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Bidirectional Active Rectifier Phase Lock Loop Software Design for More Electric Aircraft

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Abstract – The next generation aircraft will be operated first with hybrid technology and then with purely electric technology, just like in the automobile industry. More electric aircraft concepts today have brought about a reorganization of the generation, transmission and distribution of electric power. Power electronics technology plays a key role in connecting new electrical loads to the new aircraft electrical power system. One of the most important tasks of power electronics circuits in MEA is to convert aircraft variable frequency AC voltage to DC voltage of different level. Converters that perform the task are commonly known as "rectifiers". The aim of this study is to develop the grid synchronization code for a bidirectional three-phase active rectifier, which can meet the advanced requirements of more electric aircraft applications using digital signal processors. In order to test the developed code on a real microcontroller, hardware in the loop (HiL) test was carried out.

Keywords – Embedded software, More electric aircraft, Power electronics, Power factor correction.

I. INTRODUCTION

In traditional aircraft power generation systems, a heavy hydraulic transmission called an integrated propulsion generator (IDG) is connected between the engine and the generator, and a constant voltage of 400 Hz is obtained. A DC voltage is generated from the AC mains at the generator output by means of a diode rectifier with 12 or 18 pulses. This method has disadvantages in terms of weight and size.

More electric aircraft (MEA) is the conversion of mechanical, pneumatic and hydraulic systems into electrical systems. This leads to a decrease in the weight of an empty aircraft, an increase in fuel efficiency and a decrease in the required thrust from the engine. Developments in power electronics and electrical machines allow the use of electric starter generators (ESG) connected to the gas turbine engine. Voltage is generated at a frequency between 360Hz-800Hz, which is proportional to the engine speed. The energy flow can be bidirectional in the active rectifier. Thus, the ESG acts as an engine for electrically starting the gas turbine and a generator for supplying electrical loads on the aircraft. With an active rectifier, compliance with the current harmonic limits specified in the DO-160G standard becomes easier. With this method, the power factor can be increased to more than 95% [1].

In this study, it was shown that the phase lock loop is synchronized quickly between a wide input frequency without being affected by noise. The use of simulation approaches at the control system development stage allows not only to significantly reduce costs, but also to shorten the development time. But traditional simulation has the disadvantage of not being able to fully demonstrate the actual operating conditions. One way to bridge the gap between simulation and actual conditions is through hardware-in-the-loop testing . In this paper, the TMS320F28069 DSP controller is used for the development of the phase-locked algorithm of the bidirectional active rectifier. The phase locking performance under harmonic and unbalanced phase conditions at a frequency of 800 Hz was studied using the moving average filter method in the phase locked algorithm.

II. MATERIALS AND METHOD

The use of electronic equipment has emerged as a key technology to further increase efficiency and reduce aircraft fuel costs and CO_2 emissions, and is commonly known as the More electric aircraft (MEA) concept. The advantages of MEA architecture are increased payload capacity and airtime, increased maneuverability, easier and less time-consuming maintenance, less electromagnetic interference in the electrical system. The frequency of the generator typically ranges from 360Hz to 800Hz. Voltage levels in the system are 115/230 Vac, 270/540 Vdc and low voltage 28 Vdc.

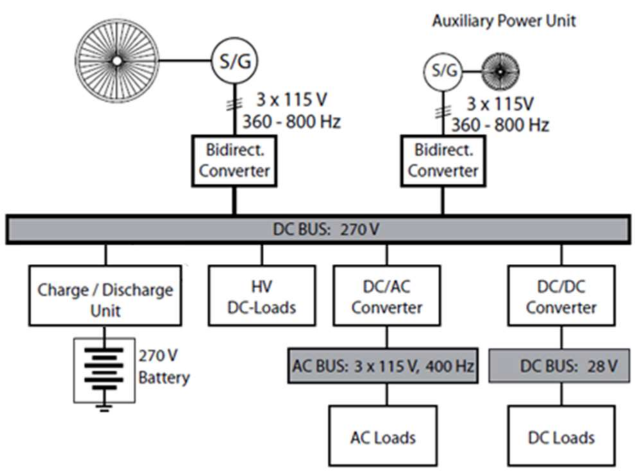

Fig. 1: MEA Electrical Power System Architecture

III. ACTIVE RECTIFIER

Power Factor is the ratio of real power to apparent power. When the power factor is less than 1, it will include phase shift, harmonic distortion or both, and both will distort the power factor. The closer the power factor is to unity, the more efficient the system. Reactive power is controlled by the active rectifier system. The efficiency of the power system is increased. The DC bus voltage is controlled independently of the generator output voltage and frequency.

In the conventional power generation systems in airplanes, the apparent line current rises due to reactive power. The capacities of circuit elements such as generators, transformers and cables are filled unnecessarily. If the generator and transformer are not chosen large enough to cover the reactive losses, it may reach the saturation point. Due to saturation, voltage and current waveforms are distorted and additional harmonics are generated. High torque oscillations may occur in the mechanical system due to saturation and harmonics, and circuit elements may also deteriorate. The disadvantages of traditional electricity generation methods are overcomed with an active rectifier.

A. Grid Synchronization Methods

The most difficult point that will affect the performance rates of bidirectional active rectifiers is the process of being synchronous to harmonic and unbalanced voltage at high frequency. There are several methods in the literature for performing synchronization. It is possible to divide the methods of being synchronous to the grid into frequency domain and time domain. Examples can be given for discrete fourier transform and kalman filter frequency domain methods. These methods work in an open-loop manner. For closed-loop methods, phase locked loop and delayed signal cancellation methods are often used in the literature.

PLL can be classified as follows;

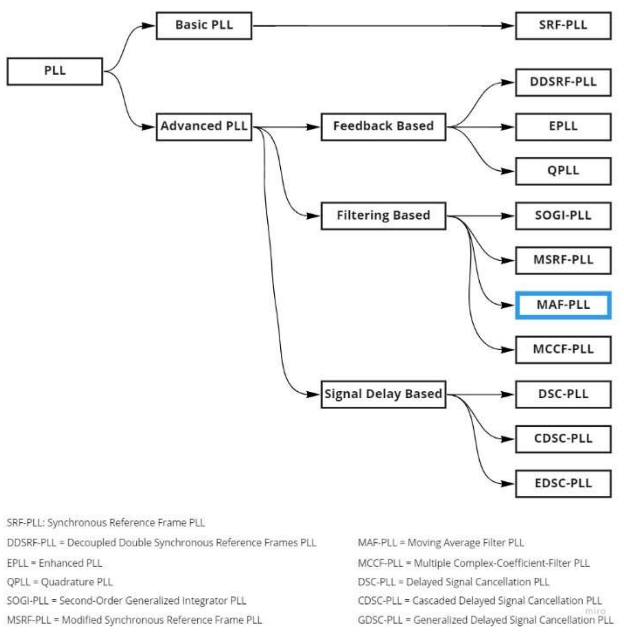

Fig. 2: PLL Varieties [2]

A high speed DSP is required to calculate the frequency of the generator voltage. Phase-locked loop (PLL) is a widely used for synchronization. A moving average filter was used to improve PLL performance. The moving average filter is the most common filter in DSP, as it is the easiest digital filter to use. Despite its simplicity, the moving average filter is ideal for reducing random noise while maintaining a sharp step response. This makes it the primary filter for time-axis signals. In this study, the Alpha-Beta Frame Moving Average Filter PLL (aßMAF-PLL) method was used.

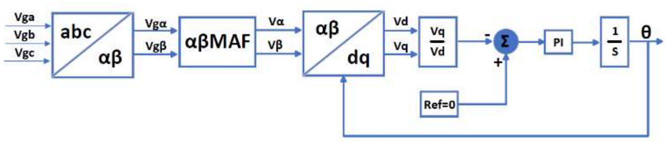

Fig. 3: αβMAF-PLL Architecture

The average number of samples taken by the filter varies adaptively according to the frequency feedback. The filter width is inversely proportional to the frequency. As the frequency decreases, a larger number of samples are averaged. The proposed architecture was run in a Simulink environment and was successfully observed to be synchronous to the generator voltages.

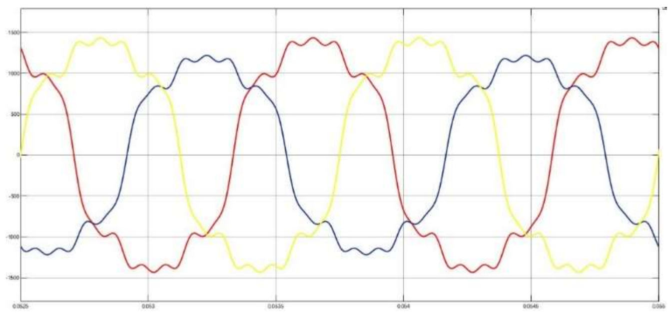

Fig. 4: ESG Output Voltage

The 3-phase voltage signal has both harmonic and unbalanced phase voltages. Despite these conditions, the synchronization process was successful. Although there is noise on the Dq values, the grid frequency has been successfully detected.

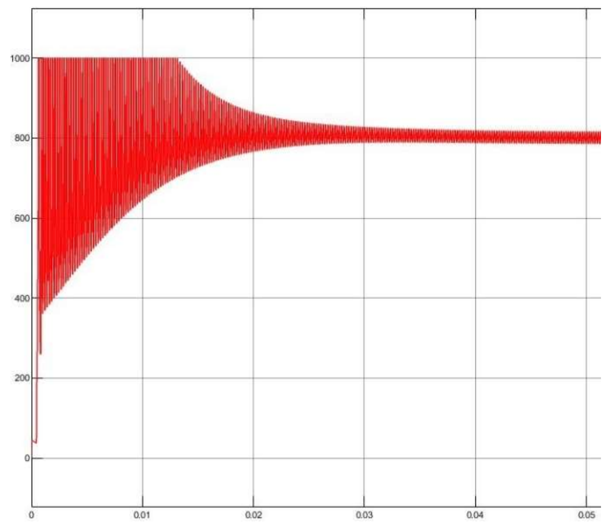

Fig. 5: PLL's Calculation of 800Hz Grid Voltage

PLL circuit was designed and simulations were carried out in Matlab/Simulink program. The grid frequency calculated according to the voltage signals in Figure 4 is shown in Figure 5. The dq parameters of the same voltage signals are shown in figure 6. The values of the DQ parameters were obtained as follows. The blue graph shows the q parameter.

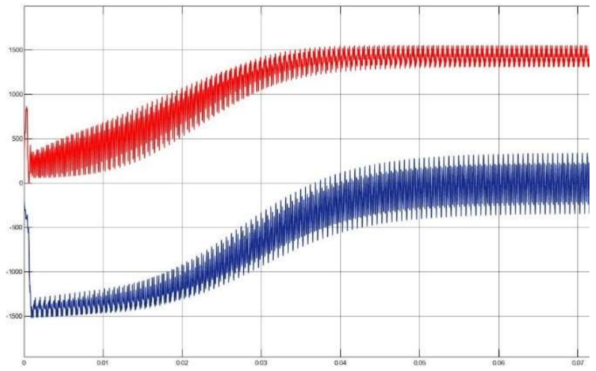

Fig. 6: DQ Value

IV. HIL TESTS AND ALGORITHM DESIGN

The Hardware-In-the-Loop technique is used in cases where it is difficult to access the actual physical system (such as space, aviation fields) or where it is risky to conduct direct tests on the actual system. With HiL, design verification and testing processes can be accelerated and cost can be reduced. The HiL system provides all the all of the required system variables. The dynamic model of the plant represents the mathematical model of the starter generator output voltage in the form of equations. The controller block represents the actual control software that processes the reference commands and outputs generated by the dynamic model of the facility and performs the necessary action.

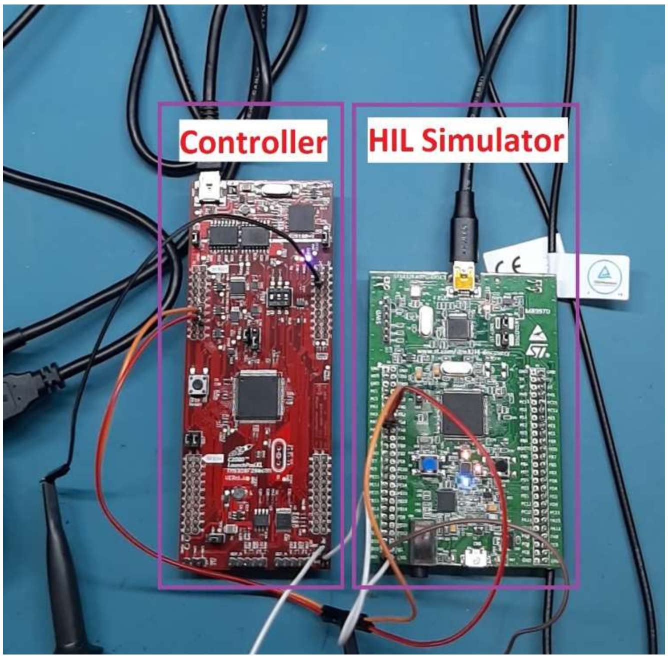

Fig. 7: Test Setup

In the HIL simulator, 3-phase voltage signals were converted to 2-phase rotating-axis αβ signals by clarke transformation. The generated signals are sent from the DAC outputs of the HIL simulator to the controller on which the algorithm is executed. The period time of a signal with a frequency of 800Hz is 1250us. The duration of the voltage signal can be verified from the oscilloscope image. The harmonic and unbalanced voltage signals transmitted between these two microcontrollers are as follows.

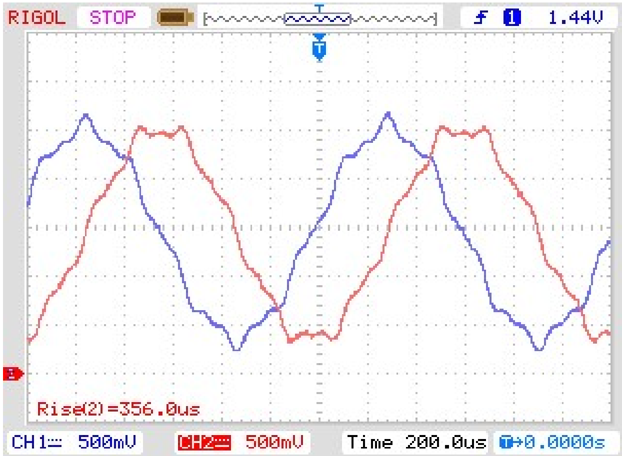

Fig. 8: 800Hz αβ Voltage from HiL Simulator

A. Algorithm Design

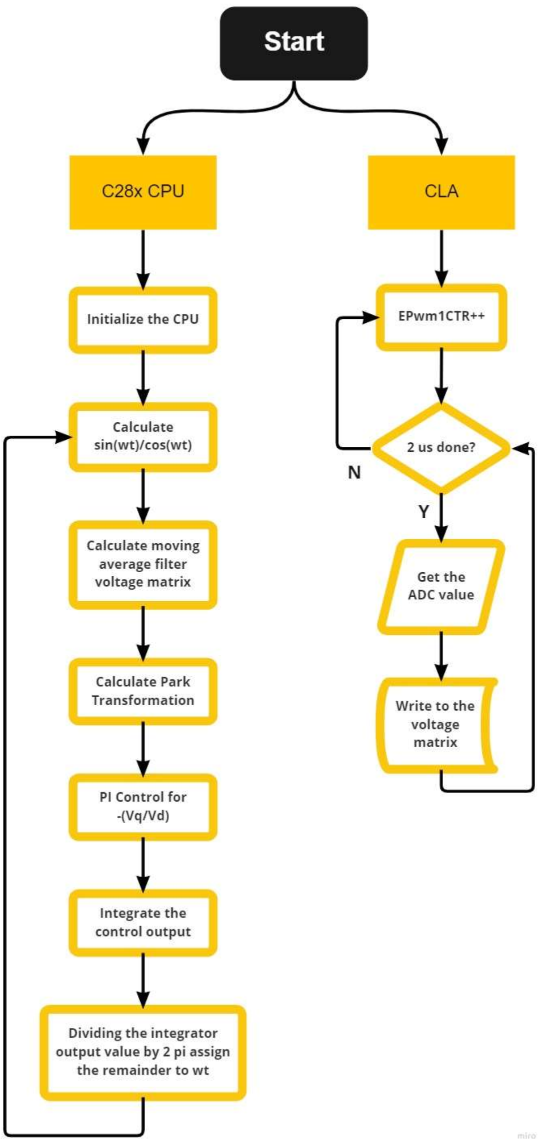

Fig. 9: Algorithm Flowchart

Linear programming technique was used because of the need to meet the high speed performance requirement. The Control Law Accelerator (CLA) is the second core that works simultaneously independently of the main processor. Calculation and analog voltage readings are performed on this unit in a very short time and sent to the main processor. This allows the main processor to dedicate more resources to other sensitive control loops. The cycle time of the designed algorithm is 30us. The blue graph in the screenshots taken from the oscilloscope below shows the voltage wave from the HiL simulator, the red graph shows the controller output. In Figure 10, the times when the phase angle is 0 degrees are determined.

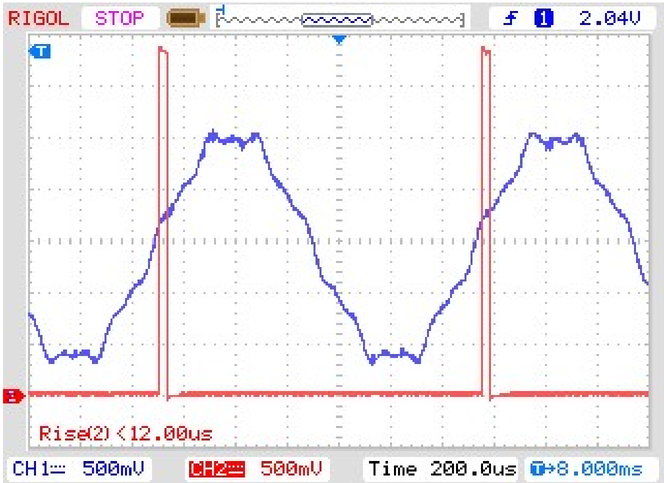

Fig. 10: Zero crossing detection

Figures 11, 12 and 13 show the phase angle information of the controller synchronously to the grid under changing grid conditions. Case1: 5, 11 and 13 th harmonics are included and THD is 11.64% . Case2: 7 and 13 th harmonics are included and THD is 8.11% .

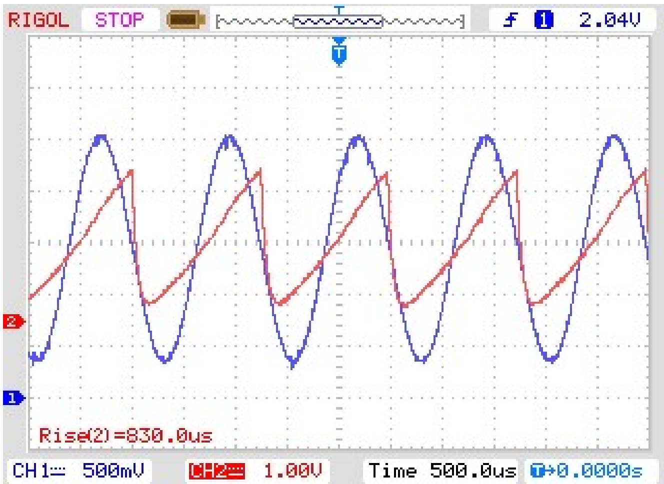

Fig. 11: 800Hz Pure Sine

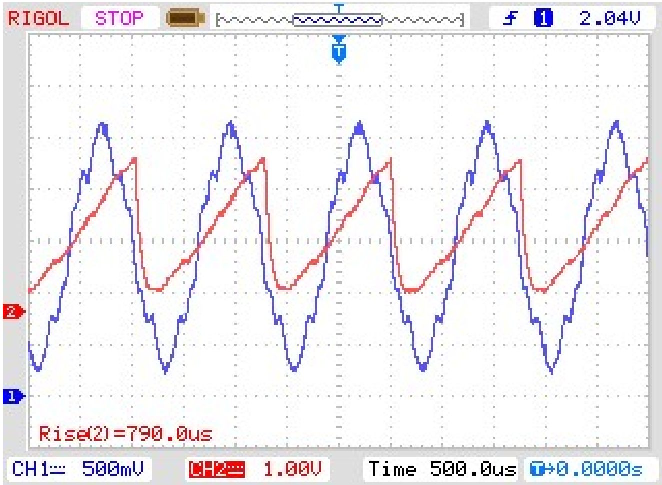

Fig. 12: PLL Result of Case-1

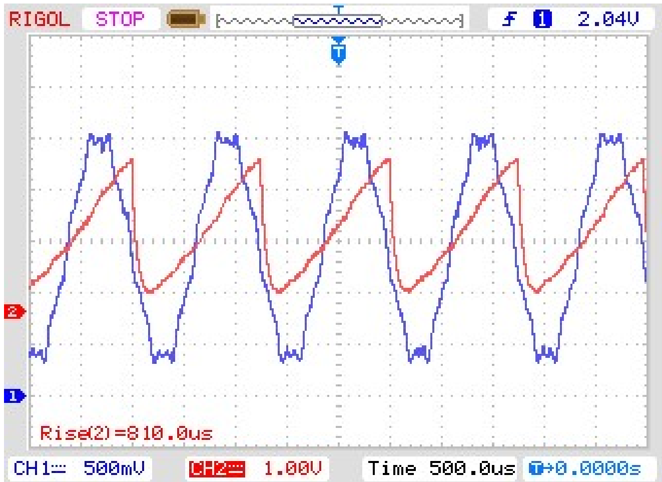

Fig. 13: PLL Result of Case-2

V. CONCLUSION

The STM32F407G card is programmed as a HiL simulator. The dq transformation was performed using the park transformation method. Voltage sampling is taken at the end of each period of the pwm. This process takes approximately 2us. The obtained value is written in the next cell of the voltage matrix. The algorithm uses the PI control method. Full synchronization to the grid takes approximately 1ms. When the synchronization process is successful, pwm channels are driven. The operating frequency of the controller is 90MHz and the ADC cycle time is 325ns. Despite these features, the control algorithm is completed in 30us.

The state of the art in this study is to determine the optimum PLL method for real-time applications and apply it to the DSP. In the HiL test activities carried out, harmonic and phase unbalance are added to the high-frequency voltage signal to show that it can be synchronized to the grid under the worst condition. It has been shown that with the existing algorithm, it can be synchronized to the 800Hz aircraft grid.

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