Rapid Prototyping Applications on Three-Phase PWM Rectifier and Shunt Active Power Filter

Kadir Vardar, Tolga Sürgevil, and Eyüp Akpınar

Dokuz Eylul University, Department of Electrical and Electronics Engineering
Kaynaklar Kampusu, 35160 Buca, Izmir, TURKEY
e-mail: kadir.vardar@deu.edu.tr , tolga.surgevil@deu.edu.tr , eyup.akpinar@deu.edu.tr

Abstract

In this paper, the design procedures of a unity power factor pulse width modulated (PWM) rectifier and shunt active power filter (APF) using MATLAB/Simulink blocksets and code generation tools for TMS320F2812 fixed-point digital signal processor (DSP) is presented. A systematic design approach is given to develop a rapid prototype system in a reliable procedure. The design procedure uses Simulink model of the rectifier and shunt APF systems, control circuitry, real-time DSP program code generation. The generated and self-developed codes on DSP are tested with Simulink models; therefore, any possible error in the controller implemented within software is eliminated before connecting the power converter to the supply. The code generation tools of Simulink provide an efficient way in the transition from the analysis stage to real system implementation. The effectiveness of this procedure for safely starting up the system is experimentally verified.

1. Introduction

The power quality issues emerging due to increasing usage of non-linear loads have been the major concern in last two decades and these problems have also created a specialized subject in power engineering. Employing active power filters (APF), Static VAR Compensators (STATCOM), universal power quality conditioners (UPQC) are some of the technologies developed as solutions to power quality issues [1-4]. In industrial applications, it is convenient to employ APFs to reduce the harmonic content of supply current in motor drives. APFs are also known to be the alternative tool for other power quality problems such as reactive power compensation, load balancing, voltage regulation, and voltage flicker compensation [5]. From another point of view, the PWM rectifiers also provide an indirect solution to power quality related problems in terms of offering salient features of operation at unity power factor and minimized harmonic current injection to the power system unlike conventional diode or thyristor controlled rectifiers. Due to their several advantages, the PWM rectifiers are also found place in applications such as ac motor drives, uninterruptible power supplies, etc. [6-9].

Nowadays, many power electronics devices are integrated with digital signals processors (DSP) that offer a generic structure and implementation of complex calculations required in a wide range of applications [10-12]. While the DSPs offer better solution to the control of many complex systems, developing a DSP code and testing it on the real system requires additional effort and attention since the design of power

electronics systems contains a background of inter-disciplinary knowledgebase [13].

The block scheme of a three-phase unity power factor PWM rectifier is given in Fig.1a. The major parts of this topology are a power converter that couples the AC supply voltages and DC link capacitor voltage through a boost inductance. In this scheme, the rectifier circuit provides a regulated dc link voltage to the load providing the ac line currents almost sinusoidal and at unity power factor. The control logic relies on measurement of dc link voltage, supply voltages and supply currents. The block scheme of a three-phase shunt APF compensating the current harmonics of a non-linear load is shown in Fig.1b. The APF power circuit topology is the same as that of PWM rectifier in parallel with the load. The load current waveforms are measured through the current sensors and their harmonic contents are extracted through instantaneous reactive power theory (IRPT) method. The inverse of the load current harmonics are injected to the electrical network through APF. This is achieved by an inner current control loop to force the APF currents track the reference current waveforms generated in DSP in a similar fashion developed in PWM rectifier. The PI controller regulates the DC bus voltage at the desired level.

In the design procedure of such devices, it is often necessary to construct the complete system model to investigate its performance through computer simulations before implementing. In [14] it was noted that the use of hardware in simulation of the power electronics converter is essential. The inclusion of DSP based design into computer simulations can be carried out by using the program of DSP and co-operation with PC. In recent years, the use of automatic code generation tools has become widespread. These tools can be used effectively to make a rapid prototyping and hardware-in-the-loop testing of controllers possible [15]. From this point of view, the Embedded Target tools that integrate the MATLAB/Simulink and Texas Instruments TMS320C2000 DSP platforms are useful to develop and validate the designs rapidly. These tools are used to generate a program in C-language for real-time implementation of the Simulink model and also provide a flexibility to test the generated code with other Simulink models [16].

In this paper, a design procedure for three-phase unity power factor PWM rectifier and shunt APF using MATLAB/Simulink and TMS320F2812 DSP is presented. The procedure contains the modeling of the system in Simulink, real-time code generation, testing the developed code on DSP with Simulink model, and experimental tests carried on the prototype system. In Section 2, the Simulink modeling for computer simulations, real-time code generation for DSP controller and simultaneous operation of DSP with Simulink for PWM rectifier are presented. In Section 3, the same procedure is applied for shunt APF and the self-developed DSP code for this application is

tested with DSP in Simulink simulations. The measured results and conclusions are given in sections 4 and 5, respectively.

2. Modelling and Code Generation for PWM Rectifier

The circuit model of the PWM rectifier is constructed in MATLAB/Simulink, which contains power system and power electronics tools to analyse the systems and specific blocks used in code generation for C2000 DSPs. This model contains the measurement of voltage and current signals in the power circuit via analog-to-digital conversion and digital processes that should be developed on DSP as shown in Fig.2. Here, the DSP section is performing calculations for the control circuitry and generating the gate pulses of IGBTs. This block is designed as a subsystem and contains the part from which the DSP code will be generated.

Once the stable operation of the system is ensured in simulations, the C-code of the DSP block is generated using MATLAB C2000 code generation tools. The voltage and current waveforms generated in simulation model are fed to DSP in order to emulate the signals from the sensors of the physical system. The DSP processes these waveforms and generates the switching patterns at each simulation step. Here, the generated code by Simulink contains the part after the measured signals are read from analog-to-digital converter (ADC) registers and before the gate signals are written into PWM registers only. So, the initialization of these registers that should be done in the complete DSP code developed for the designed system operation is not included in the Simulink DSP subsystem. In that way, the generated DSP code for current control loop and dc link PI controller can be tested without using the real system in order to avoid any failure and physical damage to IGBTs and other power devices.

2.1. Simulink Model of PWM Rectifier

In the MATLAB/Simulink model of PWM rectifier, the voltage and current signals are conditioned to 0-3V ADC levels of F2812 DSP. The gains of the sensors, signal conditioning circuits and ADC are defined in the main model as shown in Fig.2. The system is simulated using discrete-time simulation option and the integration step size of the solver is chosen to be 4 microseconds. The rectifier parameters are given in Appendix. Zero order hold (ZOH) blocks in the main model and the DSP subsystem represents the sampling rate of the DSP including the analog-to-digital conversion and execution time that is to complete one cycle of calculations in the main program. Once the execution time on the DSP is measured, the sampling rate of the ZOH blocks in the model is set to an appropriate value larger than the execution time considering the analog-to-digital conversion brings about an extra conversion time. Here it must be noted that the integration step size should be kept as low as possible with respect to the defined sampling rate (T_{smp}) of ZOH blocks. That is because of the data transfer rate's being limited to the sampling rate while the electrical quantities in the model is changing during this time interval and the states of the model should be solved during this interval with smaller step sizes.

In the model of the PWM rectifier, the DSP Section subsystem includes the program part that is loaded to DSP after code generation. The DSP section is constructed for closed-loop control incorporating the DC link voltage PI controller. In this block, the gains of measurement device and ADC are transformed back to the real voltage and current values. The reference current waveforms are generated from the supply

voltages with a gain. The switching pulses are generated in hysteresis current control block, which ensures the actual currents are forced to track reference current waveforms in a specified hysteresis band. The output of the DC link voltage PI controller is calculated as follows [17]:

$$I_{cm}(k) = I_{cm}(k-1) + K_{\Delta e}[e(k) - e(k-1)] + K_e e(k) \qquad (1)$$

where I_{cm} is the ac line current magnitude, e is the error between the reference and the actual values of the dc link voltage, and $K_{\Delta e}$ and K_e are the proportional and integral gains for a given sampling rate. The indexes (k) and (k-1) indicates the sampled values at the present and the previous sampling instants, respectively. The sampling rate for the digital PI controller is defined as the sampling rate of the ZOH blocks in the model. The system parameters are given in Appendix.
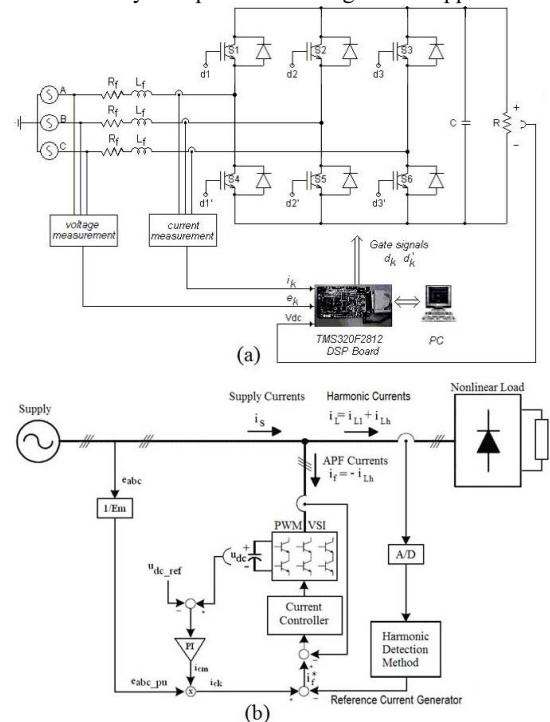

Fig. 1. Block schemes of the two designed systems a) PWM rectifier circuit b) shunt APF circuit

2.2. Code Generation and Simulation of PWM Rectifier with DSP

The Simulink block scheme in Fig.3 is used for testing the switching signals of IGBTs before connecting the DSP to IGBT block in the system. This model acquires the switching signals, which are generated by DSP, and applies them to IGBT bridge block in Simulink. The memory locations are defined on DSP for voltages, currents, and gate pulses. Simulink accesses these memory locations when simulating the system with DSP and writes the variables into the specified memory locations at each numerical solver integration step. In order to ensure the operation of DSP at the sampling rate defined in Simulink, an additional memory location, which is accessed both Simulink and DSP is also defined. The status of this memory location is toggled at the beginning of each sampling interval defined in Simulink. When the Simulink model allows the DSP to execute its code to obtain the switching states for the next sampling

interval, the calculations are performed on the DSP and switching signals are written into the memory locations. Then, the Simulink is enabled to read these values to perform the next step of simulation. Hence, the calculations for the complete system operation are performed in Simulink and DSP sequentially: This kind of operation is essential especially in PI controlled scheme, because the controller needs the previous values of the sampled variables as shown in (1).

After generating the DSP code by using Simulink, the DSP Section in the Simulink model is replaced by a developed Simulink-Code Composer Studio (CCS) interface block. This interface block in the model is an s-function [18] that provides access to the memory locations reserved for the signals on DSP. This s-function is created for the system designed. Hence, before running the simulations with DSP, the generated code is loaded to DSP and the communication between the MATLAB and CCS was established.

Simulations are performed at fixed integration step size, which is set forth in the Simulation Parameters in Simulink. The proper operation of DSP code is tested before connecting it to the real system. The DSP execution time is measured to be 50 microseconds for closed-loop rectifier operation in the generated code. Hence, the sampling rates are set to the values slightly larger than these measured values. The results obtained from Simulink alone and Simulink connected to DSP are obtained to be very similar to each other. In Fig.4, the results for closed-loop operation with DC link voltage PI controller are given. Since the results of both simulation and DSP in simulation are identical, the results of PI controlled rectifier are given for DSP in simulation only. The DC link voltage reference was set to 300V and actual DC link voltage settles to its steady-state value in 0.15s as shown in Fig.4.

3. Code Development for Shunt APF and its Simulation with DSP

When the model in the Simulink program is converted to DSP code using Matlab DSP toolbox as being described in Section 2, the sampling frequency of ADC is the main cycling frequency and this becomes the switching frequency of currents compared in hysteresis band. This frequency is getting lower as the number of inputs read by ADC. In shunt APF application, the mathematical burden of the DSP is much more than that of the case in PWM rectifier, because the DSP should also calculate the load harmonic content, produce filter reference currents through IRPT algorithm, and dc link PI controller. Also, in the APF application, there are six currents and four voltages read by DSP. The shunt APF application requires an input boost inductance chosen at a considerably lower value in order to achieve higher switching frequencies to eliminate a large portion of the load harmonic current content. This necessitates faster switching of IGBTs and current tracking. From this point of view, the code generation through Simulink DSP tools may not be effective. For instance, the execution time of the DSP is obtained approximately 50 microseconds in closed-loop controlled PWM rectifier given in the previous section and this corresponds to a sampling rate of 20kHz, which is the rate of updating the states of the switching signals. Considering the IRPT algorithm implemented in the APF application, it is an obvious fact that this rate will decrease to a lower value since the algorithm requires complex calculations. Because of this reason, the DSP code is developed by user in C-language in order to keep the execution time as low as possible.
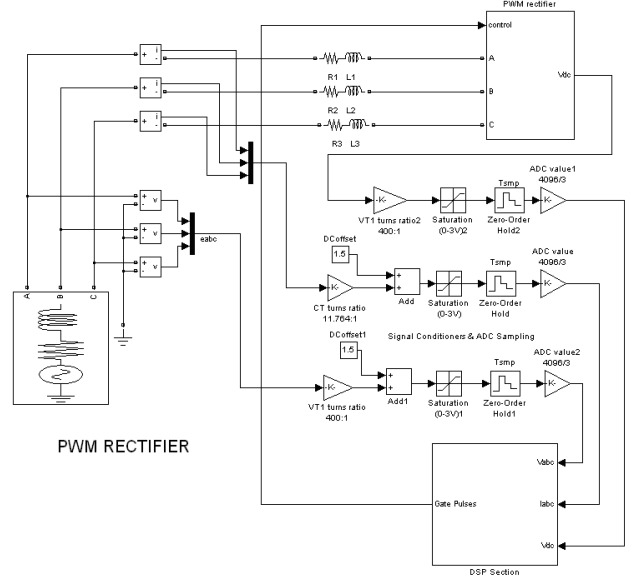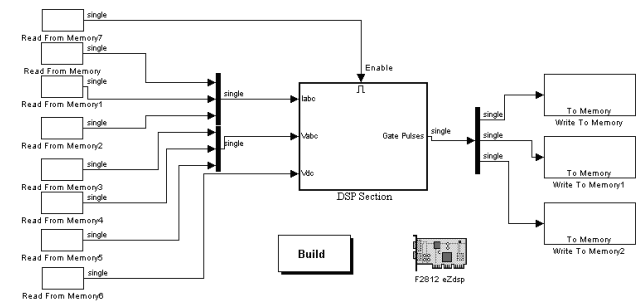

Fig. 2. The Simulink model of PWM rectifier

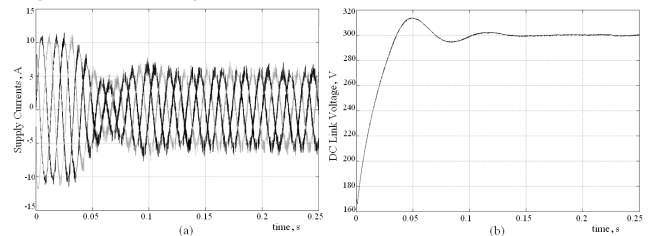**Fig. 3.** DSP code generation block in Simulink

Fig. 4. Simulation result of simultaneous operation of Simulink with DSP for PWM rectifier a) AC line currents b) DC Link voltage

In order to increase the comparison frequency between actual and reference currents in hysteresis band, the reference current generation and hysteresis current controller are operated as two independent tasks in the DSP code of shunt APF. The instantaneous reactive power calculation and extraction of harmonics are performed in other dedicated routine called by main program. While the reference current generation is performed in the main program cycle at a rate of 10kHz, the hysteresis current controller compares the actual and reference current values and updates the switching signals at a 100kHz rate in an interrupt service routine (ISR).

The operation of DSP with Simulink model of shunt APF is also carried out in a similar way as mentioned in PWM rectifier section. The Simulink model reads the switching signals generated by DSP to perform numerical solver operation in simulation and writes the results to the memory locations, which are defined on DSP for line voltages, filter currents, load

currents, and dc link voltage at each integration step of the numerical solver. While testing the DSP code with Simulink model, the sampling rate in the model is set to 100kHz, which is the rate of ADC and hysteresis current control (HCC) switching. So, the interrupt service routine for HCC is removed into main program cycle, which is not the case in the real system operation. Finally, the rate for updating reference current value was measured to be approximately 10kHz in the developed program, these values are updated in the simulations over 10 main program cycle. The Simulink model of the system is shown in Fig.5. A switching ripple filter is also connected to the input terminals of APF to trap the high frequency components that would appear on the filter currents and parameters of this circuit are given in Appendix.

The communication between the MATLAB and CCS is established using the s-function mentioned in Section 2.2 with a few modifications to define additional memory locations. The proper operation of DSP code for shunt APF is assured before connecting it to the gate drive circuit of IGBTs in the prototype system. The entire circuit and control parameters of shunt APF are given in Appendix. Fig.6 shows the results of obtained from simultaneous operation of DSP with Simulink.

4. Result of Implementation

In the power converter part of the hardware, SEMIKRON SEMITEACH three-phase IGBT module was used. This module is equipped with built-in gate drive circuits and protection circuits for short-circuit, overheating, and supply under-voltage protection. The three-phase voltage and current waveforms are measured via Hall-effect voltage transducers (LV-25P) and current transducers (HXS20). The measured voltage and current waveforms are input to ADC ports of the TMS320F2812 DSP by conditioning these signals to 0-3V ADC voltage levels.

4.1. PWM Rectifier

Once the control algorithm is tested using the DSP and Matlab-Simulink in a simultaneous operation, the DSP can be connected to the power block having IGBTs, gate drives and signal conditioning circuits. In the closed-loop control, the DSP can perform calculations and generate switching pulses in 50 microseconds with standard floating-point operations, which is satisfactory for the control of the complete system. The results of closed-loop operation of the real system at the start-up transient and steady-state are shown in Fig.7. Since the simulations are performed under ideal conditions neglecting noise effect on signal conditioning, the noise and switching ripples due to the turn-on and turn-off characteristics of IGBTs do not appear in the simulation results unlike the real system. The reference currents are updated in the main program cycle at the rate of 20kHz, which is a satisfactory for rectifier operation.

4.2. Shunt APF

The experimental results obtained when shunt APF compensating the current harmonics of a diode rectifier load are shown in Fig.8. During experiments, the dc link voltage is boosted to 650V and the APF reference currents for harmonic compensation are generated approximately 4 cycles after the dc link voltage is settled to its reference value. The APF reference currents are updated in the main program cycle at a rate of 10kHz, which is a satisfactory frequency range for the compensation of load harmonics.
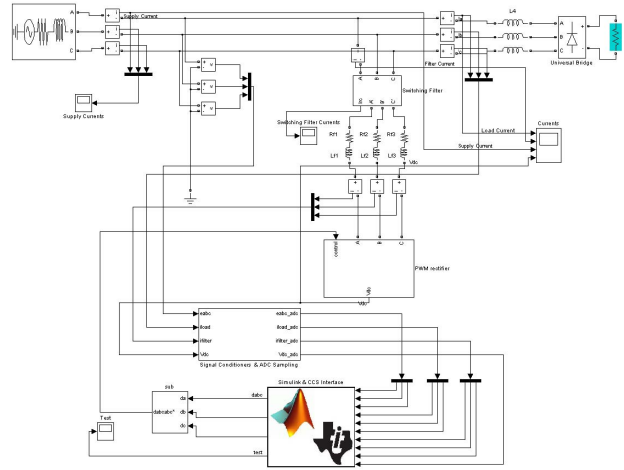

Fig. 5. The model of simultaneous operation of shunt APF model in MATLAB/Simulink and TMS320F2812 DSP
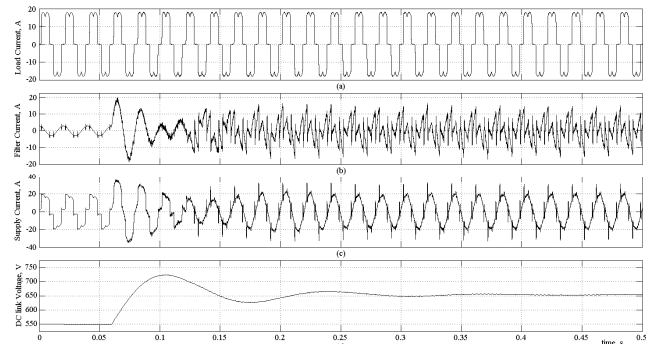

Fig. 6. Simulation results obtained from simultaneous operation of Simulink with DSP for shunt APF a) Diode rectifier currents b) APF currents c) supply currents d) APF dc link voltage

5. Conclusions

The DSP program of a 3-phase unity power factor PWM rectifier is prepared by using MATLAB package program. This is implemented using the facilities of MATLAB Simulink and TMS320F2812 DSP tools. These embedded code generation facilities provide a safe transition from the analysis stage to implementation one in power electronics applications. The approaches given here can be implemented for rapid prototyping of the system in industrial applications. The proper operation of the DSP is guaranteed through simulations before testing the code on physical system. The simultaneous operation of the DSP with the Simulink models was also established by the developed model structure. This approach has been further extended to shunt APF application in this work. MATLAB code generation tools for the applications requiring a large amount of mathematical computations such as IRPT in shunt APF maybe inefficient; therefore, the structure of the DSP program can be reorganized and developed by the user and tested in simulation model. Code generations tools of MATLAB can be considered to be useful in providing rapid prototyping applications that requires less mathematical computations. Even though the structure of the system needs more time consuming in execution, the procedure described here can still provide an efficient and safe way in testing the DSP codes prepared for real system implementation.

Appendix

Parameter	Symbol	Value
PARAMERTS OF PWM RECTIFIER:		
Parameter	Symbol	Value
Supply voltage peak value	E_m	100V
AC side filter inductance	L_f	13 mH
Resistance of filter inductance	R_f	0.1 ohms
DC link capacitor	C	1.1 mF
Load resistance	R	100 ohms
DC link voltage initial value	$V_{dc}(0)$	160 V
Hysteresis band width	ε_h	0.2 A
PI controller gains	K_e	0.001
	$K_{\Delta e}$	0.1
PARAMETERS OF SHUNT APF		
Parameter	Symbol	Value
Supply voltage peak value	E_m	310V
AC side filter inductance	L_f	1.8 mH
Resistance of filter inductance	R_f	0.1 ohms
AC side supply inductance	L_s	100 μH
DC link capacitor	C	2.35 mF
Diode rectifier load resistance	R_L	30 ohms
DC link voltage initial value	$V_{dc}(0)$	550 V
Hysteresis band width	ε_h	0.2 A
PI controller gains	K_e	0.001
	$K_{\Delta e}$	0.1
Switching ripple filter components	L	0.25mH,
	R	3 ohms,
	C	30 μF

6. References

[1] H. Akagi, 'Trends in active power line conditioners', *IEEE Trans. Power Electronics*, 1994, vol.9, no.3, pp. 263-268.

[2] M.K. Mishra, K. Karthikeyan, and P.K. Linash, 'A development and implementation of DSP based DSTATCOM to compensate unbalanced nonlinear loads'. *Proc. IEEE Power India Conf.,* New Delhi, India, April 2006, 8 pp.

[3] Akagi, H.: 'New trends in active filters for power conditioning', *IEEE Trans. Ind. Applications,* 1996, vol.32, no.6, pp. 1312-1322.

[4] B. Singh, K. Al-Haddad, and A. Chandra, 'A review of active power filters for power quality improvement', *IEEE Trans. Industrial Electronics*, 1999, vol.46, no.5, pp. 960-971.

[5] A.Emadi, A. Nasiri, and S.B. Bekiarov, 'Uninterruptible Power Supplies and Active Filters' (*CRC Press*, 2005).

[6] E.B. Barcenas, V. Cardenas, and J.A. Roffiel, 'Shunt Active Power Filters and PWM Rectifiers in Three-Phase Three Wire Systems: A Survey'. *Applied Power Electronics Conference and Exposition*, Dallas, Texas, March 2006, pp.1307-1313.

[7] M.P. Kazmierkowski, and L. Malesani, 'Current control techniques for three-phase voltage-source PWM converters: a survey', *IEEE Trans. Industrial Electronics*, 1998, vol.45, no.5, pp. 691-703.
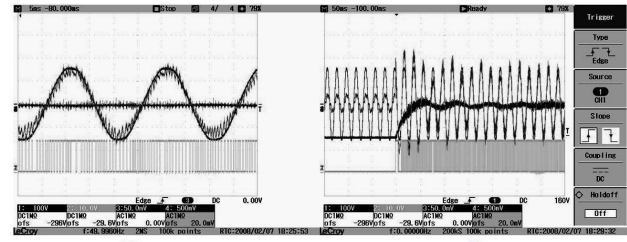
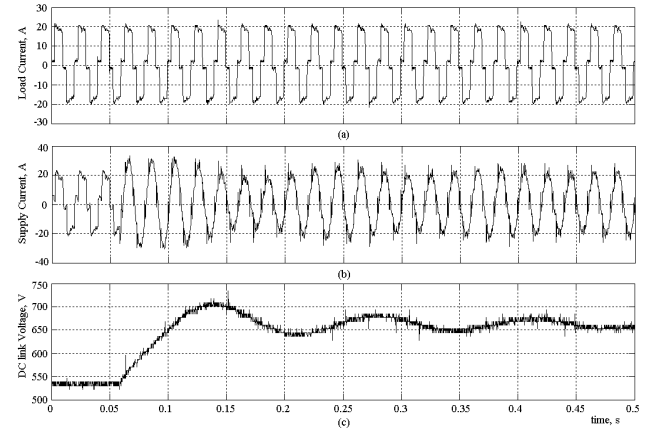Fig. 7. The dc link voltage and line current of PWM rectifier a) steady-state b) startup transient

Fig. 8. Experimental results of the shunt APF a) load currents b) supply currents c) APF dc link voltage.

[8] M.P. Kazmierkowski, 'Control strategies for PWM rectifier/inverter-fed induction motors'. *Proc. IEEE Int. Symp. on Industrial Electronics*, Puebla, Mexico, December 2000, pp.15-23.

[9] M. Cichowlas, M. Malinowski, M. Jasinski, and M.P. Kazmierkowski, 'DSP based direct power control for three-phase PWM rectifier with active filtering function'. *Proc. IEEE Int. Symp. on Ind. Elect..*, Brasil, June 2003, pp.831-835

[10] M. Aredes, J.A.M. Neto, J.C.C. Ferreira, L.F.C. Monteiro, R.M. Fernandes, and M.J.V. Siqueira, 'A simplified control strategy for a unified power quality conditioner prototype'. *Proc. IEEE Power Electronics Specialist Conf.*, Brasil, June 2005, pp.2592-2597.

[11] E. Ozdemir, M. Ucar, M. Kesler, and M. Kale, 'The design and implementation of a shunt active power filter based on source current measurement'. *Proc. IEEE Int. Electric Machines & Drives Conf.*, Antalya, Turkey, May 2007, pp.608-613.

[12] C. Yanbo, Z. Fudan, and K.W.E. Cheng, 'Shunt active power filter-SIMULINK simulation and DSP-based hardware realization'. *Proc. Int. Conf. on Power Electronics Systems and Applications*, Hong Kong, November 2006, pp. 120-125.

[13] R. S. Balog, Z. Sorchini, J. W. Kimball, P. L. Chapman, and P. T. Krein, 'Modern Laboratory-based education for power electronics and electric machines', *IEEE Trans. Power Systems*, 2005, vol.20, no.2, pp. 538-547.

[14] M. Dawande, V. Donescu, Z. Yao, and V. Rajagopalan, ' Recent advances in simulation of power electronics converter systems', *Springer India*, 1997, vol.22, no.6, pp. 689-704.

[15] C. Defour, S. Abourida, and J. Belanger, 'Hardware-in-the-loop simulation of power drives with RT-LAB'. *Proc. Int. Conf Power Electr. and Drives Systems*, Canada, 2005, pp. 1646–1651.

[16] The Mathworks, Inc.: 'Embedded Target for the TI TMS320C2000TM DSP Platform for use with Simulink-User's Guide Version 1' (The Mathworks, Inc., 2003).

[17] T. Surgevil, and E. Akpinar, 'Modelling of a 5-kW wind energy conversion system with induction generator and comparison with experimental results', *Renewable Energy*, 2005, 30, pp. 913-29.

[18] 'Writing s-functions' (The Mathwoks, Inc., 2003).