DESIGN OF HARDWARE IN THE LOOP (HIL) SIMULATOR BOARD FOR POWER ELECTRONIC SYSTEMS AND ITS IMPLEMENTATION FOR ACTIVE POWER FILTERS

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Abstract: In this study, firstly, a general-purpose test simulator circuit was developed that could test the response of the circuits used in power electronic systems on hardware under various operating conditions (hardware in the loop). In the next step, a control board to be used for Shunt Active Power Filters (SAPF) was designed. The control software for SAPF was prepared using CubeMX IDE compiler for two different harmonic extraction methods using instantaneous reactive power theory (IRPT) and synchronous rotating reference frame (SRF) methods. Finally, before connecting the prototype SAPF control board and software to the real system, it had been verified to work safely using the designed test system. With this study, both the SAPF prototype circuit was prepared and a cost-effective system that could be found in the market was designed.

Keywords: HIL Simulations, Functional Testing, Active Power Filters, STM32F4, Rapid Prototype

Güç Elektroniği Sistemleri için HIL (Hardware In The Loop) Simülatör Kartı Tasarımı ve Aktif Güç Filtreleri için Uygulanması

Öz: Bu çalışmada, ilk olarak güç elektroniği sistemlerinde kullanılan devrelerin donanım üzerinde çeşitli çalışma şartlarındaki tepkilerini test edebilecek (hardware in the loop) bir genel amaçlı test simülatör devresi geliştirilmiştir. Sonraki aşamada, PAGF için kullanılacak bir kontrol kartı tasarlanmıştır. PAGF için anlık reaktif güç teorisi (IRPT) ve senkron dönen referans çerçeve (SRF) metotlarını kullanan 2 farklı harmonik çıkarım metodu için kontrol yazılımı CubeMX IDE derleyicisi kullanılarak hazırlanmıştır. Son olarak, oluşturulan prototip PAGF kontrol kartı ve yazılımı gerçek sisteme bağlamadan önce tasarlanan test sistemini kullanarak güvenli bir şekilde çalıştığı doğrulanmıştır. Bu çalışma ile hem PAGF prototip devresi hazırlanmış hem de bir donanım test simülatör sistemi uygun maliyetli olarak tasarlanmıştır.

Anahtar Kelimeler: HIL Simülatör, Fonksiyon Testleri, Aktif Güç Filtreleri, STM32F4, Hızlı Prototipleme

1. INTRODUCTION

Electrical energy quality is important for producers as well as users. The factors affecting the energy quality are oscillations in frequency, distortion of the waveform in voltages, instantaneous voltage rises and falls, and the percentage of harmonics in the current waveform drawn by the loads. In recent years, the widespread use of AC-DC conversions of electrical devices in the industry has increased the harmonic pollution in modern power transmission /

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distribution systems. Harmonics produced by non-linear loads can cause additional power losses and affect nearby communication networks and sensitive loads. Therefore, many international standards such as IEEE 519-1992 and IEC 61000-3-2 have been proposed to limit harmonic pollution (Bhattacharya et al.,2009; Kürker and Taşaltın, 2016; Singh et al.,1999; Wei et al., 2014).

Traditionally, high-efficiency low-cost passive power filters (PPF) are widely used to eliminate harmonics. However, PPFs only can filter out fixed 3,5,7th harmonics and their performance degrades due to aging of the circuit elements. In addition, their filtering properties are highly dependent on the power grid parameters and therefore they can easily resonate with the grid (Nassif et al.,2009). These disadvantages can be overcome by power converter-based active power filters (APF). APFs are much more effective at filtering out dynamic harmonics than PPFs. However, The cost of APF is higher (Corradini et al.,2008; Costa-Castello et al.,2009; El-Kholy et al.,2006; Patnaik et al.,2013; Peng et al.,1999; Tangtheerajaroonwong et al.,2007; Zhou and Liu,2012).

Widely used in industrial applications, APFs are encountered as an alternative power electronics application for other power quality issues such as reducing the harmonic content of the motor driver's current, reactive power compensation, voltage regulation, load balancing, and voltage flicker compensation. There are many studies in the literature about APF topologies, control methods and practical applications. In this study, the use of the basic APF structure was preferred because of these important and wide usage areas (Balikci et al.,2022; Mehrasa et al.,2016; Costa- Mohd Zainuri et al.,2018; Tsengenes and Adamidis,2011; Çolak et al.,2011; Arya and Singh, 2014; Verne and Valla,2010; Patnaik and Panda, 2014; Kumar and Bansal,2019; Assiene Mouodo et al.,2022; Kale and Özdemir, 2015; Vardar et al.,2019; Tan et al.,2019; Kükrer et al.,2019).

In the development process of a power electronics circuit, first, the circuit is modelled using different simulation software. With simulation studies called Model in the Loop-MIL, it is possible to work in software without damaging a power electronics element or controller. Afterwards, the stage of preparing the necessary software for the controller to be used in the implementation phase of the simulated power electronics circuit is started. In a simulation environment, if the software prepared for the controller has the opportunity to run, the source code is embedded in the simulation and the test is performed. This process is called Software in the Loop-SIL. And so, the verification of the prepared controller software can be done. If the simulation software does not have the feature to run source code, first the source code is loaded into the controller hardware. Controller hardware and simulation software are operated jointly by sharing data (Processor in the Loop-PIL). Here, the controller hardware is tested by exchanging data from the simulation instead of the real system. In PIL simulations, all current and voltage values required by the controller are given digitally (via serial communication channels such as RS232 or USB) and the controller is provided to make calculations over these data. In this method, although the software of the controller is tested, the tests related to the peripheral units are left to the real environment (Bouscayrol,2010; Karimi et al.,2010; Lauss and Strunz,2021; Yarıkkaya and Vardar,2020).

Designed control circuits; may also include various signal conditioner, filters, analog/digital converters, protection and logic circuits. Another verification method for these control circuits is simulation studies (Hardware in the Loop-HIL) performed with all hardware components. Thus, it is ensured that the produced electronic cards and the software are tested together. There are three types of HIL simulations in the literature. These; Signal (controller) level is called HIL simulation, Power level is HIL simulation, and Mechanical level is HIL simulation (Bouscayrol, 2010).

In this study, a signal level HIL simulator circuit and software has been developed that performs the testing of power electronic systems prototype circuits by transferring information at the signal level (analog generation of current and voltage information and reading of digital

PWM gate pulses). With this HIL test equipment, the current and voltage values required by the control card are produced as analog signals by using the values obtained from the simulation model, which is created in the computer environment and includes the power elements. These generated current and voltage values are applied to the control card and the control output information (PWM gate pulses) produced by the card is read digitally by the test equipment and sent to the simulation software in the computer environment. Thus, it can be tested whether the control card's hardware and software function correctly.

In the second section of the study, information is given about the design of the SAPF and the prototype control board. In the third section, the structure, programming and use of the designed signal level HIL simulator board are explained in detail. In the fourth section, the results obtained from the simulation of SAPF and the performance of HIL tests are given and compared. In the fifth section, the obtained results are presented.

2. SHUNT ACTIVE POWER FILTERS

APFs are used in power systems to correct the increasing power quality problems, especially due to the increasing use of nonlinear loads. The power circuit of their SAPF consists of PWM converters with current or voltage sources. The SAPF is placed parallel to the load at the point of common coupling (PCC) between the harmonic generating load and the source. In the SAPF control structure, the current measurement taken over the load is transferred to a signal processor. The harmonic components of the load are determined by a harmonic inference method using load current information. It sends the compensation current of equal amplitude and opposite sign of the obtained harmonic currents to the PCC point. At the same time, it draws a low amount of current at the basic frequency from the source so that it can perform the filtering function and compensate for its own losses. (Figure.1)

Figure 1:
Single Line diagram of Shunt APF (Vardar et al.,2019).

The control board belonging to SAPF was realized using the STM32F407VG coded processor belonging to ST company. The STM32F407VG is a microcontroller with a Floating point unit at a speed of 168 MHz with a 32-bit ARM-based Cortex-M4 core. This microcontroller has a sufficient number of timers, (Pulse-width modulation) PWM, serial communication units, 12bit (Analog-to-Digital-Converter) ADC units to be used on the control board belonging to the SAPF.

The SAPF software was developed in the C language using the CubeMX IDE compiler belonging to the ST company. In the software, IRPT and SRF methods were used as harmonic inference methods. As a current controller, Hysteresis current controller was preferred because it provides convenience in performing HIL simulation.

3. SIGNAL LEVEL HIL SIMULATOR BOARD DESIGN AND SOFTWARE

HIL simulator circuits can be used to test the accuracy of control boards during the design or production phase of a power electronic system. This type of equipment is widely used in the tests of components of various land and air vehicles, especially in the automotive sector. In Hardware in the Loop-HIL simulations, the power parts of the power electronic system to be tested is modelled in the software environment and the data in this system is sent to the prototype control board. The data, which is the output of the control board, is read and transferred to the simulation. The interface circuit that performs this information transfer between the simulation and the hardware is called the HIL simulator tester (board). According to the characteristics of the data transferred in HIL simulations, it is divided into three as signal level, power level or mechanical level. The data (e.g. current, voltage) from the signal level HIL simulation is transmitted to the control board as a low voltage, as if outputting from a sensor. Similarly, the control pulses of the power electronics elements, which are the output of the control boards, are read as signals and sent to the simulation. In power level HIL simulations, data from the HIL simulation (e.g. current, voltage) are physically generated using emulator circuits. In the mechanical level HIL simulations, there are mechanical elements in the structure (Bouscayrol, 2010).

In this study, a signal level HIL simulator board was designed to perform HIL tests of power electronic systems and its block diagram is presented in Figure 2. It is planned to use MATLAB/Simulink for modelling power electronic systems. Due to the running speed of the simulation created in MATLAB/Simulink and the delays caused by data communication, the HIL test performed with the designed HIL simulator is not performed in real time. However, with the program codes that provide synchronization added to the control structure, results of real-time operation are obtained. The HIL simulator board structure and its components are presented below in detail.
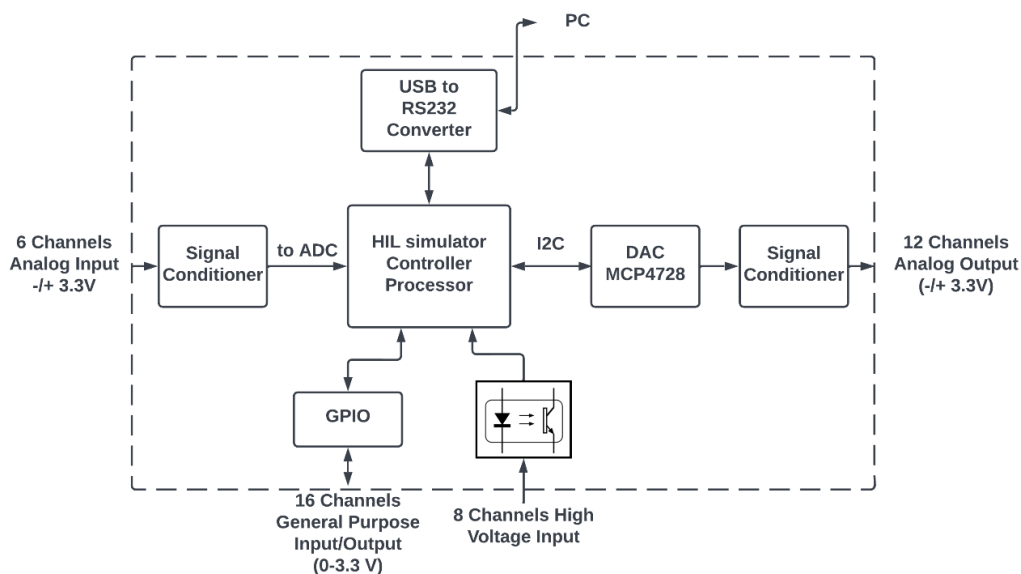
Figure 2:
Block diagram of the designed Signal Level HIL Simulator Test Board.

The HIL simulator board is designed using the 168 Mhz STM32f407 coded processor belonging to STM company. The prepared simulator board is connected to 12 12-bit Digital-Analog Converters (DAC), 6 12-bit Analog-to-Digital Converters (ADC), 8 high-voltage inputs (12 volts) IO ports, 16 low-voltage inputs (3.3 volts) IO ports and It has one USB serial port converter.

12 DAC units are placed on the simulator board to be used to send analog information to the boards to be tested. For this process, Microchip company's MCP4728-E coded IC was used. The analog output signal information sent from the MATLAB environment to the power electric circuit to be tested first comes to the HIL simulator circuit via USB. This information is transmitted digitally by the processor in the simulator to the MCP4728-E DAC integrated with the I2C protocol. The output voltage of the DAC integrated circuit is in the range of 0-3.3V. This information is transmitted to a signal conditioner circuit (for adding gain and offset) designed using the TL072 opamp IC. The transmitted information is created as an analog value between ±3.3V at the output of the signal conditioner circuit and is driven to the output port, applicable to the circuit to be tested. Thus, the information from the MATLAB/Simulink software can be applied to the power electronics circuit (SAPF control board) to be tested as if it is being read from the current or voltage sensor in the power circuit.

In the structure of the simulator board, 6 ADC units are located in order to read and send the analog data from the power electronics circuit to be tested to the simulation software. Since the number of ADCs and resolutions found in the main processor of the simulator board is sufficient, there is no need for an external ADC IC. The ADC modules on this processor are 12 bits and analog values between 0-3.3V can be sampled. The analog inputs of the designed HIL simulator board were applied to the ADC inputs of the processor via a signal conditioner circuit. With this circuit, analog information at the voltage level between ±3.3V applied from the input of the HIL simulator can be processed by shifting it to the level that the ADC can measure. Thus, analog data (PWM gate pulses, etc) coming from the power electronics circuit to be tested can be transferred to the simulation prepared in Matlab/Simulink software.

A 12-volt input port with 8 optical isolators has been added on the HIL simulator board to receive logic information at signal levels higher than 3.3V. This voltage value can be increased to higher levels with a series resistor to be added to the signal input. These ports are unidirectional and are used for input purposes only.

16 ports have been created inside the simulator board that can be used to send or receive logic signals to the boards to be tested. These ports can be set as input or output according to need. The input voltage to be applied to the ports is in the range of 0-3.3V. Within the scope of this article, the operations of reading and transferring the IGBT gate signals over the SAPF control board to the computer environment and transmitting the information that the case has changed from the computer to the control board are done with these ports.

There is a CH340 RS232/USB converter unit on the HIL Simulator board to exchange data with Matlab/Simulink software. A Matlab/Simulink block shown in Figure 3 was designed to perform data communication with the simulator board prepared within the scope of this study. There are inputs on the left side of this block and the signals to be sent from the software to the test board are applied. On the right side, the outputs are located and the data from the power electronics circuit to be tested are transferred to the simulation via these terminals. For the purpose of this block to work, an S-function code has been prepared. This s-function code sends and receives data to the HIL simulator board at each step of the simulation created for testing (Yarıkkaya and Vardar,2020).
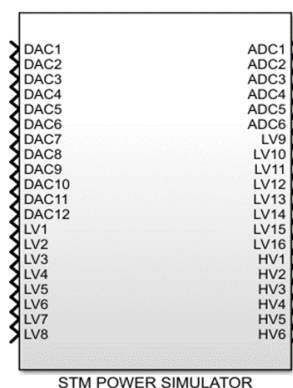
Figure 3:
Signal level HIL Simulator – Matlab/Simulink communication block.

In addition, the source code is written in C language using the CubeMX IDE compiler in the STM32f407 processor on the HIL simulator board. This code of the HIL simulator board performs the communication with Matlab at each simulation step, sending the incoming data to the output ports or DACs, and transferring the data received from the ADC and input ports to Matlab/Simulink.
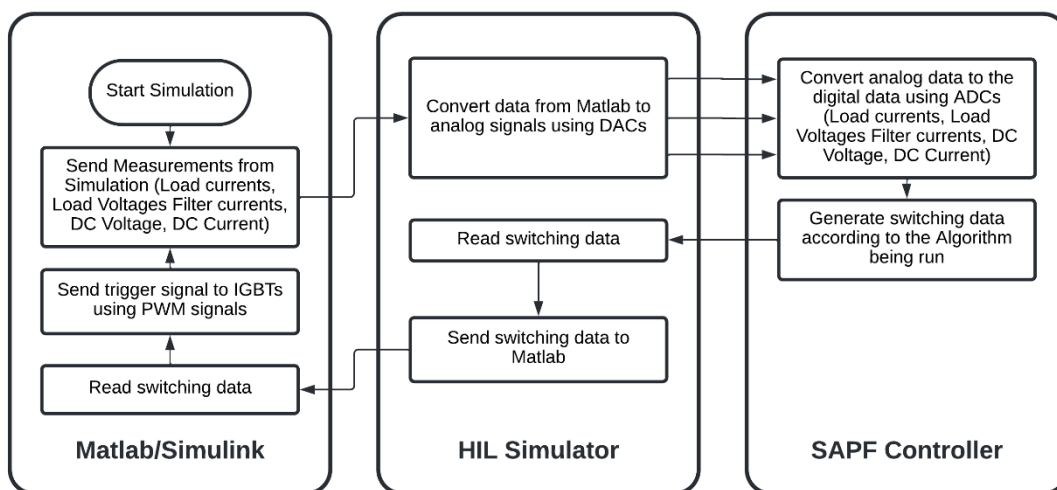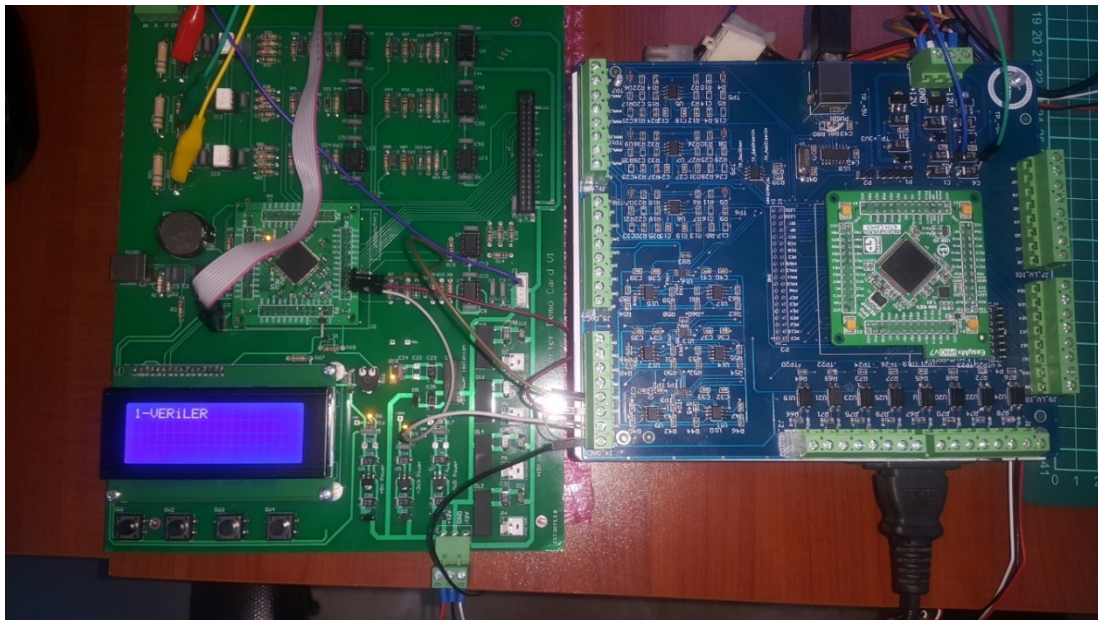

Figure 4:
HIL simulation process steps.

Firstly, as mentioned above, prototype SAPF control board and software, and HIL simulator test board and software were developed. In the second stage, a model created in the MATLAB environment, the HIL test card and the prototype SAPF circuit were run together (co-operation) and the accuracy of their functions were tested. For this process, the data used in the control algorithm, such as the current and voltage values of the power stage in the simulation prepared in the MATLAB application, are sent to the simulation board via the USB port. The simulation hardware converts the necessary supply voltages, load currents, filter currents and DC link voltage values into analog data with the help of DACs and applies them to the inputs of the control board of the SAPF, according to these incoming data (Figure 2). The voltage levels to be converted are set to have the same values as the sensor outputs. Thus, the tests are carried out on hardware such as signal conditioners etc. in control board. The analog or digital inputs of the control board are converted into digital data with the help of the appropriate ports on the

simulation board and sent back to the simulation software via USB. Thus, all functions of the designed control board are tested at the hardware level. The process flows of the HIL simulation are presented in Figure 4.

4. MIL AND HIL SIMULATION WORKS FOR SHUNT ACTIVE POWER FILTERS

In this section, the HIL simulation was performed and verified with the help of Matlab/Simulink using the designed prototype SAPF control board and the designed HIL simulator board. The photograph of the test setup created for this purpose is given in Figure 5. The software for the SAPF board is prepared using two different harmonic extraction methods, instantaneous reactive power theory (IRPT) and synchronous reference frame (SRF). Firstly, a simulation was prepared entirely in Matlab/Simulink environment for these two different methods (MIL simulation). Here, the control software, grid, load, power electronics circuits are all simulated. In the second stage, the HIL simulation model for SAPF was obtained by removing the control blocks from this created MIL simulation and adding a block that enables communication with the HIL simulator board (Figure 3). And thus, the HIL simulator board is properly connected to the prototype SAPF board (as in Figure 5), and the HIL simulation of the board is performed. The block diagram of the simulation prepared in MATLAB/Simulink, which performs the HIL test of SAPF for both methods, is given in Figure 6.

Figure 5:
The experimental setup used in the HIL test of the APF control board (left) and the simulator test board (right).

To summarize the operation of the HIL simulation structure: In the HIL simulation created in MATLAB/Simulink, the grid, load and power electronics circuits are in the simulation. The current and voltage data obtained at each time step of the simulation is first applied to the HIL simulator board using the communication block, and then to the prototype SAPF control board as if it is coming from a sensor. The control software on the SAPF control board receives this information through the signal conditioner circuits, runs the sampling and control algorithms. At the end of this process, the control board generates (updates their state) control outputs (IGBT gate pulses) corresponding to the current inputs. The HIL tester reads these new states and sends them to the software in MATLAB/Simulink. The updated IGBT gate pulses in the simulation in MATLAB are applied to the power stage and the current and voltage information generated in

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the system changes. The simulation works cyclically in this way, and the hardware and software components of the prototype SAPF control board are tested with HIL simulation (Figure 4).

The testing phase of proposed HIL simulation does not run in real time. There is a communication pin for timing synchronization between the processors of the HIL simulator board and the SAPF board. Since the HIL simulator board receives a new data from the simulation, it reflects it to the outputs and notifies the SAPF software that the data is renewed. The SAPF software also runs the control algorithm once and renews the outputs, and notifies the simulator that this refresh process is completed. When the simulation step time and the control algorithm run time value in the Matlab environment are selected equal to each other, this cyclical operation will give us the results in real-time operation. Since HIL supports time synchronization in simulation, hysteresis current controller is used as current controller in SAPF software.
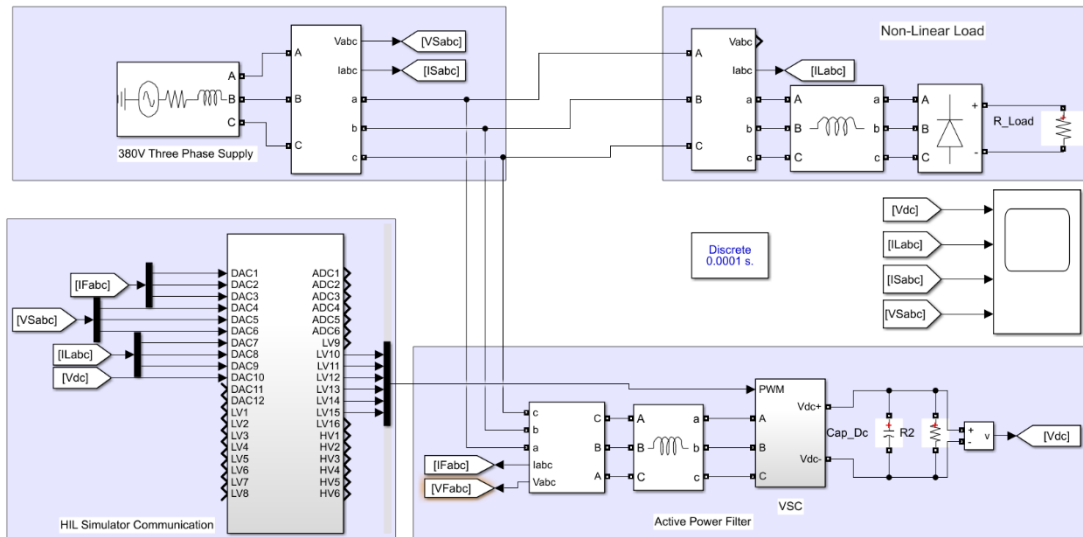
Figure 6:
HIL test simulation blocks prepared in Matlab/Simulink for SAPF.

In this study, MIL and HIL simulation studies performed with two different harmonic extraction methods prepared for SAPF are presented and compared below. The parameters used in the simulations are given in Table 1. The Diode Rectifier circuit is used as harmonic current source in simulations. The resistance value used at the diode rectifier output increases the amplitude of the load and harmonic currents, but does not change the THD value. The series inductor connected to the diode rectifier input to the AC line, the harmonic content of the currents varies between 30.5% and 28% and the APF performance increases.

Table 1. System parameters for MIL and HIL simulations.

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AC source parameters	380V,50Hz, 0.001 Ω, 100uH
DC bus capacitors	4500μF
DC bus reference voltage	650V
Filter inductors	1.8 mH
Non-linear Load	200μH Serial Inductor + Diode Rectifier + 10 Ω Resistive Load
Simulation Ts	1e-5 s
Sample time for methods	10 kHz

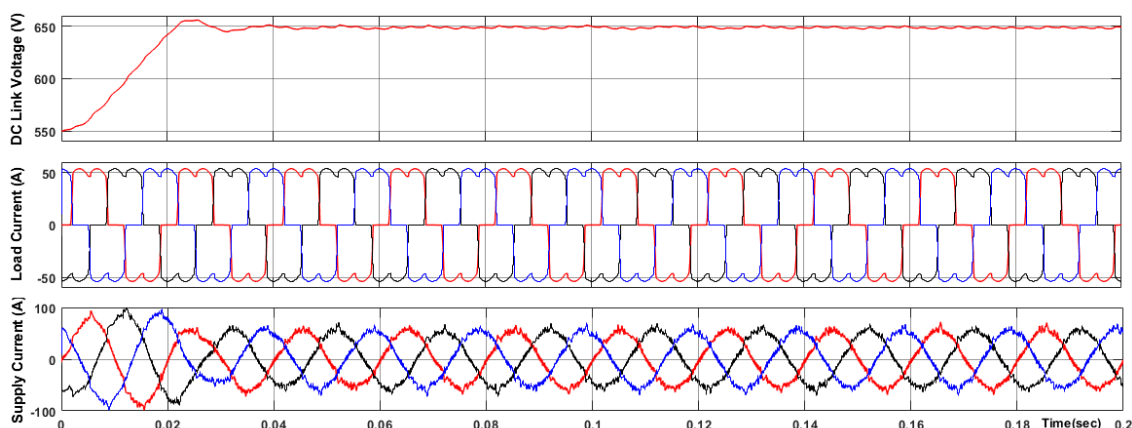### 4.1. MIL and HIL Simulations for SAPF Structure Using SRF Method

The MIL simulation structure of the SAPF structure using the SRF method is given in Figure 7. The simulation results of this structure are presented in Figure 8 for normal simulation (MIL), and the results obtained with the co-operation work (HIL simulation) using the Matlab-HIL simulator test board are presented in Figure 9. The waveform of the current of a phase of the supply belonging to MIL and HIL simulations can be seen in detail in Fig.10.
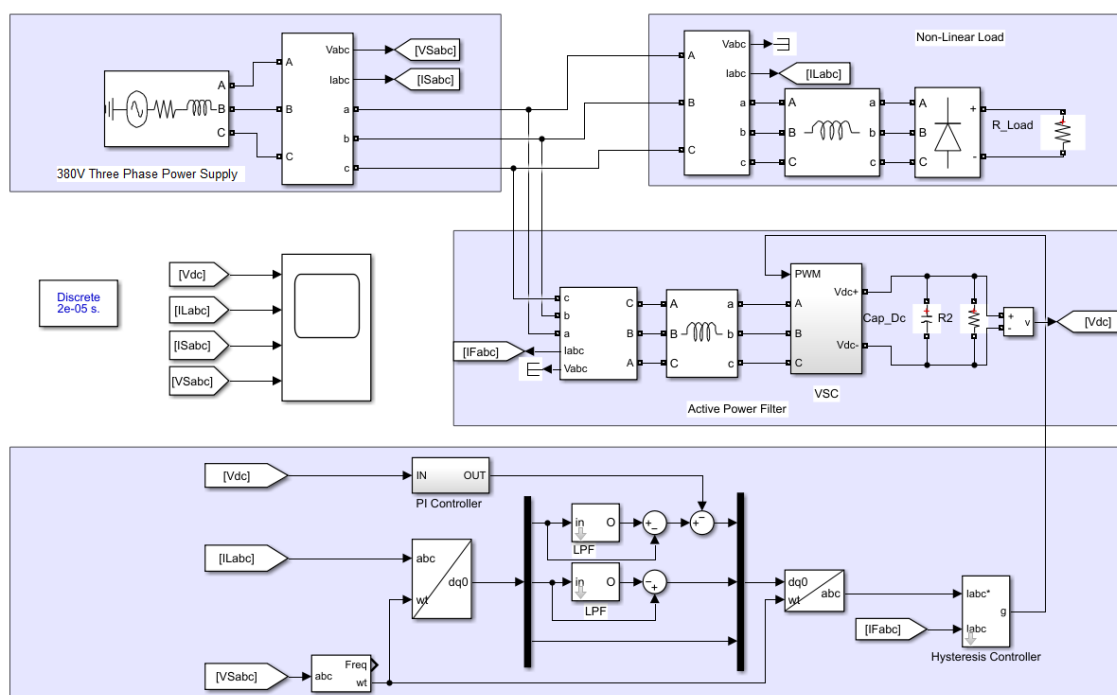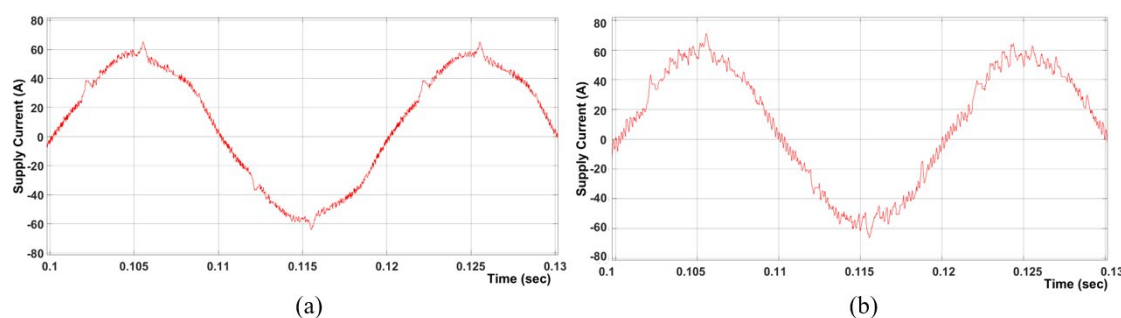

Figure 7:
MIL simulation general blocks for SAPF structure using SRF method.
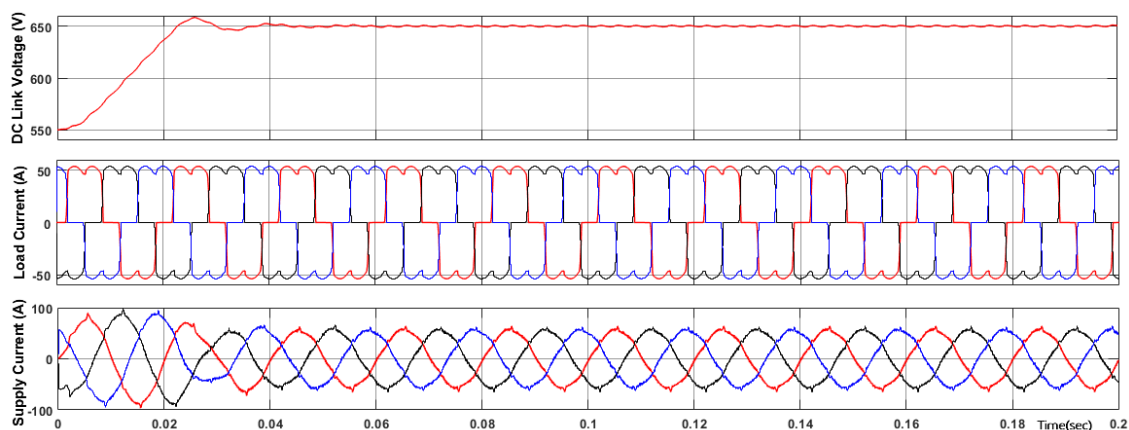
Figure 8:
MIL simulation results for SAPF structure using SRF method (Vdc, Iload, Isupply).

Figure 9:
HIL simulation results for SAPF structure using SRF method (Vdc, Iload, Isupply).


| (a) | (b) |

Figure 10:
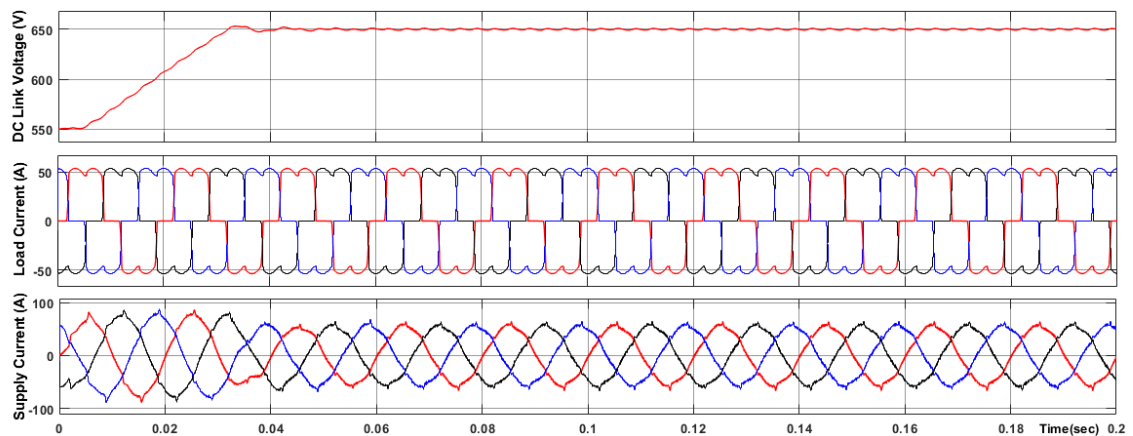*Detailed view of the supply current a) MIL simulation b) HIL simulation.*

According to the results; under both operating conditions, the active filter has successfully deleted the harmonic currents generated on the load side, and the supply currents approached sinusoidal. The DC bus voltage of the active filter is kept stable at the set point in both simulation situations. When the harmonic content is examined, the THD value, which was 28% when APF was not working, was reduced to 5.68% for MIL simulation and 9.01% for HIL simulation. It has been tested that the prototype SAPF control board circuit and software designed with this HIL simulation work correctly.

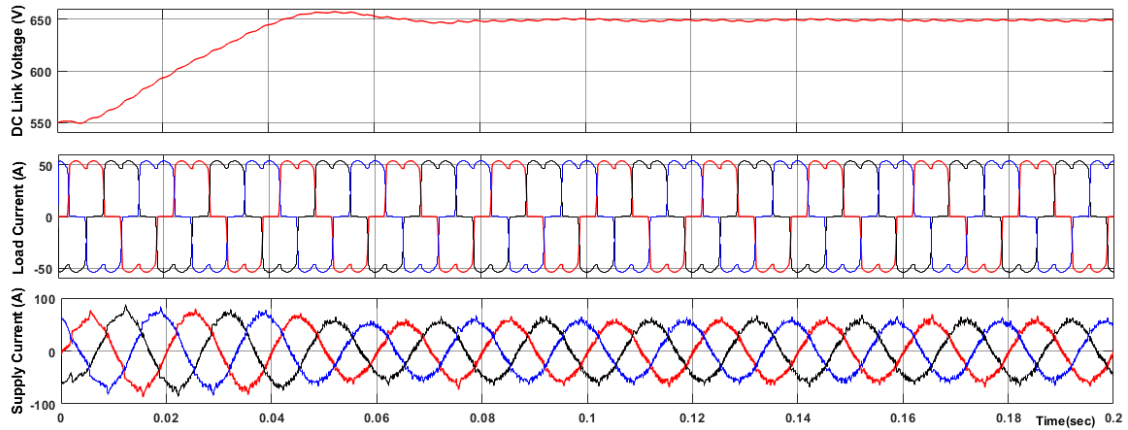### 4.2. MIL and HIL Simulations for SAPF Structure Using IRPT Method

Similarly, the MIL simulation structure prepared in the SAPF structure using the IRPT method is given in Figure 11. The simulation results of this structure are presented in Figure 12 for normal simulation (MIL), and the results obtained by co-operation work (HIL simulation) using the Matlab/HIL simulator test board are presented in Figure 13. According to the results of both simulations, the active filter has successfully eliminated the harmonic currents produced on the load side and the supply currents have taken a form close to sinusoidal. The DC bus voltage of the active filter is stable at the set point in both simulation conditions. When the harmonic content is examined, the THD value, which was 28.18% when APF was not working, was reduced to 6.06% for MIL simulation and 7.86% for HIL simulation. The functionality of the prototype SAPF control board circuit and software designed using HIL simulation has been tested.
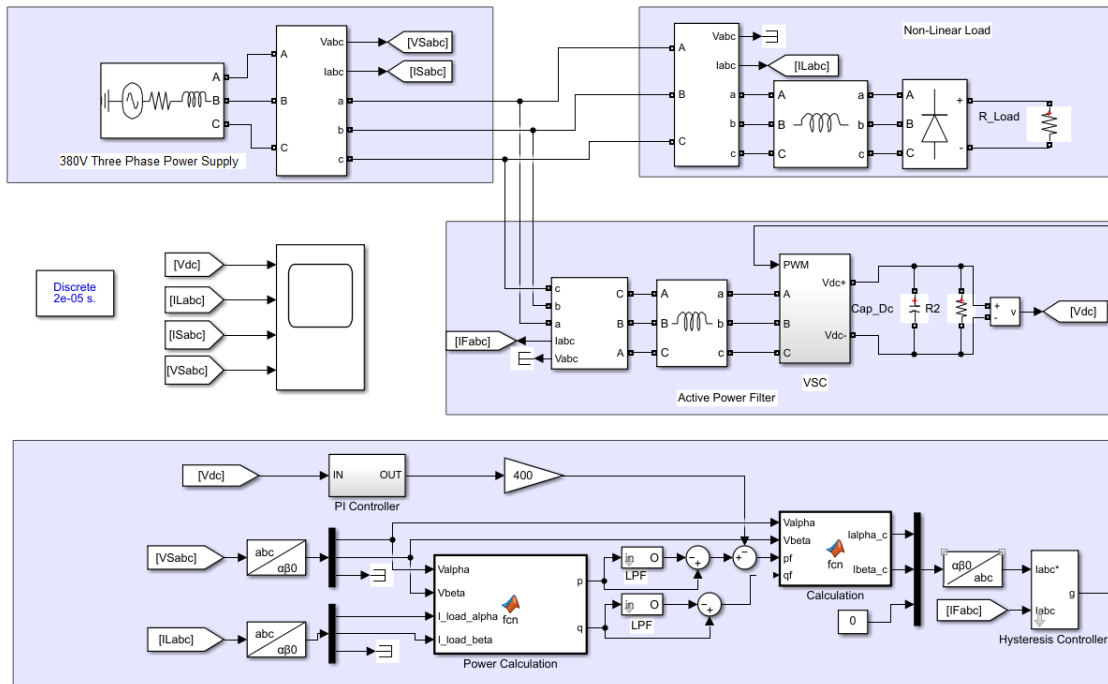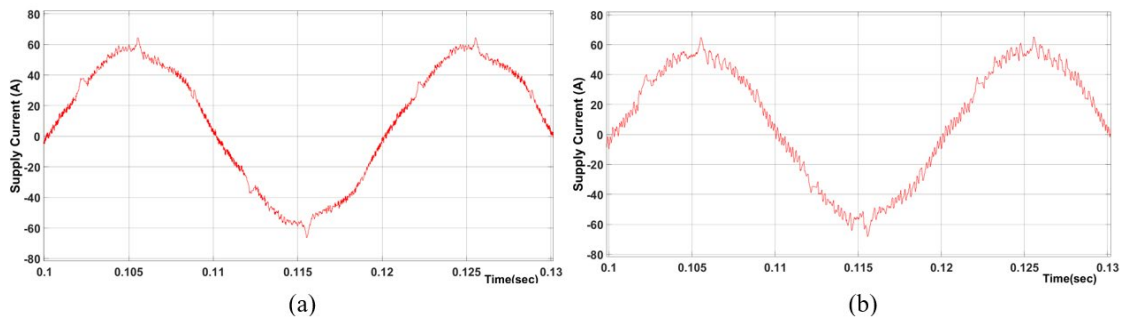
Figure 11:
MIL simulation general blocks for SAPF structure using IRPT method.

Figure 12:
MIL simulation results for SAPF structure using IRPT method (Vdc, Iload, Isupply).

Figure 13:
HIL simulation results for SAPF structure using IRPT method (Vdc, Iload, Isupply).

(a)   (b)

Figure 14:
Detailed view of the supply current a) MIL simulation b) HIL simulation.

With these two different studies, all software and hardware components prepared for SAPF have been successfully and safely verified. In addition, a cost-effective general purpose HIL tester system that can be used in validation tests in research and production of power electronic systems has been designed.

5. CONCLUSION

In this study, first of all, the control circuit design for the SAPF was carried out. SAPF control board prototype was designed using STM32f407 ARM processor. The control software for SAPF was prepared using CubeMX IDE compiler for two different harmonic extraction methods (IRPT and SRF).

In the second stage, a general-purpose, low-cost HIL simulation board design that could be used in the testing of many electronic boards and in the design of power electronic systems (solar inverter, motor driver, STATCOM, DC/DC converters, etc.) was made. Designed with the STM32f407 ARM processor, the software in this board was prepared using the CubeMX IDE compiler. In addition, the block that would enable communication with MATLAB in HIL simulation was created using the s-function structure.

In the final stage, MIL and HIL simulations were performed to minimize possible errors before connecting the prototype to the real power stage of the SAPF control board. The prototype SAPF control board operated with the designed HIL simulator circuit, similar results were obtained with the MIL simulation and the functions of all software/hardware components were tested to work correctly.

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CONFLICT OF INTEREST

The author (s) acknowledge that there is no known conflict of interest or common interest with any institution / organization or person.

AUTHOR CONTRIBUTION

Ferzende Tekce worked on simulation studies, preparation and production of printed circuits, software development, testing obtaining results and writing works.

Kadir Vardar worked on the simulation studies, conceptual design of hardware and software components, software development and article writing.

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APPENDIX: Simplified schematic of the HIL simulator board.