Introduction to the model-free control of microgrids

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Abstract
This letter presents the application of the model-free control approach to the microgrid control. We show in simulation that the method allows to control, with a simple controller, voltage, current and power of inverter-based microgrids.
1 Introduction

The model-free control methodology, originally proposed by [1], has been widely successfully applied to many mechanical and electrical processes. The model-free control provides good performances in disturbances rejection and an efficient robustness to the process internal changes. The control of inverter-based microgrids has been deeply studied and some advanced methods have been successfully developed and tested (e.g. [3] [4] [5]). A preliminary work in power electronics [2] presents the successful application of the model-free control method to the control of dc/dc converters. This paper extends the previous results to the control of inverter-based microgrids in different situations relating to the islanded and grid-connected modes. In particular, we will show that the proposed control method is robust to strong load changes either in voltage, current or power control. Simulations have been performed using the averaging method [6] with $\Sigma \Phi - PES^{*}$ [7].

The paper is structured as follows. Section II presents an overview of the model-free control methodology including its advantages in comparison with classical methodologies. Section III discusses the application of the model-free control to inverters. Some concluding remarks may be found in Section IV.

2 Model-free control: a brief overview

2.1 General principles

2.1.1 The ultra-local model

We only assume that the plant behavior is well approximated in its operational range by a system of ordinary differential equations, which might be highly nonlinear and time-varying. The system, which is SISO, may be therefore described by the input-output equation

$$E(t, y, \dot{y}, \ldots, y^{(\kappa)}, u, \dot{u}, \ldots, u^{(\kappa)}) = 0$$

where

- $u$ and $y$ are the input and output variables,
- $E$, which might be unknown, is assumed to be a sufficiently smooth function of its arguments.

*\$\Sigma \Phi - PES$ is a complete simulation platform that allows to perform co-simulation with C-written / GNU Bison algorithms and SPICE OPUS; this software is particularly useful to simulate control law and power circuits whose topologies may switch during the simulation.

$\dagger$A new version that allows to drive SPICE OPUS under Matlab® has been released.

$\ddagger$See [1, 8] for further details.
Assume that for some integer \( n, 0 < n \leq \iota \), \( \frac{\partial E}{\partial y^{(n)}} \neq 0 \). From the implicit function theorem we may write locally
\[
y^{(n)} = \mathcal{E}(t, y, \dot{y}, \ldots, y^{(n-1)}, y^{(n+1)}, \ldots, y^{(\iota)}, u, \dot{u}, \ldots, u^{(\kappa)})
\]
By setting \( \mathcal{E} = F + \alpha u \) we obtain the ultra-local model.

**Definition 2.1** [1] If \( u \) and \( y \) are respectively the variables of input and output of a system to be controlled, then this system admits the ultra-local model defined by:
\[
y^{(n)} = F + \alpha u
\]
where
- \( \alpha \in \mathbb{R} \) is a non-physical constant parameter, such that \( F \) and \( \alpha u \) are of the same magnitude;
- the numerical value of \( F \), which contains the whole "structural information", is determined thanks to the knowledge of \( u, \alpha \), and of the estimate of the derivative \( y^{(n)} \).

In all the numerous known examples it was possible to set \( n = 1 \) or 2.

### 2.1.2 Numerical value of \( \alpha \)

Let us emphasize that one only needs to give an approximate numerical value to \( \alpha \). It would be meaningless to refer to a precise value of this parameter.

### 2.2 Intelligent PI controllers

#### 2.2.1 Generalities

**Definition 2.2** [1] If \( n = 1 \), we close the loop via the intelligent PI controller, or i-PI controller,
\[
u = -\frac{F}{\alpha} + \frac{\dot{y}^*}{\alpha} + C(\varepsilon)
\]
where
- \( y^* \) is the output reference trajectory, which is determined via the rules of flatness-based control ([9, 10]);
- \( e = y^* - y \) is the tracking error;
- \( C(\varepsilon) \) is of the form \( K_P \varepsilon + K_I \int \varepsilon \). \( K_P, K_I \) are the usual tuning gains.

Equation (3) is called model-free control law or model-free law.

The i-PI controller is compensating the poorly known term \( F \). Controlling the system therefore boils down to the control of a precise and elementary pure integrator. The tuning of the gains \( K_P \) and \( K_I \) becomes therefore quite straightforward.
2.2.2 Classic controllers

See [11] for a comparison with classic PI controllers.

2.2.3 Applications

See [12, 13, 14, 15, 16, 17, 18, 2] for already existing applications in various domains.

2.3 Numerical differentiation of noisy signals

Numerical differentiation, which is a classic field of investigation in engineering and in applied mathematics, is a key ingredient for implementing the feedback loop 3. Our solution has already played an important role in model-based nonlinear control and in signal processing (see [19] for further details and related references).

The estimate of the 1st order derivative of a noisy signal \( y \) reads (see, e.g., [20])

\[
\hat{\dot{y}} = -\frac{3!}{T^3} \int_0^T (T - 2t) y(t) dt
\]

where \([0,T]\) is a quite “short” time window. This window is sliding in order to get this estimate at each time instant.

Denoising of \( y \) leads to the estimate

\[
\hat{y} = \frac{2!}{T^2} \int_0^T (2T - 3t) y(t) dt
\]

The above results are the basis of our estimation techniques. Important theoretical developments, which are of utmost importance for the computer implementation, may be found in [21]. We establish the following hypothesis:

**Hypothesis 2.1** [8] *The estimate of the derivative is realized with an high bandwidth and is not biased; in particular compared to the noise.*

2.4 A first academic example: a stable monovariable linear system

Introduce as in [1, 8] the stable transfer function

\[
\frac{(s + 2)^2}{(s + 1)^3}
\]  

(4)

2.4.1 A classic PID controller

We apply the well known method due to Broïda (see, e.g., [22]) by approximating System 4 via the following delay system

\[
\frac{Ke^{-\tau s}}{(Ts + 1)}
\]

§It implies in other words that we obtain real-time techniques.
\( K = 4, T = 2.018, \tau = 0.2424 \) are obtained thanks to graphical techniques. The gain of the PID controller are then deduced \([22]\): 
\[
K_P = \frac{100(0.4\tau + T)}{120K\tau} = 1.8181, \quad K_I = \frac{1}{1.33K\tau} = 0.7754, \quad K_D = \frac{0.35T}{K} = 0.1766.
\]

### 2.4.2 i-PI.

We are employing \( \dot{y} = F + u \) and the i-PI controller
\[
u = -[F]e + \dot{y}^* + C(\varepsilon)
\]
where

- \([F]e = [\dot{y}]e - u,
- \(y^*\) is a reference trajectory,
- \(\varepsilon = y^* - y,
- \(C(\varepsilon)\) is an usual PI controller.

### 2.4.3 Numerical simulations

Figure 1(a) shows that the i-PI controller behaves only slightly better than the classic PID controller (Fig. 1(b)). When taking into account on the other hand the ageing process and some fault accommodation there is a dramatic change of situation: Figure 1(c) indicates a clear cut superiority of our i-PI controller if the ageing process corresponds to a shift of the pole from 1 to 1.5, and if the previous graphical identification is not repeated (Fig. 1(d)).

### 2.4.4 Some consequences

- It might be useless to introduce delay systems of the type
\[
T(s)e^{-Ls}, \quad T \in \mathbb{R}(s), \quad L \geq 0
\]

for tuning classic PID controllers, as often done today in spite of the quite involved identification procedure.

- This example demonstrates also that the usual mathematical criteria for robust control become to a large irrelevant.

- As also shown by this example some fault accommodation may also be achieved without having recourse to a general theory of diagnosis.
3 Control of inverter-based microgrid

We apply in this section the model-free control to the control of inverters used in typical configurations within microgrid \[23\] in both stand-alone mode and grid-connected mode. We will show in simulation that the model-free control is robust to grid disturbances, load changes / load addition and efficient in direct abc frame (three-phase systems) control as well as in power control.

All the inductors and capacitors described on the schemes have their values respectively close to 1 mH and 10 µF. The dc bus voltage \(E\) is equal to 400 V.

3.1 Voltage-controlled inverter

3.1.1 Single load

Consider a single-phase inverter working in stand-alone mode for which the output voltage is controlled (Fig. 2). The load is a resistor \(R\) that switches from \(R \approx 10 \Omega\) to \(R \approx 1000 \Omega\) at \(t = 0.02\) s. Figure 3 presents the output voltage response \(V_{out}\) of the inverter alone (without control - \(V_{out}^*\) corresponds here to the PWM signal) and shows clearly that it exists a resonant effect after the load change (the \(LC\) filter becomes
less damped). Figures 4 and 5 present the output voltage response of the inverter according to the output voltage reference $V_{out}^*$ when a classical PI controller and an i-PI controller are considered.

![Full bridge inverter with a load.](image)

**Figure 2:** Full bridge inverter with a load.

![Response of the inverter alone.](image)

**Figure 3:** Response of the inverter alone.
Figure 4: Comparison between the PI and i-PI control for the voltage-controlled inverter ($K_p = 20$, $K_i = 0$).
It is difficult to adjust the PI controller in order to stabilize the system considering the load change. However, tuning the i-PI controller allows to adjust the dynamic transient response (Fig. 5) especially during the starting transient of the inverter.

Figure 5: Improvement of the transient dynamic performances using $K_p = 400$, $K_i = 100$.

3.1.2 Multiple loads

Consider a single-phase inverter working in stand-alone mode for which the output voltage is controlled (Fig. 6).

The inverter is firstly loaded by a resistor (load "1") and then a second unknown load (load "2") is added at $t = 0.0042$ s. Figure 7 shows the output voltage response of the inverter. Figure 8 presents the response for a PI control. Figure 9 presents the inverter output voltage response with an i-PI controller under different parameters.
Figure 7: Response of the inverter alone (the second load ”2” is connected at \(t = 0.0042\text{ s}\)).

Figure 8: PI control (\(K_p = 2\)).
Figure 9: i-PI control.
3.2 Three-phase current-controlled inverter

Consider a three-phase inverter working in both stand-alone mode / grid-connected mode and controlled in current. The current in each phase is controlled (Fig. 10) by i-PI (each phase has its own i-PI controller); \( I_{L1a}, I_{L2a}, I_{L3a} \) are the controlled currents going through the inductors \( L_{1a}, L_{2a}, L_{3a} \) and \( I^{*}_{L1a}, I^{*}_{L2a}, I^{*}_{L3a} \) are the corresponding reference currents. The load is composed of a three-phase resistor (\( \approx 10\, \Omega \)) and a three-phase capacitor (\( \approx 10\, \mu F \)). Figure 11 presents the voltages and currents of the inverter in stand-alone mode with a three-phase load change (\( R = 1000\, \Omega, C = 0.1\, \mu F \)) at \( t = 0.012\, s \). Results are similar in the case of unbalanced conditions.

A grid disconnection is presented Fig. 12: a sinusoidal perturbation of 25 % of the grid amplitude at 500 Hz is added to the grid and the inverter is disconnected from the grid at \( t = 0.015\, s \).

![Figure 10: Three-phase bridge inverter connected to the grid.](image)

![Figure 11: Stand-alone mode controlled inverter with load changes.](image)
Figure 12: Perturbated grid and disconnection from the grid.

(a) Inverter alone (without control).

(b) i-PI control.
3.3 Power-controlled inverter

Controlling the output power of an inverter is important when considering parallelization of inverters and load sharing [24] [25].

Consider the single-phase full bridge inverter described Fig. 2 working in stand-alone mode; the load is a resistor \( R = 100 \Omega \). We consider in this section the control of the active power at the output of the inverter. The active power \( P \) is defined by:

\[
P = \int_0^t v_{out} i_L dt
\]

and its estimator is based on a moving-average filter. This is a direct control and the i-PI controller corrects the amplitude of the output sinusoidal signal in order to satisfy the power reference \( P^* \). Figure 13 shows the active output estimated power of the inverter controlled by i-PI. A load change occurs \( R = 50 \Omega \) at \( t = 0.01 \) s. This strategy can also work in three-phase systems.

![Power-controlled inverter](image)

Figure 13: Power-controlled inverter.

3.4 Parallel inverters

Consider two single-phase inverters connected in parallel and working in stand-alone mode (Fig. 14). According to the power sharing methodology [26], the inverter ”1” is controlling the output voltage \( v_{out} \) and the inverter ”2” is controlling the current \( i_{L2} \). Figure 15 shows the output controlled voltage of the associated inverters.
Figure 14: Parallelization of inverters.

Figure 15: Output voltage of the parallelized inverters.
4 Concluding remarks

We presented the model-free control methodology as a distributed control in an electrical network environment. Simulations show encouraging results and show that the model-free control has the following features:

- robust to strong load changes (i.e. in case of the inverter loaded by a resistor, strong change of the resistor value);
- robust to topological load changes (e.g. change of the load or addition of a load that may increase the order of the whole system);
- robust to external perturbations (e.g. grid sinusoidal perturbation);
- direct control in abc frame for three-phase systems;
- non-linear control (e.g. power control).

A combination of the proposed control strategies allows to extended the results to the control of multiple sources considering simultaneously voltage, current and power control. Further work will concern the study of the stability of the model-free control in networked systems.

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