Three-Phase Four-Wire Active Power Conditioners for Weak Grids

Ionel Vechiu, Ciprian Balanuta, and Gelu Gurguiatu

***Abstract*—A micro-grid is a weak electrical grid, which can be easily subject to disturbances because it includes a variety of intermittent power sources, single-phase, three-phase and nonlinear loads, which can have a dynamic impact on power quality. The unbalance and the harmonic components in current and voltage waveforms are the most important among these. In this paper, the topologies and the control strategy of two Active Power Conditioners (APC) have been investigated in order to improve the operation of a micro-grid. The APC topologies presented in this paper act as an interface between renewable energy sources and the AC bus of a micro-grid. They also use an improved control strategy, which makes possible to inject energy in the micro-grid, compensate the current harmonics and correct the power factor. Moreover, the proposed control strategy allows the line current at the point of common coupling (PCC) to be balanced and sinusoidal even when the load is unbalanced. Consequently, the voltage at the PPC becomes balanced. The validity of the innovative control strategy has been proved in simulation using Matlab/Simulink environment.**

***Index Terms*—Active power conditioner, current control, micro-grids, renewable energy.**

I. Introduction

Uring the past few years and especially post-Fukushima, for the first time in history, many countries with a nuclear past have considered the level of future demand for electricity to be unclear. The Fukushima crisis only exacerbates the major changes that the energy sector is facing due to a combination of environmental, resource and demand factors. Under such circumstances, the advantages of renewable and distributed energy generation offer an attractive alternative for power supply.

The increasing penetration level of the renewable energy sources and their variability can make the electrical grid become weak and compromise its proper operation.

Among the different investigated solutions to overcome the above mentioned drawback, the most promising consists in splitting the electric grid into micro-grids. Thanks to the role of power electronics, the micro-grids are expected to contribute to improve energy efficiency and power supply reliability as well as to increase the use of renewable energy sources [1]. A micro-grid can be defined as a portion of an electric power distribution system that is located downstream of the distribution substation and includes a variety of distributed generation and storage systems and various loads.

A micro-grid is different from a main grid system, which can be considered as an unlimited power so that load variations do not affect the stability of the system. On the contrary, in a micro-grid, large and sudden changes in the load may result in voltage transient of large magnitudes in the AC bus. Moreover, the proliferation of switching power converters and nonlinear loads with large rated power can increase the contamination level in voltage and current waveforms in a micro-grid, forcing to improve the compensation characteristics required to satisfy more stringent harmonics standards.

The APC has proved to be an important alternative to compensate current and voltage disturbances in power distribution systems [2], [3]. Different APC topologies have been presented in the technical literature [4], but most of them are not adapted for micro-grids applications.

This paper presents a comparison between two four-wire APC used to improve the power quality in a micro-grid. The first one uses two capacitors to split the DC link and tie the neutral point to the mid-point of the two capacitors. The second one provides a neutral connection for three-phase four-wire systems using a four-leg. The attention will be mainly focused on the innovative control strategy used to control the two APC, which allows injecting energy in the micro-grid, compensating the current harmonics, correcting the power factor and balancing the supply voltage at the PCC.

II. Active Power Conditioner Topologies

Generally, in industrial installations, power is distributed through a three-phase four-wire system.

In this kind of system, the loads could be single as well as three-phase. When several nonlinear single-phase loads are placed on a distribution system, the power required by each of these loads can cause unbalance in the power system and neutral currents flows [4]. As mentioned before, switching high power converters and nonlinear loads can increase the contamination level in voltages and currents waveforms in a grid. The use of a three-phase three-wire shunt active power filter cannot effectively reduce or eliminate line harmonics in this case [5]. An effective solution to this problem is to use a three-phase four-wire active power filter [6], [7]. If the system requires a neutral point connection, a simple approach is to use an APC with two capacitors to split the DC link and tie the neutral point to the mid-point of the two capacitors. This topology allows the current to flow in both directions through the switches and the capacitors and can generate voltage deviation between the DC capacitors.

Manuscript received October 18, 2012; revised November 29, 2012

I. Vechiu is with ESTIA, F-64210 Bidart, France, (e-mail: i.vechiu@estia.fr).

C. Balanuta and G. Gurguiatu are with “Dunare de Jos” University of Galati, Romania (e-mail: daniel.balanuta@ugal.ro, gelu.gurguiatu@ugal.ro).

DOI: 10.7763/IJCEE.2013.V5.689

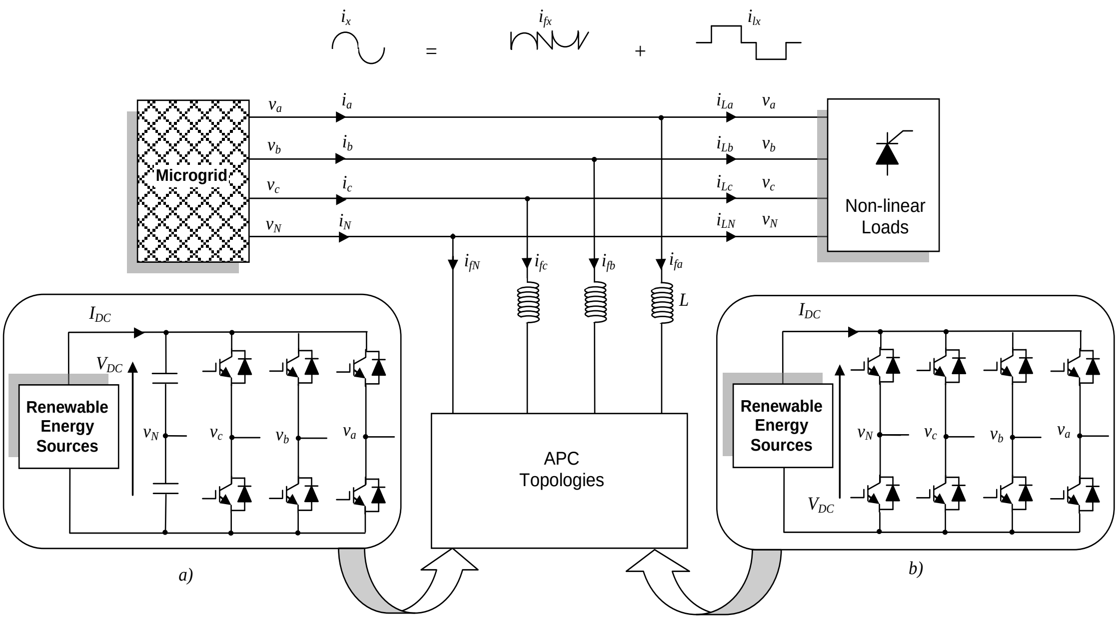

Fig. 1. Four-wire three-leg APC control strategy

Another option is to consider a three-phase four-leg APC. This topology involves an additional leg, expanding the control capabilities of the inverter using the same DC-link voltage. The fourth leg provides a path for the neutral current when the load is unbalanced. The topologies of the investigated APC and its interconnection with the micro-grid are presented in Fig. 1 and 2. For both topologies, the neutral current is defined as:

$$i_{fa} + i_{fb} + i_{fc} = i_{fN} \tag{1}$$

where,

i_{fa}, i_{fb}, i_{fc} are phase APC currents and i_{fN} is the APC neutral current.

Therefore, the total DC voltage will oscillate not only at the switching frequency but also at the corresponding frequency of the neutral current. As shown in [2], if the current control is made by hysteresis, the above mentioned drawback can be limited with a dynamic offset level added to both limits of the hysteresis band.

For the investigated topologies presented in Fig. 1 and 2, the current at PCC is:

$$i_x = i_{lx} + i_{fx} \tag{2}$$

i_x, i_{lx}, i_{fx} are the micro-grid side current, the load current and the APC current respectively. The x index points the a, b and c current phases.

The instantaneous load current is:

$$i_{lx} = i^1_{lx} + i_{lxk} + i_{lxq} \tag{3}$$

where,

i^1_{lx} the fundamental active current component;

i_{lxk} the addition of current harmonics;

i_{lxq} the reactive current component.

The three-phase APC current is given by:

$$i_{fx} = i^1_{fx} + \tilde{i}_{fx} \tag{4}$$

i^1_{fx} the fundamental conditioner current component;

$\tilde{i}_{fx}$ the deforming component of the current.

As shown in Fig. 2, the current drawn from the grid has to be sinusoidal and moreover, in phase with the voltage at PCC. Consequently, the control strategy for the APC has to be designed in order to ensure a sinusoidal wave for the grid current:

$$i^1_{lx} + i_{lxk} + i_{lxq} + i^1_{fx} + \tilde{i}_{fx} = i_x \tag{5}$$

The APC switches generate undesirable current harmonics around the switching frequency and its multiples. Considering the switching frequency of the APC sufficiently high, these undesirable current harmonics can be filtered with the LR passive filter.

III. Control of The APCs

A. Control Strategy

Different control algorithms for the APC can be found in the literature [8], [9]. Generally, the controller design is made considering that the grid voltage at the PCC is balanced. In a micro-grid, the supply voltage itself can be distorted and/or unbalanced. Consequently, the controller of an APC used to improve the power quality in the micro-grid has to be designed according to the weakness of this kind of grid.

The proposed control algorithm is a compensation method that makes the APC compensate the current of a non-linear load by forcing the micro-grid side current to become sinusoidal and balanced (Fig. 2 and 3). The controller requires the three-phase grid current (i_a, i_b, i_c), the three-phase voltage at the PCC (v_a, v_b, v_c) and the DC-link voltage (V_{DC}). As shown in Fig. 3, the sinusoidal waveform and the phase of the grid current reference (i_a*, i_b*, i_c*) comes from the line voltage thanks to a PLL. The magnitude of the same current is obtained by passing the error signal between the DC-link voltage (V_{DC}) and a reference voltage (V_{DC}*) through a PI controller.

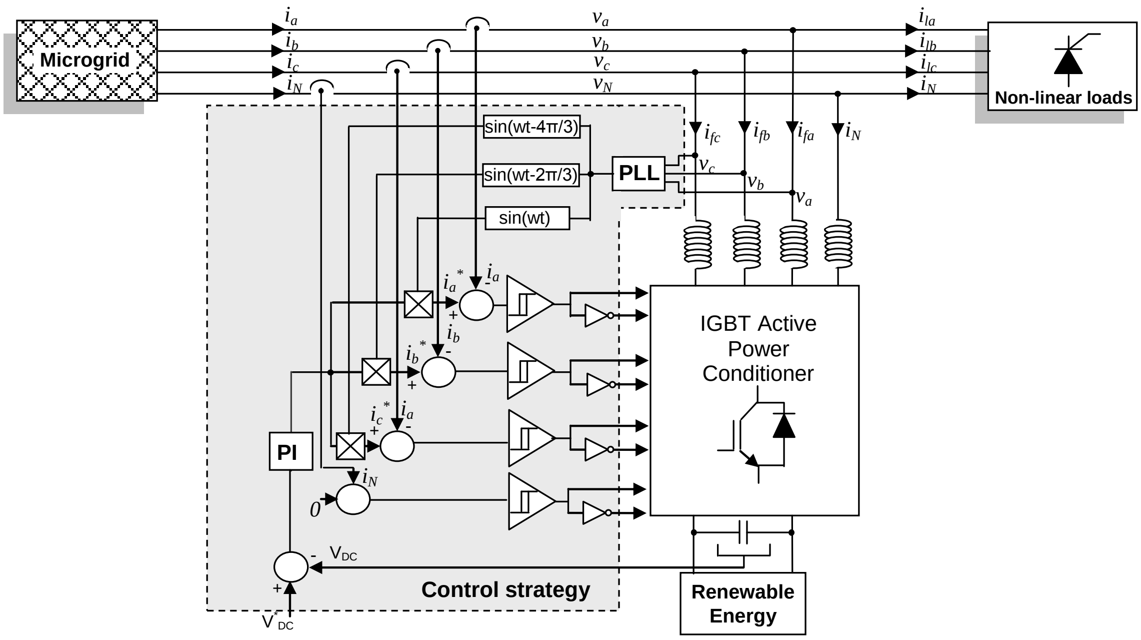

Fig. 2. Four-wire four-leg APC control strategy

Using this magnitude and phase displacement of 120 °and 240 °respectively, the reference three-phase grid currents i_a*, i_b* and i_c* can be expressed as:

$$i_a^* = (PI) \cdot \sin(\omega t) \tag{6}$$

$$i_b^* = (PI) \cdot \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{7}$$

$$i_c^* = (PI) \cdot \sin\left(\omega t - \frac{4\pi}{3}\right) \tag{8}$$

As shown in Fig. 2, in the case of the four-wire, four-leg APC control strategy, a fourth loop is added in order to control the neutral current. In order to ensure a balanced three-phase grid voltage even when the load is unbalanced, the neutral current is forced to be zero using the degree of freedom available with the fourth leg.

B. Switching Control

For the two topologies, the hysteresis control has been used to keep the controlled current within a defined band around the references. The status of the switches is determined according to the error. When the current is increasing and the error exceeds a certain positive value, the status of the switches changes and the current begins to decrease until the error reaches a certain negative value. Then, the switches status changes again.

Compared with linear controllers, the non-linear ones based on hysteresis strategies allow faster dynamic response and better robustness with respect to the variation of the non-linear load. A drawback of the hysteresis strategies is the switching frequency, which is not constant and can generate a large side harmonics band around the switching frequency.

To avoid this drawback, the switching frequency can be fixed using different solutions, like variable hysteresis bandwidth [10] or modulated hysteresis [11]. For the present study, the hysteresis band (HB) is modulated at different points of fundamental frequency cycle to control the switching pattern of the inverter [12]:

$$HB = \left\{ \frac{0.125 \cdot V_{dc}}{f_c \cdot L} \left[1 - \frac{4L^2}{V_{dc}^2} \left(\frac{v_s}{L} + \frac{di^*}{dt} \right)^2 \right] \right\} \tag{9}$$

where f_c is modulation frequency, v_s is the phase voltage, i^* is the phase reference current and L the AC passive filter inductance.

IV. Simulation Results

The two APCs equipped with the proposed control algorithm have been analyzed during many simulations in various operating conditions using Matlab, SimPowerSystems toolbox. All the APCs parameters are shown in Table I.

During all the simulations, the power coming from the renewable energy sources is considered unvarying (around 11 kW) and the short-circuit power at the PCC is weak compared to the maximum power of the system ($R_{cc}=S_{cc}/P=5$, where S_{cc} is the short-circuit power at the PCC and P is the power of the system).

The operation of the three-leg and four-leg APCs has been analyzed in simulation according with the following power quality indicators: THD (Total Harmonic Distortion), power factor and voltage unbalance.

TABLE I: PARAMETERS OF THE APCS

Parameters	Value
AC voltage vg,abc [V]	230
DC-link voltage (VDC) [V]	750
Inductor (L) [mH]	3
Capacitor 3-ph APC (C) [μF]	2x4700
Capacitor 4-ph APC (C) [μF]	3300
Medium Frequency [kHz]	20

A. *Power System without APC*

In order to illustrate the effects of a high-distorted three-phase load, the power system has been first analyzed when the weak grid directly supplies the load without compensation. A three-phase diode bridge rectifier connected in parallel with a three-phase RL load whose total active power is 19.8kW and the total reactive power is 12.9 k VAR composes the total load. For this case study, the RL three-phase load induces the unbalance. The phases *a*, *b* and *c* of the load are charged with the active and reactive power presented in Table II.

TABLE II: POWER QUALITY INDICATORS WITHOUT APC

	THD i_g [%]	THD v_g [%]	P [W]	Q [VAR]	PF	Unbalance [%]
a	17.93	2.35	4040	1530	0.93	6.37
b	11.81	2.52	5738	3194	0.87	
c	6.27	3.59	9903	7342	0.80	

Fig. 3 shows the load currents and supply voltage. As it can be seen, for this case study, the load is highly non-linear and consequently, the current and the voltage are highly distorted. The THD, the voltage unbalance and the power factor (PF) values are shown in Table II. The THD current and the voltage are also illustrated in Fig. 4.

B. *Power System with a 3-Leg APC*

Fig. 5 shows the currents and supply voltage at the PCC when the four-wire three-leg APC and control illustrated in Fig. 1 is used to improve the power quality. As it can be seen, most of the current required by the load ($i_{l,abcn}$) is injected by the APC (renewable energies, $i_{f,abcn}$) and the balance comes from the micro-grid, $i_{q,abcn}$.

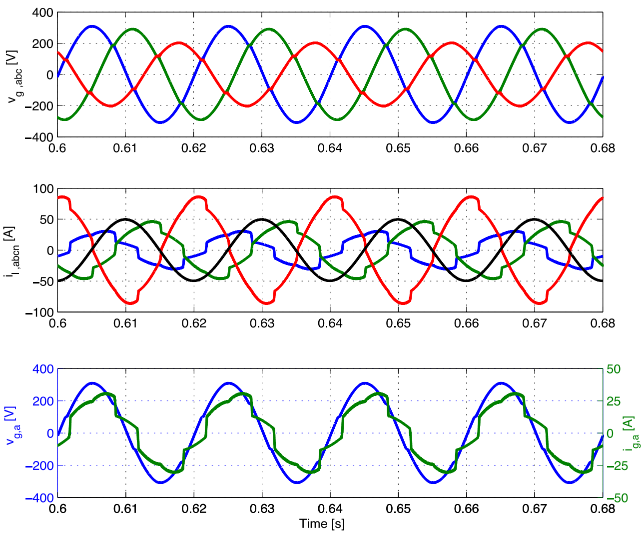

Fig. 3. Load current and voltage without APC

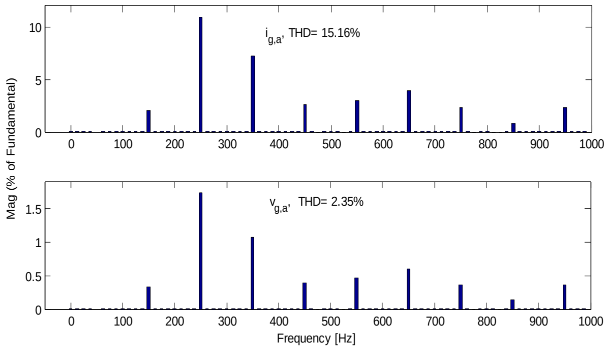

Fig. 4. THD of the micro-grid side current and voltage without APC

When several single-phase loads are unequally distributed on a distribution system, the fluctuating power required from each of these loads can cause unbalanced voltage in a weak power system. Under unbalanced conditions, the distribution system will incur more losses and heating effects and will be less stable.

For this case study, the investigated power quality indicators are illustrated in Table III.

TABLE III: POWER QUALITY INDICATORS WITH THE FOUR-WIRE 3-LEG APC

	THD i_g [%]	THD v_g [%]	Unbalance v_g [%]
a	5.07	4.02	2.3
b	5.37	3.84	
c	6.44	4.59	

As illustrated in Fig. 5 and 6, the proposed control strategy is able to improve the THD of the micro-grid side current, to impose a unity power factor between the micro-grid side currents and the supply voltage, but the micro-grid side currents are not exactly sinusoidal. This is due to the high unbalance of the load that produces a neutral current, which cannot be handled by the DC-bus capacitors.

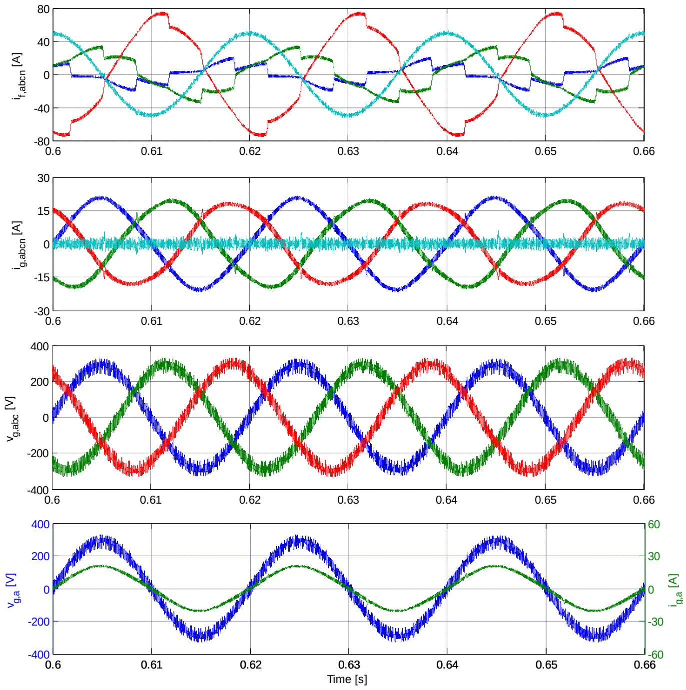

Fig. 5. Currents and voltage in the PCC during compensation with 3ph-APC

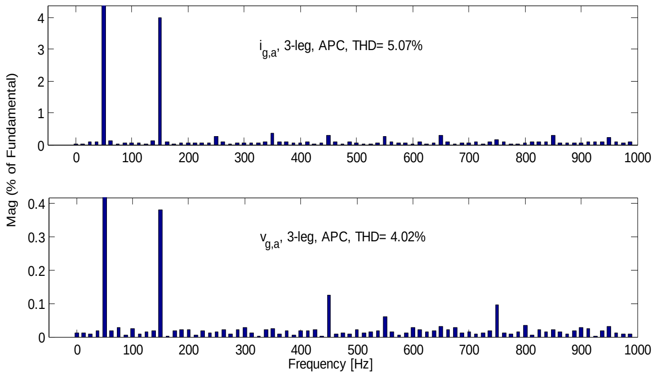

Fig. 6. THD of the micro-grid side current and voltage with 3-leg APC

C. *Power System with a 4-leg APC*

The same operation conditions have been used to illustrate the results at the PCC when the four-wire four-leg APC (Fig. 2) is used to improve the power quality.

Fig. 7 and Fig. 8 as well as Table IV show that the investigated power quality indicators are better controlled when the neutral current is handled using a four-leg APC.

TABLE IV: POWER QUALITY INDICATORS WITH THE FOUR-WIRE 4-LEG APC

	THD i_g [%]	THD v_g [%]	Unbalance v_g [%]
a	4.65	2.86	
b	4.64	2.94	2
c	4.85	2.92	

In this case, the micro-grid side current becomes balanced, sinusoidal and consequently, the voltage at the PCC is also balanced. The level of the voltage unbalance is expressed in accordance with the definition of the ‘‘degree of unbalance in three-phase systems’’, which has to be lower than 2% (standard EN 50160).

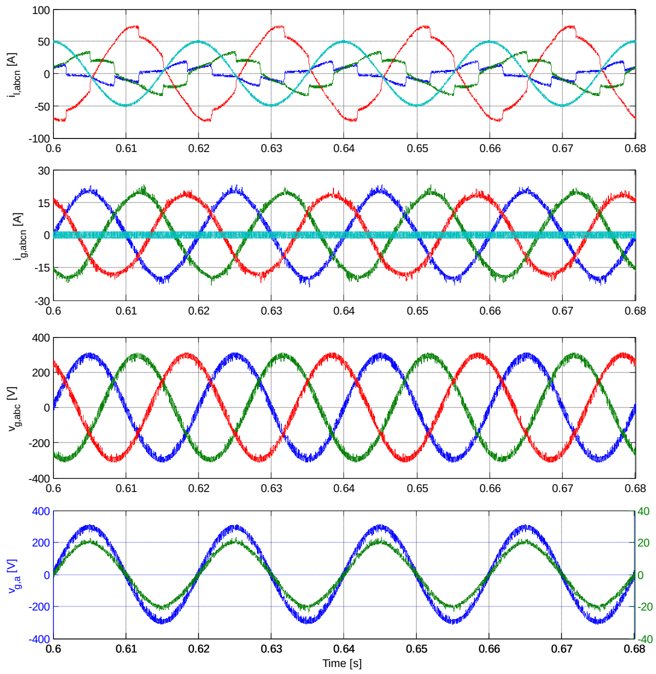

Fig 7. Currents and voltage in the PCC during compensation with 4ph-APC

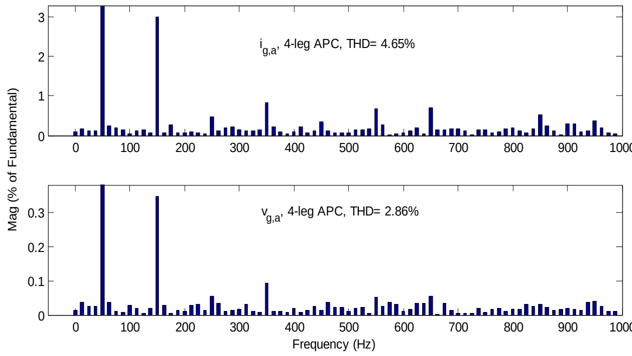

Fig. 8. THD of the micro-grid side current and voltage with 4-leg APC

V. CONCLUSION

In this paper, a three-leg and a four-leg APC have been compared in order to improve power quality in micro-grids based on renewable energy. The APCs are controlled using an innovative control strategy allowing the line current at the point of common coupling to be balanced and sinusoidal even when the load is unbalanced.

This approach presents the following advantages:

- The control system is simpler, because only three sinusoidal waveforms have to be generated for the reference currents.
- These sinusoidal waveforms to control the current are generated in phase with the main supply, allowing unity power-factor operation.
- The control of the three-phase line current enables the three-phase voltage balance at the PCC, allowing excellent regulation characteristics.

Different extreme case studies have been investigated with the APCs simulated using Matlab Sym Power System and the simulations results have shown that the use of a four-leg APC together with the proposed control strategy offer better power quality performances in a weak grid context.

REFERENCES

[1] D. Cornforth, T. Moore, and S. Sayeef, "Challenges and opportunities for inverters in microgrids," in *Proc. IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, 2011, pp. 3111 –3116.

[2] M. Abdusalam, P. Poure, S. Karimi, and S. Saadate, "New digital reference current generation for shunt active power filter under distorted voltage conditions," *Electric Power Systems Research*, vol. 79, no. 5, pp. 759–765, 2009.

[3] M. I. M. Montero, E. R. Cadaval, and F. B. Gonzalez, "Comparison of Control Strategies for Shunt Active Power Filters in Three-Phase Four-Wire Systems," *IEEE Transactions on Power Electronics*, vol. 22, no. 1, pp. 229 –236, 2007.

[4] H. Golwala and R. Chudamani, "Simulation of three-phase four-wire shunt active power filter using novel switching technique," in *Proc. 2010 Joint International Conference on Power Electronics, Drives and Energy Systems (PEDES) 2010 Power India*, 2010, pp. 1 –7.

[5] H. Golwala and R. Chudamani, "Comparative study of switching signal generation techniques for three phase four wire shunt active power filter," in *Electric Machines Drives Conference (IEMDC), 2011 IEEE International*, 2011, pp. 1409 –1414.

[6] S. Orts-Grau, F. J. Gimeno-Sales, A. Abella - Garcia, S. Segui-Chilet, and J. C. Alfonso-Gil, "Improved Shunt Active Power Compensator for IEEE Standard 1459 Compliance," in *Proc. IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2692 –2701, Oct. 2010.

[7] P. Salmeron, J. C. Montano, J. R. Vazquez, J. Prieto, and A. Perez, "Compensation in nonsinusoidal, unbalanced three-phase four-wire systems with active power-line conditioner," *IEEE Transactions on Power Delivery*, vol. 19, no. 4, pp. 1968 – 1974, Oct. 2004.

[8] A. Luo, Z. Shuai, W. Zhu, R. Fan, and C. Tu, "Development of Hybrid Active Power Filter Based on the Adaptive Fuzzy Dividing Frequency-Control Method," *IEEE Transactions on Power Delivery*, vol. 24, no. 1, pp. 424 –432, Jan. 2009.

[9] B. S. Chen and G. Joos, "Direct Power Control of Active Filters With Averaged Switching Frequency Regulation," *IEEE Transactions on Power Electronics*, vol. 23, no. 6, pp. 2729 –2737, Nov. 2008.

[10] M. Kale and E. Ozdemir, "An adaptive hysteresis band current controller for shunt active power filter," *Electric Power Systems Research*, vol. 73, no. 2, pp. 113–119, Jan. 2005.

[11] M. A. S. Nejad, S. Pierfederici, J. P. Martin, and F. Meibody-Tabar, "Study of an Hybrid Current Controller Suitable for DC -DC or DC -AC Applications," *IEEE Transactions on Power Electronics*, vol. 22, no. 6, pp. 2176 –2186, Nov. 2007.

[12] M. Kale and E. Ozdemir, "An adaptive hysteresis band current controller for shunt active power filter," *Electric Power Systems Research*, vol. 73, no. 2, pp. 113–119, 2005.

Ionel Vechiu was born in Focsani, Romania, in 1977. He received the Dipl. Eng. degree in electrical engineering from Galati University, Romania, in 2001 and the M.Sc. and Ph.D. degrees from the University of Le Havre, France, in 2002 and 2005, respectively.

Since 2005, he has been a Researcher with ESTIA-Research laboratory, Bidart, France. His research interests include the power electronics applied to renewable energy conversion and storage, in modelling and simulation of systems, including control strategies and control circuits.

Ciprian Balanuta was born in TULCEA, ROMANIA, in 1983. He received the Engineer diploma and the Master’s degree from "Dunarea de Jos" University of Galati. He is currently pursuing the Ph.D. with the same University.

Since 2008, he has been an Assistant with "Dunarea de Jos" University of Galati. His current research interests include power quality problems, mircogrid applications, and active power filter.

Gelu Gurguiatu was born in Focsani, Romania in 1980. He graduated the faculty of Electrical Engineering and Computer Science, “Dunare de Jos” University of Galati, Romania in 2003 and he received the M.Sc. and Ph.D. degrees from the same University, in 2005 and 2011 respectively.

Since 2011, he has been a Researcher with AIE department of “Dunare de Jos” University of Galati, Romania. His field of interest is power electronics for grid power quality.