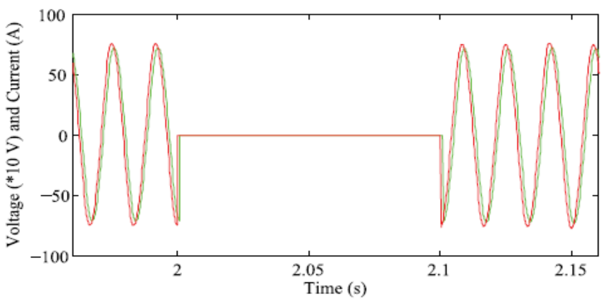

Fig. 8. Performance under a single-phase short-circuit fault (Red line—grid current with the RPFBLSS and green line—grid current with the PFBLS).

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model. However, the robust partial feedback linearizing stabilization scheme (RPFBLSS) maintains the operation of the system at unity power factor (red line).

2) Case 2 (Controller performance under changing atmospheric conditions):

At this stage, it is considered as solar unit operates under standard atmospheric conditions until 1 s. At t = 1 s, the atmospheric condition changes in such a way that the solar irradiation of the PV unit reduces to 70% from the standard value.

Under this situation, although the PFBLS is able to maintain the stability of the system but still there are some phase differences between the grid current and voltage, but with the RPFBLSS, there are no phase differences. Thus, the designed scheme performs well under a changing condition that is shown in Fig. 6 from where it can be seen that the PV unit operate under standard atmospheric condition up to 1.1 s and changing atmospheric conditions up to 1.2 s. After then, it operates under standard conditions, and the designed controller maintains the operation of the system at unity power factor.

3) Case 3 (Performance during short-circuit faults within the system):

A three-phase fault is the most severe disturbance in power system applications. In this simulation, a symmetrical three-phase fault is applied at the terminal of the PV unit, and the following fault sequence is considered to evaluate the robustness of the designed scheme: a) Fault occurs at t = 1.5 s. b) Fault is cleared at t = 1.6 s.

With this fault sequence, the performance of the PFBLS and RPFBLSS is shown in Fig. 7. In this case study, the pre fault and post fault conditions are considered as

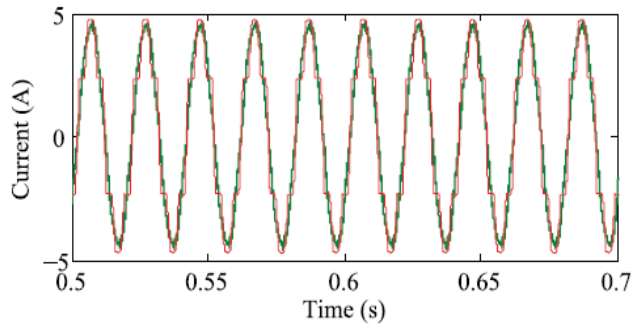

Fig. 10. Current injected into the grid under standard conditions (red line—current with the PI controller and green line—current with the proposed scheme).

the system is at normal operation at t = 0.92 s. These results ensure the operation of a three-phase grid-connected system at unity power factor.

VII. CONCLUSION

In this paper, a robust stabilization scheme is considered by modeling the uncertainties of a three-phase grid-connected solar system based on the satisfaction of matching conditions to ensure the operation of the system at unity power factor. In order to design the robust partial scheme, we are using partial feedback linearization approach, and with the designed scheme, only the upper bounds of the PV systems' parameters and states need to be known rather than network parameters and nature of the faults. The resulting robust scheme enhances the overall stability of a three-phase grid connected PV system, considering admissible network uncertainties. Thus, this stabilization scheme has good robustness against the PV system parameter variations, irrespective of the network parameters and configuration. Future work will include the implementation of the proposed scheme on a practical system.

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