Nonlinear Observer-Based Control for Three phase Grid Connected Photovoltaic System

Hicham Bahri, Khadija Oualifi, Mohamed Aboulfatah, M’hammed Guisser, Oluwaseun Simon Adekanle, Mohammed El Malah
Department of Applied Physics
University hassan I
ASTI Laboratory
Morocco
hbahri.inf@gmail.com

Abstract: - This paper presents a nonlinear observer-based control strategy for a photovoltaic system. This last consists of a photovoltaic generator PVG coupled to a three phase load and three phase grid by a three phase voltage source inverter VSI without DC-DC converter. The controller is developed by using Backstepping method based on d-q transformation of a new model of the global system. Then, to minimize the number of sensors used for the implantation of the controller, a nonlinear state observer is proposed for estimate the inverter current. The main objectives of this control strategy are to extract maximum power from the PV array with very good effectiveness and to achieve the unity power factor and low harmonic distortion in the level of the grid power flow. The simulation results proved that the observer-based control method has been achieved all the objectives with high dynamic performance under different operating conditions such as atmospheric conditions changes and system disturbance.

Key-Words: - Voltage source Inverter; Maximum Power Point; Unity power factor; Photovoltaic Generator; Power Conversion Harmonics; Pulse Width Modulation Converters; Reactive Power compensation; Nonlinear load; Bakstepping; State observer.

1 Introduction
The Global Energy demand is increasing due to Technological development, Industrial growth and rising population density [1]. At the same time, pollution from the use of fossil fuels urges for a need to find an alternate source of energy. In this way, photovoltaic energy is one of the most important sources of renewable energy, and the photovoltaic system is one of the most important energy solutions; the energy generated by photovoltaic system represents a large part of the total amount of solar energy produced [2]. We find two types of photovoltaic systems, the autonomous system and grid connected photovoltaic system. The grid-connected PV system is becoming more used to meet global demand for electrical energy [3].

This paper presents an advanced control strategy using Backstepping method and nonlinear state observer of a three phase grid single stage connected photovoltaic system feeding non-linear load. The main objectives of this observer-based control are:

- Minimizing the number of the sensors used in the global PV system
- Extracting maximum output power from the PV array.
- Operation with a unity power factor UPF and low harmonic distortion.
- Controlling the power flow between the grid and the rest of grid connected PV system.

There are some research efforts to realize these goals [3]-[5]. The above works have not been able to achieve these objectives with a good performance and they haven’t considered all the constraints of the photovoltaic system. Moreover, these researches don’t try to minimize the number of sensors used in the implementation of the controller which have some effects. Indeed, the integration of large number of both voltage and current sensors decreases the controller efficiency and increases system complexity, cost, space, and reduces system reliability. Hence, the necessity of using an observer in the control loops to complete the information about the state variables. A few works have been realized in order to reduce the current sensors for older categories of PV system [6], [7], [8]. The work presented in [8] proposed a simplify method to control a single-phase single-stage grid-connected PV inverter with a low number of sensors. The direct MPPT developed in this work has been achieved the MPPT with a best efficiency than the performance of the controller developed in [9 10 11 12]. But the work proposed by [8] presents also some drawbacks. Indeed, the controlled PV system track the MPPT with bad response time more than 2s and it oscillates around the PVG MPP. This fact is not normal, because the system output PV power can’t exceed the normal MPP of the PVG. Furthermore, the research described in [8] don’t try to achieve the UPF; Knowing that in single stage PV grid connected system the MPPT...
and UPF must be controlled simultaneously, a task that is quite complex[13]. So, we can see that the work [8] is limited and incomplete even if the experimentation validation has been carried out.

In this paper the nonlinear state observer is proposed to minimize the number of sensors used by the Backstepping controller. This observer is designed to directly estimate the dq0 transformation components of the inverter current [14]. That permits to eliminate the inverter current sensor and the dq0 transformation block applied to convert the three phase current to double phase current. The elimination of this sensor reduces de complexity of the global PV system installation and enhances the robustness of the Backstepping controller in front of noise measurement. Furthermore, this control strategy can operate independently of sensor calibration and accuracy failures, data acquisition and processing errors.

The elaborated state observer has correctly estimated the inverter current with a very good precision and fast response time less than the dynamic behavior variation of the system. Using the information generated by the observer, the Backstepping controller has achieved the MPPT with very good performances during sudden atmospheric conditions changes. The observer-based control has controlled also the inverter to compensate with a good precision the reactive power caused by the load, which assures the unity power factor operation of the system. Moreover, this strategy has demonstrated a very good robustness in the presence of the system disturbance. Mathematical analyses and simulation results have proved the high performance of this control strategy. The rest of the paper is organized as follows: the system description and mathematical model of the global system are present in Section II. The controller design for the global system is illustrated in Section III. In Section IV, a high gain state observer is developed to estimate the inverter current. Section V shows the simulation results.

Finally, a short conclusion will be presented.

2 System Description and Modelling

Fig. 1 shows a PVG connected to the grid. It consists of a PVG coupled to a three phase grid by an input capacitor \( C_p \), Voltage Source Inverter VSI and low pass filter \((L, r)\). Moreover, a three phase load is also coupled to the system; this load can be supplied by the PVG power if it is sufficient, if it isn’t enough the load will be supplied by the PVG and the grid. But when there is no sunlight, the load will be provided by the grid and the inverter will just compensate the Reactive Power caused by this load. The input capacitor \( C_p \) is used to store the energy extracted from the PVG and smooth the inverter input voltage ripple. The filter is integrated to filter out harmonic distortion provoked by the inverter switching.

The elaborated state observer has correctly estimated the inverter current with a very good precision and fast response time less than the dynamic behavior variation of the system. Using the information generated by the observer, the Backstepping controller has achieved the MPPT with very good performances during sudden atmospheric conditions changes. The observer-based control has controlled also the inverter to compensate with a good precision the reactive power caused by the load, which assures the unity power factor operation of the system. Moreover, this strategy has demonstrated a very good robustness in the presence of the system disturbance. Mathematical analyses and simulation results have proved the high performance of this control strategy. The rest of the paper is organized as follows: the system description and mathematical model of the global system are present in Section II. The controller design for the global system is illustrated in Section III. In Section IV, a high gain state observer is developed to estimate the inverter current. Section V shows the simulation results.

Finally, a short conclusion will be presented.

2 System Description and Modelling

Fig. 1 shows a PVG connected to the three phase grid and nonlinear load. The PVG power equation is given by:

\[ P_v = v_p \times i_p \] (1)

Where \( v_p \) and \( i_p \) are the PVG voltage and current respectively.

The mathematical model of the global system is given by:

\[
\begin{align*}
\frac{dv_p}{dt} &= \frac{1}{C_p} P_v - \frac{1}{C_p} P_i \\
\frac{di_d}{dt} &= -\frac{r}{L} i_d - \frac{1}{L} e_a + \frac{1}{L} v_a \\
\frac{di_b}{dt} &= -\frac{r}{L} i_b - \frac{1}{L} e_b + \frac{1}{L} v_b \\
\frac{di_c}{dt} &= -\frac{r}{L} i_c - \frac{1}{L} e_c + \frac{1}{L} v_c
\end{align*}
\] (2)

Where \( P_i \) is the inverter Active Power, \((i_d, i_b, i_c)\) and \((v_a, v_b, v_c)\) are the inverter currents and voltages, \((v_a, v_b, v_c)\) represents also the PWM references of the inverter, \((e_a, e_b, e_c)\) are the three grid voltages, \( C_p \) is the input capacitor, \( L \) is the filter’s inductance and \( r \) is the filter’s resistance.

The model of the global system in the park axes is given by the following equation:

\[
\begin{align*}
\frac{dv_a}{dt} &= v_p - \frac{1}{C_p} P_v - \frac{1}{C_p} P_i - \frac{2}{3} E_d i_d \\
\frac{di_d}{dt} &= -\frac{r}{L} i_d + w i_q - \frac{1}{L} E_d - \frac{1}{L} v_d \\
\frac{di_q}{dt} &= -\frac{1}{L} i_q + w i_d - \frac{1}{L} E_q - \frac{1}{L} v_q
\end{align*}
\] (3)

Where:

\[
\begin{align*}
E_d &= p_{dq0}^{abc} (e_a, e_b, e_c) i_d \\
E_q &= p_{dq0}^{abc} (e_a, e_b, e_c) i_q
\end{align*}
\]

\((i_d, i_q)\). \((v_a, v_q)\) and \((E_d, E_q)\) are respectively the coordinates in the d-q axis of the inverter current, the PWM references and the grid voltages, \( w \) is the grid pulsation. With \( p_{dq0}^{abc} \) is the Park transformation matrix which is given below [14]:

\[
p_{dq0}^{abc} = \frac{2}{3}
\begin{pmatrix}
\sin(0) & \sin(0 - \frac{2\pi}{3}) & \sin(0 - \frac{4\pi}{3}) \\
\cos(0) & \cos(0 - \frac{2\pi}{3}) & \cos(0 - \frac{4\pi}{3}) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{pmatrix}
\] (4)
0 represents the phase angle of the grid calculated by the PLL technique [15].

After having modelled the system, the next section will illustrate the design of the control strategy.

3 Nonlinear observer and Control Strategy

3.1 Nonlinear State Observer Design

To estimate unmeasured state variables or replace high priced sensors the observers are designed. An observer can estimate also the full state using knowledge of the available measurements output and input of the system. In this work, the nonlinear observer is used to estimate the d-q components of the inverter current \( I_d, I_q \).

The model of the global system in the Park axes (3) can be represented in a general form which belong to the class of state affine systems uniformly observable allowing the synthesis of the state observer [16], [17], [18], [19], [20].

The global system (5) can be represented in a general form which is defined by:

\[
\dot{Z} = A(U)Z + \varphi(U, s) - S
\]

Where:

\[
A = \begin{pmatrix}
0 & -\frac{1}{C_p^2}E_d & 0 \\
0 & 0 & w \\
0 & 0 & 0
\end{pmatrix}
\]

\[
\varphi(x, U, s) = \varphi(x, U, s)
\]

And:

\[
C = [1 \quad 0 \quad 0], \quad A = \begin{pmatrix}
0 & -\frac{1}{C_p^2}E_d & 0 \\
0 & 0 & w \\
0 & 0 & 0
\end{pmatrix}
\]

\[
\varphi(x, U, s) \text{ is a locally Lipschitz function [20].}
\]

The control input \( U \) is assumed to be regularly persistent [21].

The following form is estimating states by the high-gain nonlinear observer:

\[
\begin{cases}
\dot{\hat{x}} = A(U)\hat{x} + \varphi(\hat{x}, U, s) - S^{-1}C^T(\hat{y}_m - y_m) \\
\dot{S} = -\beta S - A^T(U)S - SA(U) + C^TC \quad (7)
\end{cases}
\]

Where:

\[
S \text{ is symmetric positive definite matrix and a solution of the differential Lyapunov equation, } \beta \text{ is the setting parameter of the observer which must be positive and sufficiently large, } \hat{x} = (\hat{Z}, \hat{I}_d, \hat{I}_q) \text{ is the estimation of the full state vector.}
\]

Applying this observer method the estimation error \( \hat{y}_m - y_m \) converge exponentially to zero in function of the setting parameter value \( \beta \) which means that the estimation vector \( \hat{x} \) tracks with a good effectiveness the real state vector of the PV system if \( \beta \) is sufficiently large. \( \hat{x} \) will be used by the Backstepping control laws developed after.

3.2 Nonlinear observer based control strategy

The control strategy has been design by the Backstepping method [22] in order to realize the following objectives under climatic condition changes and system perturbation with a very good performance and high robustness:

- Extract maximum output power from the PVG and convert all this power on Active Power.
- Compensate Reactive Power and harmonic distortion caused by any kind of load.

3.2.1 MPPT and Active Power Controller

The output selected to control the MPPT is the derivative of the PVG power with respect to the PVG voltage. Its form is defined by:

\[
\frac{\partial P_v}{\partial V_p} = i_p + v_p \frac{\partial i_p}{\partial V_p} \quad (8)
\]

This output must converge to zero in order to extract the MPP from the PVG with a very good precision [23], [24].

The Backstepping control of the first output is designed as follows:

Defining the first tracking error between the output and its reference as:
\[
\epsilon_1 = \delta_p + \partial_p = 0 = I_p + v_p \frac{\partial i_p}{\partial p} \tag{9}
\]

Using model (3), the derivative of \(\epsilon_1\) can be developed as:
\[
\dot{\epsilon}_1 = (2 \frac{\partial i_p}{\partial p} + v_p \frac{\partial^2 i_p}{\partial p^2}) \left( \frac{1}{c_p} \frac{p_v}{c_v} - \frac{1}{c_p} \frac{1}{c_p} \frac{1}{c_v} E_d \right) \tag{10}
\]

The candidate Lyapunov function is chosen as:
\[
V_1 = \frac{1}{2} \epsilon_1^2 \tag{11}
\]

Its derivative is as follows:
\[
\dot{V}_1 = \epsilon_1 \dot{\epsilon}_1 = \epsilon_1 \left( 2 \frac{\partial i_p}{\partial p} + v_p \frac{\partial^2 i_p}{\partial p^2} \right) \left( \frac{1}{c_p} \frac{p_v}{c_v} - \frac{1}{c_p} \frac{1}{c_p} \frac{1}{c_v} E_d \right) \tag{12}
\]

This derivative must be negative. For that a virtual control law \(\alpha\) is chosen to get the following equation:
\[
\alpha = (I_d) \text{desired} \tag{13}
\]

Where:
\[
\alpha = \left( I_d - \frac{1}{c_p} \frac{p_v}{c_v} \right) \tag{14}
\]

\(k_1\) is a positive setting parameter of the controller.

Using equation (13), the expression of \(\alpha\) is developed as:
\[
\dot{\alpha} = -\frac{1}{c_p} \frac{p_v}{c_v} \left( \frac{1}{c_p} \frac{p_v}{c_v} - \frac{1}{c_p} \frac{1}{c_p} \frac{1}{c_v} E_d \right) \tag{15}
\]

Its derivative is calculated as follows:
\[
\dot{\dot{\alpha}} = -\frac{1}{c_p} \frac{p_v}{c_v} \left( \frac{1}{c_p} \frac{p_v}{c_v} - \frac{1}{c_p} \frac{1}{c_p} \frac{1}{c_v} E_d \right) \tag{16}
\]

With the above choice, the derivative of the Lyapunov function becomes necessarily negative. Its expression is given by using (12), (13) and (14):
\[
V_1 = -k_1 \epsilon_1^2 \tag{17}
\]

Equation (15) assumes that the virtual control law \(\alpha\) is equal to the estimated direct current component \(I_d\). Moreover, in reality there is an error between them. This error is defined as:
\[
\epsilon_2 = I_d - \alpha \tag{18}
\]

So,
\[
I_d = \epsilon_2 + \alpha \tag{19}
\]

Substituting (19) in (12) and using (13), the novel expression of \(V_1\) is given by:
\[
\dot{V}_1 = -k_1 \epsilon_1^2 - \left( 2 \frac{\partial i_p}{\partial p} + v_p \frac{\partial^2 i_p}{\partial p^2} \right) \left( \frac{1}{c_p} \frac{p_v}{c_v} \right) E_d \epsilon_1 \epsilon_2 \tag{20}
\]

Therefore, \(\dot{V}_1\) is no longer necessarily negative. For that a second Lyapunov function is proposed which is defined by:
\[
V_2 = V_1 + \frac{1}{2} \epsilon_2^2 \tag{21}
\]

Its derivative is given by:
\[
\dot{V}_2 = \dot{V}_1 + \epsilon_2 \dot{\epsilon}_2 \tag{22}
\]

By using (19), the derivative of \(\epsilon_2\) is given by:
\[
\dot{\epsilon}_2 = I_d - \alpha = -\frac{1}{c_p} \frac{p_v}{c_v} + w i_q - \frac{1}{c_p} E_d + \frac{1}{c_p} V_d - \dot{\alpha} \tag{23}
\]

Substituting (20) and (23) in (22) the final expression of \(\dot{V}_2\) is as follows:
\[
\dot{V}_2 = -k_1 \epsilon_1^2 - \left( 2 \frac{\partial i_p}{\partial p} + v_p \frac{\partial^2 i_p}{\partial p^2} \right) \left( \frac{1}{c_p} \frac{p_v}{c_v} \right) E_d \epsilon_1 + \left( -\frac{1}{c_p} \frac{p_v}{c_v} + w i_q - \frac{1}{c_p} E_d + \frac{1}{c_p} V_d - \dot{\alpha} \right) \epsilon_2 \tag{24}
\]

In order to stabilize \(\epsilon_1\) and \(\epsilon_2\) to zero, \(\dot{V}_2\) must be strictly negative. For this reason, the following equality is imposed:
\[
-\left( 2 \frac{\partial i_p}{\partial p} + v_p \frac{\partial^2 i_p}{\partial p^2} \right) \left( \frac{1}{c_p} \frac{p_v}{c_v} \right) E_d \epsilon_1 + \left( -\frac{1}{c_p} \frac{p_v}{c_v} + w i_q - \frac{1}{c_p} E_d + \frac{1}{c_p} V_d - \dot{\alpha} \right) \epsilon_2 = -k_2 \epsilon_2 \tag{25}
\]

Where \(k_2\) is a positive control parameter.

By substituting (25) into (24), the desired form of \(\dot{V}_2\) is obtained as:
\[
\dot{V}_2 = -k_1 \epsilon_1^2 - k_2 \epsilon_2^2 \tag{26}
\]

Using (25) and replacing the d-q components of the inverter current \((I_d, I_q)\) with their estimated values \((I_d, I_q)\), the expression of real control law which guarantees the desired form of \(\dot{V}_2\) is as follows:
\[
\dot{V}_d = L \left[ -k_2 \epsilon_2^2 + \left( 2 \frac{\partial i_p}{\partial p} + v_p \frac{\partial^2 i_p}{\partial p^2} \right) \left( \frac{1}{c_p} \frac{p_v}{c_v} \right) E_d \epsilon_1 - \left( -\frac{1}{c_p} \frac{p_v}{c_v} + w i_q - \frac{1}{c_p} E_d - \dot{\alpha} \right) \right] \tag{27}
\]

By applying this control law, \(\dot{V}_2\) become obligatorily strictly negative and \(\epsilon_2\) converge asymptotically to zero, which guarantees the pursuit of the MPP with a very good precision and fast response time. Moreover, the input voltage is
constant; consequently all the PVG power will be converted by the inverter to active power which means that the Active Power delivered by the inverter is maximized.

In this part, the maximization of the inverter Active Power output has been realized; the next part consists of controlling the inverter Reactive Power.

### 3.2.2 Reactive Power Controller

The objective in this subsection is to compensate the Reactive Power and harmonic distortion caused by the load, in order to achieve the Unity Power Factor in the level of the power exchange between the grid and the PVG system. For that, the inverter must inject Reactive Power caused by the load, in order to compensate the Reactive Power and harmonic developed as:

\[
PVG \rightarrow -\frac{1}{L} I_q - w L d - \frac{1}{L} E_q + \frac{1}{L} V_q - I_{qref} = -k_3 \varepsilon_3
\]  

(36)

With \(k_3\) is a positive setting parameter.

Therefore, the new expression of \(V_3\) is given by using (35) and (36) as follows:

\[
V_3 = -k_3 \varepsilon_3^2
\]  

(37)

Therefore, \(V_3\) is negative.

By using (36) and introducing estimated values \((I_d, I_q)\) of the d-q components of the inverter current \((I_d, I_q)\), the control law \(V_q\) is given by:

\[
V_q = L \left[ -k_3 \varepsilon_3 + \frac{w}{L} I_d + \frac{1}{L} E_q + \frac{1}{L} I_{qref} \right]
\]  

(38)

The quadratic control law \(V_q\) forces the Lyapunov function \(\dot{V}_3\) to be negative and the tracking error \(\varepsilon_3\) to converge to zero, which guarantees the asymptotic convergence of the quadratic component estimates \(I_q\) to its reference \(I_{qref}\). Finally, the Reactive Power and harmonic component caused by the load have been compensated with a very good performance.

The fig. 2 illustrates the block diagram of the PV system with the High-gain nonlinear observer and the Backstepping controller.

---

**Fig.2.** Block diagram of the PV system and the nonlinear observer based Backstepping controller.

The PWM references \(R_p\), \(R_r\) and \(R_n\) are generated by the inverse dq0 transformation of the control laws \(V_d\) and \(V_q\). The PWM outputs \(\mu_1\), \(\mu_2\) and \(\mu_3\) are used to generate the switching signals of the inverter \(G_{1+}, G_{2+}, G_{3+}\) able to achieve the controller objectives with a very good efficiency.

Where:
μi=1..3 = \begin{cases} 1 \rightarrow G_i^+ : \text{on}; S_i^- : \text{off} \\ 0 \rightarrow S_i^+ : \text{off}; S_i^- : \text{on} \end{cases}

All the performances of the nonlinear observer-based Backstepping controller will be illustrated in the next section by using the simulation results under MATLAB/SIMULINK.

4 Simulation Results and Analysis
In order to verify the performance and robustness of the proposed observer and control strategy, a PVG system and the nonlinear observer based Backstepping control is built in Simulink/Matlab. The parameters of both the PV system and the observer-based controller are summarized in Table 1. The scenarios used in this simulation are shown in Figure 3. It considers a solar irradiation changes from 600W/m$^2$ to 100W/m$^2$ at 0.5s and from 100 W/m$^2$ to 1000W/m$^2$ at 1s. It considers also a temperature changes from 25°C to 50°C at 1.5s. At 2s the disturbance of the input capacitor $C_p$ by 40% of its nominal value is introduced. In the end of the scenarios, the load current harmonic pollution by 6% of its fundamental value is applied from 2.5s to 3s.

The maximum power of the simulated PVG is about 55,94KW under the standard atmospheric conditions.

The nonlinear load can be any kind of load; In fact, the observer based Backstepping controller is designed independently of the kind of load. In this simulation we considered an inductive load.

Table 1: The parameters of the PV system and the controller

<table>
<thead>
<tr>
<th>System Parameters</th>
<th>Controller and observer parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input capacity: $C_p$=4700 $\mu$F</td>
<td>$k_1$=50, $k_2$=5000</td>
</tr>
<tr>
<td>Filter inductance: $L$=3 mH</td>
<td>$k_3$=1100</td>
</tr>
<tr>
<td>Filter resistance: $r$=0.002Ω</td>
<td></td>
</tr>
<tr>
<td>Load inductance: $L_c$=20 mH</td>
<td>PWM frequency: 10 KHz</td>
</tr>
<tr>
<td>Load resistance: $R_c$=10Ω</td>
<td></td>
</tr>
<tr>
<td>Grid voltage: 380V</td>
<td>$\theta=50000$</td>
</tr>
<tr>
<td>Grid frequency: 50 Hz</td>
<td></td>
</tr>
</tbody>
</table>

The curve of the second output $l_q$ is shown in fig. 12. It converges very quickly to its reference with very good precision. This realization compensates the harmonic distortion and Reactive Power caused by the load under any condition as shown in fig. 13. From fig. 14 it’s clear that the Reactive Power in the level of grid power flow is null.

Fig. 15, fig. 16 and fig. 17 show the high performances of the UPF achievement under atmospheric condition changes, system parameters disturbance and load current harmonic pollution. Indeed, the grid current is in phase with the grid voltage during the simulation conditions.
Fig. 3. Simulation scenarios.

Fig. 4. Real and estimated voltage.

Fig. 5. Real and estimated direct component of the inverter current.

Fig. 6. Real and estimated quadratic component of the inverter current.

Fig. 7. The inverter PWM references.

Fig. 8. The curve of the derivative of the PVG power with respect to PVG voltage $\frac{\delta P}{\delta v}$.

Fig. 9. MPPT achievement under the scenarios conditions.

Fig. 10. The behavior of the inverter Active Power in function of the fast variation of the PVG power.

Fig. 11. Active Power exchanges between the inverter, the grid and the load.
4 Conclusion
This paper presented a nonlinear observer-based control strategy for a three phase load and grid connected PV system. The nonlinear observer proposed in order to estimate the inverter current allows to minimize the number of sensors used in the PV installation, which decreases mainly system cost and reduces instability of the controller by elimination of measurement noise. A Backstepping method based on Lyapunov stability approach and dq0 transformation of the PV system model is employed to design the controller. The main focus of this control strategy is to achieve the UPF and MPPT under different conditions by controlling the power switches of DC/AC inverter. The best advantage of this controller with less sensors is its robustness in the presence of system disturbance and abrupt climatic condition changes. Mathematical studied has been demonstrated the Lyapunov stability of the global system and simulation results proved that the proposed control strategy has realized the MPPT and the UPF with a very good precision and fast response time in presence of any operation conditions, which demonstrates the Efficiency and robustness of this strategy. The next step will be devoted to experimental validation of the nonlinear observer-based controller.

References:


