ISIE'2007 - IEEE International Symposium on Industrial Electronics
Vigo, Espanha, 4-7 Junho de 2007, ISBN: 1-4244-0755-9

Custom Power Interfaces for Renewable Energy Sources

L. G. B. Rolim, A. Ortiz, M. Aredes
Power Electronics Lab. – COPPE/UFRJ
Federal University of Rio de Janeiro
Rio de Janeiro, Brazil
Email: {rolim|abnery|aredes}@coe.ufrj.br

R. Pregitzer, J. G. Pinto, João L. Afonso
Industrial Electronics Department
University of Minho
Guimarães, Portugal
Email: {jla|rpregitzer|gpinto}@dei.uminho.pt

***Abstract*—Interface converters for renewable energy sources can be regarded as custom power devices. Thus they can be designed and operated so as to improve power quality at their connecting locations. This paper presents examples of converter designs based on p-q theory for different applications. Modeling, simulations and experimental results are given for converter prototypes operating either as active power filter (APF) or static compensator (STATCOM), while transferring real power to the utility grid. Compensation of harmonic distortions, power factor control, reactive support and voltage control are achieved with the proposed circuits.**

I. Introduction

Electricity generation from renewable energy sources is expected to grow steadily in next years [1]. Data shown in Fig. 1 let anticipate a worldwide average increase of about 20GW per year in renewable generating capacity for the upcoming decades. Due to the distributed nature of renewable resources, many installations are likely to be situated in remote locations, where public electric utility grids are weak or even unavailable. Moreover, because most renewable sources do not produce ac electricity with inherent voltage and frequency regulation, power electronic converters must be used as interface circuits for connection to the local grid or ac loads [2][3].

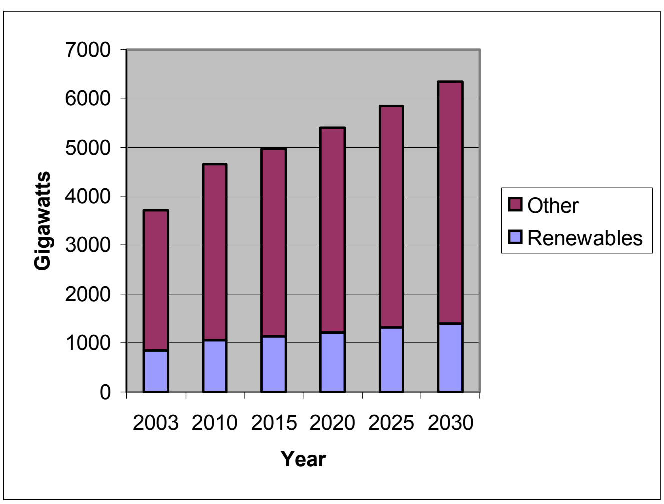

Fig. 1. World Electricity Generating Capacity. Sources: 2003: Derived from Energy Information Administration (EIA), International Energy Annual 2003 (May-July 2005), web site www.eia.doe.gov/iea/. 2010-2030: EIA, System for the Analysis of Global Energy Markets (2006).

Though deployment of renewable energy generation systems still requires high investments, cost-effectiveness of required equipment can be improved if additional control functions are incorporated to the interface converters, with the aim of improving power quality at the connecting point. In this sense, interface converters for renewable sources can be treated as custom power devices [4]. Thus every new installation of renewable generation can be seen as an opportunity to add custom power features, to improve quality of supply in locations where electric grids are weak or where sensitive loads need to be protected against power quality problems from the supply mains.

In this paper, p-q theory [5][6][7] is used in the control of custom power interface circuits for renewable energy sources, in different applications. Modeling, simulations and experimental results are given for converter prototypes operating either as active power filter (APF) or static compensator (STATCOM), while simultaneously transferring real power from the renewable energy sources to the utility grid. Previous work [8] has demonstrated the use of p-q theory to control injection of real power into the grid, without harmonic compensation. In contrast, compensation of harmonic distortions is achieved with the APF application described herein. Additionally, power factor control, reactive support and voltage control are achieved with the proposed circuits.

II. Basic Topology and Control Aspects

Several types of renewable energy sources, especially in the low to medium power ranges, produce dc output with either voltage source or current source characteristics. As examples can be mentioned: photovoltaic generators, permanent-magnet alternators with diode rectifiers and fuel cells. Delivery of output power from such dc circuits to the utility grid or to ac loads is typically achieved through the dc link of a front-end inverter circuit. Hence it is often required to use a dc/dc (chopper) power stage to control the operating point of the renewable energy source. Maximum power point tracking (MPPT) strategies are commonly employed to control these choppers, using buck and/or boost topologies.

Fig. 2 shows a possible arrangement for grid-connected operation of a hybrid system, where two different sources (wind and photovoltaic) are connected to a shared dc link.

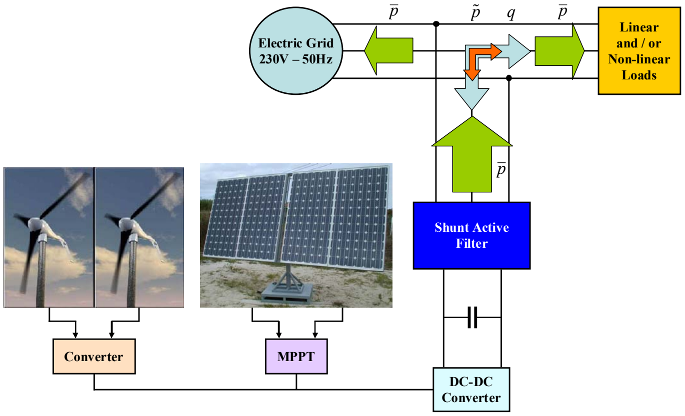

Fig. 2. Interface circuits and p-q theory power components.

Instantaneous (p-q) power components are also indicated in Fig. 2. In accordance with the p-q theory, a custom power interface circuit can be ideally designed to supply all the imaginary power components (oscillating part $\tilde{q}$ as well as the non-oscillating part $\bar{q}$) demanded by a three-phase ac load, plus the oscillating part ($\tilde{p}$) of the real power. Excess of power supplied by the renewable energy sources can be transferred to the ac grid purely in the form of non-oscillating real power ($\bar{p}$).

Inverter topologies with shunt capacitors in the dc link are found as a front-end interface at the grid side in most applications. Thus regulation of dc link voltage is the key to maintain equilibrium of input and output powers. Depending on which method is chosen to manage the power exchanges between the renewable energy sources, the dc link and the ac output, different control strategies might be employed to achieve dc link voltage regulation.

For grid-connected systems, a fraction of the real power that flows through the grid-side converter (p_{reg}) can be used to regulate the dc link voltage. In that case, p_{reg} should appear as the output signal of a feedback controller that operates on the error signal derived from the mismatch between the measured dc link voltage and a given reference value. Simple controller structures such as proportional or PI are adequate for dc link voltage regulation when connected to the ac grid in most cases.

For isolated or stand-alone operation, more elaborate control strategies are needed for dc link regulation, due to absence of the ac grid. Some kind of dispatch strategy must be established in order to coordinate the dc link voltage regulation and the control of power generated by the separate sources. Use of energy storage devices may be required if the total generation cannot match the load at all times. Nevertheless, separation of p-q components is no longer needed on the ac side, since the inverter must deliver the entirety of the instantaneous power demanded by the ac load.

With the purpose of evaluating the performance of custom power interface circuits with control algorithms based on p-q theory, two laboratory prototypes have been built, independently comprising APF and STATCOM functions. Detailed description of each prototype is given in the next sections.

III. APF and STATCOM Prototypes

Control algorithms implemented in both prototypes are based on the well-known relationships given by the p-q theory. The output currents on the ac side, which are required for achieving harmonic compensation and/or reactive injection subject to power factor correction or voltage control, are calculated as given by (1).

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \qquad (1)$$

Subscripts α and β in (1) denote the Clarke components of voltages and currents on the ac side, whilst p_c and q_c are the real and imaginary powers that should be delivered by the inverter. Different custom power functions can be obtained by defining different methods to calculate p_C and q_C.

A. APF Prototype

In the APF, the output currents synthesized by the inverter should contain all of the oscillating components $\tilde{p}_{load}$ and $\tilde{q}_{load}$ demanded by the load, in order to achieve full harmonic compensation of load currents. To calculate the real power component (p_C) required in (1), the power injected by renewable energy sources (p_G) should be added to $\tilde{p}_{load}$ and p_{reg} yielding

$$p_C = p_G - p_{reg} + \tilde{p}_{load}\,. \qquad (2)$$

In an actual application, p_G would be obtained as the output from the MPPT controller, and p_{reg} would come from a dc-link voltage controller. As a result, p_G was treated as a fixed reference input, and p_{reg} was not needed. However, in this APF prototype, the MPPT behavior was simulated by means of a fixed dc voltage source directly connected to the dc link. A scheme in term of compensation currents of this arrangement is shown in Fig. 3.

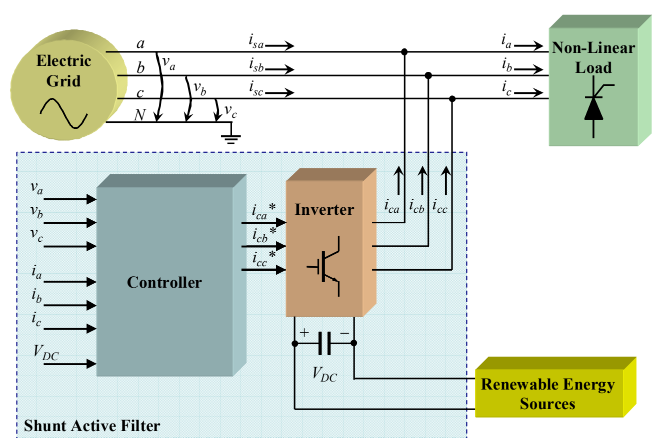

Fig. 3. Block diagram of three-phase three-wire APF operating as an interface for renewable energy sources.

B. STATCOM Prototype

A back-to-back connection between two three-phase power converters was carried out, as shown in Fig. 4. One of them, hereafter called STATCOM-RES, simulates a Renewable Energy Source by transferring a given amount of real power p_C from the ac grid into the dc link. The other converter was designed with a control algorithm that is capable for producing controlled reactive support like a STATCOM. Additionally, it can transfer incoming real power from the dc into the ac grid ($-p_C$). This is easily performed by the dc-link voltage regulator of the STATCOM, as it will be shown later.

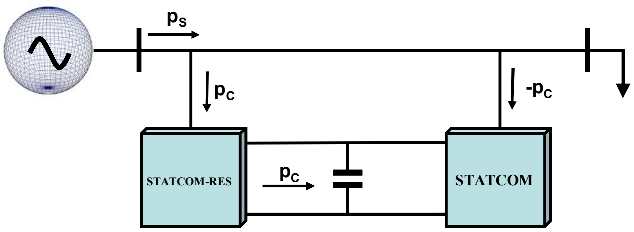

Fig. 4. Back to back connection of two STATCOM, with one of them working as a renewable energy source (STATCOM – RES).

Considering the power inward the converter as positive, the currents synthesized by the STATCOM-RES are given by (1), with p_C given as an arbitrary value, and $q_C = 0$. This simulates a fixed power supply by the renewable energy source.

On the other hand, the controller of the STATCOM provides its own reference values for p_C and q_C. Reference p_C comes naturally from the dc-link regulator implemented in the STATCOM controller. Reference q_C is calculated by the STATCOM controller, according to the method that is selected to be used as its compensation strategy. Two methods can be chosen for calculation of q_C. The first one compensates the load power factor and the second one regulates the voltage magnitude of a controlled ac bus.

IV. SIMULATION AND EXPERIMENTAL RESULTS

In this section simulations and experimental results are shown for both prototypes described above. Specifications of both prototypes are given in table I.

TABLE I
SPECIFICATIONS OF APF AND STATCOM PROTOTYPES

Acronym	Ratings			
	ac Phase Voltage	dc Link Voltage	Power	dc Link Capacitor.
APF	75V	240V	3.2kVA	630µF
STATCOM-RES	127V	400V	7.5kVA	4700µF
STATCOM	127V	400V	25kVA	9400µF

As a first step before carrying out experiments, computer simulations were done using detailed system models including switch-mode representation of power converters. In this stage, preliminary tuning of control parameters was obtained and correctness of control algorithms was verified. Matlab/Simulink and PSCAD/EMTDC were used in the APF simulations.

A. APF Prototype

The system shown in Fig. 5 was simulated using Matlab/Simulink. In order to observe the function of the APF as a custom power interface, different cases were simulated. Simulation results show the APF behavior in steady state, simultaneously compensating for power quality problems and injecting active power to the utility grid. The following results have been obtained with two loads:

- a three phase RL load (R = 5.85Ω; L = 32.25mH) that consumes 6.75 kW with a power factor of 0.5;
- a non controlled bridge rectifier with a series RL load (R = 28Ω ; L = 146mH) that consumes 10.2 kW with a power factor of 1.0.

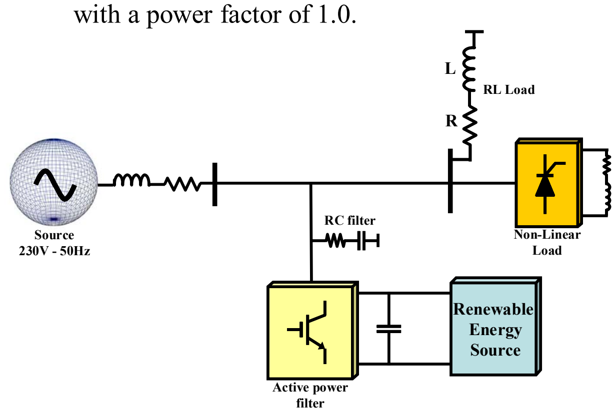

Fig. 5. Simplified block diagram of the APF simulation using a renewable energy source as energy storage.

Fig. 6 shows voltages and currents supplied by the source when the APF is not operating. When the APF is operating during off-peak hours, capacitive reactive power must not be generated by consumers, according to Portuguese regulations.

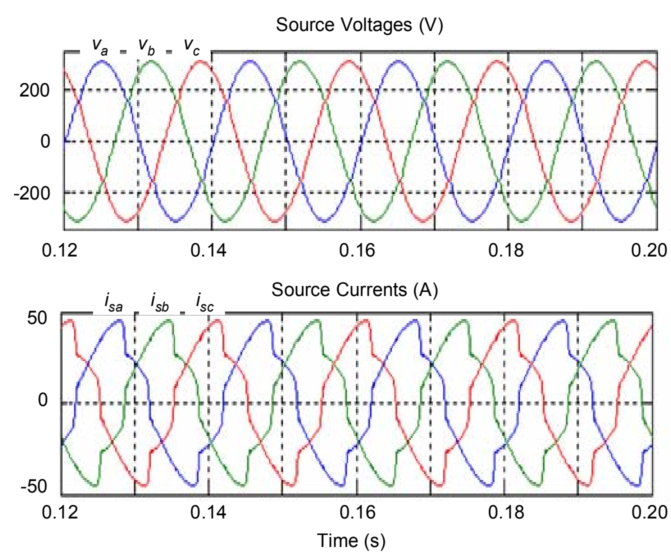

Fig. 6. Source voltages and currents when APF is not operating (simulation).

This can be verified, taking into account that the current i_{sa} in Fig. 7 is in counter-phase with respect to the source voltage v_{sa} in Fig. 6. In this example, the power injected by APF in the utility grid is 7.2 kW.

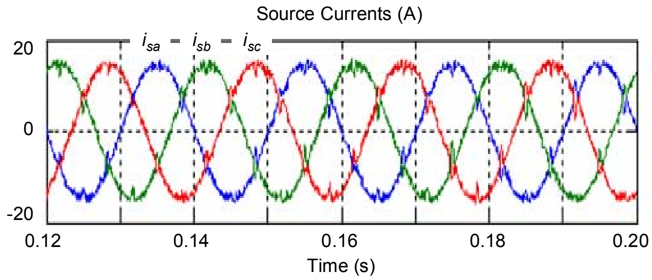

Fig. 7. Source currents when APF is operating off-peak (simulation).

Fig. 8 shows source voltages and currents when the APF is operating during peak hours. In that case, it has to generate a capacitive reactive power that corresponds to 40% of the injected active power. Since the injected active power is 7.2kW, the leading currents in Fig. 8 generate 3.15kvar.

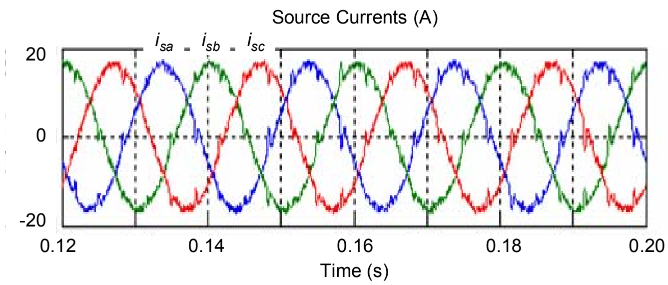

Fig. 8. Source currents when APF is operating during peak hours (simulation).

A 3.2kVA experimental prototype was built for verification. For simulating the renewable energy source, a dc source of 240V was used. This voltage level is enough for synthesizing the compensation currents.

In one of the experiments the APF experimental prototype compensates harmonic and unbalance currents, together with power factor correction. Fig. 9 shows the waveforms corresponding to voltage v_b and load currents i_a, i_b and i_c. These load currents correspond to a three-phase Y–connected reactor bank of L = 50mH, and a single-phase diode rectifier connected between phases a and b, feeding a RL dc load of R = 33 ohm, L = 59 mH. Table II summarizes the characteristics of the total load currents shown in Fig. 9.

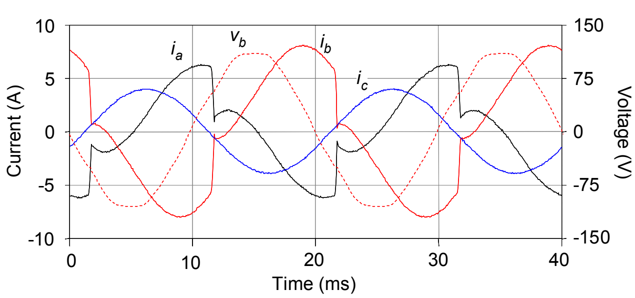

Fig. 9. Experimental supply voltage and load currents.

TABLE II
LOAD CURRENT CHARACTERISTICS

	Phase A	Phase B	Phase C
Current (A)	5.1	7.3	3.8
Power Factor	0.86	0.5	0.15
THD (%)	24.4	17.5	1.8

Fig. 10 shows the compensated currents drawn from the network when the APF is operating. They are almost sinusoidal and balanced, and producing unity power factor. The current spikes are due to delays in the digital controller, and this problem can be solved by using a delay compensation algorithm [10].

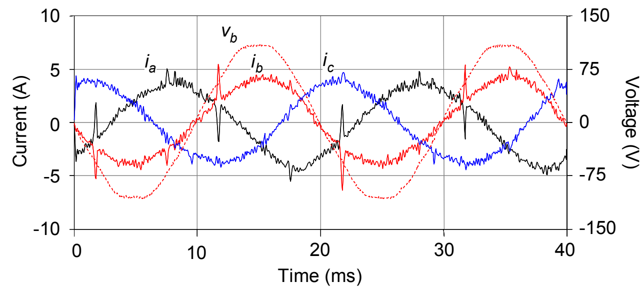

Fig. 10. Experimental supply voltage and currents when the APF is fully compensating harmonic distortion and reactive power of the load.

In this experimental case the APF prototype is only performing active filtering, without injecting active power to the network. Power quality improvements are achieved, as can be confirmed by the calculated performance indexes shown in Table III.

TABLE III
SOURCE CURRENT CHARACTERISTICS BEFORE COMPENSATION

	Phase A	Phase B	Phase C
Current (A)	3.7	4.1	3.7
Power Factor	0.99	1.00	1.00
THD (%)	14.2	15.0	8.2

Finally, another experiment was carried out, in order to demonstrate the APF performing both functionalities, i.e. active filtering and custom power interface for renewable energy source. Fig. 11 shows the waveforms corresponding to voltage v_b and compensated currents i_a, i_b and i_c drawn from the network. Voltage v_b and current i_b are almost in counter-phase, showing that the APF prototype is fully supplying the load power, as well as injecting an extra amount into the network.

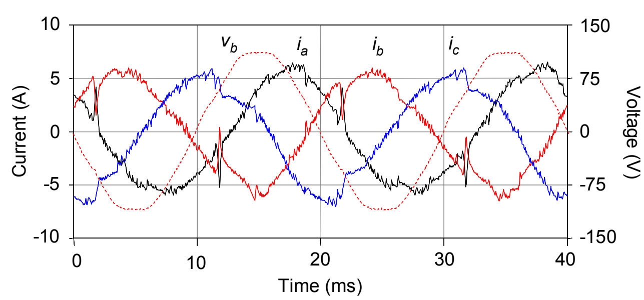

Fig. 11. Source currents when APF compensates and injects active and reactive energy (experiments).

B. STATCOM Prototype

A 7.5kVA experimental prototype was used in order to simulate a renewable energy source (STATCOM-RES), which injects its full rated power into dc link. A second prototype rated 25kVA (STATCOM) was connected back-to-back to the first one, in order to perform both capabilities: producing controlled reactive support like a STATCOM, and custom power interface for renewable energy source.

Two experiments were carried out, in order to demonstrate separately both functionalities. Fig. 12 shows experimental results of the first experiment, with the STATCOM dynamically compensating the power factor of the load.

The upper traces in Fig. 12 show the voltage and compensated current of phase A, while the lower traces correspond to the phase B. This transient corresponds to the start of a 60000 BTU air conditioner, while the STATCOM is operating. During all the time, the supply currents are almost in phase with the corresponding voltage. If the STATCOM would not be in operation, the load would demand supply currents two times higher and significantly inductive. In this experimental case the STATCOM prototype is only performing reactive-power compensation, without injecting active power to the network.

The control software used in the digital controller of the STATCOM is the same for both experimental cases. However, in the second experiment the reactive power compensation functionality was deactivated, leaving only the dc-link voltage regulation active. This is enough to ensure that all the active power injected by the renewable energy source into the dc link goes out into the network.

Fig. 13 shows experimental results for the second experiment, when the STATCOM is only injecting active power into the network, without performing reactive-power compensation. The uppermost trace in Fig. 13 shows the dynamic response of the dc-link voltage to a step change in the reference value of the active power injected into the dc link by the STATCOM-RES. This converter simulates the active power injection that would be produced by a renewable energy source.

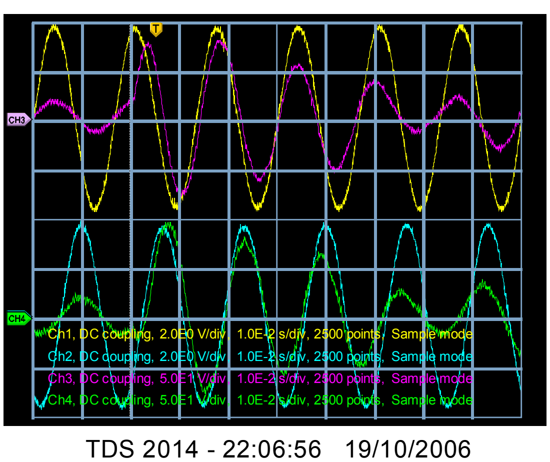

Fig. 12. Experimental results of 25kVA STATCOM dynamically compensating power factor of the load.

The corresponding reference value for the dc link voltage is 400V. The dc-link voltage regulation is based on a PI controller that is tuned to allow a maximum of approximately 5% overshoot in the dc link voltage during a full-power step change in the renewable source generation.

The second trace in Fig. 13 (i_{dc}) corresponds to the dc current that flows between the STATCOM-RES and the STATCOM. It undergoes a sudden change, when the active power reference of the STATCOM-RES changes from zero to 1 p.u., indicating that active power instantly begins to flow between the two converters.

All the principal ac quantities of both converters are plotted together in the lower traces of Fig. 13 for the same phase. They are: the phase-to-neutral supply voltage v_s, the input current of the STATCOM-RES ($i_{statcom\text{-}res}$) and the output current of the STATCOM ($i_{statcom}$). Like the dc current, the current $i_{statcom\text{-}res}$ presents an instantaneous increase in its magnitude, while the output current $i_{statcom}$ increases slowly. This slow response of $i_{statcom}$ is dictated by the dynamic behavior of the PI controller in the dc-voltage regulator. The output of this PI controller is used as the compensating power signal p_C in (1), in order to obtain reference values for $i_{statcom}$.

A detailed view of waveforms v_s, $i_{statcom\text{-}res}$ and $i_{statcom}$ in steady-state is shown in Fig. 14. Since the current direction chosen as reference for STATCOM-RES and STATCOM is the same, and corresponds to current flowing into the converter in both cases, they must be in counter-phase. While $i_{statcom\text{-}res}$ is in phase with v_s, indicating active power flowing from the network into the dc link, $i_{statcom}$ is 180º displaced with respect to v_s, producing active power flowing back to the network.

Both converters operate with 10kHz switching frequency. However, the commutation inductance of the 25kVA STATCOM is 400μH, while that of the STACOM-RES is 1.5mH. As a result, the switching ripple in $i_{statcom}$ is far greater than that of $i_{statcom\text{-}res}$, as can be seen in Fig. 14.

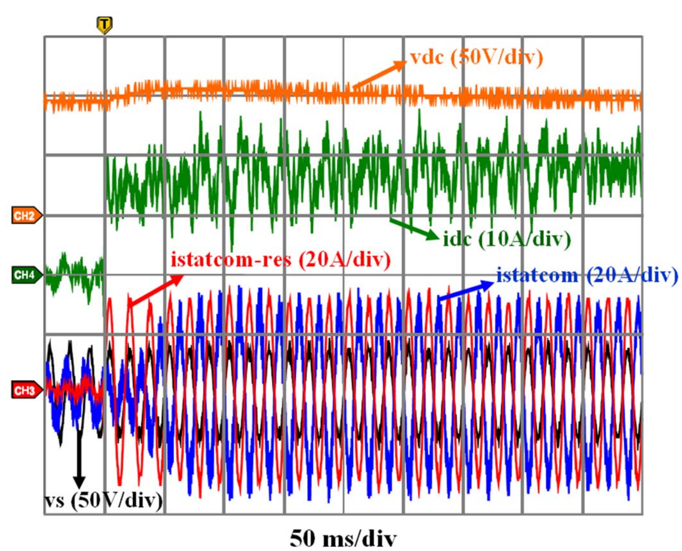

Fig. 13. Experimental results of 25kVA STATCOM with a renewable energy source supplying active power into the dc link.

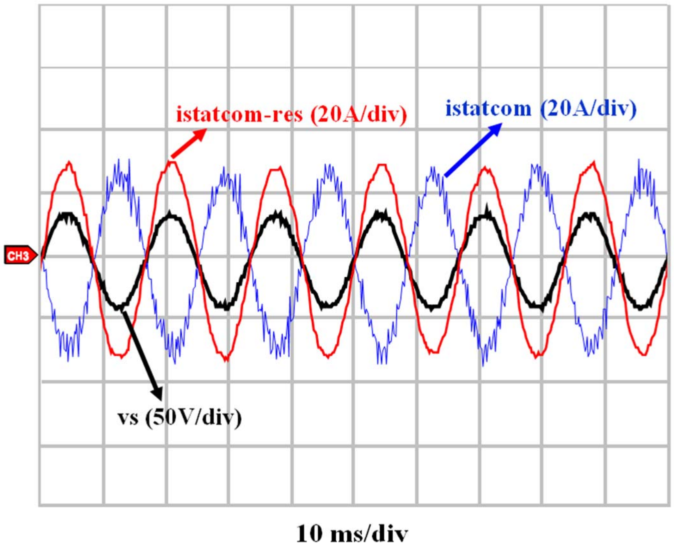

Fig. 14. Experimental results of STATCOM prototype in steady-state.

V. CONCLUSIONS

In this paper, two examples of custom power interfaces for renewable energy sources have been developed. Using control algorithms based on the same fundamental equation (1) derived from the pq theory, different functionalities have been implemented. In the first approach, active power injection from a simulated renewable source was combined with active filtering functionalities (APF), while the second approach combines reactive power support (STATCOM functionalities) and active power injection.

Experimental results obtained from prototypes of both APF and STATCOM systems have shown the feasibility of combining active power injection from renewable energy sources with custom power functionalities, employing the pq theory in the control. Good dynamic properties are achievable with the demonstrated approaches, and this can be used to deal with power quality issues within the sub-cycle range in modern power systems with sensitive loads.

The use of the pq theory makes the combination of different functionalities in a single controller quite straightforward, without impairing each other's performance.

REFERENCES

[1] U.S. D.O.E. Energy Information Administration, "International Energy Outlook 2006," Report #:DOE/EIA-0484(2006), June 2006.

[2] F. Blaabjerg, Z. Chen and S.B.Kjaer, "Power electronics as efficient interface of renewable energy sources," *IPEMC 2004 Conference Proceedings*, vol. 3, pp. 1731-1739, August 2004.

[3] F. Blaabjerg, Z. Chen and S.B.Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Transactions on Power Electronics,* vol. 19, pp. 1184-1194, September 2004.

[4] N.G. Hingorani, "Introducing custom power", *IEEE Spectrum*, pp. 41-48, June 1995.

[5] H. Akagi, Y. Kanazawa and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits", *IPEC'83 – Int. Power Electronics Conf.*, pp. 1375-1386, 1983.

[6] H. Akagi, Y. Kanazawa and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components", *IEEE Transactions on Industry Applications*, Vol. IA-20, No. 3, pp. 625-630, 1984.

[7] E. H. Watanabe, R. M. Stephan and M. Aredes, "New Concepts of Instantaneous Active Power in Electrical Systems with Generic Loads", *IEEE Transaction on Power Delivery*, Vol. 8, No. 2, 1993.

[8] P.G. Barbosa, L.G.B. Rolim, E.H. Watanabe, R. Hanitsch, "Control strategy for grid-connected DC–AC converters with load power factor correction", *IEE Proc. – Generation, Transmission and Distribution*, Vol. 145, pp. 487-491, 1998.

[9] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galván, R. C. P. Guisado, M. A. M. Prats, J. I. León, N. Moreno – Alfonso, "Power-Electronics Systems for the Grid Integration of Renewable Energy Sources: A Survey", *IEEE Transactions on Industrial Electronics, Vol. 53, No 4, August 2006*.

[10] J. L. Afonso, "Filtro Activo Paralelo com Controlo Digital para Melhoria da Qualidade de Energia Eléctrica", Ph.D. dissertation, Dept. Industrial Electronics, Univ. Minho, Portugal, 2000.