DC-DC Converters in Wind Systems for Micro-generation: A Systematic Review

Convertidores DC-DC en sistemas de micro-generación eólica: una revisión sistemática

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Key words
Converters control, converters design, literature review, power converters, wind generators.

Abstract
This paper presents a literature review analyzing four topics concerning wind systems for micro-generation: system topologies, system modeling, power converters design, and power converter controllers. The review also reveals the open research problems in the literature, and the opportunities to improve commonly adopted solutions.

Palabras clave
Aerogeneradores, control de convertidores, convertidores de potencia, diseño de convertidores, revisión de la literatura.

Resumen
Este artículo presenta una revisión de la literatura sobre sistemas eólicos de micro generación. La revisión analiza cuatro tópicos: la topología del sistema, su modelado, el diseño de los convertidores de potencia y el control de los mismos. Finalmente, la revisión resalta los problemas de investigación abiertos, así como las oportunidades para mejorar soluciones comúnmente utilizadas.

Introduction

Given that fossil fuel consumption is one of the main causes of global warming (Barroso, Rudrick, Sensfuss & Linares, 2010), it is vital to reduce our dependence on such fuels for electric energy generation. One strategy for replacing fossil fuels is the use of alternative electric energy sources. Among these, eolic energy production has become hugely important in promoting the development of such technologies in recent years.

Small wind generators are installed on the rooftops of houses and buildings for what is known as micro-generation. For example, 400 W to 1,500 W micro-turbines are commercially available in the United Kingdom (Bahaj, Myers & James, 2007), and statistics indicate that 87% of micro-turbines installed in the United Kingdom generate less than 1,500 W.

The power of the wind generator defines the characteristics of the converters used in the extraction of wind electric power. The designs of such converters are based on the requirements of the generation source and the electric load. An optimal design may enhance the efficiency of the generation system and extend the life of its elements. However, recent investigations have not addressed the methods for the design of power converters based on wind generator requirements or on the working lifespans of the elements involved in the wind energy system.

The present work is a systematic review focused on the design of converters used with micro wind generators, in the 2 kW range. The review includes 24 articles on the design of converters used in micro wind generators. It remarks on relevant design issues such as the required design methodology for DC-DC converters taking into account the source and load requirements and basic aspects such as the elements that make up the wind generation system, the types of converters, and their controllers.

The remaining part of the paper is organized as follows: Section 2 presents the methodology to develop the literature review. Section 3 provides the results in two tables and the discussion of the results. In Section 4, we present the conclusions and finally, the acknowledgements and references are presented in the last two sections.

Methodology

To develop the systematic review, the main area of interest, DC-DC converters in wind systems for micro-generation, was divided into four topics: Topology of the wind energy generation systems, modeling of the elements, design of the converter and its control. Several questions were formulated per topic and were answered for each analyzed paper. Finally an assessment system is proposed to highlight the open research problems of the proposed topics.

Topics and questions about small wind energy generation systems

Topic 1 refers to the topology of the small wind energy generation system. This topic is analyzed through two review questions:

a. What is the connection type reported for the wind energy generation system?
b. What are the elements of the wind generation system?

The modeling of a small wind energy generation systems is addressed in topic 2 and is analyzed through the next review questions:

a. What is the model used for the generator?
b. What is the model used for the rectifier?
c. What is the model used for the wind turbine?

Topic 3 concerns the DC-DC power converter design, and the review questions are the following:

a. What kind of converter is used?
b. What types of problems in the electric generator and the load can arise from the use of DC-DC converters?
c. What method is used to calculate the elements of the DC-DC converters used in the wind energy generation system?

Finally, topic 4 refers to the control of DC-DC converters. From this topic, the following questions were formulated:

a. What strategies are used for the control of the converters?
b. What are the controlled variables in the converters?
c. What performance criteria are used for the design of the controllers?

An assessment system to identify the open research subareas

To establish the existence of a gap, the percentage of articles that answer each of the questions (PAA%) was calculated using (1). Next, the average of these percentages was calculated (APAA%) using (2), and the result or average percentage of articles that answer the review question was then divided by three to obtain a cutoff percentage (MAPAA%) using (3). When the PAA% of a single question was lower than the MAPAA%, a detailed review of the articles included in the PAA% was performed to evaluate whether the articles fully answered the review question or whether additional efforts were required to answer it. When the latter occurred, it was because a gap was identified in the literature.

$$PAA\%(n) = \frac{\text{Total articles that answer question}}{\text{Total articles}} \cdot 100\% \quad (1)$$

$$APPA\% = \frac{PAA\%(1) + PAA\%(2) + \cdots PAA(n)}{\text{Total number of questions}} \quad (2)$$

$$MAPAA\% = \frac{APAA\%}{3} \quad (3)$$

Results and discussion

To record the information, two result tables were constructed: Table 1 summarizes the answers to the review questions of topics 1 and 2. Table 2 presents the answers to the questions from topics 3 and 4. Cells marked with an “X” indicate that the article does not specify an answer to that question.

In Table 1, Question *a*, topic 1 was answered by 100% of the articles, revealing that the small wind energy generation systems are mainly connected in two forms; 33.33% of the articles report a connection to the electrical grid, and the remaining 66.67% report a connection to an isolated load. Among the latter connections, 50% of the articles report a connection to an AC load, and the remaining 50% report a connection to a DC load. Hence, low power wind systems are mostly designed for isolated applications and, therefore, special attention must be devoted to integrate storage and management devices for wind systems in order to supply a required load profile.

Question *b*, topic 1 was answered by 100% of the selected works. It is observed that all micro wind generation systems have a wind turbine, a permanent magnet generator, and a rectifier; therefore, these elements are not reported in Table 1. A reluctance synchronous generator is only reported in (Goto, Guo & Ichinokura, 2009) and (Whaley, Ertasgin, Soong, Ertugrul, Darbyshire, Dehboeni & Nayar, 2006). The remaining elements in the generation system vary depending on the connection type. 54.17% of the papers report the use of an inverter (“I”), where the micro generation system is connected to the grid or an AC load. Batteries (“B”) are used for storage in 20.83% of the reviewed papers, while Electric Double Layer Capacitors (“EDLC”) are used in (Goto, Guo & Ichinokura, 2009). In (Hua & Cheng, 2010), a bidirectional DC-DC converter is used to manage the power exchanged with the battery. As such, the use of DC-DC converters (“C”) is reported in 70.83% of the articles.

Table 1. Answers to topic 1 and topic 2 review questions

Articles	Topic 1		Topic 2		
	Q a	Q b	Q a	Q b	Q c
(Deng & Chen, 2013)	Isolated DC load	C	X	Uncontrolled rectifier model	Static model
(Fan, Ma, Lim & Williams, 2013)	Electrical grid	C, I	X	Uncontrolled rectifier model	Static model
(Suskis & Rankis, 2012)	Isolated DC load	LC filter, C	DC voltage source model	Uncontrolled rectifier model	X
(Rashmi, Suresh & Kamalakkannan, 2012)	Isolated DC load	C	Single-phase source model	Uncontrolled rectifier model	X
(Bisenieks, Vinnikov & Galkin, 2011)	Electrical grid	C, I	Three-phase source model	Controlled rectifier model	X
(Arifujjaman, 2010)	Electrical grid	C, I	Three-phase source model	Uncontrolled rectifier model	Dynamic model
(Alepuz, Calle, Busquets-Monge, Bordonau, Kouro & Wu, 2010)	Electrical grid	I	Park's model	X	X
(Meiqin, Jidong, Ding, Nayar & Chang, 2010)	Electrical grid	I, Filter	DC current source model	Current source model considering the generator	X
(Hua & Cheng, 2010)	Isolated AC load	C, I, bidirectional C, B	X	X	Static model
(Sinha, Kumar, Samuel & Gupta, 2009)	Isolated AC load	C, I	X	Uncontrolled rectifier model	X
(Nagliero, Liserre, Orlando, Mastromauro & Dell'Aquila, 2009)	Electrical grid	I, LC filter	X	X	X
(Lazarov, Roye & Zarkov, 2009)	Electrical grid	C, I, Transformer	Three-phase source model	X	X
(Morales, Ordoñez, Morales & Flores, 2009)	Isolated AC load	C, I	Park's model	X	X
(López & Vannier, 2009)	Isolated DC load	C, B	X	X	Static model
(Goto, Guo & Ichinokura, 2009)	Isolated DC load	C, EDLC	PMRG model	X	Static model
(Sinha, Kumar, Samuel & Gupta, 2008)	Isolated AC load	C, B, I	X	Uncontrolled rectifier model	Static model
(Chiniforoosh, Alaeinovin, Davoudi, Jatskevich & Chapman, 2008)	Isolated DC load	LC filter, C	Park's model	X	X
(Arifujjaman, Iqbal & Quaicoe, 2008)	Isolated AC load	I	Park's model	Uncontrolled rectifier model	Static model
(Eren, Hui, To & Yazdani, 2006)	Isolated DC load	C, B	X	Uncontrolled rectifier model	Static model
(Tafticht, Agbossou & Cheriti, 2006)	Isolated DC load	C, B	Three-phase source model	Uncontrolled rectifier model	Static model
(Whaley, Ertasgin, Soong, Ertugrul, Darbyshire, Dehboeni & Nayar, 2006)	Electrical grid	C, I	Three-phase source model	X	X
PAA%	100 %	100 %	54.17 %	50.00 %	41.67 %

Question *a*, topic 2 was answered by 54.17% of the articles, and we found that there are five different ways to model the permanent magnet synchronous generator. Among them, the most common representations are a three-phase source in series with a reactance element, and the model based on Park's transformation. Question *b* was answered by 50.00% of the reviewed articles, whereby 83.33% of those papers use an uncontrolled rectifier model. In contrast, (Bisenieks et al., 2011) uses a controlled rectifier model, while (Meiqin et al., 2010) models the rectifier merged with the generator as a current source. Question *c*, topic 2 was answered by 41.67% of the articles, where most of them consider a static model for the turbine, while a dynamic model is presented only in (Arifujjaman, 2010). Such results shed light on two main trends: first, the modeling of the wind turbine, generator and the rectifier by a static relation; and second, the dynamics of the turbine and generator. In the former, the power system control is designed from the dynamics of the converter, while the generator and turbine dynamics are considered perturbations, which simplifies the design. In contrast, the latter allows us to include protectors for the generator and the turbine in the control design, e.g. over voltage and over speed protection.

In Table 2, Question *a*, topic 3 was answered by 87.50% of the articles; among them, 35.29% reported the use of a boost converter; 23.53%, the use a buck converter; 11.76%, the use a buck-boost converter, and 11.76%, the use of a back-to-back configuration, whereas (Goto, 2009) reported the use of a qZS DC-DC converter. Such results show that classical converters are often used to step-up and/or step-down small power loads. Hence, there is an opportunity for designing specialized converters aimed at optimizing the small power wind systems, e.g. improve the efficiency.

Table 2. Answers to topic 3 and topic 4 review questions

Articles	Topic 3	Topic 4		
	Q a	Q a	Q b	Q c
(Deng & Chen, 2013)	IFBTL	Lookup table, PI	Input voltage	Maximize the power production
(Fan, Ma, Lim & Williams, 2013)	LCC resonant converter	PI	Input current, Output voltage	Maximize the power production
(Suskis & Rankis, 2012)	Buck-Boost	Algebraic relation voltage/duty cycle	Output voltage	Regulate a constant DC link voltage
(Rashmi, Suresh & Kamalakkannan, 2012)	Four port DC-DC	X	Three input port voltages	X
(Bisenieks, Vinnikov & Galkin, 2011)	qZS	X	X	X
(Arifujjaman, 2010)	Boost	PI	Input current	Regulate a constant DC link voltage
(Alepuz, Calle, Busquets-Monge, Bordonau, Kouro & Wu, 2010)	Back-to-back	PI	Generator speed, output voltage, and power factor	Regulate the required power
(Meiqin, Jidong, Ding, Nayar & Chang, 2010)	X	PI	Generator speed and current sent to the grid	Provide a sinusoidal waveform of the current sent to the grid
(Hua & Cheng, 2010)	Boost and a bidirectional one	Algorithm for battery management	Load power	Regulate a constant load power
(Sinha, Kumar, Samuel & Gupta, 2009)	Buck	PI	Output voltage	Monitor and regulate the constant DC link voltage
(Nagliero, Liserre, Orlando, Mastromauro & Dell'Aquila, 2009)	Back-to-back	P and PI	Output voltage and power factor sent to the grid	Regulate a DC link voltage and power factor equal to one
(Lazarov, Roye & Zarkov, 2009)	Boost	X	Output voltage	Cutoff frequency 400 Hz and 20 dB/dec
(Morales, Ordoñez, Morales & Flores, 2009)	Boost	PI	Output voltage	Regulate the voltage and frequency of an AC load
(López & Vannier, 2009)	Boost and a Buck	PI in cascade	Input and output voltage	X
(Goto, Guo & Ichinokura, 2009)	Normal and Bidirectional Buck-Boost	Optimization algorithm and charge balance	Extracted power and load voltage	X
(Sinha, Kumar, Samuel & Gupta, 2008)	Buck	X	Output voltage	Monitor and regulate the constant DC link voltage
(Chiniforoosh, Alaeinovin, Davoudi, Jatskevich & Chapman, 2008)	Boost	PI	Output voltage	X
(Arifujjaman, Iqbal & Quaicoe, 2008)	X	PID	Load effective value	X
(Eren, Hui, To & Yazdani, 2006)	Buck	X	Output current Output voltage	Charge the battery
(Tafticht, Agbossou & Cheriti, 2006)	Buck-Boost	MPPT control algorithm	Constant voltage-current	X
(Whaley, Ertasgin, Soong, Ertugrul, Darbyshire, Dehboeni & Nayar, 2006)	X	Lookup table	Current to the grid	Provide a sinusoidal current in phase with voltage
PAA%	87.50 %	79.17 %	95.83 %	70.83 %

Question *b*, topic 3 was only answered by (Lazarov et al., 2009), who reported that the presence of harmonics increases losses in the generator, which decreases its efficiency. Similarly, Question *c*, topic 3 was only answered by (Sinha et al., 2008) and (Eren et al., 2006), who impose a maximum ripple of 5%. Again, such results make evident the requirement for design specialized converters for wind power systems, which needs to analyze the effects of DC-DC converters in the generator of those applications, e.g. maximum ripple level, the permissible level of harmonics in the generator or the load. For the sake of brevity, Questions *b* and *c* are not present in Table 2 due to the small number of answers.

Question *a*, topic 4 was answered by 79.17% of the articles, where the most frequently used control strategies are the proportional-integral-derivative (P, PI, PID) with 45.83% of the studies. Additionally, custom algorithms are used to perform several specific tasks such as the charge management of a battery bank, track the maximum power, interfacing with the grid, etc.

Question *b*, topic 4 was answered by 95.83% of the articles, where the control variable depends on the application. For this reason, each article includes one or more variables of interest, among them are: the output voltage of the inverter, the generator speed, the generator output current, the power delivered to the load, etc. Question *c*, topic 4 was answered by 70.83% of the papers, where the criteria most frequently adopted was to track a reference variable in 50.00% of papers, e.g. the generator output current, voltage supplied to the load, among others. Such results show that the control variable and performance criteria strongly depend on the application, hence there is no clear trend: regulate dc-link or load voltage, regulate generator current, maximize the power production, etc. Similarly, P, PI, PID controllers are commonly used, which brings to light an opportunity to improve the wind power systems by adopting non-linear controllers to ensure the desired system performance beyond the linearization condition imposed by linear approaches.

Based on the PAA% of the review questions, the APAA% is 61.74% and the MAPAA% is 20.58%.

Every question with a PAA% lower than MAPAA% reveals an open problem not addressed in the literature. Questions *b* and *c* of topic 3 fall into this category, with PAA% equal to 4.16% and 8.33% respectively, which refers to the converter effects on the wind power systems, and the associated converter design to avoid, or at least to mitigate, the negative effects.

Conclusions

The wind low-power systems are commonly constructed using a wind turbine, a synchronous permanent magnet generator, an uncontrolled rectifier, a DC-DC converter, a battery bank for isolated operation, and/or an inverter for AC loads or grid connection. The review reveals that isolated applications are the most commonly addressed with these kinds of systems, where storage management is an open problem. Another topic not fully addressed in literature concerns the inclusion of turbine and generator dynamic models for control design, which are required to develop protection and optimization algorithms.

Concerning the DC-DC converters, the review points out the opportunity to design specialized converters to replace the classical structures used in current literature. The aim of the new converters could include the improvement of the energy efficiency, cost reduction, and the avoidance of transformers, among others. But such a design process requires analyzing the effects of DC-DC converters in the generator and turbine first—another open problem—to propose a suitable methodology for designing the converter components, e.g. inductor and capacitor sizes. Finally, the review also shows that current literature mainly adopts classical controllers to regulate the converter operation, which made clear the opportunity to propose non-linear controllers to improve system performance in operating points far from the linearization condition imposed in linear solutions.

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