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Fractional order control for bidirectional converter operating in a DC microgrid

Control de orden fraccionario para un convertidor bidireccional operando en un microrred DC

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Abstract

This paper presents the control design of a bidirectional converter used to support a DC microgrid. The chosen topology for this purpose is the bidirectional buck-boost converter, for which its mathematical model is obtained. Next, a brief introduction of fractional order control is presented and the structure of a fractional order PID controller is shown. The tuning process of this controller is obtained by means of an arithmetic method whose parameters are set to control the bidirectional converter. In order to evaluate the performance of the converter and its fractional-order controller, this is simulated under different situations that represent different operating conditions, such as changes in battery voltage levels, climatic conditions, and uncertainty in the parameters. The simulation results of this controller are analyzed and compared with a classical PID. Finally, the conclusions are presented.

Keywords: bidirectional converter; DC microgrid; fractional-order control; robustness.

Resumen

Este artículo presenta el diseño del control de un convertidor bidireccional el cual es usado para brindar soporte eléctrico a una microrred DC. La topología elegida para este propósito es un convertidor bidireccional Buck-boost, para el cual se obtiene el modelo matemático. A continuación se presenta una breve introducción al concepto de control de orden fraccionario, en donde se muestra la estructura de un PID de orden fraccionario. Luego se muestra el proceso de sintonización de los parámetros de este controlador usando un método aritmético. Con el objetivo de evaluar el desempeño del convertidor y su controlador de orden fraccionario, se simula bajo diferentes situaciones que representan distintas condiciones de operación, tales como cambios en los niveles de tensión de la batería, condiciones climáticas e incertidumbre en los parámetros. Se analizan y comparan los resultados de simulación del controlador con los obtenidos de un PID clásico. Finalmente, se presentan las conclusiones.

Palabras clave: convertidor bidireccional, control de orden fraccionario, microrred DC, robustez.

1. Introduction

Currently, distributed generation systems (DG) such as wind and PV farms, have received great attention worldwide as an effective solution for problems such as the increasing of the load factor, which could reach the current limit capacity of power systems (Lee; Kang; Park, 2016). In addition, DGs offer great technical and economic benefits, but the unification of several electric features into a single unit is needed (Perez; Kagan, 2016). This kind of unit is called microgrids. These systems are electric power grids confined locally and whose purpose is to integrate alternative energy sources with the loads, making stable and efficient systems (Krishnamurthy; Kwasinski, 2016). Until now, AC microgrids are the most common ones, however, low and medium DC power distribution systems, used in telecommunication systems and electric vehicle (EV) charging infrastructures as shown in Figure 1, are widely used because they do not have problems of synchronism and harmonic distortion (Sirsi; Prasad; Sonawane; Lokhande, 2016). In the study of Manandhar; Ukil and Jonathan (2015) is presented the DC and AC systems modeling including their power converters, power cable losses and loads. Then, these systems are simulated, finding efficiency of 78.24 % and 84.6 % for low voltage AC and DC systems respectively. This shows that the efficiency of the DC systems is higher than the AC systems under some conditions (Lee *et al.*, 2016), which makes DC grids more efficient systems.

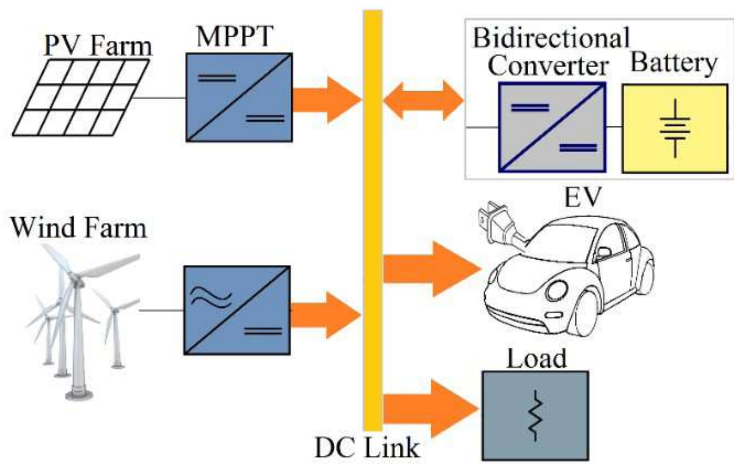

Figure 1. General microgrid scheme
Source: authors.

A lot of DC microgrids include photovoltaic and wind power sources, which dependent on weather conditions, resulting in power fluctuations that affect the power flow between the sources and the load (Alam; Muttaqi; Sutanto, 2013; Takagi *et al.*, 2013; Tamura, 2016) and the hybrid energy storage system (HESS). Additionally, changes in load and generation levels lead to voltage disturbances in the DC link. These changes affect the power quality managed by the microgrid and produce malfunction of devices and loads connected to it. For these reasons, it is necessary to include an energy storage system with bidirectional DC-DC converters to ensure energy storage when there is a surplus or delivery it when the sources cannot give enough energy to the loads. However, these converters must meet some requirements, and one of them is high efficiency. Another requirement is to respond quickly to any voltage level fluctuation on the DC link and any other disturbance (Tummuru; Mishra; Srinivas, 2015). There are several topologies such as dual active bridge and bidirectional flyback, which offer galvanic isolation and high energy density. Another group of topologies is the non-isolated converters, where the most common ones are: zeta, zepic, cuck/cuck, and buck-boost topologies. Nevertheless, this last group does not have high-frequency transformers and does not offer high energy density. Moreover, this converter has low voltage gain, although some modified versions can be found in academic literature. One example of this is the buck-boost modified converter propose in Banaei and Sani (2018), which structure contains only one switch and, unlike many other DC converters, has low stress across the only switch. Notwithstanding, owing to this topology is not bidirectional, it is needed to connect the two voltage levels by two converters, one for each power flow direction.

One of the most used controllers is the PID controller owing to its simplicity and good performance. However, other controllers such as a fuzzy logic controller, adaptive or predictive controller can offer better performance but have a more complex structure. Thus, it is necessary to compare performance with complexity and then to choose the better option. Some works have tackled this issue from different perspectives, which is one of them the passivity control used in Montoya-Giraldo; Garcés-Ruiz; Ortega-Velázquez; Espinosa-Pérez (2018). However, passivity control in itself is no robust which means it is sensible to perturbations in the system. For this, additional strategies have to be added to control passivity to allow an acceptable performance of the converter in real conditions. In Sanchez-Choachí (2019) an adaptative strategy is used to improve the passivity control performance, and additionally, instead of controlling the battery current as in Montoya *et al.*, (2018), the output voltage is regulated indirectly to keep the DC voltage at the reference level.

Fractional order control (FOC) is one of the control techniques whose structure is similar to PID's, but it has additional parameters. Nevertheless, it is simpler than others like compensation nets, fuzzy controllers, among others. Other significant advantages are higher robustness level and ease of design. For this reason, this kind of controllers is used in mechanical, automatic, thermal and pressure areas (Kanagaraj; Al-Dhaifalla; Nisar, 2017). Until now, there are three fractional order control generations, where the first-generation control is the simplest, and it is the one is used in this paper. In some studies like Lei; Xiong; Lei (2017), FOCs are applied to different converters; however, none of them are applied to a bidirectional converter.

This paper presents the modeling of a bidirectional buck-boost converter and develops its fractional order controller (FOC). The tuning detailed process of this FOC is shown with all its numeric parameters. Then, this FOC is approximated using linear filters. Next, the converter and the designed FOC are simulated for different operating conditions. These simulation results are compared with a classical PID controller. Finally, the conclusions about the design process and the outcomes of this work are shown.

2. Converter modeling

As was mentioned previously, there are a lot of conversion topologies that raise or reduce the voltage level between its output terminals. One of these topologies is the buck-boost converter, shown in Figure 2. In this figure, i_p is the current generated by the microgrid sources, E is the battery voltage, v_c is the capacitor voltage which is the DC link voltage too, i_L is the current across the inductor (L) and R_{DC} is the grid load. The current (i_p) represents the grid sources, whose current value can change in order to simulate different weather conditions. Additionally, *Rs* are included to represent generation and conversion losses.

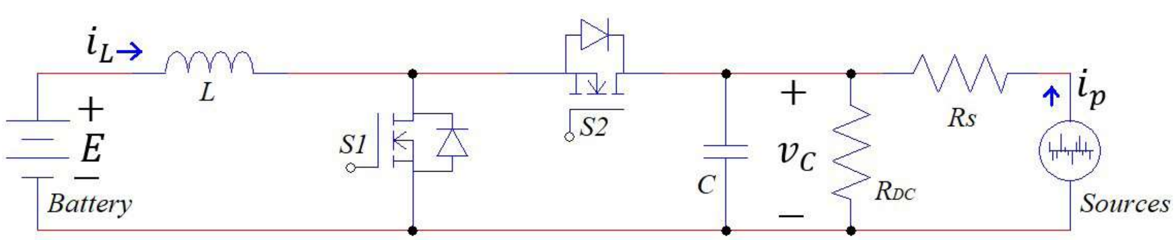

Figure 2. Bidirectional Buck-boost topology
Source: Authors.

This topology is typically used for low voltage applications due to its low ratio conversion. However, this converter can be used for high voltage applications using it to build a modular multilevel converter by means of using methodologies as proposed in Kung and Kish (2018). This methodology apportions the semiconductor devices into switching cells (with $n \geq 2$), then using a harmonic power balance concept, the direction of average ac power flow is identified. Once this is done, the original cells are replaced with new switching cells comprised of series/cascaded subsystems that allow the required ac power flow. Finally, the fundamental frequency ac currents are canceled by interleaving multiple strings subsystems. In fact, the aforementioned methodology is used on the buck-boost converter yielding a new topology.

The buck-boost bidirectional power converter operates as a boost converter if the power flows from the battery to the DC link and operates as a buck converter if the current goes from the DC link to the battery. For this reason, v_c voltage must be larger than *E*. Another restriction of this converter is that *S1* and *S2* diodes have to be fast recovery to avoid working failures since the *S2* diode works when the current goes from *E* to v_c and *S1* diode operates in the opposite case. Therefore, slow current or voltage transitions affect the converter efficiency and behavior (Chun; Rui; Hongwen; Xiaofeng; Weixiang, 2016).

The mathematical model of this converter is developed by assuming that the system is operating in a stationary point so v_c has a constant value. Moreover, the voltage drop in the diode (v_d) is included to consider electrical losses in the model. Then, the average model of the buck-boost converter is obtained by evaluating the state of *S1* and *S2* and remembering that these states are opposite, which means that if *S1* is open then *S2* is closed and vice versa. This mathematical model is shown in equation (1), where *u* is the period percentage in which *S1* is closed. This variable is known as the duty cycle.

$$L\frac{di_L}{dt} = E - v_C(1-u) - v_d(1-u)$$
$$C\frac{dv_C}{dt} = i_L(1-u) - i_p - \frac{v_C}{R_{DC}} \tag{1}$$

3. Fractional order control

This kind of control is similar to traditional linear controllers, but instead of using traditional calculus, it uses the fractional order calculus. This calculus, developed by Riemann and Liouville, is a generalization of the differentiation concept, where its order can be a real number or even a complex number. The differentiation operator can be represented by the operator D_a which is defined by the equation (2) when it operates over a generic function *f (t)*. In this equation, $a \in R$ is the fractional-order and it is in the numeric interval *(n, n + 1)*, being *n* the closest integer to *a* (but *n < a*) (but) and is the gamma function.

$$D_{\propto} = \frac{1}{\Gamma(n-\propto)}\frac{d^n}{dt^n}\int_a^t \frac{f(\tau)}{(t-\tau)^{\propto-n+1}}d\tau \tag{2}$$

The equation (2) is known as Cauchy's formula. If initial conditions are assumed zero, this formula represents the *f (t)* repeated integral of order *n* by means of a unique integral pondered by the gamma function. With this representation, the integration and derivative concept can be generalized and take a fractional order. Initially, this concept only had mathematical worth because its physical meaning was not considered since physical laws are understood from integer order calculus. Nevertheless, recent research has shown fractional-order calculus is useful to model complex liquids, thermal processes, mechanical systems, signal and image processing and materials (Sun; Zhang; Baleanu, Chen; Chen, 2018).

Using equation (2) to incorporate fractional order calculus in control theory, some common tools can be improved. For instance, in the Laplace domain, the generalized structure of a fractional order PID (FOPID) is given by the equation (3), where k_p, k_I and k_D are the proportional, integral and derivative gains respectively and are the fractional orders of the derivative and integration operator. These two new parameters, that PID controllers do not have, allow us to control more system response features that could improve the plant's behavior, maintaining a simple control structure.

$$C_{FO} = k_p + \frac{k_I}{S^{\propto}} + k_D S^{\beta} = \frac{k_p S^{\propto} + k_I + k_D S^{\beta+\propto}}{S^{\propto}} \tag{3}$$

Unfortunately, fractional order controllers have infinite dimensions, so, an approximation using linear filters is needed to implement an FOC. This approximation can be developed by different methods; however, the simplest one is the CRONE (Non-Integer Order Robust Control) approximation. The first step of this approximation is restricting the frequency band on which the designed FOC operation is required (from ω_h to ω_b). Next, poles and zeros corner frequencies (ω_k and respectively) have to be distributed in order to emulate the FOC behavior. This approximation is represented by equation (4) and it is the product of N poles and N zeros, where the number of linear filters (N) is chosen as is shown by equation (5).

$$D_a^{\alpha}(s) = C\left(\frac{1+\frac{S}{\omega_h}}{1+\frac{S}{\omega_b}}\right)^{\alpha} \approx C\frac{\prod_{k=1}^{N}\left(1+\frac{S}{\widetilde{\omega_k}}\right)}{\prod_{k=1}^{N}\left(1+\frac{S}{\omega_k}\right)} \quad (4)$$

The corner frequencies ω_k and $\tilde{\omega}_k$ must be distributed recursively to obtain the required frequency behavior and to approximate the FOC performance. However, there is a numeric method used to determinate each ω_k and $\tilde{\omega}_k$ This method is an iterative process described by the equation (5), where once the first converter frequency () is defined, the other frequencies are established.

$$\begin{aligned} \widetilde{\omega_1} &= \alpha\omega_1 & \omega_1 &= \mu^{0,5}\omega_b \\ \widetilde{\omega_{k+1}} &= \alpha\mu\widetilde{\omega_k} & \omega_{k+1} &= \alpha\mu\omega_k \\ \mu &= \frac{\log(\alpha)}{\log(\alpha\mu)} & N &= \frac{\log(\omega_h/\omega_b)}{\log(\alpha\mu)} \end{aligned} \quad (5)$$

The number of linear filters (N) has to be approximated the closest integer, but less than the indicated value by equation (5). However, because of the infinite dimension of the FO controller, the larger is, the better is the approximation to FO controller behavior. So, if increasing the number of linear filters is desired, ω_1 has to be closer to ω_b .

4. Control design

It is possible to find several tuning methods such as Grunwald-Letnikoff or Matsuda approximation, but this paper uses the analytic method described below. This method is based on four parameters: phase margin, φ_m, gain margin, g_m, gain crossover frequency, ω_C, phase crossover frequency, ω_P, and phase flatness. According to the system needs, the above parameters are set and by using the equations (6), the k_p, k_I, k_D, and β values are established.

$$\begin{aligned} k_p + \frac{k_I e^{-j\alpha\pi/2}}{{\omega_c}^{\alpha}} + k_d {\omega_c}^{\beta} e^{j\beta\pi/2} &= \frac{e^{j(-\pi+\varphi_m - Ang(G(j\omega_c)))}}{|G(j\omega_c)|} \\ k_p + \frac{k_I e^{-j\alpha\pi/2}}{{\omega_p}^{\alpha}} + k_d {\omega_p}^{\beta} e^{j\beta\pi/2} &= \frac{e^{j(-\pi - Ang(G(j\omega_p)))}}{g_m|G(j\omega_p)|} \\ \left.\frac{d(C_{FO}G)}{d\omega}\right|_{\omega_s} &= 0 \end{aligned} \quad (6)$$