5th International Conference on Control Engineering&Information Technology (CEIT-2017)
Proceeding of Engineering and Technology –PET
Vol.33 pp. 1-7

Power Quality Improvement in Distributed Generation based Islanded Microgrid Applications

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***Abstract*— This paper deals with power quality improvement in distributed generation based standalone microgrid applications. Indeed, a new configuration of microgrids is preconized based on the integration of active power filters with the aim to enhance the power quality and increase the power factor in microgrids by compensatingfor both harmonic and reactive current components. A fuzzy based control strategy is proposed to control the active filter based on its Takagi-Sugueno multi-models fuzzy representation. A co-simulation is carried out combining Matlab/Simulink and PSIM environments in order to highlight the effectiveness of the global control structure and the suitability of the proposed microgrid configuration that shows enhanced power quality even in presence of highly nonlinear loads.**

Keywords—Microgrid; Distributed Generation; Power Quality; Active Filter, Fuzzy Modelling; Fuzzy Control

I. INTRODUCTION

Power quality is an ongoing challenge and a major concern not only in conventional electricity grids, but also in standalone microgrids because of the necessity to supply both linear and nonlinear loads with a high quality energy[1]. The prominence of nonlinear loads accentuates further these concerns with negative consequences over many appliances[2]. Indeed, nonlinear loads drain partially or completely distorted currents, which increases the proportion of harmonic currents in microgrids and reduces power quality at all point of common coupling (PCC)[3]. In this way, and in order to limit the propagation of these perturbations in microgrids and comply with most of energy quality requirements, different techniques can be employed including either active, passive or hybrid filtering strategies with series or parallel connection topologies[4]. According to IEEE 519 and IEC 61000 standards, if the total harmonic distortion of the line currents does not exceed 50%, normal operation of connected equipment is ensured even if beyond 10% , oversizing cables and sources is necessary in order to counteract the effects of heating. On the other hand, if the harmonic content of the line current exceeds 50%, significant malfunctions are likely to be and the installation of power quality improvement systems is mandatory[5], [6]. Although the aforementioned limits are related to the conventional electricity networks, these can be extended to distributed generation based microgrids[7]. Consequently, in view of standalone microgrid power-quality requirements, the reconfiguration of microgrids based on the integration of shunt active power filters is proposed in this paper (Fig.1) with the aim to improve power quality by reducing the proportion of reactive and harmonic line currents' components introduced by the presence of highly nonlinear loads in microgrids.

Several control strategies are proposed in the literature for active power filtering systems. The use of linear control including essentially Proportional Integral and Resonant controller, nonlinear control, and advanced control strategies is usually preconized[8]–[13]. However, these control techniques are subject to numerous limitations owing to their sensitivity to model uncertainties and parameters variations since they basically require a precise model of the system. Meanwhile, the unpredictable nature of both microgrids's DG units and loads makes the establishment of the establishment of a comprehensive model of microgrids remains fairly complex[14]. In this sense, multi-model representation becomes a natural alternative to model complex systems around different points and zones of operation. The main idea of this approach is to build a global model of the system to be controlled based on the aggregation of a set of sub-models[15]. Thus, the development of the controller will be based on the resulting global model. In this way, a fuzzy based control strategy is proposed in this paper based on the Takagi-Sugeno (T-S) multi-models fuzzy representation of the associated active power filter. Indeed, the fuzzy description of the system is used to design the developed fuzzy controller based on the parallel distributed compensation approach.

The remaining of this paper describes in section 2 the modeling of shunt active power filters, while section 3 develops the proposed fuzzy based control strategy, section 4 displays the co-simulations results, and section 5 concludes.

ISSN 2356-5608

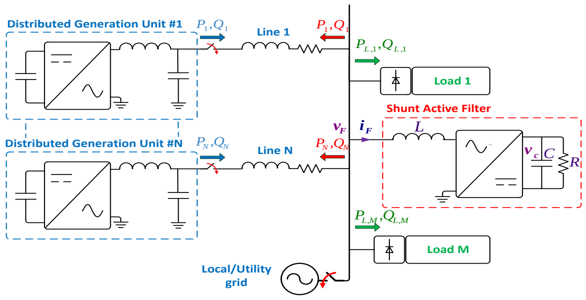


Fig. 1. Block diagram of the proposed microgrid configuration

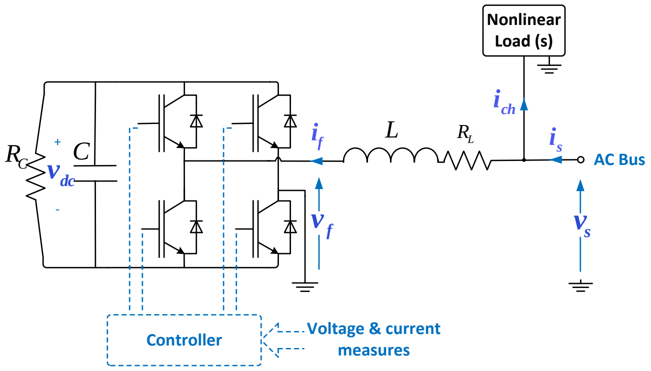


Fig. 2. Power circuit of the active power filter

II. SYSTEM DESCRIPTION

The studied active filtering system consists essentially of a single-phase full-bridge inverter. An inductive output filter is also employed to avoid the introduction of high frequency harmonics due to switching. A resistor with a high-value is introduced to ensure the discharge of the DC side capacitor during end of operation. The active filter is connected in parallel with the pollutant loads and the microgrid AC bus with the objective to relieve the sinusoidal form of the line current $i_s$by compensating for the harmonic and reactive current components via the injection/absorption of the compensating current $i_f$given that loads absorb a currenti_{ch}. The line current results from the currents supplied by the parallel connected distributed generators.

The bilinear differential equations describing the dynamics of the output current and voltage of the single-phase full bridge shunt active filter, shown by Fig.2, are given as follows:

$$\begin{cases} L\dfrac{di_f}{dt} = v_s - Sv_{dc} \\ C\dfrac{dv_{dc}}{dt} = Si_f - \dfrac{v_{dc}}{R_C} \end{cases} \quad (1)$$

where, $v_s$represents the voltage at the microgrid point of common coupling (PCC). v_f is the output voltage of the inverter, being $v_f = S \times v_{dc}$, where $v_{dc}$is the DC bus voltage across, and $S \subset \{-1, +1\}$ the switching state obtained based on a bipolar switching strategy, while i_f represent the active filter compensating current. R_C and C represent respectively the parallel resistor and the DC side capacitor of the active filter, while L represents the output inductance of the active filter.

Based on equation (1) and assuming that the switching frequency is sufficiently high, the average model of the system during a switching period can be set as follows:

$$\begin{cases} L\dfrac{di_f}{dt} = v_s - (1-2\,u)v_{dc} \\ C\dfrac{dv_{dc}}{dt} = (1-2\,u)i_f - \dfrac{v_{dc}}{R_C} \end{cases} \quad (2)$$

where, $u \in [0\ 1]$ représents the duty cycle.

The state space representation of the above equation is given by:

$$\dot{x} = Ax + Bxu + Ew \quad (3)$$

where, $\boldsymbol{x} = [i_f \quad v_{dc}]^T$ is the state vector, $w = v_s$.
The coefficients are given by:

$$A = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & -\frac{1}{R_C C} \end{bmatrix}, B = \begin{bmatrix} 0 & \frac{2}{L} \\ -\frac{2}{C} & 0 \end{bmatrix}, \text{et } E = \begin{bmatrix} \frac{1}{L} & 0 \end{bmatrix}^T$$

III. DESIGN OF THE PROPOSED CONTROL STRATEGY

A. T-S Fuzzy modelling of the Shunt Active Filter

Takagi-Sugeno's multi-model fuzzy based representation allows representing complex systems through the interpolation of several sub-models characterizing different operating zones. The resulting representation is the weighted sum of local models based on if-then rules. The number of local models depends on the desired precision and the complexity of the system under study. Several approaches are used to obtain the sub-models of a system. Among others, the sectorial approach wherein the system' non-linearities are bounded by minima and maxima [16], [17], as well as the approach described by [18], which consists in linearizing the system around different operating points. The last method, is based on the resolution of an identification problem with the possibility to reduce the problem of identification of the global system to the identification of sub-systems that define linear local models.

In the following, sub-models are obtained based on the linearization of the system described by (3). Indeed, equation (3) can be developed as Taylor's series around the point (x_0, u_0):

$$\dot{\boldsymbol{x}} = f(\boldsymbol{x_0}, u_0) + \frac{df}{d\boldsymbol{x}}\Big|_{\substack{x=x_0\\u=u_0}} (\boldsymbol{x} - \boldsymbol{x}_0) + \frac{df}{du}\Big|_{\substack{x=x_0\\u=u_0}} (u - u_0) + \text{H.O.T} \quad (4)$$

where, $f(\boldsymbol{x_0}, u_0) = \boldsymbol{Ax_0} + \boldsymbol{Bx_0}u_0 + \boldsymbol{E}w$. Besides, if$(\boldsymbol{x_0}, u_0)$is an equilibrium point of (3), $\dot{\boldsymbol{x}} = 0$, the system's dynamic can be linearized around the equilibrium pointas follows:

$$\dot{\boldsymbol{x}}_\delta = \boldsymbol{A}_\delta \boldsymbol{x}_\delta + \boldsymbol{B}_\delta u_\delta \quad (5)$$

where, $\boldsymbol{x}_\delta = \boldsymbol{x} - \boldsymbol{x_0}$, $u_\delta = u - u_0$,

$$A_\delta = \frac{df}{dx}\Big|_{\substack{x=x_0\\u=u_0}} = A + Bu_0 = \begin{bmatrix} 0 & \frac{(2u_0 - 1)}{L} \\ \frac{(1-2u_0)}{C} & -\frac{1}{R_C C} \end{bmatrix}$$

and

$$B_\delta = \frac{df}{du}\Big|_{\substack{x=x_0\\u=u_0}} = Bx_0 = \begin{bmatrix} \frac{2}{L}x_{0,2} \\ -\frac{2}{C}x_{0.1} \end{bmatrix}$$

Takagi-Sugeno's multi-model fuzzy based representation of (3) is built based on if-then rules. The premise variables, also called decision variables, are chosen as a function of the voltage v_{dc} variation given its importance to secure proper operation of active filters. In this way, two variables are chosen:

$$\begin{cases} z_1 = v_{dc}^* - v_{dc} \\ z_2 = \int_0^t (v_{dc}^* - v_{dc})dt \end{cases} \quad (6)$$

where, v_{dc}^* represents the voltage reference of the active filter DC bus.

Two fuzzy sets are used for each premise, Positive (P) and Negative (N), referring respectively to the trapezoidal function $\mu_P(z_j)$ and $\mu_N(z_j)$. The membership functions $\mu_P(z_j)$ and $\mu_N(z_j)$ are given by:

$$\mu_P(z_j) = \begin{cases} 0, & z_j < -\propto_j \\ \frac{z_j + \propto_j}{2\propto_j}, & -\propto_j \le z_j \le \propto_j \text{ , for j = 1,2} \\ 1, & z_j > \propto_j \end{cases} \quad (7)$$

and,

$$\mu_N(z_j) = \begin{cases} 0, & z_j < -\propto_j \\ \frac{z_j + \propto_j}{2\propto_j}, & -\propto_j \le z_j \le \propto_j \text{ , for j = 1,2} \\ 1, & z_j > \propto_j \end{cases} \quad (8)$$

These functions are illustrated in Fig.3. The values of $\propto_1$ and $\propto_2$ are chosen as a function of the maximum allowablerange for the DC bus voltage.

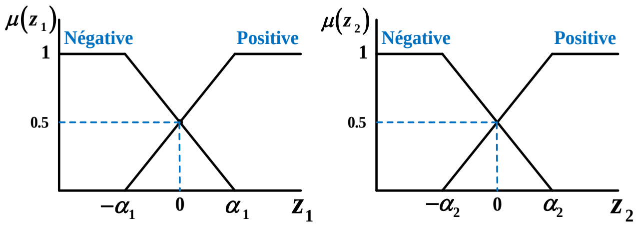


Fig. 3. Membership functions

Four if-then rules are used:

$$\begin{cases} \text{Model rule } R^1: if\ z_1 \text{ is } P\ and\ z_2\ is\ P, then\ \dot{x}_\delta = A_{\delta,1}x_\delta + B_{\delta,1}u_\delta \\ \text{Model rule } R^2: if\ z_1 \text{ is } P\ and\ z_2\ is\ N, then\ \dot{x}_\delta = A_{\delta,2}x_\delta + B_{\delta,2}u_\delta \\ \text{Model rule } R^3: if\ z_1 \text{ is } N\ and\ z_2\ is\ P, then\ \dot{x}_\delta = A_{\delta,3}x_\delta + B_{\delta,3}u_\delta \\ \text{Model rule } R^4: if\ z_1 \text{ is } N\ and\ z_2\ is\ N, then\ \dot{x}_\delta = A_{\delta,4}x_\delta + B_{\delta,4}u_\delta \end{cases} \quad (9)$$

Finally, the system (3) can be expressed by the following T-S fuzzy model.

$$\dot{x}_\delta = \hat{A}_\delta x_\delta + \hat{B}_\delta u_\delta \quad (10)$$

and,

$$\hat{A}_\delta = \sum_{i=1}^{4} h_i(z) A_{\delta,i}$$

$$\hat{B}_\delta = \sum_{i=1}^{4} h_i(z) B_{\delta,i}$$

where,

$$h_i(z) = \frac{\prod_{j=1}^{2} \mu_{j,i}(z_j)}{\sum_{i=1}^{4} \prod_{j=1}^{2} \mu_{j,i}(z_j)}$$

$$\text{and } \sum_{i=1}^{4} h_i(z) = 1\ et\ z = [z_1 \quad z_2]^T$$

The function $h_i(z)$ refers to the contribution of the local sub-model associated to the index i in the global system.

B. T-S Fuzzy model based fuzzy controller

The objective of the proposed control strategy, illustrated in Figure 4.9, is to ensure not only the control of the compensating active filter current through the control of its DC bus voltage, but also to ensure the stability of the fuzzy Takagi-Sugeno systems developed. In this way, a controller based on the Parallel Distributed Compensation (PDC) approach is used. The advantage of this technique is that it keeps the same structure as the fuzzy representation developed above.

On the basis of the model (10), the proposed fuzzy controller can be described by the following rules wherein a control gain vector is assigned for each sub-model:

$$\begin{cases} \text{Control rule } R^1: if\ z_1 \text{ is } P\ and\ z_2\ is\ P, then\ u_{\delta,1} = -K_1 x_\delta \\ \text{Control rule } R^2: if\ z_1 \text{ is } P\ and\ z_2\ is\ N, then\ u_{\delta,2} = -K_2 x_\delta \\ \text{Control rule } R^3: if\ z_1 \text{ is } N\ and\ z_2\ is\ P, then\ u_{\delta,3} = -K_3 x_\delta \\ \text{Control rule } R^4: if\ z_1 \text{ is } N\ and\ z_2\ is\ N, then\ u_{\delta,4} = -K_4 x_\delta \end{cases} \quad (11)$$

The final control law, described below, is established using the same membership functions as used in the fuzzy description of the system.

$$u_\delta = -\sum_{i=1}^{4} h_i(z)\, K_i x_\delta \quad (12)$$

The state feedback gains K_i, for i=1,2,3 and 4, are selected with the objective to secure proper and stable operation.

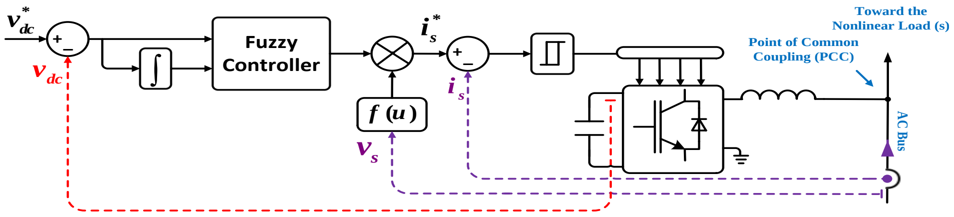


Fig. 4. Block diagram of the proposed fuzzy based control strategy

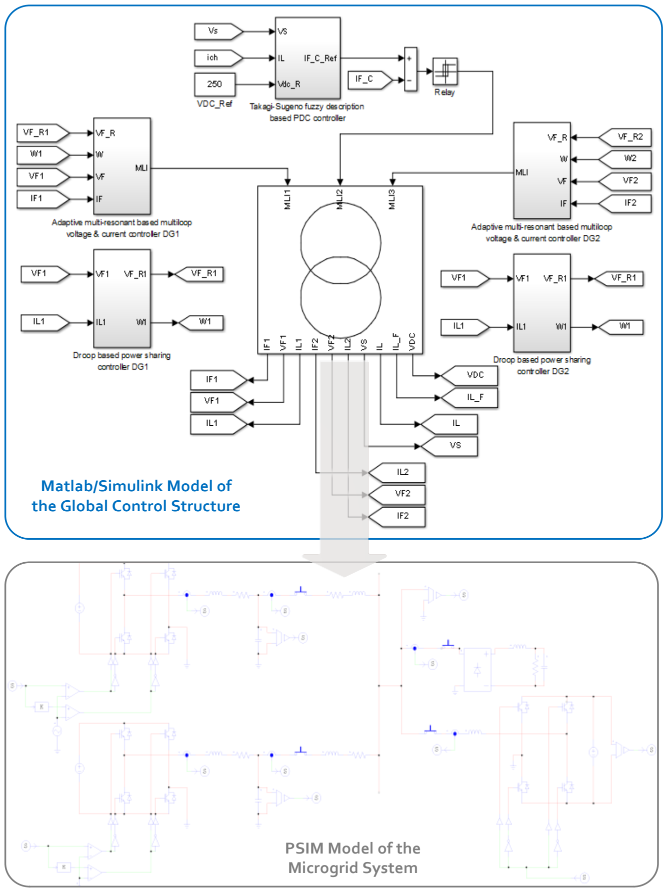


Fig. 5. Co-simulation model of the proposed microgrid configuration

IV. CO-SIMULATION RESULTS

In order to evaluate the performances of the proposed active filter fuzzy based control strategy, a simulation platformwas built combining two simulation environments, namely Matlab/Simulink and PSIM. As shown in Fig.5, the proposed microgrid configuration consists of two distributed generators supplying a rectifier type nonlinear load. The nonlinear load consists of a full-bridge single-phase rectifier delivering to a RLC load. The performance of the associated active filter and its effectiveness to improve the power quality in microgrid is investigated. The overall simulation parameters are listed in Table 11.The obtained results are shown through Fig 6to14.

The first test reveals the dynamic of the whole system against a sudden connection of the active filter to the microgrid. The results obtained are shown in Fig.6, which includes the PCC's voltage, the load current, the output currents of DG# 1 and DG# 2, the compensation current and the DC bus voltage of the associated active filter. It appears clearly that the active filter compensates for the reactive and harmonic currents initially delivered by the two interconnected generators to the non-linear load. The sinusoidal shape of the line currents is re-established within few periods after the connection of the active filter.

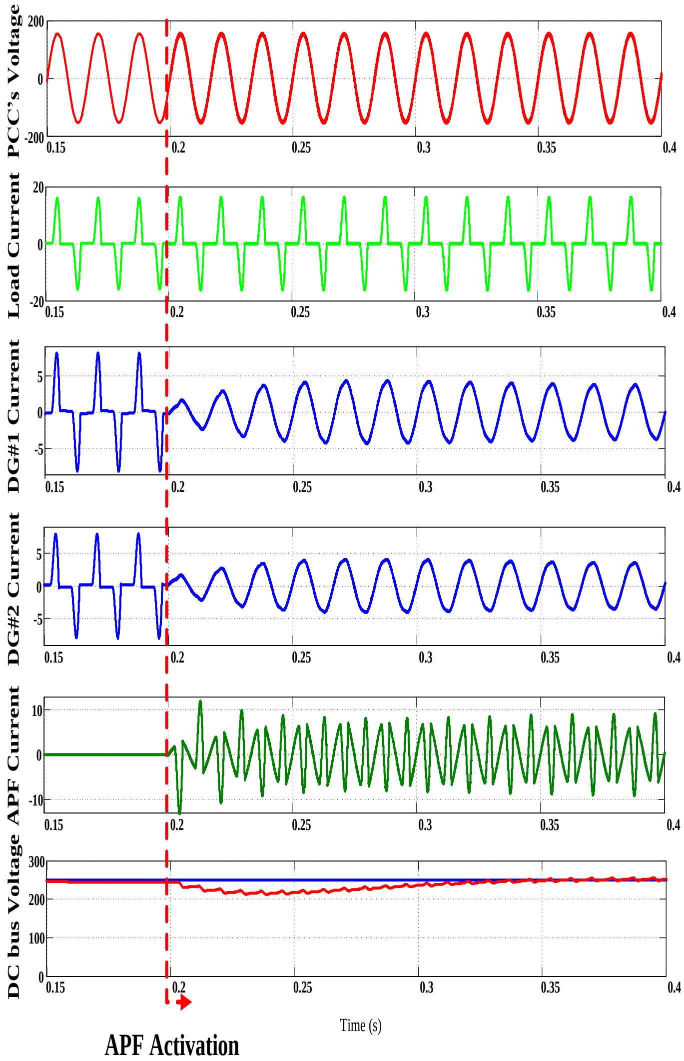


Fig. 6. Voltage and current waveforms before and after the integration of the active filter to the microgrid.).

Next, both current and voltage waveforms with their respective harmonic spectra are represented in the case where the active filter is not connected to the microgrid. The PCC's voltage waveform, illustrated in Fig 7, follows a quasi-sinusoidal shape with a small (<1%) harmonic distortion even when highly nonlinear loads are supplied. As shown by Fig.8, the load current is characterized by more than 90% harmonic distortion with the predominance of 3rd, 5th, 7th, 9th and 11th harmonics. The output currents of the parallel distributed generators, inter alia DG#1 and DG#2, shown in Fig 9 and 10, indicate the same harmonic characteristics as the load current with 88.28% and 91.47% harmonic content, respectively.

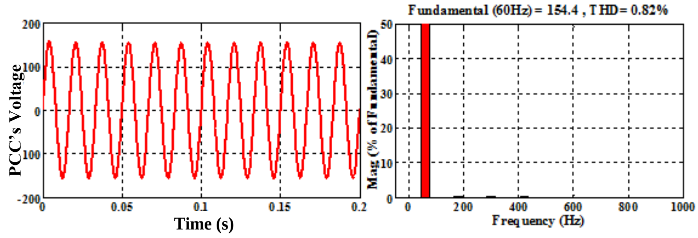


Fig. 7. PCC's voltage waveform (left) and its harmonic spectrum (right) – microgrid without an active filter.

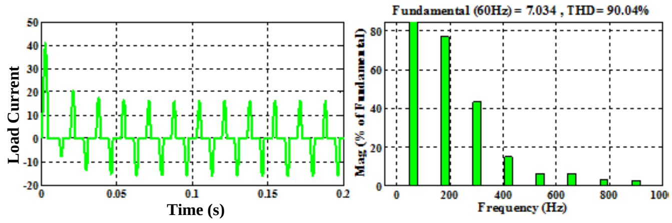


Fig. 8. Nonlinear load's current waveform (left) and its harmonic spectrum (right) – microgrid without an active filter.

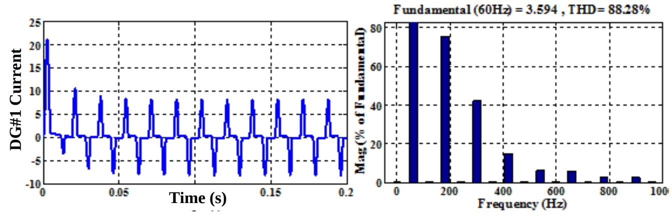


Fig. 9. Output current waveform of DG#1 (left) and its harmonic spectrum (right) – microgrid without an active filter.

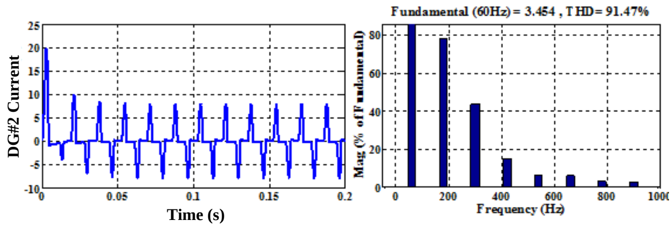


Fig. 10. Output current waveform of DG#2 (left) and its harmonic spectrum (right) – microgrid without an active filter.

The integration of the active filter aims to reduce the total harmonic distortion of the microgrid lines' currents lesser than 10% according to IEC standards or even to 5% according to IEEE standards. This objective is achieved in view of the obtained results, illustrated by Fig.11 to 14. Indeed, as shown by Fig.12 and 13, the output currents of DG#1 and DG# 2 have quasi-sinusoidal curves with a harmonic content lower than 4%. The analysis of their corresponding harmonic spectra confirms the low presence of the 3rd, 5th, 7th, 9th and 11th harmonics in the line currents thanks to the associated active filter that delivers the compensation current, illustrated in Fig.14. The harmonic spectrum of the compensation current is rich in harmonics of the same frequencies as those of the load current with an insignificant fundamental component.

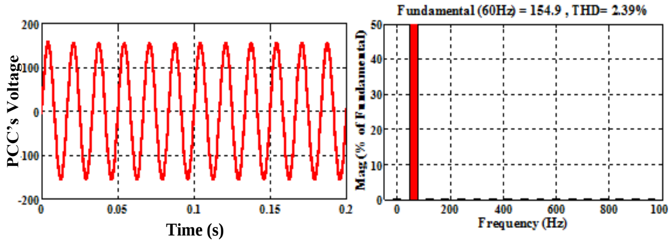


Fig. 11. PCC's voltage waveform (left) and its harmonic spectrum (right) – microgrid with an active filter.

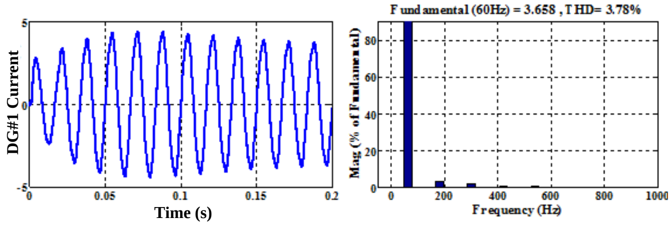
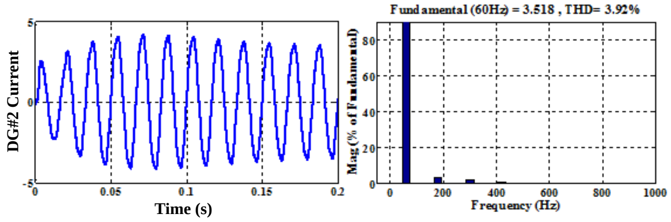


Fig. 12. Output current waveform of DG#1 (left) and its harmonic spectrum (right) – microgrid with an active filter.



The design of the active filter, inter alia the coupling inductance, is of importance since it must ensure the attenuation of the switching harmonics in order to avoid accentuating the distortion of the PCC's voltage. Indeed, as shown by Fig.11, it appears that the total harmonic distortion of the PCC's voltage increases from 0.82% to 2.39% after the integration of the active filter. The integration of the active filter will not only improve power quality in microgrids, but will offers the possibility to supply both DC and AC loads through a bidirectional power flow, which depends essentially on the DC bus voltage regulation performance.

V. CONCLUSION

The reconfiguration of microgrids through the integration of shunt active filters has been proposed in order to support the power quality in distributed generation based microgrids in presence of critical and highly nonlinear loading conditions. A fuzzy based controller was developed based on the Takagi-Sugueno multi-models fuzzy description of the associated active filter. This technique offers satisfactory performances and positions as an effective solution to surpass the unpredictable nature of microgrids. The obtained Co-simulation results allow us to assert the validity of the control strategies developed.

Fig. 13. Output current waveform of DG#2 (left) and its harmonic spectrum (right) – microgrid with an active filter.

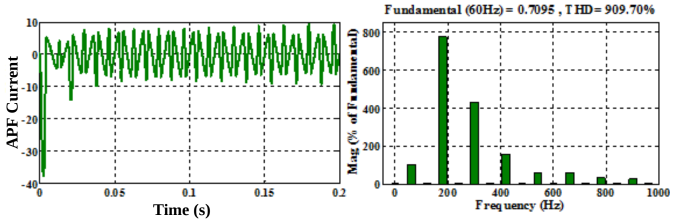


Fig. 14. Active filter compensation current waveform (left) and its harmonic spectrum (right).

TABLE I. POWER STAGE AND CONTROL PARAMETERS

Parameters	Symbol	Value
PCC's voltage	V_s	$\sqrt{2} \times 110V/60Hz$
DC bus voltage	V_{dc}	$250\ V$
Inductance	L	$4\ mH$
Capacitance	C	$1000\ \mu F$
Resistance	R_C	$10\ k\Omega$
Control gains	K_1	$[0 \quad 0.0051 \quad -0.0027]$
	K_2	$[0 \quad 0.0051 \quad -0.0027]$
	K_3	$[0 \quad 0.0055 \quad -0.0029]$
	K_4	$[0 \quad 0.0056 \quad -0.0029]$

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