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Bidirectional Power Converter with Adaptive Controller Applied in Direct-Current Microgrid Voltage Regulation

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***Abstract*—Recently, many researches have been done related with the integration of distributed generation in the distribution system. However, in large scale applications, there are several challenges in terms of control design. A simple example is the possibility to operate in island mode or connected to the main power. The operation in island mode requires that power sources should be inserted inside the microgrid structure. The use of dc microgrid is increasing because of advantages in the integration of dc charges, dc loads and storage systems through electronic converters. Between theses advantages, the elimination of frequency are reactive power control are highlighted. However, this simplification does not exempt the microgrid from stability problems, in order to achieve different voltage levels for several power devices. These converters introduce destabilizing effects on the system, leading the microgrid to show significant oscillations in the dc bus voltage. The converter control is the primary concern in operating a microgrid. This work presents a dc microgrid operating in island mode. An adaptive controller is designed to control the balancing of power through a dc-dc bidirectional converter. This converter is connected to a storage device, controlling the dc bus voltage. Simulation results allow us to validate the proposed controller under variations in the availability of energy sources and during load changes.**

***Index Terms*—distributed generation, dc microgrid, constant power load, dc-dc power converter, adaptive control.**

I. Introduction

Since its conception, the electrical system did not undergo major changes. However, there is now an imminence of a big change in existing concepts, leading the operation of the electrical system to a bidirectional scheme of power flow. Recently, much has been said about the advantages of insertion of the Distributed Generation (DG) in the distribution system. Factors such as concern about environmental impacts, the deregulated energy market, the diversification of energy sources and the increase of energy efficiency are great motivators for DG. However, in a big scale, its application presents some challenges making the system difficult to control.

An important point in development of the renewable sources in Brazil, in a small-scale system, was the stallisliment and implementation of the Normative Resolution 482/2012 (REN 482), revised in 2015, turning to the so called REN 687. The standard assigned the right, to the generation system that use renewable sources of injecting energy in parallel with the electricity grid of the country's electric distribution concessionaires. The REN create also the concept of the micro generation [1]. An alternative that has been pointed as the solution for the problems presented in the DG is the concept of Microgrid (MG). MG is defined as the aggregation of loads and sources of low power, being able to operate in stand-alone mode or connected to a main grid, in alternating current (ac) or in direct current (dc). The use of dc in MG is increasing and presents advantages in the integration of dc loads, energy storage and sources for co-generation that need electronic conversion, being able to be renewable sources of energy.

Dc system can be projected to supply rural areas or small-scale installations. If properly sized, dc MG may present superior performance over ac MG in terms of cost and efficiency. They do not need to control the bus frequency or phase or reactive power. Most devices used in residences are powered by dc. In this configuration it is possible storing the exceeding energy. If the intention is to decrease the dependency of the main system, dc system can achieve this goal more efficiently [2]. Current technologies with low power electronic devices, allow that dc grids can be build connecting devices and dc generators sources. This was still impracticable due to electrical losses along the transmission line when it was thought to transmit dc energy at low voltage. Besides that, the safety is guaranteed by reducing the risks of shocks when transmitting low dc voltage.

Research results highlight that dc networks may be more advantageous for a scenario in which there is a high degree of insertion of distributed generation and that the loads are

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predominantly electronic in order to require a dc current stage. Bidirectional converters as the power flow and ability to accommodate electricity storage systems have a wide application in this scenario.

The combination of energy storage elements can produce a controlled output power, meeting network requirements or load transients. Several technical challenges related to the control and operation of MG, which are associated with high insertion of generation systems based on static converters, must be overcame. Point-of-load converters are seen by the feeder converter as constant power loads (CPLs). This kind of load is nonlinear. The CPLs are the main cause of grid instability.

When the MG is in island mode operation, the load power demand must be provided only by the sources and storage devices connected to the dc bus. The dc bus voltage can be stabilized balancing the power generated by the sources and the load demand. This balancing generally is assigned to storage devices as a battery connected to the dc bus through a DBC, which to control the power flow of batteries and keeping the dc bus voltage constant [3].

The main purpose of this paper is to develop a dc MG in stand-alone operation and design a controller in order to regulate the grid voltage, ensuring the robustness under power variations of power (supplied and demanded) and loads and minimize the transient response during load variation events. The analysis is verified through simulations in Matlab/Simulink®.

II. The dc Microgrid

A. Dc-dc bidirectional converter

Power electronic converters are widely used in the MG concept, because they are interfaces responsible for interconnecting loads and generating units to the distribution bus, setting the voltage level generated at the terminals of these units to a desired voltage level at the dc bus and imposing a voltage standard to the equipment connected to it.

The converters are responsible for enabling the bidirectional power flow, controlling the process of charging and discharging the battery inside the system. The power converter employed in this paper is a bidirectional boost topology shown in Fig. 1.

B. The MG modeling

Fig. 2 shows the MG investigated in this work. It consists of: (i) a battery (V_{in}), considered as an ideal dc voltage source, which will store exceeding energy in the circuit or supply power if it is necessary; (ii) a dc-dc bidirectional converter (DBC), responsible for the power flow system; (iii) a resistor (R) representing loads connected directly to the bus (the sum of all resistive loads); (iv) point-of-load converters, which behave and are modeled as a constant power loads (CPLs) - P_L; and (v) sources which are connected to the dc bus through unidirectional converters, modeled as power sources (P_S) [5].

The dc bus current (i_{bus}) and the equivalent load (R_{eq}) are given by

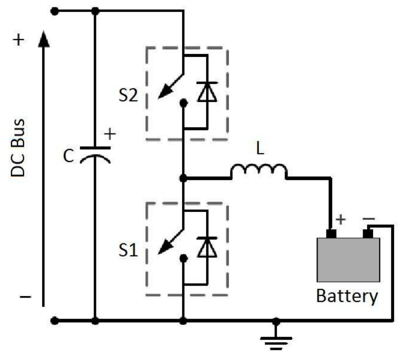

Fig. 1. Topology of bidirectional boost converter (Adapted from [4]).

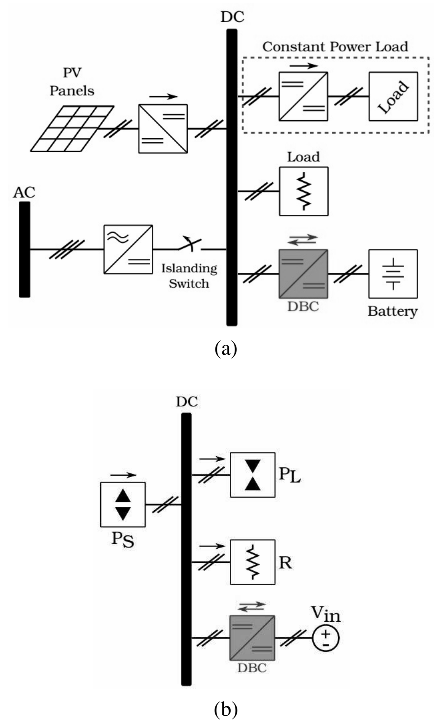

Fig. 2. Dc MG model in standalone operation. Complete model (a) and simplified model (b) [5].

$$i_{bus} = \frac{v_C}{R} + \frac{P}{v_C} \tag{1}$$

$$R_{eq} = \frac{v_C}{i_{bus}} \tag{2}$$

where v_C is the capacitor voltage, i.e., the dc bus. The dynamics of the simplified MG model can be represented as:

$$\frac{di_L}{dt} = \frac{1}{L}(V_{in} - r_L i_L - u v_C) \tag{3}$$

$$\frac{dv_C}{dt} = \frac{1}{C}(u i_L - \frac{v_C}{R} - \frac{P}{v_C}) \tag{4}$$

where i_L are the instantaneous inductor current; r_L is the equivalent series resistor of the inductor; $P = P_S - P_L$; $u = 1$ implies $S1$ is ON and $u = 0$ when $S2$ is ON.

III. MG Control

Different energy converters are involved when the subject is dc MG. These converters introduce destabilizing effects on the system, leading MG to produce significant oscillation on the dc voltage bus. The converter control is therefore the main concern in the operation of a MG.

The voltage control of the MG act on the converters and change the pulse width of the PWM used for the switching of the semiconductors, in order to avoid voltage drops on the output bus. Output voltage fluctuations caused by variations of the input voltage and/or the load connected to the output of the converter is often unwanted. But, this problem can be reduced dynamically to satisfactory levels, depending on the technique used, when applying the feedback control.

The controller is designed to smooth the transient and stabilize the grid voltage due to the possibility of the plug-and-play operation.

A. PID Control

PID controllers are extensively employed in industrial applications. According to [6], between 90 and 95% of the control problems are solved using such controllers. Its use should be developed in accordance with the operating system principle, low cost and performance with the ability to change transient behavior and the steady state of processes under control.

The integral action is directly linked to the accuracy of the system that is responsible for the steady state error. In contrast, an integral action is usually applied together with a proportional gain constituting the PI controller, whose control signal is given by 5.

$$u(t) = K[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau] \quad (5)$$

B. Sliding mode controller (SMC)

The SMC is a nonlinear controller, where the operation point (usually unknown due to large changes in the load levels and sources voltages) is tracked by integral of the voltage error. Such integral adds one more state to the system. It usually exhibits, faster dynamic response than linear controllers, due to elimination of modulators between the control and the converter switch.

From the premise of infinite and variable switching frequency, high switching losses can damage power devices, if a safe limit is not established. Besides that it makes difficult the design of filters for the current and voltage in variable frequency conditions. However, there are several researches that seek to take advantages of SMC benefits with fixed the switching frequency [3].

SMC performance is compared to other controllers.

C. Self-tuning Controllers

Component tolerances, unpredictable load changes, changes in environmental conditions, and the effects of system aging can affect controller performance. For these reasons, adaptive and self-tuning controllers are playing an increasingly important role, being able to adjust itself quickly to the parameter variations of the MG.

An adaptive controller is a controller with adjustable parameters and has a mechanism for setting the parameters. In conventional controllers (non-adaptive), the controller parameters are computed from the plant parameters. If plant parameters are not known, it is intuitive to replace them with their estimates determined by some online parameter estimator.

The basic principle of the adaptive control system is to change the controller characteristics on the bases of the characteristics of control process. Self-tuning controllers use the combination of the recursive process identification on the base of a selected model process and the controller synthesis based on knowledge of parameter estimates of controlled process. Such a control scheme is depicted in Fig. 3.

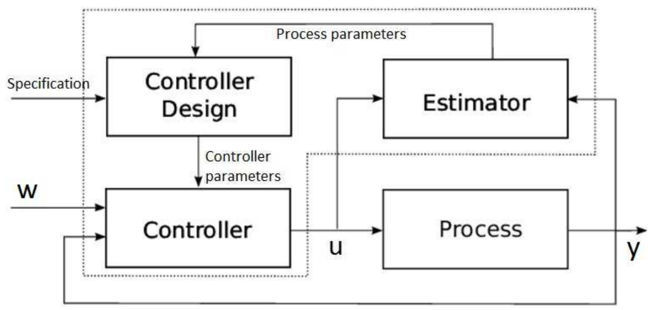

Fig. 3. Block diagram of a self-tuning regulator.

The process model and the control design are updated with each sampling time.

The general task of optimal adaptive control with online process identification is very complicated and thus the method of the forced separation of the identification and the control is often used for the design of self-tuning controllers.

This work use the Self-tuning Controllers Simulink Library (STCSL) for real time control. The STCSL was created for design, simulation verification and especially real-time implementation of single input/single output (SISO) digital self-tuning controllers. The individual self-tuning algorithms are introduced in the brief form in User's Guide that is attached into the STCSL [7]. The library use discrete ARX models of second and third order for the online system identification and consists of three basic parts:

- online identification,
- compute the controller parameters,
- compute the controller output.

D. Online Identification - Recursive Identification

The parameter estimates of the process model, which are obtained by recursive identification, are used for the controller design. It is assumed that values of these estimates correspond to their actual values.

The recursive (or online) determination of the parameters of a model is the key in adaptive control. It allows the tracking of variant parameters for this type of control causing the system model to be updated with each sampling time when new measurements are made available. This allows the controller to adjust to the new characteristics of the process to be controlled and to be tuned again if there are variations in the process dynamics.

If the system to be identified varies in time, it is necessary to provide the least squares method (LSM) with a different weighting capacity for the observations, giving greater importance to the last measurements, since they contain more updated information and must have greater influence on the parameter estimation.

Thus, to avoid that very old data prevent the information introduced by new measures causes the correction of the parameters, a forgetting is used. The choice of this value corresponds to a compromise between the ability of the estimator to follow rapid variations and the quality of the long-term estimates.

The ARX (AutoRegressive eXogenous) model of second order is used in the implementation of the online estimation of the adaptive control algorithm, using the recursive least squares method with forgetting.

Considering that the system can be described by the following transfer function:

$$G(z) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{b_1 z^{-1} + \ldots + b_m z^{-m}}{1 + a_1 z^{-1} + \ldots + a_n z^{-n}} z^{-d} \quad (6)$$

The estimated output of the process is computed on base of the previous process inputs u and outputs y according to the 7.

$$\begin{aligned}\hat{y}(k) = &-\hat{a}_1 y(k-1) - \ldots - \hat{a}_n y(k-n) \\ &+\hat{b}_1 u(k-d-1) + \ldots + \hat{b}_m u(k-d-m)\end{aligned} \quad (7)$$

where $\hat{a}_1, \ldots, \hat{a}_n, \hat{b}_1, \ldots, \hat{b}_m$ are the current estimations of the process parameters.

In vector form:

$$\hat{y}(k) = \Theta^T(k-1)\Phi(k) \quad (8)$$

$$\Theta(k-1) = [\hat{a}_1, \ldots, \hat{a}_n, \hat{b}_1, \ldots, \hat{b}_m]^T \quad (9)$$

$$\begin{aligned}\Phi(k) = [&-\hat{y}(k-1), \ldots, -\hat{y}(k-n), \\ &\hat{u}(k-d-1), \ldots, \hat{u}(k-d-m)]^T\end{aligned} \quad (10)$$

where $\Theta(k-1)$ represents the estimated parameter vector and $\Phi(k)$ the regression vector.

1) LSM with adaptive directional forgetting: The exponential forgetting method can be further improved by adaptive directional forgetting which changes forgetting coefficient with respect to changes of input and output signal. Process parameters are updated using recursive equation:

$$\begin{aligned}\Theta(k) = &\Theta(k-1) \\ &+\frac{P(k-1)\Phi(k)}{1+\xi}(y(k) - \Theta^T(k-1)\Phi(k))\end{aligned} \quad (11)$$

where

$$\xi = \Phi^T(k)P(k-1)\Phi(k) \quad (12)$$

The covariance matrix P is updated in each step, as show in 13.

$$P(k) = P(k-1) - \frac{P(k-1)\Phi(k)\Phi^T(k)P(k-1)}{\varepsilon^{-1} + \xi} \quad (13)$$

where

$$\varepsilon = \beta(k-1) - \frac{1 - \beta(k-1)}{\xi} \quad (14)$$

The forgetting coefficient, β, is updated as follows:

$$\beta(k) = \frac{1}{1 + (1+\rho)\{\ln(1+\xi) + [\frac{(\upsilon(k)+1)\eta}{1+\xi+\eta} - 1]\frac{\xi}{1+\xi}\}} \quad (15)$$

where

$$\upsilon(k) = \beta(k-1) - (\upsilon(k-1) + 1) \quad (16)$$

$$\eta = \frac{(y(k) - \Theta^T(k-1)\Phi(k))^2}{\lambda(k)} \quad (17)$$

$$\lambda(k) = \beta(k-1)[\lambda(k-1) + \frac{(y(k) - \Theta^T(k-1)\Phi(k))^2}{1+\xi}] \quad (18)$$

E. Minimum Variance Control

Adaptive and self-adjusting controllers proposed here are playing an increasingly important role in industrial process and can quickly adjust the microgrid parameter variations.

The controller parameters are adjusted by a recursive parameter estimator and a design calculation. The process model and control design are updated with each sampling time.

If the transfer function of the controlled system is represented by 19, the vector of identification initial parameter estimations is $[\hat{a}_1, \hat{a}_2, \hat{b}_1, \hat{b}_2]^T$ and the control law is given by 20, where q is the penalization factor.

$$G(z) = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \quad (19)$$

$$u(k) = \frac{1}{q}[\hat{a}_1 y(k-1) + \hat{a}_2 y(k-2) - \hat{b}_1 u(k-1) - \hat{b}_2 u(k-2) + w(k)] + u(k-1) \quad (20)$$

The penalization factor used by computation of control law parameters. This parameter specifies the measure of change of current controller output with respect to previous controller output: the smaller the penalization, the greater the possible change of controller output.

This kind of control law can be transformed to feedback feedforward form as show in 21:

$$u(k) = r_0 w(k) - q_1 y(k-1) - q_2 y(k-2) - p_1 u(k-1) - p_2 u(k-2) \quad (21)$$

where controller parameters r_0, q_1, q_2, p_1 and p_2 are calculated using following equation:

$$r_0 = \frac{1}{q};$$
$$q_1 = -\frac{\hat{a}_1}{q};$$
$$q_2 = -\frac{\hat{a}_2}{q};$$
$$p_1 = \frac{\hat{b}_1}{q} - 1;$$
$$p_2 = \frac{\hat{b}_2}{q}.$$

The adaptive controller allows the variation of control parameters over time, making it suitable for system variations.

IV. Results

The preliminary results are presented in the Fig. 6, 7 and 8. Simulation results obtained from SimPowerSystems (Matlab/Simulink blockset) are shown in order to validate the proposed controller performance under sources and load variations.

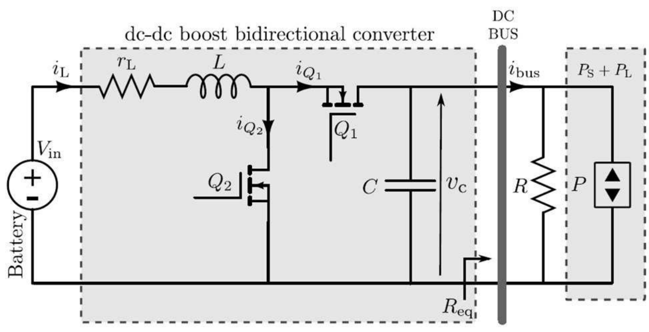

Fig. 4. Dc MG simplified model in island mode operation [5].

It was employed a DBC of $20W$ ($24V - 48V$), as shown in the Fig. 4, whose parameters are $V_{in} = 24V$, $L = 2.2mH$, $C = 10F$, $r_L = 0.5\Omega$ and reference voltage $V_{ref} = 48V$. Initially, it was considered $R = 200\Omega$. The power variation occur between $-20W < P < 20W$.

For the studied microgrid, the control system must follow the scheme of the Fig. 5.

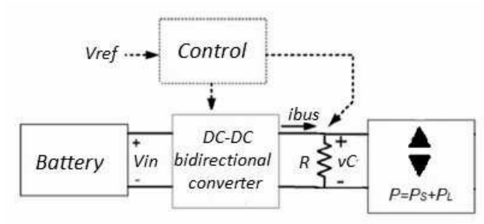

Fig. 5. Schematic diagram of the microgrid control system.

The responses to the simulated tests performed for each control method are shown in the figures in a comparative way for each experiment.

In the first experiment, the following parameters have been considered: $V_{ref} = 48V$, $R = 200\Omega$ and $20W < P < 20W$ where $P = P_S - P_L$. Four conditions for power variation have been imposed:

i) in $t_1 = 0.1s$, P varies from $0W$ to $10W$;
ii) in $t_2 = 0.2s$, P varies from $-10W$ to $5W$;
iii) in $t_3 = 0.3s$, P varies from $-5W$ to $17W$;
iv) in $t_4 = 0.4s$, P varies from $-17W$ to $9W$.

In the experiments the system was considered initially stable with the battery supplying the resistive load. Fig. 6 presents the voltage response of the dc bus (voltage, v_C, on the capacitor), in the output of the bidirectional converter, for the reference signal considered in the input.

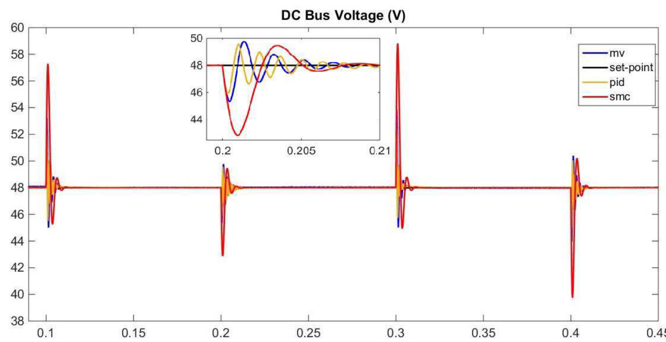

Fig. 6. System response under the first experiment of regulatory control.

One can note that the system converges to the set-point even with the variations imposed in the plant by the insertion and withdrawal of consumption and power generation units in the network.

In the second experiment the constant power loads (CPL) are made fixed, $P = 10W$, and the purely resistive loads (R)

in the network are varied. In this way three different conditions for load variation have been imposed:

i) in $t_1 = 0.1s$, P varies from $0W$ to $10W$ and R remains fixed in 100Ω;
ii) in $t_2 = 0.2s$, P remains fixed ($P = -10W$) and R varies from 100Ω to 125Ω;
iii) in $t_3 = 0.3s$, P remains fixed ($P = -10W$) and R varies from 125Ω to 37.5Ω.

It can be noted, in the Fig. 7 that the proposed controller keeps the system output in the reference $V_{ref} = 48V$ with a satisfactory behavior.

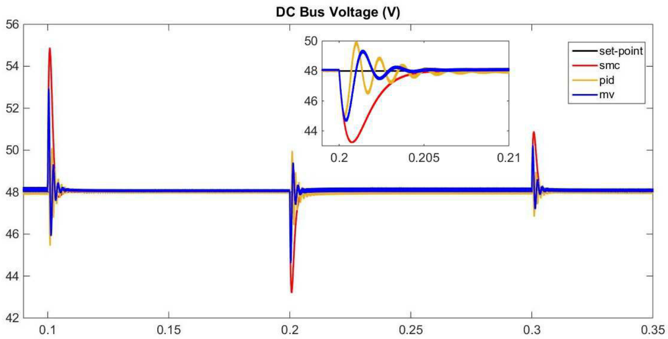

Fig. 7. System response under the second experiment of regulatory control.

In the previous experiments of regulatory control, a fixed reference was used and load perturbations were applied to the process to verify the disturb rejection capacity of the control algorithms.

In the third and last experiment, the process is subjected to changes in the reference to evaluate the tracking capability. In this test, the purely resistive loads and the power constant loads have been considered fixed, with $R = 200\Omega$ and $P = 10W$ respectively.

The following variation in the reference signal V_{ref} have been applied. Four conditions have been imposed:

i) in $t_1 = 0.1s$, V_{ref} varies from $48V$ to $95V$;
ii) in $t_2 = 0.2s$, V_{ref} varies from $95V$ to $60V$;
iii) in $t_3 = 0.3s$, V_{ref} varies from $60V$ to $35V$;
iv) in $t_4 = 0.4s$, V_{ref} varies from $35V$ to $48V$.

In this experiment, input steps (negative and positive) were employed within the set-point variation. The time-response is presented in Fig. 8.

In the tests for control validation, attention has been paid to situations in which the load demand (resistive and constant power) was both larger and smaller than the available power in the micro grid. This imposition makes it possible the evaluation of the capacity of the bidirectional converter to realize the balance of power flow, with the help of battery, and always seeking to keep the dc bus voltage constant, which is focus of this work.

V. Conclusion

This paper analyzed the performance of controllers in voltage regulation in a dc microgrid in stand-alone operation.

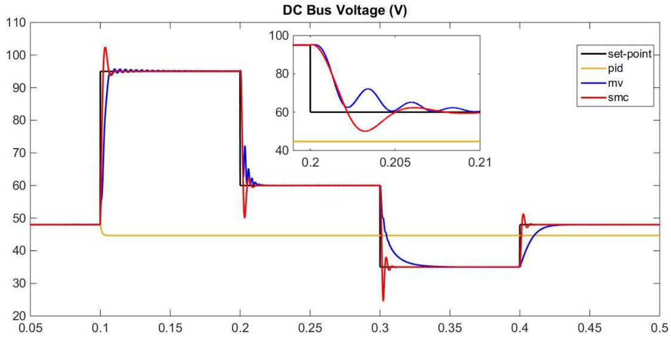

Fig. 8. Response of the dc bus voltage (v_C) when subjected to the servo control test.

Three different control structures were used for comparison purposes: the PI controller, because it is robust, simple and easy to implement; the adaptive minimum variance controller proposed here; and a nonlinear controller by sliding modes.

It can be noticed that the last two controllers were able to regulate the dc bus voltage, ensure robustness under supplied and demanded power variations, and still managed to establish a rapid transient response to the events of load variation. Oppositely, the simple PI controller did not respond satisfactorily to all tests performed. It justifies the use of self-tuning adaptive controllers due to a better plant behavior and performance requirements.

With the minimum variance control, the system parameters estimated in real time, used the forgetting factor to guarantee continuous evaluation of its nonlinear dynamics. Enhancements, such as more precise adjustment of controller gain values, can establish a smaller variation around reference values and increase system robustness.

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