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Robust Hybrid Control of Output Power for Three-Phase Grid Connected PV System

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ABSTRACT

In this paper, a new robust hybrid controller (RHC) is proposed to regulate current, voltage and, as a result, power output of a three-phase grid connected PV system. The creative process of the proposed controller consists of two steps. First, an input-output linearization method is used to eliminate system nonlinearities.Then, a robust PI controller is designed to reach the desired control objective. The robustness of PI is guaranteed by Lyapunov stability theory. Also, a maximum power point tracking (MPPT) algorithm is provided to adjust the PV output voltage for extracting MPP under various atmospheric conditions.To evaluate the performance of the proposed controller, different system conditions such as standard, considering uncertainties and three-phase short-circuit fault, are simulated and the results are compared with a feedback linearization controller (FLC). The results show superiority of the performance and robustness of the designed RHC versus various uncertainties such as solar irradiation and ambient temperature.

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I. Introduction

Due to increasing awareness of environmental issues and lack of fossil fuel reserves, the utilization of renewable energy resources has been widely growing. Among the available technologies, photovoltaic (PV) is recently being used more than ever due to technology progress and less battery cost [1]. This technology generation is highly dependent on atmospheric conditions, e.g. solar irradiation and ambient temperature. Thus, appropriate control methods have to be adopted to attain constant maximum power output. In [2]-[8], maximum power point tracking (MPPT) techniques were investigated to obtain maximum power generation under different operating conditions.In these papers, different algorithms are presented in order to maximize the output power of a PV system that perturbs andobserves, andincremental conductance methods are commonly adopted techniques for PV systems.

By designing an appropriate controller, PV system stability can be ensured against various uncertainties, such as changing atmospheric conditions and loads. In other words, with optimal system control, access to a safe, economical and reliable operation in power systems is possible [9]-[11].

In [12], a voltage controller was proposed based on a predictive model to improve inverter performance and lifetime. This method also improved the MPPT by reducing the DC link capacitance. Kadri et al. presented a modified voltage controller based on the proportional-integral (PI) controller behind the DC link capacitor [13]. The linear techniques presented in [12]-[13] were suitable for a single operating point. Since linear controllers are only acceptable in linearized systems in their operating conditions, they cannot be appropriate for nonlinear PV systems due to changes in solar irradiation and nonlinear inverter switching functions. As nonlinear PV system linear controllers affect all system variables and the PV source electrical characteristics are time-dependent, the system is not linearizable close to a

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unique operating point or trajectory to achieve good performance for different atmospheric conditions. Operating point restrictions are solvable by adopting nonlinear controllers for PV systems.

There are some intelligent techniques, e.g. the fuzzy method, which are able to solve for more complex operating points [14]-[16]. Also in [17], the particle swarm optimization (PSO) method was used to optimize the parameters of the controller for the islanded microgrid. Although the results indicated good performance of this controller, incorrect selection of the corresponding coefficients can lead to oscillatory and instability in the system. Also in [18], a PSO algorithm with the proposed cost function for island microgrid consisting of solar PV and battery unit was implemented to reduce power and frequency oscillations levels. By comparing to the results of PI-based inverter control, this control strategy improved the performance of the controller over the time domain specification and reduced overshoot of power level in the transient conditions; however, there was still a problem similar to [17] here.

In [19], a feedbacklinearization method was implemented for a reduced order PV system to control injection grid current and DC link capacitance voltage. Also, an accurate feedback linearization for a grid connected PV system has been proposed in [20]-[21] to achieve dynamic stability. The proposed controller is able to linearize the system, independent from atmospheric conditions. A sliding mode current controller is presented in [22]-[23] to reach maximum power point in a three-phase grid connected PV system to provide robustness considering uncertainties. The proposed controller is designed based on a variable-time sliding surface. However, choosing a variable-time surface is a difficult task and the system is limited to the sliding surface. Also in [24], the focus was on the control of islanded PV microgrid based on command-filtered backstepping and sliding mode control method in order to increase the robustness of the system. Checking the results showed that the system by the proposed controller had good dynamic characteristics and high power quality. However,it still had many complexities.

The main aim of this paper is to design an optimum robust control (ORC) with linearized feedback to control the grid injected current and DC link capacitance voltage considering uncertainties. As different uncertainties of distributed generation (DG) technologies, especially renewable solar energy, can lead to voltage, frequency and power fluctuations [25], the design of a suitable robust controller can increase system stability and reliability.

In [26], a robust power sharing controller designed for a multi-distributed energy resource (DER) microgrid consisting of PV units and wind turbine driven doubly fed induction generators. This controller utilizes multivariable H_∞ control that is robust to the changes in the system nonlinearities; instead, this controller is complex.

This paper is presented in five sections. The mathematical model of the investigated PV system is presented in Section 2. In Section 3, the proposed controller is designed based on input-output linearization (IOL) and ORC. The simulations conducted are presented in Section 4 and, finally, conclusions are given in Section 5.

II. The PV System Model

The PV system shown in Fig. 1 consists of a PV array, DC link capacitor, three phase inverter and an RL filter which connects the system to the main grid. The power generation of the PV system is not predictable and includes considerable volatility and fluctuation due to dependency on solar irradiation and ambient temperature. As the output power of PV systems is DC, converters are required to feed AC loads. The duty of these converters is to regulate the voltage, control the power and track the MPP (by determining the array reference voltage or current output) [27]. The main aim in this work is to control the grid injected current and DC link capacitance voltage by sending appropriate control switching signals to the inverter.

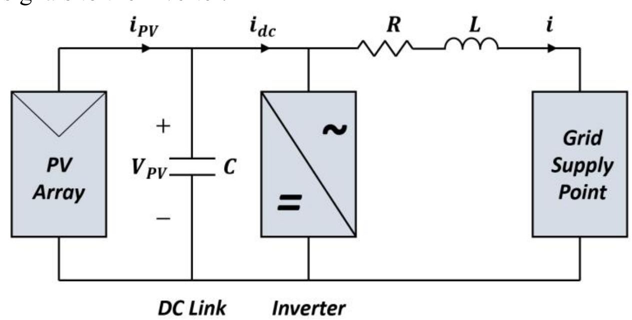

Fig. 1 The investigated PV system.

A. The PV Array Model

A PV array includes several modules, each module in turn containing several PV cells which are connected together in series and parallel. A PV cell is a semiconductor diode with its p-n junction illuminated. The output power generation depends on various factors like irradiation, the semiconductor absorption capacity and cell temperature. The equivalent dynamic model of a cell is presented in Fig. 2.

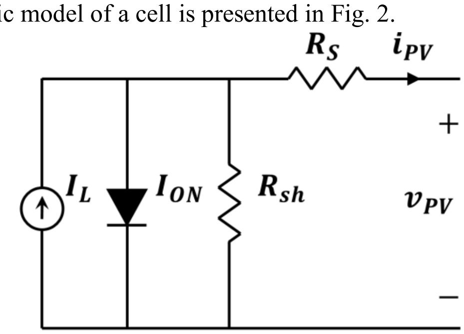

Fig. 2 The dynamic equivalent cell model.

In Fig. 2, R_s and R_{sh} are series and shunt resistance, respectively. I_L is a light-generated current source and I_{ON}

is the diode current, which can be expressed as follows [19]:

$$I_{ON} = I_s\left[\exp\left[\alpha\left(V_{pv} + R_s i_{pv}\right)\right] - 1\right] \quad (1)$$

$$\alpha = \frac{q}{AkT_C} \quad (2)$$

where I_s is the cell temperature-dependent saturation current, V_{pv} and i_{pv} are the PV array output voltage and current, respectively, q is the electrical charge, A is the connection ideality factor and$T_C$is the cell temperature. By applying Kirchhoff's' current law to the circuit in Fig. 2, i_{pv} can be expressed as Eq. (3).

$$i_{pv} = I_L - I_{ON} - \frac{V_{pv} + R_S . i_{pv}}{R_{sh}} \quad (3)$$

And the current induced due to irradiation, I_L, is [19]

$$I_L = [I_{SC} + k_i(T_C - T_{ref})]\frac{S}{1000} \quad (4)$$

where I_{SC}, T_{ref}, k_i and S are the short circuit current, cell reference temperature, cell short circuit current coefficient and solar irradiation, respectively.

Normally, a set of cells is connected in series to attain the required voltage. This set is called a module. To increase the output current of the module, the cells can be connected in parallel or their surface can be increased. A PV array consists of series and parallel connected modules. The output current of a PV array with N_s series and N_p parallel modules is presented in Eq. (5).

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

B. Grid Connected Three Phase PV System Model

The dynamic grid connected PV system model depicted in Fig. 1 is expressed in Eq. (6) using the d-q frame and the grid angular frequency [19].

$$\begin{cases} \dot{I}_d = -\frac{R}{L}I_d + \omega I_q - \frac{E_d}{L} + \frac{V_{pv}}{L}k_d \\ \dot{I}_q = -\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} + \frac{V_{pv}}{L}k_q \\ \dot{V}_{pv} = \frac{1}{C}i_{pv} - \frac{1}{C}I_d k_d - \frac{1}{C}I_q k_q \end{cases} \quad (6)$$

In the above relation, R, L and C are the connection line resistance, inductance of filter and connection line, and DC link capacitance, respectively. Also, I_d and I_q are the inverter output currents in d-q frame, E_d and E_q are grid voltages. K_d and K_q are inverter input switching signals in d-axis and q-axis, respectively. As seen in Eq. (6), the proposed model is nonlinear because of the switching and diode current functions.

The real power delivered to the grid by the PV system is presented in Eq. (7).

$$P = \frac{3}{2}\left(E_q I_q + E_d I_d\right) \quad (7)$$

In the rotational d-q frame, E_d can be considered to be zero [19] and Eq. (7) can be simplified in Eq. (8).

$$P = \frac{3}{2}E_q I_q \quad (8)$$

Thus, the real power can be controlled by controlling I_q.

III. Controller Design

A method to reduce computation effort for nonlinear systems is to eliminate some of the system nonlinearities while not affecting the simulation outcome. The method chosen in this work for this purpose is the IOL method.

A. PV System Input-Output Linearization

The nonlinear PV system equations are presented in Eqs. (9)-(14). [28]

$$\begin{cases} \dot{x} = f(x) + g(x)u + \Delta f(x) \\ y = h(x) \end{cases} \quad (9)$$

$$x = [I_d \quad I_q \quad V_{pv}]^T \quad (10)$$

$$f(x) = \frac{1}{L}\begin{bmatrix} -RI_d + \omega LI_q - E_d \\ -\omega LI_d - RI_q - E_q \\ \frac{L}{C}i_{pv} \end{bmatrix} \quad (11)$$

$$g(x) = \frac{1}{L}\begin{bmatrix} V_{pv} & 0 \\ 0 & V_{pv} \\ -\frac{L}{C}I_d & -\frac{L}{C}I_q \end{bmatrix} \quad (12)$$

$$u = [k_d \quad k_q]^T \quad (13)$$

$$h(x) = cx = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}x \quad (14)$$

In which x is the state variable, $f(x)$ is the system function, $g(x)$ and $h(x)$ are the input and output functions, respectively, u is the control input and $\Delta f(x)$ represents system uncertainties.

In the controller design process, $\Delta f(x)$ is first neglected and, then, accounted for. The IOL controller design is dependent on relative linearization degree of the studied system which, in turn, depends on the output function.

The IOL control design is introduced in three main steps [29]. First, y is differentiated and used as input vector in the output function Eq. (15) and, then, an appropriate u is chosen to eliminate nonlinearities and guarantee the tracking convergences, after which the system internal dynamics stability is studied.

The controller of the grid connected PV system is designed using zero dynamics. The conversion point and partial linearization are expressed by Eq. (15).

$$\dot{y} = c\dot{x} = cf(x) + cg(x)u \quad (15)$$

By assuming $g(x) \neq 0$ and $(x) = cg(x)$, the dynamic output of the PV system can be found.

The internal dynamic stability relation is determined and system nonlinearities are eliminated by defining appropriate u as follows:

$$u = M^{-1}(-cf(x) + v) \quad (16)$$

By adopting Eq. (16), the input-output relation is linearized and, by replacing this equation in Eq. (15), Eq. (17) is resulted.

$$\dot{y} = v \quad (17)$$

where v is a linear controller which is defined as Eq. (18).

$$v = (K_P + \frac{K_I}{S})(y_{ref} - y) \quad (18)$$

The coefficients of the PI controller which is robust against uncertainties are introduced in Eqs. (19)-(20).

$$K_P = \begin{bmatrix} K_{P_1} & 0 \\ 0 & K_{P_2} \end{bmatrix} \quad (19)$$

$$K_I = \begin{bmatrix} K_{I_1} & 0 \\ 0 & K_{I_2} \end{bmatrix} \quad (20)$$

Later, in ORC design, matrices K_P and K_I are designed to be robust against uncertainties. Now, the third-order grid connected PV system is transformed into a second order system representing external dynamic stability. A suitable controller can result in a reasonable external dynamic. If the system order is larger than the relative degree, the nonlinear system controller is practically dependent on the internal system dynamics. This dynamic stability can locally be simplified by considering zero dynamics. As the controller that is designed in step two converges by tending I_q and V_{PV} to $I_{q_{ref}}$ and $V_{PV_{ref}}$, respectively, it is clear that I_d would be the system zero dynamic. Thus, I_d dynamics can be presented as Eq. (21) to investigate the system stability.

$$\dot{I}_d = -\frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} + \frac{V_{pv}}{L}\frac{L}{V_{pv}}\left(v_1 + \omega I_d + \frac{R}{L} I_q + \frac{E_q}{L}\right) \quad (21)$$

Since the values of I_q, V_{PV} and E_d are bounded by the stability of I_d, it is clear that the zero dynamic remains bounded; therefore, the system would be stable. According to Eq. (17), the system control law can be defined as:

$$\begin{cases} \dot{I}_q = v_1 \\ \dot{V}_{pv} = v_2 \end{cases} \quad (22)$$

Using Eq. (6) and Eq. (22), the controller switching signals are expressed as Eqs. (23)-(24):

$$k_d = \frac{L}{V_{PV}}\left(v_1 + \omega I_d + \frac{R}{L} I_q + \frac{E_q}{L}\right) \quad (23)$$

$$k_q = -\frac{C}{I_q}\left(v_2 - \frac{1}{C} i_{PV} + \frac{I_d}{C} K_d\right) \quad (24)$$

B. Optimized Robust Controller

To introduce nonlinear uncertainties in the investigated three phase PV system, the below relations can be defined [28]:

$$\dot{x} = f(x) + g(x)u + \Delta f(x) \quad (25)$$

where $\Delta f(x) = g(x) \cdot \rho(x)$ is system dynamic uncertainties. Thus, it is assumed that $x = 0$ is an equilibrium point and the uncertainty function $\rho(x)$ is always less than or equal to a non-negative function ρ_{max}, as shown in Eq. (26).

$$\|\rho(x)\| \le \rho_{max}(x) \quad (26)$$

The main uncertainties of PVs are solar irradiation and ambient temperature that affect i_{pv} and V_{PV}, for which the relations are presented in Eqs. (27)-(28).

$$i_{pv} = i_{pv0} + \Delta i_{pv} \quad (27)$$

$$\dot{V}_{pv} = \frac{1}{C}\Delta i_{pv} + v_2 \quad (28)$$

where Δi_{pv} is the uncertainty as feedback linearization is adopted. The controller design bound is defined in Eq. (29).

$$\|\Delta i_{pv}\| \le L\|V_{pv}\| \quad (29)$$

Note that, the uncertainty of PV output current, $\frac{1}{C}\Delta i_{pv}$, is due to changes in solar irradiation and temperature. The bound L is obtained by ± 800 W/m^2 in solar irradiation and ± 5 ℃ in temperature. On the other hand, the uncertainty of the output current affects V_{PV} according to Eq. (6). Thus, $\frac{1}{C}\Delta i_{pv}$ is included in the voltage equation and is not dependent on the I_q equation. Therefore, optimal values of coefficients K_P and K_I are obtained by Eq. (30) in the I_q controller design.

$$\begin{cases} K_{P_1} = 2I_{q_{ref}} \\ K_{I_1} = I_{q_{ref}}^2 \end{cases} \quad (30)$$

So the closed loop poles are located at $-I_{q_{ref}}$, which is associated with the fastest case without overshoot.

To determine PI controller coefficients for V_{PV}, the robust control method must be used. First, a state space form is proposed for voltage control loop as Fig. 3 by Eq. (31)

$$\begin{bmatrix} \dot{q} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} q \\ e \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} v + \begin{bmatrix} 0 \\ -\frac{1}{C}\Delta i_{pv} \end{bmatrix} \quad (31)$$

where,

$$e = V_{pv_{ref}} - V_{pv} \quad (32)$$

$$q = \int e \quad (33)$$

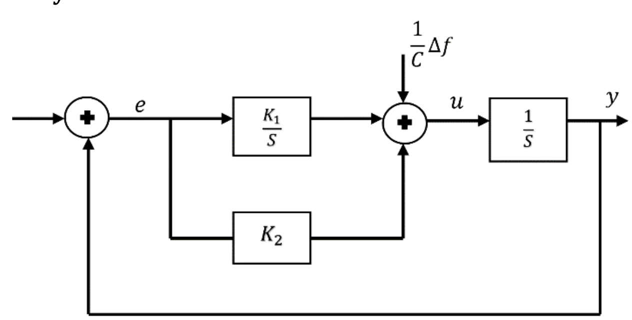

Fig. 3 ORC system block diagram.

So the control law can be written as $u = -[K_{I_2} K_{P_2}][q\ e]^T$. Let us consider the Lyapunov function as follows [28]:

$$E = e^2 + q^2 + (\frac{L}{C}e)^2 + u^2 \quad (34)$$

It can be simply be shown that $\dot{E} = -(e^2 + q^2)$ if $[K_{I_2} K_{P_2}] = [0\ 1]P$, where P is obtained by solving the following Riccati equation [28].

$$\begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} P + P \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} + + \begin{bmatrix} 0 \\ \frac{-L}{C} \end{bmatrix} \begin{bmatrix} 0 & \frac{-L}{C} \end{bmatrix} = P \begin{bmatrix} 0 \\ 1 \end{bmatrix} [0\ 1] P \quad (35)$$

IV. Maximum Power Point Tracking Algorithm

The PV output power which is the multiplication of voltage and current is dependent on atmospheric conditions, i.e. solar irradiation and temperature. The default PV output voltage is set for normal atmospheric conditions, but it changes as solar irradiation and ambient temperature vary. Thus, to attain maximum PV output power, an MPPT algorithm has to be applied to set the output voltage. Based on the MPPT concept, the derivative of the output power is zero at the MPP, positive on the left and negative on the right of the MPP, i.e.

$$\begin{cases} \frac{dP_{pv}}{dV_{pv}} = 0, \text{at MPP} \\ \frac{dP_{pv}}{dV_{pv}} < 0, right\ of\ MPP \\ \frac{dP_{pv}}{dV_{pv}} > 0, left\ of\ MPP \end{cases} \quad (36)$$

The PV output power and its derivative to output voltage are given by Eqs. (37)-(38), respectively.

$$P_{pv} = V_{pv} i_{pv} \quad (37)$$

$$\frac{dP_{pv}}{dv_{pv}} = V_{pv}\Delta i_{pv} + i_{pv}\Delta V_{pv} \quad (38)$$

By setting Eq. (38) equal to zero according to Eq. (36), the following equation is obtained:

$$\begin{cases} \frac{\Delta i_{pv}}{\Delta V_{pv}} = -\frac{i_{pv}}{V_{pv}}, \text{at MPP} \\ \frac{\Delta i_{pv}}{\Delta V_{pv}} < -\frac{i_{pv}}{V_{pv}}, \text{right of MPP} \\ \frac{\Delta i_{pv}}{\Delta V_{pv}} > -\frac{i_{pv}}{V_{pv}}, \text{left of MPP} \end{cases} \quad (39)$$

The PV reference voltage changes in accordance with the MPP condition as expressed in Eq. (40).

$$\begin{cases} V_{PV_{new,ref}} = V_{pv_{old,ref}}, \quad \text{at MPP} \\ V_{PV_{new,ref}} = V_{pv_{old,ref}} + \Delta V, \text{right of MPP} \\ V_{PV_{new,ref}} = V_{pv_{old,ref}} - \Delta V, \text{left of MPP} \end{cases} \quad (40)$$

where ΔV is the reference voltage step. Similarly, by replacing Eq. (8) in Eq. (37), $I_{q_{ref}}$ is obtained as Eq. (41).

$$I_{q_{ref}} = \frac{2}{3}\frac{P_{pv_{ref}}}{E_q} \quad (41)$$

V. Simulation Results

The investigated PV system, consisting of a PV array with nominal output current and voltage equal to 54 A and 870 V, respectively, DC link capacitor equal to 400 µF, 0.1 Ω line resistance an inductance equal to 10 mH corresponding to the system equivalent inductance, and a three phase inverter with 10 kHz switching frequency is connected to a 50 Hz, 660 V and 50 kW microgrid.

Initially, the study is performed for standard atmospheric conditions, i.e. 1000 W/m² irradiation and 20℃ ambient temperature. The comparison of output voltage of PV system for the proposed robust hybrid controller (RHC) and feedback linearization controller (FLC) is presented in Fig. 4. It is clear that, for standard atmospheric conditions, this controller has low overshoot, good performance, and quickly converges to the reference value. The control signal of phase a, using proposed controller is presented in Fig. 5. Grid current and output power of the PV system, for similar conditions, are shown in Figs. 6 and 7, respectively. The figures indicate that the designed RHC has a perfect and stable performance and track the reference values well for standard atmospheric conditions.

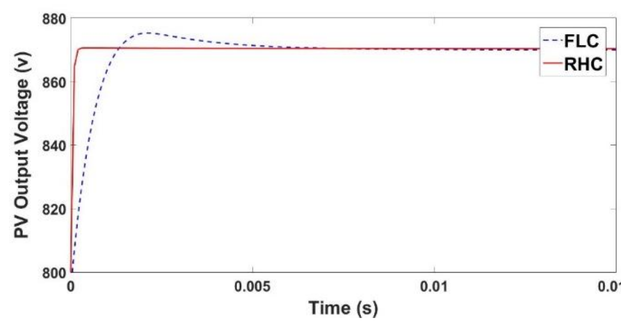

Fig. 4 Comparison of PV output voltage for the two controllers in standard atmospheric conditions.

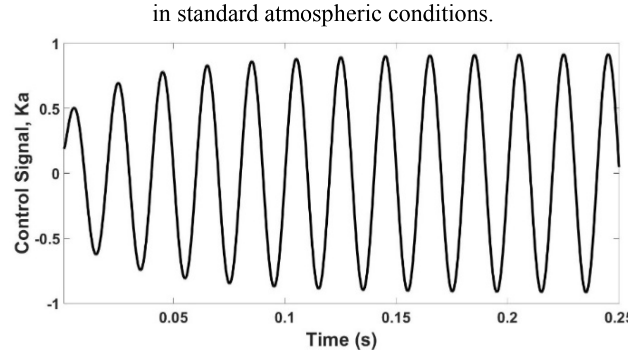

Fig. 5 Control signal in phase a, Ka, for the RHC in standard atmospheric conditions.

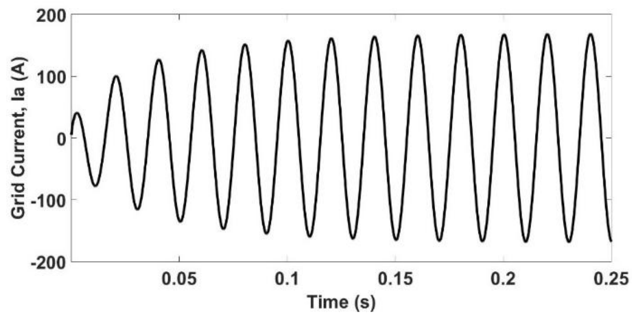

Fig. 6 Grid current of phase a, for the RHC in standard atmospheric conditions.

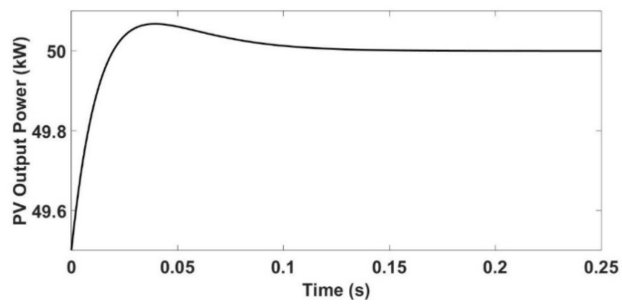

Fig. 7 PV output power for the RHC in standard atmospheric conditions.

In the second scenario uncertainty is defined by increasing the irradiation from 1000 to 1400 W/m^2 at 0.1 s and again decreases and remain at 1000 W/m^2 at 0.2s. The comparison of PV output voltage between the proposed controller and FLC is shown in Fig. 8. It is again seen that the RHC has less overshoot. It is also noticeable that the proposed controller is tracking the reference value properly.

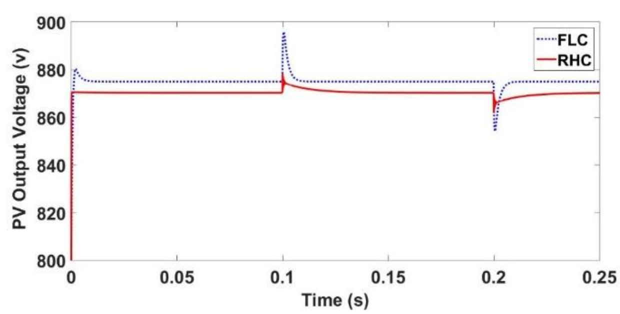

Fig. 8 Comparison of PV output voltage for the two controllers by considering uncertainties (change in irradiation).

Similarly, in the third scenario, ambient temperature increases by 2℃ at 0.1 s and, again, decreases and remains at its previous value at 0.2 s. As is seen in Fig. 9, the proposed RHC is slightly better than the FLC in controlling the PV system output voltage in terms of response time and overshoot. Below and in the fourth scenario, it is assumed that weather is cloudy and irradiation is decreased from 1000 to 600 W/m^2 and ambient temperature decreases by 1℃ in 0.1s. The control signal of the inverter in phase a, by considering these uncertainties, is shown in Fig. 10. Also, comparison of grid current of phase a for the two controllers by considering change in irradiation and ambient temperature as uncertainties is shown in Fig. 11. It is observed that the RHC is robust against uncertainties and this controller has better performance than FLC.

For the last scenario and in order to evaluate the performance of the designed controller, a three-phase short-circuit fault is applied to the bus at 0.1 s and cleared at 0.2 s. Grid voltage and current of phase a, for the designed RHC, are shown in Figs. 12 and 13. It is concluded that the performance of the proposed controller for PV system is more suitable than for three-phase short-circuit faults.

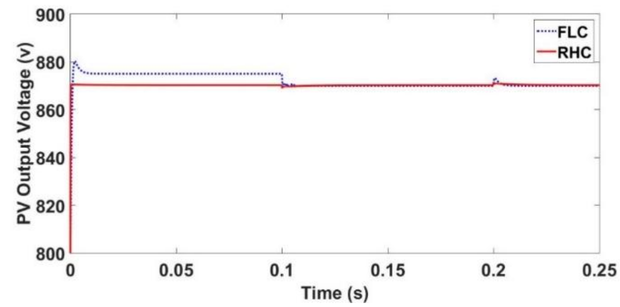

Fig. 9 Comparison of PV output voltage for the two controllers by considering uncertainties (change in ambient temperature).

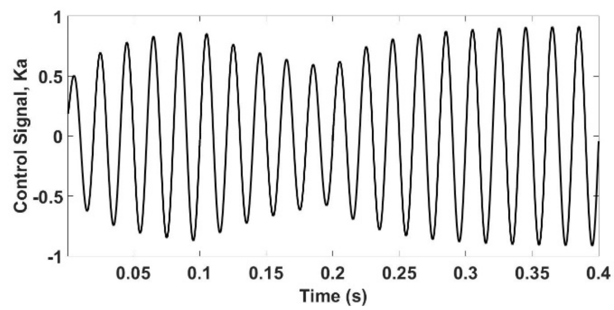

Fig. 10 Control signal in phase a, Ka, for the RHC by considering uncertainties (change in irradiation and ambient temperature).

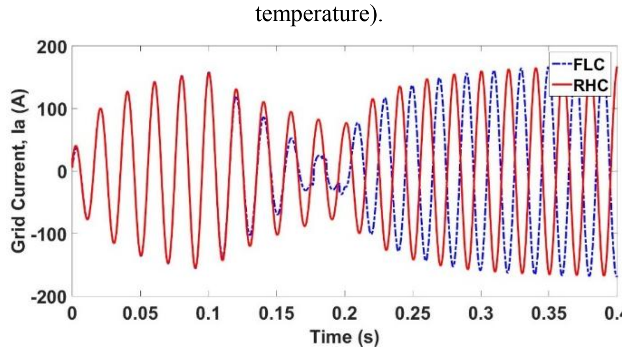

Fig. 11 Comparison of grid current of phase a for the two controllers by considering uncertainties (change in irradiation and ambient temperature).

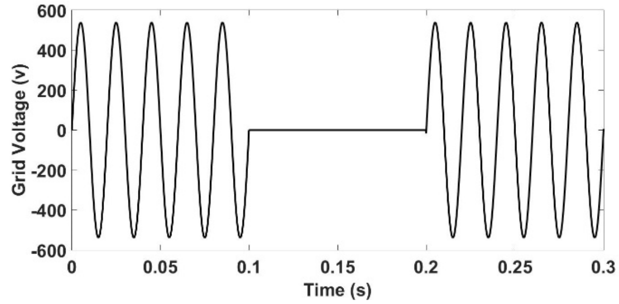

Fig. 12 Grid voltage in phase a, $\boldsymbol{E_a}$, for the RHC during three-phase short-circuit fault.

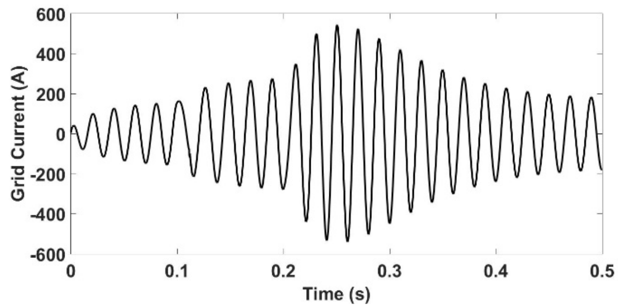

Fig. 13 Grid current in phase a, $\boldsymbol{I_a}$, for the RHC during three-phase short-circuit fault.

VI. Conclusions

As environmental considerations are made, photovoltaic systems emerge as one of the main green renewable energy generation resources in areas prone to solar irradiation. As these systems are nonlinearly affected by environmental parameters, such as irradiation and ambient temperature, a nonlinear RHC for a grid connected three-phase PV system has been proposed. By the aforementioned method, first, IOL was adopted to cancel system nonlinearities. Then a robust PI controller was implemented to increase system robustness against uncertainties, e.g. solar irradiation and ambient temperature deviations. To maximize the power output the MPPT algorithm was adopted where the PV system output voltage is regulated to track the reference voltage. The performance of the designed controller was evaluated for different scenarios; with standard conditions as the base case and considering uncertainties for the other cases. It was observed that the proposed controller had a faster response time, less overshoot, and was suitably robust and stable as uncertainties were considered. Also, the proposed controller showed of acceptable and proper performance under a three-phase short-circuit fault. In future work, the proposed method will be extended to deal with large interconnected systems considering communication delays.

References

[1] E. Planas, J. Andreu, J. I. Garate, I. Martinez de Algeria, and E. Ibarra, "AC and DC technology in microgrids: A review", *Renewable and Sustainable Energy Reviews*, Vol. 43, pp. 726-749, 2015.

[2] I. Houssamo, F. Locment, and M. Sechilariu, "Maximum power tracking for photovoltaic power system: Development and experimental comparison of two algorithms," *Renewable Energy*, Vol. 35, no. 10, pp. 2381-2387, 2010.

[3] M. Rakhshan, N. Vafamand, M.H. Khooban and F. Blaabjerg, "Maximum power point tracking control of photovoltaic systems: A polynomial fuzzy model-based approach", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, Vol. 6, no. 1, pp.292-299, 2018.

[4] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, Vol. 22, no. 2, pp. 439-449, 2007.

[5] M.A.M. Ramli, S. Twaha, K. Ishaque, and Y.A. Al-Turki, "A review on maximum power point tracking for photovoltaic systems with and without shading conditions," *Renewable and Sustainable Energy Reviews*, no. 67, pp. 144-159, 2017.

[6] M.F.N. Tajuddin, M.S. Arif, S.M. Ayob, and Z. Salam, "Perturbative methods for maximum power point tracking (MPPT) of photovoltaic (PV) systems: a review," *International Journal of Energy Research*, Vol. 39, no. 9, pp. 1153-1178, 2015.

[7] L. Chun-xia and L. Li-qun, "An improved perturbation and observation MPPT method of photovoltaic generate system," In 2009 4th IEEE Conference on Industrial Electronics and Applications 2009 May 25, pp. 2966-2970, 2009.

[8] P. Farhadi, M. Sedaghat, Sh. Sharifi, "Power point tracking in photovoltaic systems by sliding mode control", Advanced Topics in Electrical Engineering (ATEE), 2017 10th International Symposium on pp. 781-785.

[9] J. M. Guerrero, P. C. Loh, T. L. Lee, and M. Chandorkar, "Advanced control architectures for intelligent microgrids - part II: power quality, energy storage and AC/DC microgrids," *IEEE Transactions on industrial electronics*, Vol. 60, no. 4, pp. 1263-1270, 2013.

[10] C. Sun, G. Joos and F. Bouffard, "Control of microgrids with distributed energy storage operating in Islanded mode". In Electrical Power and Energy Conference (EPEC), 2017 Oct 22, pp. 1-7, 2017.

[11] L. F. Ochoa and G. P. Harrison, "Minimizing energy losses: Optimal accommodation and smart operation of renewable distributed generation," *IEEE Transactions on Power Systems*, Vol. 26, no.1, pp. 198-205, 2011.

[12] F. He, Z. Zhao, T. Lu, and L. Yuan. "Predictive DC voltage control for three-phase grid-connected PV inverters based on energy balance modeling," In The 2nd International Symposium on Power Electronics for Distributed Generation Systems, pp. 516-519, 2010.

[13] R. Kadri, J. P. Gaubert, and G. Champenois, "An improved maximum power point tracking for photovoltaic grid-connected inverter based on voltage-oriented control," *IEEE Transactions on Industrial Electronics*, Vol. 58, no. 1, pp. 66-75, 2011.

[14] I. H. Atlas and A. M. Sharaf, "A novel maximum power fuzzy logic controller for photovoltaic solar energy

systems," *Renewable Energy*, Vol. 33 no.3, pp. 388-399, 2008.

[15] O. Abednia, M. Bekravi and N. Ghadimi, "Intelligent controller based wide-area control in power system." *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, Vol. 25, No. 1, pp. 1-30, 2017.

[16] A. Messai, A. Mellit, A. Guessoum, and S. A. Kalogirou, "Maximum power point tracking using a GA optimized fuzzy logic controller and its FPGA implementation," *Solar Energy*, Vol. 85, no. 2, pp. 265-277, 2011.

[17] M. AhmadiKamarposht, "Optimal Control of Islanded Micro grid Using Particle Swarm Optimization Algorithm," *International Journal of Industrial Electronics*, Control and Optimization, Vol. 1, no. 1, pp. 53-60, 2018.

[18] A Vinayagam , A. A Alqumsan, K.S.V Swarna, S. Y Khoo, "Intelligent control strategy in the islanded network of a solar PV microgrid", *Electric Power Systems*, Vol. 155, pp. 93- 103, 2018.

[19] M. A. Mahmud, H. R. 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.

[20] A. O. Zue and A. Chandra, "State feedback linearization control of a grid connected photovoltaic interface with MPPTs, "in Proc. *IEEE Electr. Power Energy Conf.*, 2009, pp. 1-6.

[21] D. Lalili, A. Mellit, N. Lourci, B. Medjahed, and E. M. Berkouk, "Input output feedback linearization control and variable step size MPPT algorithm of a grid-connected photovoltaic inverter," *Renewable Energy,*Vol. 36, no. 12, pp. 3282-3291, 2011.

[22] I. S. Kim, Il-Song, "Sliding mode controller for the single-phase grid-connected photovoltaic system," *Applied Energy*, Vol. 83, no. 10, pp. 1101-1115, 2006.

[23] I. S. Kim, "Robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system," *Solar Energy*, Vol. 81, no. 3, pp. 405-414, 2007.

[24] D. Xu, Y. Dai, Ch. Yang, and X. Yan, " Adaptive Fuzzy Sliding Mode Command-Filtered Backstepping Control for Islanded PV Microgrid with Energy Storage System," *Journal of the Franklin Institute*, Elsevier, Vol. 356, no. 4, pp. 1880-1898, 2019.

[25] M.A. Mahmud, H.R. Pota, M.J. Hossain, and N.K. Roy, "Robust partial feedback linearizing stabilization scheme for three-phase grid-connected photovoltaic systems," IEEE *Journal of Photovoltaics*, Vol. 4, no. 1, 2014.

[26] M. J. Hossain, H.R. Pota, M.A. Mahmud, and M. Aldeen, "Robust Control for Power Sharing in Micrograms With Low-Inertia Wind and PV Generators ", *IEEE Transaction on Sustainable Energy*, Vol. 6, no. 3, pp. 1067-1077, 2015.

[27] Y. A. R. I. Mohamad, *New control algorithms for the distributed generation interface in grid-connected and micro-grid systems*, Ph.D. thesis, University of Waterloo, 2008.

[28] F. Lin, *Robust control design: an optimal control approach*, Vol. 18, John Wiley & Sons, 2007.

[29] J. J. E. Slotine, and W. Li. *Applied nonlinear control*. Englewood Cliffs, NJ: Prentice hall; 1991 Jan.

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