Indirect matrix converter contribution in microgeneration systems for a sustainable energy planning

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Abstract:

Microturbine (MT) based generation systems present suitable and short-term implementation conditions in distributed generation (DG) context. However, as the power electronic converter used in the MT industry considers a back-to-back topology (B2B), this configuration presents some major drawbacks. The bulky capacitor, located between the rectifier and inverter circuits increases the maintenance cost and decreases the reliability and efficiency of the system. On the other hand, the Indirect Matrix Converter (IMC) is a flexible power electronic converter that features the lack of the reduced lifetime capacitor, a bidirectional power flow and a controllable power factor. This work proposes a systemic approach to assess the IMC enhancement in the MT system towards a sustainable energy planning. The methodology considers the concept of sustainability as a multidimensional object with technological, social, economic and environmental dimensions. It is based on technological indicators which impacts are addressed in the economic, social and environmental dimensions. By quantifying the impact of the technological indicators, i.e. electrical efficiency, power quality and power reliability, on the different dimensions, it is verified that the IMC features better results than the B2B converter and that it is possible to define the technological solution as a contribution for a sustainable energy planning. In this sense, the present work pretends to standardize a sustainability assessment methodology for technological innovations, especially when the innovation is a component of an established solution.

Keywords:

Energy planning, sustainability assessment, indirect matrix converter, microturbine.

1. Introduction

The increasing demand on electricity consumption and the growing requirements to democratize this service, are expressed in large investments on centralized power generation (CG). Nevertheless, technical difficulties in new power plants and transmission lines construction costs, turns the CG not able to deal with reliability, efficiency and power quality. In addition, restrictions on pollutant emissions require a change to cleaner technologies.

In this scenario, the DG offers potential for improvement on the mentioned challenges. Particularly, the MT is considered one of the DG technologies better positioned due to implementation flexibility characteristics for several applications, higher reliability and lower maintenance requirements [1]. A critical component of the generation system based on MT is the power electronic converter that should work with high frequency signals [2].

MT manufacturers work with the well-known B2B converter [3], which presents a topology with a reduced lifetime capacitive element in detriment of reliability and efficiency. Characteristics such as output voltage with minimal harmonics, controllable power factor and minimum energy storage elements, currently, are the most important requirements in power electronic converters [4]. The electronic converter capable to fulfill these requirements is the IMC, which does not have energy storage elements. Thus, this work proposes the IMC implementation analysis in generation systems based on MT in order to assess its contribution for a sustainable energy planning.

According to [5] and [6] the concept of sustainability is defined by axes or fundamental dimensions. In order to define a process as sustainable it should be considered some relevant dimensions, like, the economic, social, environmental, conservation of natural resources and, in some cases, the national policy.

In order to define the IMC implementation in microgeneration systems as a contribution towards a sustainable energy planning, this work defines technical indicators that are evaluated, quantitatively and qualitatively, in the three fundamental dimensions of the sustainability concept (economical, social and environmental). This methodology also allows identifying opportunities and constraints for the implementation of the generation project.

It is worth to mention that, due to the interaction between the technology involved in the energy sector, and the overall development process in a country, this methodology exposes the relations between the fundamental dimensions of sustainability implicated in the project.

This work is organized into 5 major sections. The generation system based on MT is introduced in section 2. Section 3 presents the analytical methodology proposed for the contribution assessment of the IMC, in the micro-generation system, towards a sustainable energy planning. The results and analysis obtained by estimating the impact of the technological indicators in the economic, social and environmental dimensions are shown in Section 4. Finally, section 5 presents the main conclusions of the work.

2. Microgeneration System

Originally the gas turbine was developed for applications in transportation, but smaller-scale units currently stand as a technologically appropriate option in distributed power generation. According to [7] and [8], below is detailed the characteristics of the microgeneration system. The MT operating speed offering greater efficiency and long-term reliability tends to be high, between 30000 rpm to 120000 rpm. The MT triggers a high frequency generator, usually a synchronous permanent magnet machine. The power of the individual units ranges from 30 kW to 250 kW, and features scalability to generate more energy power. The power generation has lower levels of CO_2 and NO_x emissions, actually MT emissions can be up to eight times lower than diesel generators. Being the most common fuel the natural gas, but also diesel, biogas can be used. The electrical efficiency of the microgeneration system is 25% to 30%, but in co-generation applications reaches a total efficiency of 75%.

The MT technology for generation purposes is recent, it began to be tested by 1997 and the commercialization was only initiated in 2000. By now, the MT generation systems are offered by a small number of suppliers, but it is expected that in the coming years more manufacturers enter to the market.

Figure 1 shows the block diagram of the generation system based on MT and the relationships of each subsystem to the environmental, economic and social dimensions. The microgeneration system is composed of the following subsystems: MT, synchronous generator, input filter, electronic power converter and output filter.

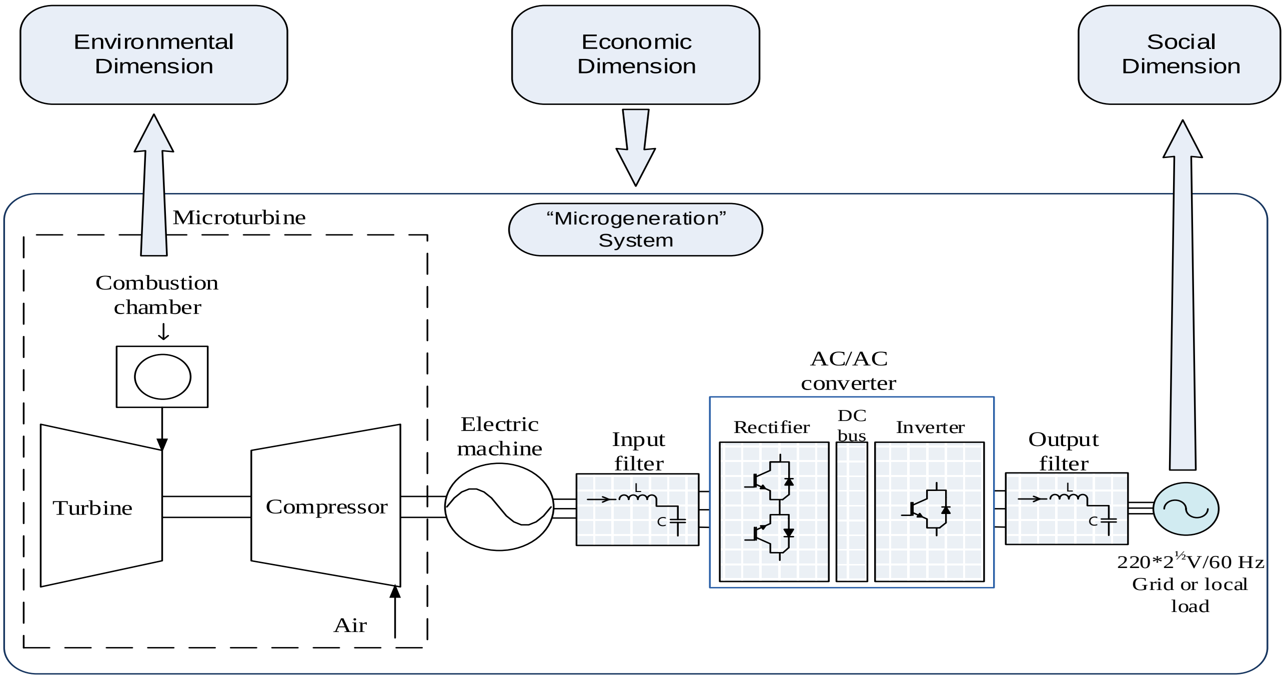

Fig. 1. Microgeneration block diagram related with the fundamental dimensions of sustainability.

The most important manufacturers of microgeneration systems, i.e. Capstone Turbine Corporation, General Electric, Ballard, Bowman and Elliott, and Xantrex, use the B2B electronic converter [9]. The B2B topology consists in two circuits, the first that converts the alternating current signal (AC) to direct current (DC), called rectifier, and the second from DC to AC, called inverter. The two circuits are connected through a DC bus regulated by a capacitive element. The DC bus capacitance is sufficiently large to act as attenuator of disturbances from the electric generator and the load, allowing the project of a simpler controller. With a limited capacitance value in the DC bus, the controller is no longer able to deal with the transients in the MT. Furthermore, it is considered that larger values of the DC bus capacitance contribute in size, weight and costs, and, on the other hand, it decreases the lifetime, reliability and efficiency.

In 90% of the industry applications the rectifier circuit is not controlled [10], i.e. the rectifier is based on diodes. This rectifier has low cost but presents less efficiency, contrary, the controlled rectifier, based on transistors, is more efficient but requires a dedicated control.

3. Methodology

The Latin American Energy Organization (OLADE) points out that the evaluation of energy processes naturally considers several sustainability indicators. According to [6], the indicators used to measure sustainable development have proven to be essential for monitoring the energy sector and the integration with the economy and the environment decisions as well as the social implications. On the other hand, in [11] indicators are considered communication tools for decision makers and consumers because they present quantitative and qualitative information about the sustainability of the energy process.

The methodology proposed to assess the IMC contribution in microgeneration systems towards a sustainable energy planning, is based on four technological indicators: displacement power factor (DPF), total harmonic distortion (THD), efficiency and reliability. The impact of these indicators is estimated, in section 4, considering the most important dimensions involved in the sustainability concept, that is, the economic, social and environmental dimension. The microgeneration system under analysis considers three electronic converters, the IMC and two B2B converters configurations, with controlled rectifier (B2BCR) and uncontrolled rectifier (B2BUR).

Table 1 presents the main relations identified between the technological indicators and the economic, environmental and social dimensions. In the following subsections, the technological indicators are presented and mathematically defined.

Table 1. Disciplinary matrix of the relations between the project indicators and the fundamental dimensions of sustainability

Technological Dimension	**Economical Dimension**	**Environmental Dimension**	**Social Dimension**
Indicators:	*Assessment:*	*Assessment:*	*Assessment:*
Efficiency (switching losses)		Efficiency impact	Efficiency impact
DPF			DPF impact
THD	THD impact		
Reliability	Reliability impact		

In the economical dimension are estimated the THD and the reliability impact. For the THD, it is analyzed the reduction on lifetime in certain equipment supplied by the generation system, which produces an early replacement of the damaged equipment. The reliability analysis considers the faults caused by the DC bus in the B2B converters, resulting in operating stops of the system. The efficiency impact is considered in the environmental dimension, assuming that an inefficient system generates less energy with the same emission levels. Finally, the impact of the efficiency and the DPF is estimated indirectly in the social dimension, it is assumed that the economics savings of the IMC based system can improve the social conditions.

3.1. Displacement power factor and total harmonic distortion

During the last decade, it has considerably increased the number of devices with high sensitive to power quality, such as, computers, process controls and communication devices among others. However, equipment like electrical machines and transformers also present high sensitivity [12].

The indicators for the power quality evaluation are the DPF and THD, both represented by the power factor (PF), defined in the following equation.

$$PF = \left(1/\sqrt{1+THD^2}\right)\cdot\left(\cos(\varphi)\right) = DF \cdot DPF \qquad (1)$$

Where, DF is the distortion factor. The THD is defined by the RMS of the current in the fundamental frequency, I_1, and the RMS of the nth harmonic of the current, I_n, as the next equation presents.

$$THD = \sqrt{\sum_{n=2}^{\infty} I_n^{\,2}} / I_1 \qquad (2)$$

A near unity PF implies low electricity losses, reduced risk of overheating, more useful energy available and low voltage variations (oscillations). On the other hand, a poor PF carries to premature aging of the equipment being supplied power.

3.2. Electrical efficiency

The development of power electronics technology has achieved a remarkable progress in the last twenty years. Nevertheless, the switching losses in these devices should be evaluated. The following equation defines the electrical efficiency by switching losses.

$$\eta_{elt} = \frac{Energy_{lost}}{Energy_{generated}} \qquad (3)$$

It should be noted that the energy waste reduction is as important as the generation, transmission and distribution of electric energy. The energy saved is considered the cheapest energy available and the efficiency control, an effective way to preserve the environment.

3.3. Reliability

The function of a generation system is to provide electrical power with a reasonable assurance of continuity and quality. According to [13], failures due to component degradation should be incorporated in the evaluation of the reliability of generation systems.

The MT has a useful lifetime (LT) that exceeds 13 years in continues operation applications and 20 year in peak power applications [14]. However, the capacitor in the DC bus, for B2B converters, exhibits a shorter operating life.

The capacitor installed on the DC bus normally has a high-energy storage capacity but also a high sensitivity to temperature, reducing its LT and increasing the microgeneration system maintenance costs [15]. The indicator used is the reliability factor of the converter, measured through the LT of the capacitor in the DC link as described in the subsequent equation.

$$C = \text{Capacitor } LT_{\text{DC bus}} \qquad (4)$$

4. Results and Analysis

The indicators impact is estimated in the following subsections, considering the description of Table 1.

4.1. Technology dimension

In this subsection is performed the indicators quantification in the technology dimension.

4.1.1. Electrical efficiency

Since the microgeneration system is a series connection of various subsystems, the energy efficiency is obtained by multiplying the efficiency of each of them. Tables 2, 3 and 4 present the electrical efficiency implication of the IMC and the B2BCR in the energy efficiency of the microgeneration system.

The efficiency of the IMC and the B2BCR are taken from [16], where it is presented a comparative study of the electrical efficiency, in terms of load capacity, considering the switching losses. The efficiency of the MT and the synchronous generator are taken from [17].

Table 2. Microgeneration system efficiency at maximum load (100 %)

Converter based on	Microturbine efficiency (%)	Synchronous Generator efficiency (%)	Electronic converter efficiency (%)	Microgeneration System efficiency (%)
B2BCR	33.7	95	92	29.45
IMC	33.7	95	94.5	30.25

Table 3. Microgeneration system efficiency at medium load (50 %)

Converter based on	Microturbine efficiency (%)	Synchronous Generator efficiency (%)	Electronic converter efficiency (%)	Microgeneration System efficiency (%)
B2BCR	33.7	95	90.7	29.03
IMC	33.7	95	95	30.41

Table 4. Microgeneration system efficiency at minimum load (25 %)

Converter based on	Microturbine efficiency (%)	Synchronous generator efficiency (%)	Electronic converter efficiency (%)	Microgeneration system efficiency (%)
B2BCR	33.7	95	87.5	28.01
IMC	33.7	95	95	30.41

Considering the three types of load capacity, it is possible to note that the energy efficiency of the microgeneration system based on IMC is slightly higher than the system based on B2BCR. Particularly, the system at minimum load presents the greatest energy efficiency difference. It should be mentioned that the B2BUR has lower electrical efficiency than the B2BCR [18].

4.1.2. Displacement power factor

Table 5 shows the DPF of the IMC and B2B converters. The B2B converters DPF is taken from the comparative study developed in [19]. For the IMC, it is considered a unitary DPF reached by means of a current control [20].

Table 5. DPF of the IMC and B2B converters

Converter	DPF
B2BUR	0.8
B2BCR	0.96
IMC	1.0

As it can be seen, the IMC reaches an optimal DPF meanwhile the B2B converters present factors less than 1.

4.1.3. Total harmonic distortion

[19] presents a current THD comparative study between the B2B converters and [21] obtains the current THD of the IMC, Table 6 summarizes these results.

Table 6. THD of the current in the IMC and B2B converters

Converter	THD
B2BUR	3.8 %
B2BCR	1.6 %
IMC	1.1 %

Table 6 shows that the IMC presents the best THD factor. Where, the B2BCR exhibits a harmonic distortion 45% higher and the B2BCR 245%.

4.1.4. Reliability

According to [22], about 30 % of the electronic equipment breakdowns are caused by the power converters. Since more than half of the converters failures are due to electrolytic capacitors [23], monitoring its LT is compulsory.

The service life of capacitors is reported in hours of operation as a function of temperature, operating voltage and ripple current. Although the capacitor LT is function of several variables, Table 7 shows the typical LT of the capacitor in a power converter at a temperature of 105 ^{o}C, this variable is estimated in the studies [24] and [15].

Table 7. DC bus capacitor LT at 105^{o}C

Capacitor type	Lifetime
Aluminum electrolytic capacitor	7000 hours
Electrolytic capacitor	10000 hours

4.2. Economic dimension

According to Table 1, the impact of the THD and the reliability in the economic dimension is assessed below.

4.2.1. Total harmonic distortion

[25] presents the mathematical model of the LT of electrical equipment and components as a function of the THD. The model shows that the LT reduction has an exponential behaviour. Moreover, [26] shows that a generation system with 10% of output current THD can decrease the LT of single-phase machines in 32.5%, of three-phase machines in 18% and of transformers in 5%.

Based on [25] and [26], it is estimated in Table 8 the LT reduction of single and three-phase machines and transformers, due to the THD that present the IMC and B2B converters in the microgeneration system.

Table 8. LT reduction (%) estimated according to the THD

Converter based on	Microgeneration system THD (%)	LT reduction of Single-phase machines (%)	LT reduction of Three-phase machines (%)	LT reduction of Transformers (%)
B2BUR	3.8	5.91	3.27	0.91
B2BCR	1.6	1.24	0.68	0.19
IMC	1.1	0.65	0.36	0.1

It can be seen that the IMC presents a smaller LT reduction than the B2B converters. The analysis of Table 8 presents the assessment of widely used equipment in the industry, however, electronic equipment also present sensitivity to harmonic distortion. A smaller reduction in LT carries to economic benefits, since the replacement of the equipment is delayed and, therefore, fewer investments are expected.

4.2.2. Reliability

The estimated LT of the MT varies from 40000 to 80000 hours [27] and the capacitor LT in the B2B converters ranges from 7000 to 10000 hours. Although the capacitor is subject to maintenance, it remains as a potential cause for an unexpected stop of the microgeneration system. According to the LT data, Table 9 presents the number of potential failures in the microgeneration system caused by the capacitor in the B2B converters. The number of potential faults is found through the division of the MT LT by the capacitor LT.

Table 9. Microgeneration system failures due to the DC bus capacitor in B2B converters

Capacitor LT→ MT LT↓	7000 hours	10000 hours
40000 hours	5.71 failures	4 failures
80000 hours	11.43 failures	8 failures

As Table 9 shows, the number of potential faults estimated in the microgeneration system due to the capacitor in the B2B converters ranges from 6 to 12 times during the LT of the MT. The MT operating stop not only implies a maintenance visit, but also involves the operation stop of the equipment being supplied. Economic losses caused by non-scheduled operation stops in some Brazilian industries [28] are presented in Table 10.

Table 10. Economic losses in Brazilian industry in an hour-long operation stop

Converter	THD
Food	3.36 USD/MWh
Footwear and Textile Articles	96.1 USD/MWh
Pharmaceutical and Veterinary	3726.22 USD/MWh

Since DG applications feature high-reliability power, any potential cause of failure, like the DC bus capacitance, should be avoided.

4.3. Environmental dimension

The impact of the electrical efficiency in the environmental dimension is assessed below.

4.3.1. Electrical Efficiency

In [29] are estimated the microgeneration system emissions in pounds per MWh at full load. From these data and Table 2, in Table 11 are estimated the emissions produced considering the B2BCR and the IMC.

Table 11 - Microgeneration system emissions (kilogram/MWh), at maximum load (100%)

Converter based on	NO_x	SO_x	PM-10	CO_2
B2BCR	0.1996	0.0036	0.0408	0.7239
IMC	0.1978	0.0036	0.0404	0.7180

Table 11 shows that due to the increased energy efficiency of the IMC, compared to the B2BCR, the emissions are reduced in the same proportion as the efficiency is increased. At full load power generation, the energy efficiency increase with the IMC is about 0.8%, thus the emissions are reduced in this percentage. The efficiency increase at medium and minimum load are 1.38% and 2.4%, hence the emissions are reduced by 1.38% and 2.4% respectively.

4.4. Social dimension

[5] defines two sustainability indicators on the social dimension, the coverage of electricity energy services and the electricity energy consumption in homes. According to [30], still there are homes in Latin America and the Caribbean that do not have complete access to electricity consumption. It is demonstrated that low diversity in energy supply causes lower rates of electricity consumption.

Since the reduction of electrical losses in the electronic converter increases the competitive of the microgeneration system, it is assumed that the economic benefits can increase the diversity in energy supply. Therefore, the decrease of the energy insufficiency should improve the social conditions.

On the other hand, it is worth to note that the increase in efficiency delays the investments in infrastructure, with social impacts (e.g., flooding and family displacements for hydroelectric power generation) and environmental impacts (e.g., deforestation). As presented in Table 1, below is shown the impact of the efficiency and the DPF in the economic dimension and indirectly in the social dimension.

4.4.1. Electrical Efficiency

The economic impact of the microgeneration system energy efficiency, due to switching losses, is evaluated in Tables 12, 13 and 14. The analysis is performed for a microgeneration system of 250kW of capacity in continuous operation (6000 hours/year). The Brazilian cost of natural gas per MMBTU is taken from [31].

Table 12. Generation cost at maximum load (100%)

Converter based on	Microgeneration system energy efficiency (%)	Power transformed in electricity (kW)	Equivalent power delivered by the fuel (kW)	Operation hours per year (hours)	Fuel consumption of the system (MMBTU)	Natural gas cost (USD/ MMBTU)	Electricity generation cost per year (USD/year)
B2BCR	29.45	250	848.90	6000	17365.93	12.69	220373.63
IMC	30.25	250	826.45	6000	16906.66	12.69	214545.57
						Difference:	5828.06

Table 13. Generation cost at medium load (50%)

Converter based on	Microgeneration system energy efficiency (%)	Power transformed in electricity (kW)	Equivalent power delivered by the fuel (kW)	Operation hours per year (hours)	Fuel consumption of the system (MMBTU)	Natural gas cost (USD/ MMBTU)	Electricity generation cost per year (USD/year)
B2BCR	29.03	250	861.18	6000	17617.18	12.69	223561.95
IMC	30.41	250	822.10	6000	16817.71	12.69	213416.75
						Difference:	10145.20

Table 14. Generation cost at minimum load (25%)

Converter based on	Microgeneration system energy efficiency (%)	Power transformed in electricity (kW)	Equivalent power delivered by the fuel (kW)	Operation hours per year (hours)	Fuel consumption of the system (MMBTU)	Natural gas cost (USD/ MMBTU)	Electricity generation cost per year (USD/year)
B2BCR	28.01	250	892.54	6000	18258.71	12.69	231703.09
IMC	30.41	250	822.10	6000	16817.71	12.69	213416.75
						Difference:	18286.33

The equivalent power delivered by the fuel is calculated dividing the power transformed in electricity by the microgeneration system energy efficiency. The fuel consumption of the system is calculated multiplying the equivalent power delivered by the fuel by the operation hours per year, it is applied a energy unit conversion from kWh to MMBTU. Finally, the total generation cost per year is obtained multiplying the fuel consumption of the system by the natural gas cost.

At maximum load, Table 12, the IMC implementation provides a gain in the generation costs of USD 5828.06 per year. At medium and minimum load, tables 13 and 14 respectively, the gain is USD 10145.20 and USD 18286.33 respectively. Analyzing the first case, the most efficient use of the MT, the IMC economic gain during the LT of the MT, approximately 13 years in continuous operation, reaches a total amount of USD 69936.76, an amount that represents a considerable value.

4.4.2. Displacement Power factor

The economic impact of losses due to the DPF is evaluated in Table 15. The analysis is performed for a MT of 250 kW of capacity in continuous operation, the Brazilian cost of electricity per kWh generated is taken from [32].

Table 14. Economic losses due to the DPF

Converter based on	DPF	Microgeneration system power (kW)	Real power loss (kW)	Operation hours per year (hours)	Electricity cost (USD/ kWh)	Reactive power cost per year (USD)
B2BUR	0.8	250	50	6000	0.164	49200.00
B2BCR	0.96	250	10	6000	0.164	9840.00
IMC	1.0	250	0	6000	0.164	0.00

The economic impact of the real power loss refers to the reactive power that is generated due to the inefficient DPF, less than one. The economic loss of the B2BCR, due to the DPF, reaches USD 9840.00 per year, amount even greater than the economic loss due to the efficiency.

5. Conclusions

The concept of sustainability requires a complete analysis considering a systemic approach of at least the technological, social, economic and environmental dimensions. Additionally, a sustainability assessment to define technology solutions as sustainable energy planning contributions is required. In this sense, this work proposes a methodology based on technology indicators in order to establish solutions as contributions towards a sustainable energy planning.

The proposed methodology quantifies the impact of the technological indicators: electrical efficiency, power quality and power reliability, in all three dimensions of the sustainability concept, i.e. the social, economic and environmental dimensions. The presented results determine better conditions of the IMC in the microgeneration system, than the B2B converters used in the MT industry, to contribute in a sustainable energy planning.

Acknowledgments

The authors acknowledge UFABC (Universidade Federal do ABC) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for the financial support.

Nomenclature

MT	Microturbine
DG	Distributed generation
B2B	Back-to-back converter
IMC	Indirect matrix converter
CG	Centralized generation
CO_2	Carbon dioxide
NO_x	Nitrogen oxides
SO_x	Sulfur oxides
PM-10	Particulate Matter up to 10 micrometers in size
AC	Alternating current
DC	Direct current
DPF	Displacement power factor
THD	Total harmonic distortion
B2BCR	Back-to-back converter with controlled rectifier
B2BUR	Back-to-back converter with uncontrolled rectifier

PF	Power factor
DF	Distortion factor
LT	Lifetime
USD	United States Dollar

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