FPGA Implementation for Rapid Prototyping of High Performance Voltage Source Inverters

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Abstract—Field-programmable gate array (FPGA) is a powerful platform that can play an essential role in high-performance digital control of power electronics systems. However, the FPGA system's design is quite different from that of a traditional microprocessor or a digital signal processor (DSP). Instead of sequential programming using high-level languages, such as C/C++, FPGA controller implementation requires a hardware description language (HDL) such as Verilog and VHDL, which requires extensive verification and optimization during the design process. This paper proposes a systematic FPGA design methodology with optimum resource utilization for rapid prototyping of high-performance power electronics applications to facilitate the widespread adoption of FPGA technology in power electronics. The FPGA controller design is concurrent with the power stage and utilizes high-level synthesis (HLS) tools and Simulink code generation toolbox. This paper covers the detailed design, implementation, and experimental validation of two specific applications, i.e., an active power filter (APF) and a motor emulator (ME), demonstrating the generalized features of the methodology. Employing fundamentally different control structures, both application examples achieve ultra-high current control bandwidth leveraging SiC MOSFETs switching at no less than 100 kHz.

Index Terms—Field-programmable gate array (FPGA), model predictive control, voltage source inverter, wide band gap device.

I. INTRODUCTION

AS the field-programmable gate array (FPGA) becomes more accessible and powerful due to the advance in integrated circuit technology, the FPGA application in power electronics is becoming popular. FPGA's concurrent nature and powerful computation resources make it more suitable for some applications over the traditional microcontrollers and digital signal processors (DSPs). The detailed comparison between DSP/microcontroller and FPGA is presented in [1]. Sensorless motor drive control using FPGA was presented in [2]. Computationally heavy control method like model predictive control (MPC) [3]–[7] was also implemented in FPGA. Due to multiple I/O pins and logic resources, FPGA is very suitable

for applications that require complex modulation strategies [8], [9].

The adoption rate of wide-bandgap devices, such as Silicon Carbide (SiC), is steadily increasing in power electronics with the advances in manufacturing processes. The faster switching capability of wide-bandgap devices than that of Si devices provides an opportunity to improve control bandwidth and poses challenges in device protection. A FPGA-based short-circuit protection circuit for the 10-kV SiC MOSFET is proposed in [10]. To fully utilize the high switching frequency capability to boost the control performance, the FPGA-based high-performance digital control platform provides a better choice since the increased switching frequency poses a limitation on the allowable latency for the digital system, including the sampling and control algorithm computation delay. In [11], high bandwidth VIENNA rectifier with over 1 MHz switching frequency was achieved using a FPGA based control platform.

FPGA-based system development using hardware description language (HDL) is a rigorous and cumbersome process. Fortunately, FPGA manufacturers have introduced high-level design tools, such as high-level synthesis (HLS) [12], and block diagram based design toolbox, such as System Generator for DSP from Xilinx and DSP Builder from Altera, to help expedite the development process. A critical step to accelerate the development process is to efficiently incorporate these high-level design tools into the existing design workflow in power electronics. Examples of previous work on the FPGA controller development process include predictive control in FPGA design using HLS [3], resource streaming design technique in motor drive applications [5], and block diagram based FPGA design [13]. In [14], detailed design and implementation of an impedance identification algorithm block for resonant inverter using HLS were presented. In this work, the digital control platform chosen is the SoC type (ARM+FPGA) in order to bring more flexibility in the system design and deliver high bandwidth, low latency power electronic controllers. This paper presents the design methodology using a toolchain involving multiple software applications while illustrating the merit of this type of platform. Two examples are provided with different implementation strategies. Compared to other FPGA implementation papers [15], [16] which focus on only specific function block or design tool, this paper provides a more systematic high-level perspective and methodology for designing digital systems requiring high control bandwidth, high fidelity modeling, and low latency for rapid prototyping of power elec-

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TABLE I
COMPARISON BETWEEN DIFFERENT TYPE OF FPGA PLATFORM

	Type 1	Type 2	Type 3	Type 4
Architecture	Pure FPGA	FPGA+DSP	SoC	Third party solution
Toolchain	Native	Native	Native	Third party software
Merit	1. Simple one chip solution. 2. Highly customizable.	1. Highly customizable. 2. 28 Abundant peripherals.	1. Simple one chip solution. 2. Highly customizable. 3. Abundant peripherals.	1. High level graphic development tool is easy to learn. 2. No need for low level FPGA design knowledge.
Demerit	1. The lack of peripherals. 2. Require knowledge on low level FPGA design.	1. Hardware design is complicated. 2. Require knowledge on low level FPGA design.	1. Require knowledge on low level FPGA design. 2. Logic resource may be limited.	1. Hardware is not customizable. 2. Performance of the FPGA may be limited by the third party development software.

tronics applications.

The proposed rapid prototyping approach not only maximizes the FPGA resource utilization, but also can be naturally integrated into the existing design workflow of power electronics applications. Moreover, this paper divulges how to assign various power electronics digital control tasks, like ADC, reference frame transformation, control algorithm, PWM generation, and communication, to different parts (ARM core or FPGA) of the SoC platform according to system-level priority requirement, latency requirement, and implementation complexity. Two specific examples with detailed implementation and decision-making for each function block are presented. The first example illustrates a high bandwidth active power filter (APF) capable of compensating up to 51st harmonic utilizing an interleaved SiC voltage source inverter (VSI). The second example is a high bandwidth motor emulator (ME) utilizing a SiC VSI, which can emulate the high-frequency ripple current caused by the inverter's switching under test (IUT).

The rest of the paper is organized as follows: In Section II, FPGA platform selection and design toolchain are introduced. In Section III, the proposed design methodology is presented. In Section IV, APF example with detailed implementation and experimental results are covered. In Section V, the ME example is illustrated with implementation details and experimental results. Finally, conclusions are drawn in Section VI.

II. FPGA PLATFORM & TOOLCHAIN

There are quite a few ways to use FPGA in real-time control systems. In Table I, four types of FPGA digital system architecture are listed and compared. Type 1, denoted as pure FPGA architecture, is the bare FPGA structure that does not provide the peripherals and requires low-level design knowledge. Type 2 solution combines the abundant peripherals of DSP with the powerful FPGA [17]; however, building a fast and reliable communication link between DSP and FPGA could be pretty challenging. Furthermore, the two-chip solution complicates the controller board design. Type 3 is the FPGA-embedded general-purpose processor system-on-chip (SoC) platform, which typically includes many peripherals, like CAN, USB, Ethernet and UART, and analog-to-digital converter. These

peripherals can make the platform more flexible and save FPGA's logic resource for computational use compared with Type 1 architecture. Third-party FPGA solution is denoted as Type 4. Companies, such as National Instruments, provide their hardware consisting of a FPGA chip from Xilinx or Altera and their own high-level block diagram-based development software such as LabVIEW FPGA. This solution provides an easier learning curve for FPGA programming but has several limitations. First, this platform's flexibility is limited since the hardware cannot be customized to achieve specific functionality. Second, the FPGA performance might not be fully utilized since the third-party software's code optimization is usually subpar compared to that of the native development tools.

In this work, we opt for the Type 3 implementation using the ZYNQ-7000 family from Xilinx for efficient development and effective resource utilization. The ZYNQ-7000 System-on-Chip (SoC) integrates a dual-core ARM Cortex-A9 based processing system (PS) and 28 nm Xilinx programmable logic (PL) in a single device. This solution provides better communication performance between processor and FPGA and simplicity of controller board design over Type 2 solution using separate DSP and FPGA chips. A PicoZed system on module (SoM) board (XC7Z015-1SBG485) from Avnet is used for design simplicity. It is worth noting that the selected board is not the most powerful option from the PicoZed family. The selected option provides 3.3 V I/O voltage level whereas more powerful and faster devices can only support 1.8 V or 2.5 V I/O voltage levels. I/O pins with lower voltage levels have lower noise immunity. In power electronics applications, especially with fast switching SiC devices, signal noise is a big concern, and hence, the selection is made for better noise immunity.

The development toolchain used for ZYNQ-7000 SoC in this work includes Xilinx Vivado, Xilinx software development kit (SDK), Vivado High-Level Synthesis (HLS), and System Generator for DSP. The Vivado is for the system-level synthesis and implementation of the FPGA hardware design. The Xilinx SDK is used to program the ARM core (PS) within the ZYNQ-7000 SoC. The Vivado HLS is used for designing the FPGA IP core using C/C++. Last but not least, System Generator for DSP is a block diagram-based MATLAB Simulink toolbox into which HDL and HLS designs can be im-

Fig. 1. Workflow of proposed FPGA design methodology for rapid prototyping in power electronics.

ported. It should be pointed out that other FPGA manufacturers have similar toolchains for the same purpose.

III. DESIGN METHODOLOGY

The workflow of the proposed FPGA design methodology for rapid prototyping digitally controlled power electronics system is shown in Fig. 1. The design methodology emphasizes the concurrent design of the power stage and digital controller, which enables high-level system performance and optimum resource utilization. The power stage's basic specifications include topology, power device performance, passive component values, and sensor performance. These hardware specifications could also affect the digital control system's design, such as the controller structure, controller parameters, and control iteration speed. Using software like PLECS and Simulink, the power stage can be accurately represented by the circuit diagram. Simultaneously, the function blocks like C-Script and S-Function could simulate the C code-based digital controller's behavior. This way, the preliminary system specifications can be established.

After the preliminary round of design iteration, we should have a functional prototype C code for the digital controller. The next question is whether to implement the control algorithm in PS or PL cores. The PS CPU is versatile and easy to program using high-level languages. However, the PS's sequential nature means the absolute performance (algorithm execution time) for a specific task is no match to the PL. Although there are HLS tools to simplify FPGA's design process, it is still more complicated than the PS design. Also, the hardware resource of FPGA would limit how many algorithms can be executed concurrently. Resource utilization and clock speed are trade-offs. If the resource utilization is very high, there is less placing and routing flexibility, resulting in slower clock speed, with techniques like loop unrolling, loop merge, loop flattening, pipelining, and resource sharing, FPGA clock speed,

```

void apint_arith(dinA_t inA, dinB_t inB,
                dout1_t *out1
) {
    dout2_t temp;
    #pragma HLS RESOURCE variable=temp core=AddSub_DSP
    temp = inB + inA;
    *out1 = temp;
}

```

Fig. 2. Example code snippet with HLS pragma for resource utilization optimization [18].

and latency can be improved. Even though the latency may increase slightly, the total execution time could be reduced with faster clock speed. With the help of tools like HLS, those optimization techniques can be easily applied using corresponding directives [18]. Whereas using the conventional FPGA design method, the exploration of the design space might not be sufficiently rigorous. In Sections IV and V, two examples of the detailed decision-making between PL and PS are presented.

For implementation in PS, this prototype code can be directly applied with minor modification. However, if the algorithm is to be implemented in PL, HLS would be a good choice. The Xilinx HLS tool synthesizes a C function into an IP block to integrate into a hardware system. It is tightly integrated with the rest of the Xilinx design tools and provides comprehensive language support, and features for creating the optimal implementation for a C algorithm [18]. The design flow of HLS contains the following stages:

- 1) Compile, execute, and debug the C algorithm.
- 2) Synthesize the C algorithm into an RTL implementation, optionally using user optimization directives.
- 3) Generate comprehensive reports and analyze the design.
- 4) Verify the RTL implementation using a push button flow.
- 5) Package the RTL implementation into a selection of IP formats.

Fig. 3. Co-simulation setup in Simulink environment, with the source for different blocks labelled.

In this paper, to better tailor this design flow for power electronics applications, stages 4 and 5 are replaced by System Generator for DSP toolbox. In stage 1, the adaption of code style is needed for better results. For example, avoiding too many arithmetic operations within one line of code could improve resource utilization, as discussed in Chapter 3 of [18]. After the code style optimization, the next step is to add directives to define device constraints, and resource utilization preference, described in stage 2, such as setting the clock speed and using DSP core to implement a multiplier [18]. In Fig. 2, an example code snippet with pragma directive to select DSP core for summation operation is presented. More information regarding how to apply directives and pragma can be found in Chapter 1 of [18]. Moreover, different interfaces, like AXI4 and RAM, can be added to HLS design using corresponding directives. In stage 3, timing, latency, and resource utilization estimation are provided after C synthesis in a few minutes. This feature significantly accelerates the performance optimization process of HLS design.

Another critical step in the workflow is the functional verification of the HLS design. In [14], a C-based test bench was preferred for fast verification of the design in HLS, referred to as stage 4. However, for power electronics application, System Generator for DSP toolbox is preferred for verification purpose in this paper. System Generator for DSP is a design tool in the Vivado Design Suite that enables the MathWorks model-based Simulink design environment for FPGA design. Previous experience with Xilinx FPGA devices or RTL design methodologies is not required when using System Generator. Designs are captured in the Simulink modeling environment using a Xilinx-specific block set. Downstream FPGA steps, including RTL synthesis and implementation, are automatically performed to produce a FPGA programming bitstream [19]. Design in M-code, HDL code, and C/C++ code (HLS) can be imported to the System Generator environment for simulation and verification using MCode, Black Box, and Vivado HLS block, respectively, described in Lab 2 of [19]. As mentioned

Fig. 4. The configuration menu in System Generator for DSP can be accessed by double-click the red Xilinx icon in Fig. 3. The target device, system constraints, and export preference can be defined in this menu.

before, the power stage is modeled in the PLECS environment. With the PLECS blockset, the PLECS model can be imported to the Simulink environment. Therefore, the co-simulation between digital control algorithm, modeled in System Generator, and power stage, modeled in PLECS blockset, can be easily carried out in Simulink. The screenshot of the Simulink co-simulation setup is shown in Fig. 3. In Fig. 3, the blocks with white background are native Simulink blocks, enclosed in the red rectangle. The blocks with yellow background, enclosed in orange rectangle, are from PLECS blockset, in which power stage can be modeled. The blocks with Xilinx icon, enclosed in purple rectangle, are from System Generator for DSP toolbox. It is worth noting that the gateway blocks in blue rectangle and the configuration menu icon in the green rectangle are also

TABLE II
COMPARISON OF INTERNAL AXI INTERFACE

Name	AXI4-Lite	AXI4	AXI4-Stream
Implementation Complexity	Low	Medium	High
Address Format	Memory-mapped	Memory-mapped	No address
Throughput	Low	Medium	High
Overhead	Low	Medium	High
Targeted Application	Mainly for IP core control purpose	For bulk data transmission	For image and video processing application

from System Generator toolbox. The gateway blocks are used to define the boundary of HDL design. While in the configuration menu, the target device, system constraints, and export preference can be established. The detail of this menu is shown in Fig. 4. Admittedly, the C-based simulation in HLS is faster than the co-simulation in Simulink. However, with the existing power stage model in PLECS, the co-simulation method can be integrated into the traditional design workflow of power electronics more naturally and is still faster than the conventional RTL-based design verification [14]. Furthermore, with the fully functional prototype C code, a high number of design iterations are not expected in the co-simulation stage.

With the successful verification, the System Generator for DSP can package the design as an intellectual property (IP) core and export it to Vivado for system-level RTL synthesis and bitstream generation. The System Generator export setting can be accessed in the menu by double-clicking the Xilinx logo in Fig. 3. In the menu presented in Fig. 4, one can set the target device and clock speed and the IP export directory. More details regarding this menu setting can be found in Lab 3 of [19]. Once the setting is finalized, the IP can be generated at the designated directory by hitting the “Generate” button. To use the IP in Vivado, the IP directory should be added to the IP catalog. With all the necessary IPs added to Vivado, system-level design can be synthesized and implemented, followed by the bitstream generation.

Then the bitstream can be exported to Xilinx SDK. Once the hardware design is transferred to the SDK environment, the board support package (BSP) with all the peripheral driver application programming interface (API) is generated. Finally, the application software for the ME system can be developed. The Xilinx SDK comes with great example designs for almost all the APIs. Since the Xilinx ZYNQ-7000 SoC platform selected for the examples of this paper contains a dual-core ARM processor (PS) and the FPGA (PL), there is more flexibility in the digital system design. The PS system development is quite similar to that of a DSP or microprocessor and beyond the scope of this paper. However, the PS and PL’s interconnection is essential for system performance and should not be ignored. The ZYNQ-7000 device provides a powerful internal bus called AXI4 (Advanced eXtensible Interface 4) to transfer data between the PL and the PS. There are three variations of the AXI interface for different application purposes. The comparison of the three variations is presented in Table II. The detailed decision-makings for each function block and AXI interface are illustrated in the examples provided in Section IV and Section V.

Fig. 5. Active Power Filter (APF) architecture.

Fig. 6. APF multiple resonant-plug in repetitive controller (MR-PIRC) current controller structure.

IV. ACTIVE POWER FILTER (APF) EXAMPLE

Active power filter can eliminate the grid current harmonics by actively compensating harmonic currents required by non-linear loads. A shunt APF utilizing interleaved SiC VSI and high-performance FPGA platform is presented in this section with implementation details. The topology of the interleaved APF architecture is presented in Fig. 5. The interleaving enables the reduction of passive component sizes of the LCL filter. The current controller for the APF is a hybrid combination of multiple resonant (MR) and plug-in repetitive (PIRC) compensators represented in Fig. 6. The developed APF is rated for 125 kVA operation and can compensate up to 51st order of harmonic with effective switching frequency of 300 kHz. The APF’s rating and parameters are listed in Table III. The detailed controller design is illustrated in our previous work [20].

A. FPGA Based Implementation

The first decision to be made is whether a subsystem should be implemented in PS or PL. For the APF, the controller is set

TABLE III
APF RATINGS & PARAMETERS

S_{rated}	Rated power	125 kVA
V_0	Nominal voltage	480 V
ω_0	Nominal frequency	$2\pi(60)$ rad/s
f_{sw}	Switching frequency	100 kHz
f_s	Sampling frequency	100 kHz
v_{dc}^*	Nominal DC bus voltage	860 V
C_{dc}	DC bus capacitor	1.5 mF
L_{sph}	Converter-side sub-phase inductor	40 μH
L_g	Network-side inductor	40 μH
C_f	Filter capacitor	2 μF

Fig. 7. ZYNQ-7000 design block diagram for APF.

to be iterating at 100 kHz. The less computation intense controller structure [20] coupled with relative slow iteration speed makes it possible to implement most of the control algorithm in PS. Also, the parameters' fine-tuning during the experiments could be faster if the controllers are implemented in PS. The exception is the sub-phase current balancing control. The reasons for this decision are twofold: First, the results of the external ADC ICs are obtained in PL, which means AXI interface is needed to transfer the data to the controller on the PS side. As introduced in Table II, the most basic AXI4-Lite interface is suitable for this single shot small data transmission with the low overhead requirement. As presented in Fig. 5, there are 15 quantities needed to be sampled at 100 kHz for the APF controller — three grid currents, nine sub-phase currents, the DC bus voltage, and two phase to phase grid voltages. If the sub-phase current balancing control is implemented in PS, then there will be 108 (9×12) bits of additional data needed to be transferred from PL to PS in each control period. This would significantly increase the execution time, considering the utilization of the AXI4-Lite bus, and compromise the digital control performance. Second, ideally, the nine sub-phase balancing controllers for each sub-phase should be running concurrently to reduce the latency. The parallelism nature of FPGA makes the PL very suitable for this task.

The overall implementation block diagram for APF is presented in Fig. 7. In addition to the control subsystem, the CAN communication is also implemented in PS. The embedded peripherals, like CAN and Ethernet, make it convenient to run communication tasks in PS. ADC interface, PWM generation, and sub-phase current balancing are assigned to the PL. In this

Fig. 8. Task parallelism & latency analysis for APF.

example, most of the tasks are executed sequentially without much parallelism. The functional blocks in the PL part can be divided into two categories. The sub-phase current balancing block is essentially computation cores. The ADC interface and PWM generator are sequential logic blocks. All the functional blocks except the CAN communication are iterating at 100 kHz.

The sub-phase balancing included nine PI compensators; the implementation of computation cores in PL via HLS is covered in Chapter A of Section V. The concurrent nature of the PL hardware suits the requirements of PWM and ADC interface very well. Moreover, most of the I/O pins of the ZYNQ-7000 SoC are connected to the PL side. The PWM generation can be implemented with simple logic components such as counters and comparators. The ADC interface design is more complicated due to the large number of signals involved. As mentioned above, there are 15 quantities needed to be sampled at 100 kHz rate, which exceeds the performance limit of the internal ADC of ZYNQ-7000 SoC. Therefore, four external ADC ICs (two ADS7865 and two MAX1304) are utilized to carry out the sampling task. Both ADC ICs have 12-bit parallel interface for data transmission. Therefore, to save I/O pin resources and increase FPGA routing flexibility, all four ICs share one 12-bit data bus, but with individual control bus. The increase in latency due to the shared data bus is acceptable considering the relatively slow control frequency of 100 kHz. Since all four ICs share the same data bus, one high level state machine is required to coordinate the operation across the ADC ICs. The interface can be programmed either with HDL or System Generator for DSP.

With all the necessary data sampled and transferred to PS, the main current control can be executed. All the computation in PS is executed in floating-point format. The complicated APF controller can finish calculation in time due to the high CPU clock rate of 666.7 MHz. Once the control computation is complete, the results are transferred back to PL. In PL, the current balancing controller outputs are added to the results from the main APF controller in PS before the final PWM generation. The sequence and run-time of the designed digital system are shown in Fig. 8.

B. Verification & Performance Analysis

As mentioned before, the majority of the control for APF is executed in PS, and the corresponding software is developed using C code. The controller's verification developed in C can be easily carried out in numerical simulation platforms

Resource	Utilization	Available	Utilization %
LUT	3370	46200	7.29
LUTRAM	262	14400	1.82
FF	4716	92400	5.10
BRAM	0.50	95	0.53
DSP	24	160	15.00
IO	51	150	34.00
BUFG	3	32	9.38

Fig. 9. Resource utilization report for APF.

Fig. 10. Compensated open loop response.

Fig. 11. Converter admittance $Y_d(s) = i_{gd}(s)/v_{gd}(s) = i_{gq}(s)/v_{gq}(s)$.

such as PLECS. The rapid verification method for PL design is covered in Chapter B of Section V. As shown in Fig. 8, the most time-intensive task is the main current control algorithm and the ADC. The delay caused by the data transfer between PS and PL is not significant in this application. The total time required to execute all the tasks is 6.4 μ s. When designing a FPGA-based embedded system, two key performance indicators are clock speed and resource utilization. Faster clock speed means a shorter execution time. However, if the clock speed is too high, the design would have setup or hold timing violation. The FPGA clock is set to be 200 MHz. According to the timing analysis, the slowest path still has 0.13 ns slack with no hold violation. The resource utilization report is presented in Fig. 9. The utilization of all the resources is pretty low since most of the computation burden is on the PS. The most utilized resource is the I/O pin; this is due to the large number of gating

Fig. 12. Steady state operation waveform for APF.

signals and external ADC ICs. However, through the data bus sharing, the utilization is controlled to a relatively low level at 34%.

C. Controller Analysis & Experimental Results

With the proposed controller structure, shown in Fig. 6, and the short sampling time, thanks to the powerful FPGA and proposed design methodology, the system can achieve great transient and steady-state responses and stability irrespective of the grid impedance variation without any active or passive resonance damping measure. The compensated open-loop transfer function $G_{OL}(s)$ is derived in [20], which includes the non-linearity in real hardware implementation, like implementation delay, the sampling by the digital controller, and the PWM process. From the frequency response of the compensated open-loop response $G_{OL}(s)$ of the current control loop shown in Fig. 10, a gain margin of ≈ 9.3 dB and a phase margin of $\approx 50^\circ$ are achieved despite the high LCL resonance peak.

The converter admittance $Y_d(s) = i_{gd}(s)/v_{gd}(s) = i_{gq}(s)/v_{gq}(s)$, shown in Fig. 11, achieves passivity up to ≈ 16 kHz. The passive admittance guarantees damping of any resonance caused by uncertain grid impedance in the corresponding frequency range. More discussions regarding controller design and passivity theory based stability demonstration can be found in our previous work [20].

Experiments have been carried out using a full-scale prototype to demonstrate the proposed APF system. This APF is designed for a chiller, which has a diode bridge as the front end. Therefore the non-linear load used in the experiment is a diode bridge. The experimental waveform for steady-state operation is shown in Fig. 12. The FFT results for non-linear load current and grid current is presented in Fig. 13. For a load current of 36.7% THD, the APF achieves 2.35% THD in grid current. It can be seen that the harmonic current requested by the non-linear load is supplied by the APF instead of the grid, and up to 51st harmonics are compensated.

Compared with conventional grid-tied LCL converter solutions which require passive [21], or active damping [22] to stabilize the system, the high control update rate in this application, enabled by the powerful FPGA platform and proposed

Fig. 13. Spectral content in non-linear load current and in grid current (normalized by fundamental frequency component).

Fig. 14. ME architecture with FPGA implementation overview.

design methodology, eliminates the need for any damping measure.

V. MOTOR EMULATOR (ME) EXAMPLE

Motor emulator (ME) is a power hardware-in-the-loop device that can replicate an electric motor's terminal electrical characteristic. It can be used for testing the motor drive inverter, denoted as inverter under test (IUT) henceforth, without the actual motor and expensive dyno setup. An overview of the system architecture is shown in Fig. 14. The high-performance current controller of the ME is a hybrid combination of integral and finite control set MPC compensators represented in Fig. 15. With two-level VSI topology and a much higher switching frequency than IUT, this high bandwidth ME can emulate high-frequency ripple current caused by the switching of the IUT enabled by the hybrid MPC-based current controller. The ME parameters are listed in Table IV. Furthermore, the controller design details are covered in our previous work [23].

A. FPGA Based Implementation

As shown in Fig. 14, the computation cores for ME contains high fidelity motor model iterating at 1 MHz, a hybrid MPC

Fig. 15. ME system model with hybrid MPC compensator for small signal analysis.

TABLE IV
ME PARAMETERS

V_{DC}^{IUT}	IUT DC bus voltage	300 V
V_{DC}^{ME}	ME DC bus voltage	300 V
f_{sw}^{IUT}	IUT switching frequency	10 kHz
f_c^{ME}	ME control frequency	400 kHz
L_l	Line inductance	0.15 mH
L_d	Target motor inductance	0.4 mH
L_q	Target motor inductance	0.6 mH
R_s	Target motor resistance	0.1 Ω
λ_{pm}	Target motor PM flux	0.1 Wb
P	Target motor pole number	8
t_{DB}^{IUT}	IUT dead-band time	2000 ns
t_{DB}^{ME}	ME dead-band time	200 ns

current controller iterating at 400 kHz, and resolver emulator iterating at 1 MHz. To achieved satisfactory run-time performance, those three tasks should be executed in parallel. Implementing all three computation cores in PL ensures parallelism and eliminated the data transmission requirement between PS and PL for control purposes. Therefore, the entire digital system for ME is implemented in PL, except the Ethernet communication. The Ethernet is mainly for data logging and monitoring purposes. The Ethernet communication between ZYNQ-7000 SoC and PC happens every 5 ms, and the PS handles the Ethernet communication. Transferring data from the controller and motor model (located in PL) to the PS is the key to communication. For the ME application, although a small amount of data is generated every 400 kHz or 1 MHz, the single-shot AXI4-Lite interface is too slow to finish the transmission within the control period according to the APF result in Fig. 8; a higher performance interface is needed for the ME application. As pointed out in Table II, the higher performance interface has a large overhead. A block memory in PL is utilized as a buffer to bulk the data up for easier high-performance interface implementation to address the issue. AXI4 interface is eventually selected for this application. AXI4-Stream is overkill, and the PL implementation is more complicated. The AXI4 transaction will initiate every 5 ms to move the data in the buffer to the on-board memory for the PS. Then the Ethernet user datagram protocol (UDP) is initiated to send the data to the PC. This way, the data logging is running entirely in parallel with the control algorithm. The overall implementation block diagram

Fig. 16. ZYNQ-7000 design block diagram for ME.

Fig. 17. Task parallelism and latency analysis for ME.

for ME is presented in Fig. 16. ADC interface and PWM block are also assigned to the PL part of the ZYNQ-7000 SoC.

Based on the iteration speed, the digital system for ME can be divided into three subsystems. The first one iterates at 1 MHz, which contains the real-time motor model and resolver emulator. The second one iterates at 400 kHz system, consisting of MPC, ADC, and PWM generation. The third one is the 200 Hz system, which is for the communication between the SoC and the PC laptop. Those three subsystems are running in parallel with each other. The sequence of operation for the 1 MHz and 400 kHz subsystems is presented in Fig. 17. The motor model update is concurrent with the resolver emulation. The ADC for the resolver emulation has significant latency; therefore, it is done in parallel with the resolver computation and the DAC. This way, the 1 MHz iteration speed is achieved at the price of slightly longer latency. As for the 400 kHz subsystem, at the very start of the 2.5 μ s control period, the duty cycle calculated during the last control period is loaded into the PWM generation block. Also, the ADC for the phase current and DC bus voltage starts at the beginning of the 2.5 μ s control period. When the conversion is finished, then the MPC and integral (I) controller update are initiated. The newly calculated duty cycle is applied at the start of the next control cycle.

For PL computation core design, the workflow in Fig. 1 is followed. One critical decision to make is whether to use floating-point or fixed-point arithmetic. The main advantage of floating-point data type is the ease of implementation, and the PL of ZYNQ-7000 SoC also supports floating-point data types. However, since both the real-time motor model and MPC require lots of computation and low latency, the full floating-point implementation would exceed the limit of on-chip resources and timing requirement. Thus in this application, the

TABLE V
COMPARISON OF RESOURCE UTILIZATION AND LATENCY FOR
ONLINE MOTOR MODEL BLOCK

	W/ code style adaption and pipelining	W/O code style adaption	W/O pipelining
Latency	29 CLK	41 CLK	33 CLK
DSP	38%	61%	38%
BRAM	17%	17%	12%
Flip-flop	5%	8%	4%
LUT	2%	4%	2%

fixed-point data type is used. Xilinx provides a fixed point data type called `ap_fixed` in the high-level synthesis (HLS) software [24], which makes it easy to use fixed-point data types in the design. As mentioned above, the coding style adaption and pipelining are also crucial to optimizing latency and resource utilization. In Table V, the comparison of resource utilization and latency of the online motor model block with and without code style adaption and pipelining is shown. It can be seen that the code style adaption significantly reduces the resource and clock cycle required for the computation core, while the pipelining improves the latency at the cost of slightly more resource utilization. Once the design in HLS is finished, it can be verified using the workflow shown in Fig. 1.

For the sequential logic blocks, the PWM generation block consists of several counters and logic gates, designed using library blocks from the System Generator for DSP toolbox in Simulink. However, the ADC interface requires careful design. There are five physical quantities in the ME application that need to be sampled at 400 kHz rate. Three-phase current and two DC bus voltages, one for ME, another one for IUT. To reduce the latency, four external ADC ICs are utilized. Three of them are MAX1304, one for each phase current. The other ADC IC is ADS7865, for two DC bus voltage sensing. Since the timing requirement is much higher than the APF, each ADC IC can have a dedicated 12-bit parallel data bus and control bus to execute the conversion concurrently. This way, the conversion for all five quantities can be finished within 1.25 μ s.

B. Verification & Performance Analysis

The clock speed for PL (200 MHz) and PS (666.7 MHz) is kept the same as in the APF application. The motor model and resolver emulator are iterating at 1 MHz. Simultaneously, the current sensing and current controller are running at 400 kHz. The latency result shown in Fig. 17 for each task is highly satisfactory, which is achieved since all the intensive computation is executed in PL, and the pipelining technique improves the clock speed. The results also demonstrate the effectiveness of the proposed methodology. If all the computation cores were to be implemented in PS, the additional time it takes to transmit the data between PL and PS could make the whole execution time longer than the control period, let alone the slower computation of PS. As indicated in the figure, the most time-consuming task is the ADC for current sensing. According to the timing analysis, the system's slowest path still has 0.17 ns

Resource	Utilization	Available	Utilization %
LUT	7558	46200	16.36
LUTRAM	797	14400	5.53
FF	10792	92400	11.68
BRAM	62	95	65.26
DSP	89	160	55.62
IO	77	150	51.33
BUFG	2	32	6.25

Fig. 18. ZYNQ-7000 resource utilization report for ME.

Fig. 19. Compensated open loop response.

slack, and there is no hold violation. If the traditional FPGA design method were to be used, this high timing requirement would be difficult to meet. For resource utilization, the I/O pins and DSP core are the most utilized resource at 51.33% and 55.62%, respectively. This is mainly due to the various peripheral circuits like ADC and DAC needed for sensing and resolver emulation and intense computation of the model predictive control and motor model. It is worth mentioning that the utilization of BRAM is relatively high at 65.26%. However, this is mainly consumed by the Integrated Logic Analyzer (ILA) for debugging purposes. Once development is finished, the BRAM space could be freed up for other use, such as integrating the more accurate and complicated finite element analysis (FEA) based motor model. All other resource utilization rates are relatively low, as shown in Fig. 18.

C. Controller Analysis & Experimental Results

With the controller structure in Fig. 15 and very short sampling time of 2.5 μ s, 20 kHz control bandwidth can be achieved, as represented in the compensated open-loop response with different parasitic resistance value in Fig. 19. Furthermore, to improve the disturbance rejection response during the switching transient of IUT, the gate stitching modulation strategy [23] is proposed to achieve accurate IUT terminal voltage feedforward. The proposed modulation scheme takes advantage of the inherent logic gates in FPGA to achieve the function efficiently. Fig. 20 shows the comparison of frequency responses of $Y_{dr}(s) = i_x(s)/v_x(s)$ with and without the pulse voltage feedforward. Apparently, without the gate stitching, the disturbance rejection

Fig. 20. Disturbance rejection response $Y_{dr} = i_x(s)/v_x(s)$ of the MPC with and without the IUT pulse voltage feedforward.

response would deteriorate to the blue trace during the switching transients of IUT. More details of the controller design and analysis can be found in our previous work [23].

Full-scale experiments have been carried out to demonstrate the proposed high bandwidth ME system. The experimental results are given in Fig. 18 where the current reference from the motor model is compared with the actual current in the system. The FFT results are also included to evaluate the current controller tracking performance. The current feedback matches the current reference very well, up to twice the switching frequency of IUT (20 kHz). The matching of the harmonic order is important since this is related to the motor torque ripple order, and the inverter experiences the exact conditions as with a real motor. Moreover, the current tracking error does not vary much with the phase current amplitude, as shown in Fig. 21(a) and Fig. 21(b). Therefore, it is safe to say that even under high phase current operations, the current tracking error would still be maintained at a relatively low level. The high-frequency ripple current caused by the 10 kHz switching of IUT can be accurately emulated in the system. Overall, the proposed ME achieves control bandwidth of 20 kHz [23].

Compared with the existing ME solutions [25], [26], the proposed system provides the high bandwidth current emulation capability up to several times the switching frequency of IUT without the need for complicated power stage topology and inductor design. The FPGA platform and the newly proposed design methodology are the critical enablers for this achievement.

VI. CONCLUSION

This paper presents a FPGA design methodology for rapid prototyping in power electronics applications. The proposed method utilizes the HLS tool and Simulink code generation blockset to minimize the need for HDL programming during the system design and expedite the verification process while not compromising the FPGA platform's performance. High FPGA clock speed (200 MHz) and low control latency are achieved with reasonable resource consumption. The methodology applies to FPGA-based digital systems available from

Fig. 21. Comparison between current reference and current feedback at 400 Hz (6000 rpm) with FFT analysis.

different manufacturers for various power electronics applications. Two ultra high bandwidth power electronics implementation examples are discussed in the paper to demonstrate this design method's effectiveness. The first example is an interleaved high bandwidth active power filter (APF) utilizing SiC MOSFET switching at 100 kHz. The second one is a high bandwidth motor emulator (ME) based on a SiC power converter with control bandwidth over 20 kHz. The two examples have different controller structures and control period requirements, which introduces differences in the implemented digital system structures. Experimental results of two examples demonstrate the effectiveness of the proposed methodology based on the two key performance indicators of clock speed and resource utilization for a FPGA-based embedded system.

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REFERENCES

- [1] T. Kahl and S. Dieckerhoff, "Comparison of FPGA- and microcontroller-based control of a high-dynamic power electronic converter," in *Proceedings of 2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, Stanford, CA, USA, Jul. 2017, pp. 1–6.
- [2] Z. Ma, J. Gao, and R. Kennel, "FPGA implementation of a hybrid sensorless control of SMPMSM in the whole speed range," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1253–1261, Aug. 2013.
- [3] S. Lucia, D. Navarro, Ó. Lucía, P. Zometa, and R. Findeisen, "Optimized FPGA implementation of model predictive control for embedded systems using high-level synthesis tool," in *IEEE Transactions on Industrial Informatics*, vol. 14, no. 1, pp. 137–145, Jan. 2018.
- [4] W. Tu, G. Luo, Z. Chen, C. Liu, and L. Cui, "FPGA implementation of predictive cascaded speed and current control of PMSM drives with two-time-scale optimization," in *IEEE Transactions on Industrial Informatics*, vol. 15, no. 9, pp. 5276–5288, Sept. 2019.
- [5] S. Wendel, A. Dietz, and R. Kennel, "FPGA based finite-set model predictive current control for small PMSM drives with efficient resource streaming," in *Proceedings of 2017 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, Pilsen, Czech Republic, Sept. 2017, pp. 66–71.
- [6] T. J. Vyncke, S. Thielemans, and J. A. Melkebeek, "Finite-set model based predictive control for flying-capacitor converters: cost function design and efficient FPGA implementation," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 2, pp. 1113–1121, May 2013.
- [7] Z. Zhang, F. Wang, T. Sun, J. Rodríguez, and R. Kennel, "FPGA-based experimental investigation of a quasi-centralized model predictive control for back-to-back converters," in *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 662–674, Jan. 2016.
- [8] E. Lupon, S. Busquets-Monge, and J. Nicolas-Apruzzese, "FPGA implementation of a PWM for a three-phase DC-AC multilevel active-clamped converter," in *IEEE Transactions on Industrial Informatics*, vol. 10, no. 2, pp. 1296–1306, May 2014.
- [9] J. Holtz, M. Höltingen, and J. O. Krah, "A space vector modulator for the high-switching frequency control of three-level SiC inverters," in *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2618–2626, May 2014.
- [10] S. Ji, M. Laitinen, X. Huang, J. Sun, W. Giewont, F. Wang, and L. M. Tolbert, "Short-circuit characterization and protection of 10 kV SiC MOSFET," in *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1755–1764, Feb. 2019.
- [11] M. Hartmann, S. D. Round, H. Ertl, and J. W. Kolar, "Digital current controller for a 1 MHz, 10 kW three-phase VIENNA rectifier," in *IEEE Transactions on Power Electronics*, vol. 24, no. 11, pp. 2496–2508, Nov. 2009.
- [12] G. Martin and G. Smith, "High-level synthesis: Past, present, and future," in *IEEE Design & Test of Computers*, vol. 26, no. 4, pp. 18–25, Jul.–Aug. 2009.
- [13] E. Guerrero, E. Guzmán, J. Linares, A. Martínez, and G. Guerrero, "FPGA-based active disturbance rejection velocity control for a parallel DC/DC buck converter-DC motor system," in *IET Power Electronics*, vol. 13, no. 2, pp. 356–367, 2020.
- [14] D. Navarro, Ó. Lucía, L. A. Barragán, I. Urriza, and Ó. Jiménez, "High-level synthesis for accelerating the FPGA implementation of computationally demanding control algorithms for power converters," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1371–1379, Aug. 2013.
- [15] O. Gulbudak and E. Santi, "FPGA-based model predictive controller for direct matrix converter," in *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4560–4570, Jul. 2016.
- [16] R. Wiśniewski, G. Bazydło, P. Szcześniak, and M. Wojnakowski, "Petri net-based specification of cyber-physical systems oriented to control direct matrix converters with space vector modulation," in *IEEE Access*, vol. 7, pp. 23407–23420, Feb. 2019.
- [17] M. Hamouda, H. F. Blanchette, K. Al-Haddad, and F. Fnaiech, "An

efficient DSP-FPGA-based real-time implementation method of SVM algorithms for an indirect matrix converter,” in *IEEE Transactions on Industrial Electronics*, vol. 58, no. 11, pp. 5024–5031, Nov. 2011.

- [18] “Vivado Design Suite User Guide: High-Level Synthesis,” 2018. [Online]. Available: <https://www.xilinx.com/support/documentation/swmanuals/xilinx2018/3/ug902-vivado-high-level-synthesis.pdf>
- [19] “Vivado Design Suite Tutorial: Model-Based DSP Design Using System Generator,” 2020. [Online]. Available: <https://www.xilinx.com/support/documentation/sw%20manuals/xilinx2020/1/ug948-vivado-sysgen-tutorial.pdf>
- [20] M. A. Awal, Y. Luo, D. Rahman, L. Yang, W. Yu, and I. Husain, “SiC based interleaved voltage source converter for active power filter applications,” in *Proceedings of 2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, New Orleans, LA, USA, 2020.
- [21] R. Peña-Alzola, M. Liserre, F. Blaabjerg, R. Sebastián, J. Dannehl, and F. W. Fuchs, “Analysis of the passive damping losses in LCL-filter-based grid converters,” in *IEEE Transactions on Power Electronics*, vol. 28, no. 6, pp. 2642–2646, Jun. 2013.
- [22] J. Dannehl, F. W. Fuchs, S. Hansen, and P. B. Thøgersen, “Investigation of active damping approaches for PI-based current control of grid-connected pulse width modulation converters with LCL filters,” in *IEEE Transactions on Industry Applications*, vol. 46, no. 4, pp. 1509–1517, Jul. 2010.
- [23] Y. Luo, M. A. Awal, W. Yu, and I. Husain, “FPGA-based high bandwidth motor emulator for interior permanent magnet machine utilizing SiC power converter,” in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 4, pp. 4340–4353, Aug. 2021.
- [24] A. Finnerty and H. Ratigner, “Reduce Power and Cost by Converting from Floating Point to Fixed Point,” 2020. [Online]. Available: https://www.xilinx.com/support/documentation/white_papers/wp491-floating-to-fixed-point.pdf
- [25] S. Grubic, B. Amlang, W. Schumacher, and A. Wenzel, “A high performance electronic hardware-in-the-loop drive-load simulation using a linear inverter (LinVerter),” in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1208–1216, Apr. 2010.
- [26] D. Uebener and J. BÖcke, “Application of an e-machine emulator for power converter tests in the development of electric drives,” in *Proceedings of EVEC 2012 – European Electric Vehicle Congress*, Brussels, Belgium, 2012.

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