The Organizing Committee of the *International Congress on Energy and Environment Engineering and Management* certifies that

H. Gholami-Khesht

M. Monfared

Made in this congress the Oral presentation of the work with title

*Adaptive Predictive-DPC for a Grid Connected Low-Cost PV Generator*

The reference of the work is RE009.

Anabela de Sousa Oliveira

Vice-President of the Organizing Committee

Paris, 24th July 2015
Adaptive Predictive-DPC for a Grid Connected Low-Cost PV Generator

H. Gholami-Khesht, M. Monfared *

Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
gholami.hosien@yahoo.com, *corresponding m.monfared@um.ac.ir, +985138805017

1. Introduction – Pulse-width modulated (PWM) voltage source converters (VSCs) with various control strategies are used as PV inverters. Recently, methods based on predictive control have become of great interest due to various advantages they offer, the main being superior dynamic behavior, simple structure and concepts and ease of implementation and accordance to inherent discrete nature of power electronic converters. In this study, an augmented discrete model for the VSC is derived, based on which, an improved deadbeat-DPC scheme for the grid connected PWM-VSC which utilizes the adaptive observer in its structure is proposed. The proposed structure is depicted in Fig. 1. States and input disturbances are estimated by using full order adaptive observer in next sampling period and then by using the system model, the converter reference voltage is selected so that the power errors become zero in the end of the two next sampling periods. It provides the sensorless operation of the converter by eliminating the filter current sensor, that reduces the inverter cost and helps compensate for uncertainties by one step ahead estimation of parameters and un-modeled dynamics.

2. Results and Discussion - The performance of the proposed method is confirmed by extensive simulation tests as shown in Fig.2. Simulation results confirm the excellent performance of the proposed method in steady state and dynamic conditions under a wide range of parameter uncertainties.

3. Conclusions - This paper attempts to improve the performance of predictive-DPC by combining the deadbeat control theory with the full order adaptive observer. The most important advantages of the proposed control method are: good dynamic and steady-state performance, decoupled active and reactive power control, simple structure and concepts and ease to digital implementation, proper compensation for delays of digital implementation, robustness to parameter uncertainties, un-modeled dynamics and other disturbances and reduced cost, size and improved reliability of the system, which are consequences of eliminating the current sensors.

Fig. 1. Single line diagram of proposed control method

Fig. 2. Start-up and transient performance of the proposed adaptive P-DPC

(c) Injected active and reactive powers at PCC
(b) Three-phase output currents (Injected currents at PCC)
(a) Three-phase output voltages (Three-phase voltages at PCC)
Adaptive Predictive-DPC for a Grid Connected Low-Cost PV Generator

Hosein Gholami-Khesht (1), Mohammad Monfared (1)

(1) Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.
gholami.hosien@yahoo.com, m.monfared@um.ac.ir

1. Introduction – Nowadays, the clean energy sources, such as sun and wind are more attractive because of global concerns about the environmental pollution, as well as running down the conventional energy sources [1-2]. The energy produced by a renewable source must be injected into the electric grid, according to pre-established quality and reliability standards [2]. In distributed power generation plants such as photovoltaic and wind turbine systems, the pulse-width modulated (PWM) voltage source converters (VSCs) are responsible to accomplish these requirements [1-9]. Consequently, in order to achieve better results, various control strategies to control the grid connected PWM-VSCs are already proposed, such as voltage oriented control (VOC) [2-3], proportional-resonant (PR) current control [4] and direct power control (DPC) [5-7]. Recently, methods based on the predictive control (such as deadbeat control and finite control set model predictive control (FCS-MPC)) [5-9] have become of great interest due to various advantages they offer, the main being superior dynamic behavior, simple structure and concept and ease of implementation and accordance to inherent discrete nature of power electronic converter systems. In spite of these advantages, the performance is sensitive to system parameter uncertainties and in practice, the delay of digital control system deteriorates the performance and may even result in instability.

In this paper and in order to alleviate the problems of steady-state error and poor stability, originated from parameters uncertainties and control delays a novel predictive controller is proposed. To this end, firstly a detailed (augmented) discrete model of the converter system is derived. Based on the augmented state-space model, an adaptive predictive-DPC scheme for the grid connected PWM-VSC is proposed, which utilizes the adaptive observer in its structure. States and input disturbances are estimated by using a full order adaptive observer for the next sampling period and then by using the system model, the appropriate converter reference voltage is selected, so that the power errors become zero at the end of the two next sampling periods (Image 1).

Other major advantages of using the adaptive observer in the proposed control scheme are: I) sensorless operation of the converter by eliminating the filter current sensors and II) compensation of uncertainties and un-modeled dynamics by one step ahead estimation of them.

Finally, the performance of the proposed method is confirmed by extensive simulation tests. The results confirm the excellent performance of the proposed method in steady-state and dynamic conditions.
2. System modelling - The simplified structure of the grid connected three-phase PWM VSC considered in this study is shown in Image 1, which includes the power grid, the LC-type smoothing filter, the six IGBT switches PWM-VSC and the DC link capacitors. In this section, an augmented discrete state-space model is derived. Using the nominal system parameters and considering the inverter current \( i \) as a dynamic disturbance, the system dynamics can be written as follows:

\[
\frac{dx(t)}{dt} = Ax(t) + Bu(t) + Dw(t)
\]

where

\[
x = [i_v, v_o]^T, u = [w_1, w_2]^T = [(r_n + \Delta r_i)(i_v - i) + \Delta L \frac{di_v}{dt} - (L_n + \Delta L) \frac{di_v}{dt} + n_1]
\]

\[
x = -i + \Delta C \frac{dv_o}{dt} + n_2
\]

\[
A = \begin{bmatrix} 0 & -1 \\ -1 & C_n \end{bmatrix}, B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, D = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}
\]

and, \( v, v_o, i_v, i, \) and \( i \) are the converter voltage, output voltage (voltage at PCC), inverter current, grid current and capacitor current, respectively. Also, \( C, L \) and \( r_i \) are filter capacitance, inductance and equivalent series resistance, respectively. In addition, symbols "\( n \)" and "\( \Delta \)" denote the nominal values and the deviations from the nominal values, respectively. Also, \( n_1 \) and \( n_2 \) represent other uncertainties due to un-modeled dynamics. As seen in (1), in the augmented model, all uncertainties caused by parameter mismatches, inverter current disturbances and un-modeled dynamics are all lumped in \( n(t) \) as a disturbance input to the system.

Practical implementation of the predictive control algorithm is based on a discrete state-space model of the plant dynamics. Discretizing (1) with the sampling period \( T_s \), yields the following discrete state-space equations [9]:

\[
\begin{align*}
x(k+1) &= A_p x(k) + B_p u(k) + D_p w(k) \\
A_p &= L^p [sI - A]^p \approx I + AT_s, B_p = \int_0^{T_s} A_p(T_s - \tau) B d\tau \approx BT_s, D_p = \int_0^{T_s} A_p(T_s - \tau) D d\tau \approx DT_s
\end{align*}
\]  

(2)

3. Robust predictive power controller - The developed adaptive predictive-DPC scheme is based on the two step deadbeat control. In each sampling period, the required converter voltage for the next control period is computed from the predictions provided by the augmented state space model and the reference powers. The optimal converter voltage is then applied at the start of the next sampling period. Consequently, a whole sampling period is available to perform all calculations and the control delays due to the computations are compensated.

The proposed predictive-DPC is based on the two-sample ahead predicted powers that can be expressed as:

\[
S(k+2) = p(k+2) + jq(k+2) = v_o(k+2) i_v(k+2)^*(*) = \text{conjugate}
\]  

(3)

where, \( S(k+2), v_o(k+2) \) and \( i_v(k+2) \) are the complex power at the beginning of the \((k+2)\)th sampling period (that must be controlled during the \((k+1)\)th period), predicted output voltage and output current that can be calculated from (2) as follows:

\[
x(k+1) = A_p x(k+1) + B_p u(k+1) + D_p w(k+1)
\]  

(4)

In the above equations, \( x(k+1) \) is estimated from the augmented model (2) based on the measured signals at instant \( k \), i.e. \( x(k) \).

Finally, by substituting (4) into (3) and replacing \( S(k+2) \) with the reference powers at the next sampling period \( (S_{ref}(k+1)) \) and performing some simple manipulations, the required converter voltage can be obtained as:

\[
v_{ref} (k+1) = (-\alpha \beta i_v(k+1) + \beta i_v(k+1) - \alpha \beta v_v(k+1))^2 \times (S_{ref}(k+1) - S(k+1) - \alpha \beta S(k+1)^2 + \alpha i_v(k+1)^2)
\]

(5)
where, $\alpha = \frac{T_s}{C}, \beta = \frac{T_s}{L}$ and $S(k + 1) = v_c(k + 1)i_c(k + 1)^*$ is calculated from the outputs of the augmented model (2).

4. **Disturbance estimation based on the adaptive observer**

As obvious from (2), the augmented state space model assumes that the disturbance input $w(k)$ is known. This section presents a simple technique for online estimation of the disturbance input by using an adaptive observer and with a low computational burden. Based on the augmented model (2), a simple adaptive observer can be formed as follows [10]:

$$
\begin{align*}
\hat{x}(k + 1) &= A_x x(k) + B_x u(k) + D_x \hat{w}(k) \\
\hat{w}(k + 1) &= \hat{w}(k) + \lambda D_x e
\end{align*}
$$

where $\hat{x}(k + 1)$ is the output of the adaptive observer, $\hat{w}$ is the estimated disturbance input and $\lambda$ is a positive adaptation gain, which its value is a compromise between the rate of the convergence and the system stability. Too large value for $\lambda$ causes overshoot or in the worst case instability and also, too small value gives a low convergence rate and high computational burden. Therefore adaptive gain selection has an important impact on the adaptive observer stability and efficiency.

5. **Results** — The performance of the proposed method is confirmed by extensive simulation tests as shown in Images. 3 and 4. These images confirm the sinusoidal current generation and fast and decoupled power control at PCC of the proposed control technique and also, successful performance of the proposed adaptive observer under start-up and transient conditions. It is worth pointing out that these perfect results are obtained under a wide range of parameter uncertainties ($\Delta C = +%50, \Delta L = -%50$), which verify the good robustness of the proposed method.

6. **Conclusions** — This paper suggests improving the performance of the predictive-DPC by combining the predictive control theory with the full order adaptive observer. The most important advantages of the proposed control method are: I) good dynamic and steady-state performance, II) decoupled active and reactive power control, III) simple structure and concept and convenient for digital implementation, IV) proper compensation of delays, V) robustness to parameter uncertainties, un-modeled dynamics and other disturbances, VI) constant switching frequency, VII) no need for coordinate transformations and any PLL, VIII) reduced cost, size and improved reliability of the system, which are consequences of eliminating the current sensors.

7. **References:**


**Image 3.** Start-up and transient performance of the proposed adaptive predictive-DPC.

(a) Outputs of adaptive observer (voltage and current at PCC)
(b) Estimated disturbance input

**Image 4.** Performance of the adaptive observer under start-up and transient conditions.