Digital Twin Modeling of Power Electronic Converters

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***Abstract*—A real-time digital twin of a DC-DC boost converter is developed and verified experimentally using various load scenarios. The developed DT can be used to provide a comprehensive understanding of the system's behavior and support improved decision-making and predictive maintenance. Moreover, this digital twin can be integrated into a larger digital twin system that represents the entire power system hardware. By connecting these digital twins together, a complete digital model of the power system can be created. Results confirm the capability of the developed digital twin and its hardware to reflect the electrical behaviors of the physical twin in real-time. The maximum deviation between the digital twin and the physical twin was $\pm 2\%$.**

***Index Terms*—Digital Twin Modeling, Power Electronics, Digital Twin Hierarchy, Power Systems, Electric Ships**

I INTRODUCTION

A Digital Twin (DT) refers to a collection of dynamic digital models that precisely represent an existing physical system or subsystem. The DT models accurately replicate the behavior of the physical system during its operational state. Digital twin technology is one of the most promising drivers of digitalization across multiple industries [1]. The digital twins can be applied in many sectors. For example in the aerospace sector, a digital twin model has been used to precisely evaluate the wear and fatigue of an aircraft throughout its operational life [2]. In industrial manufacturing, digital twins are utilized to predict the optimal time for maintenance schedules [3]. This is achieved by continually gathering operating data to determine a reference basis for the maintenance cycle. The automotive industry has made use of DTs for various purposes. Digital twins play a crucial role in enhancing the value of a vehicle throughout its lifespan and in optimizing the design of future vehicles [4]. The potential for DT technology to impact electric vehicles is significant. This technology has captured the attention of the maritime industry because of its great potential [5].

The US Navy is moving towards electrification of its naval systems, which will demand higher levels of electric power compared to older generations. The power consumption will increase and become more dynamic, with larger, pulsed loads like air and missile defense radars, and directed energy weapons driving the change [6]. Due to the growing prevalence of DC power sources in naval operations, the Navy is now exploring the potential adoption of DC distribution systems [7]. The addition of pulsed loads and energy magazines will make the power system of the vessel more complex to design. Furthermore, monitoring and controlling the system becomes more challenging. As a result, utilizing DTs can aid in overcoming these challenges. The integration of DT technology into key power system components on shipboards will greatly enhance the overall effiecincy of the power system. The implementation of DTs in naval ships has the potential to significantly enhance the capabilities and efficiency of the ship through the ability to conduct simulations in multiple scenarios under varying conditions.

In the context of power electronic converters, a DT can be used to predict the behavior and performance of the converter under various operating conditions. It can be used for real-time monitoring and control of the converter during operation, enabling predictive maintenance and helping to identify potential issues prior to their occurrence. In creating a DT of a power electronic converter, various electrical and thermal models can be combined to accurately represent the converter behavior. This can involve the use of mathematical models and simulation softwares, which can take into account the effects of various parameters such as input voltage, current, and temperature on the converter performance. It can also improve the overall reliability and performance of the converter, helping to ensure that it operates within its specified parameters and meets the requirements of the application.

Power electronic converters are essential components of modern power systems, they are used to regulate, control, and convert electrical energy. The design, analysis, and optimization of power electronic converters can be a challenging task due to the complexity of the system and the high switching frequencies involved. Real-time digital twin technology provides a solution to these challenges by creating a virtual replica of the physical system that can be used for simulation, analysis, and optimization. By implementing DT technology in any sector, a range of benefits can be achieved, such as decreased operational costs and streamlined processes, enhanced productivity, improved decision-making, advanced predictive and preventive maintenance.

This work explores the development of a real-time digital twin that can replicate the behavior of the physical system with high accuracy under dynamic load conditions using a simple DC-DC power converter topology. A real-time DT model of a DC-DC converter was designed and implemented on the FPGA board of a National Instrument (NI) Compact RIO (cRIO). The use of an NI-cRIO allows for the integration of high-performance computing and data acquisition capabilities, enabling the digital twin to operate in real-time and respond quickly to changes in the physical system. Traditionally, power electronic converter models have been implemented using simulation software, which can accurately replicate the behavior of the system but lacks the real-time performance required for dynamic operation. By deploying the model on an NI-cRIO, the digital twin can operate in real-time, enabling the system to be monitored and controlled continuously. Additionally, this equipment provides several advantages, including the ability to integrate with other hardware and software components, such as sensors, actuators, and control systems. This allows for a more comprehensive digital twin that can reflect the behavior of the physical system under a wide range of conditions. Section II provides details on the modeling of the converter and the steps for developing and deploying the DT on the FPGA board of the cRIO. Experimental setup and the hardware used in this work are provided in Section III. Experimental results are provided in Section IV, and Section V provides conclusions and a discussion of ongoing and future work.

II POWER CONVERTER DIGITAL TWIN

A digital twin requires an accurate model to represent the system. To better understand the capabilities and limitations of the real-time digital twin, a simple boost converter is used as the physical system. Since this topology is well understood, any dissonance between the physical twin and digital twin is due to physical hardware nonidealities or the limitations of the simulating hardware and communications.

In the field of power electronics, modeling switching power converters is a common practice for design and troubleshooting. These converters use switches to alter their electrical topology to produce a desired outcome. However, modeling these switching events can be computationally expensive. As a result, researchers often opt for a simpler modeling method known as the averaged switching model. The averaged switching model is a simplified mathematical representation of a switching converter. It uses time averaging to smooth out the fast switching transitions and create a continuous model. This model provides an approximation of the average behavior of the converter. This simplifies the simulation and reduces computational cost [8]. An averaged switching model DC-DC boost converter is used as the DT. The converter model is shown in Fig. 1.

III EXPERIMENTAL SETUP

The averaged switching model boost converter from Fig. 1 was built in Matlab Simulink with the required controls to maintain and regulate the bus voltage while the load changed. After verifying the Simulink model, a compatible version of the model was created using C code for the NI-cRIO. Subsequently, an NI VeriStand file was generated, which defines the custom FPGA-based I/O interfaces required for simulation on the real-time target. Once the model was deployed on the NI-cRIO's FPGA, NI LabView was used to program the DT to transmit the responses through Ethernet to a host computer and receive real-time data from the physical twin. To account for non-linearities caused by the saturation limits on the voltage and current controllers of the hardware, the DT duplicated the nested loop controls of the power converter.

The constructed DT is equipped to transmit and receive data via Ethernet connection in real-time. By means of an Ethernet connection, the real-time digital twin is connected to the sensing and control systems of the physical twin, allowing it to receive voltage reference points and load data. After deploying the model on the FPGA target, experimental verifications are necessary to conduct real-time simulations and compare the results with the physical twin in order to verify the speed of the DT model and its communications.

To demonstrate the ability of the developed DT to simulate in real-time and shadow the physical twin, a representative electrical power system, shown in Fig. 2, is employed. The system includes a single DC power supply and a variable DC load. The power supply is interfaced to the DC bus through a DC-DC boost converter that steps up the voltage from 200 V to 400 V.

The digital and physical twin are coupled through Ethernet, as shown in Fig. 3. The physical twin of the boost converter is an Imperix PEB8032 half-bridge module, operating at a frequency of 20 kHz. These modules are equipped with optical gate drive circuits that regulate two IGBTs, capable of handling continuous currents of up to 32 A rms [9]. A

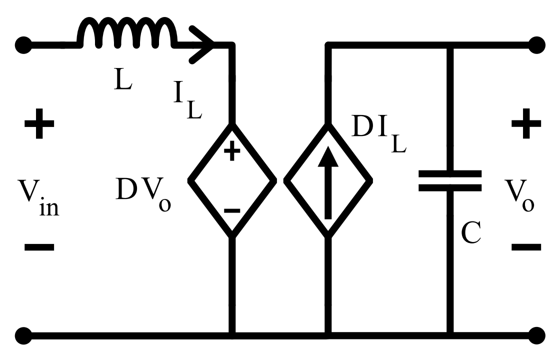

Fig. 1: Averaged switching model of a boost converter.

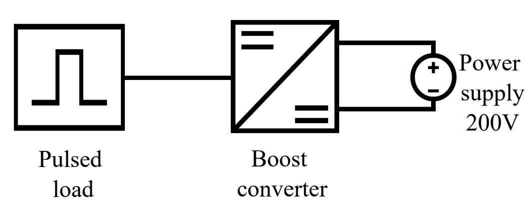

Fig. 2: Power system demonstrator for the real-time digital twin.

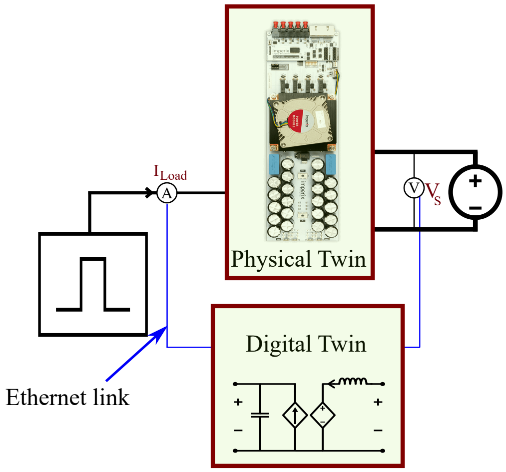

Fig. 3: Physical and digital twin coupling.

1.25 mH inductor was chosen for the boost converter design. The bus voltage was monitored using an Imperix DIN800V sensor, while the inductor current was measured with the built-in current sensor of the PEB8032 module [10]. An Imperix external DIN50A current sensor was connected in series with the converter output to measure the load current [11], and this signal is transmitted to the DT via Ethernet. The converter was driven by nested loop controls, which were integrated into an Imperix B-Box control platform [12]. To test the converter, a Chroma DC electronic load was utilized to handle both constant, ramped, and pulsed loads. The Imperix Simulink blockset facilitated programming of the controls through code generation. The hardware setup is shown in Fig. 4.

Different load scenarios were used to test the ability of the developed DT to respond to transients. Responses from both the physical and digital twin were transmitted to a host computer for visualization.

IV EXPERIMENTAL RESULTS

To validate a digital twin, the first step is to ensure that the model used to create the digital twin accurately captures the behavior of the physical system. This involves comparing the inputs and outputs of the digital twin with the corresponding inputs and outputs of the physical twin. Once the model has been validated, the next step is to compare the behavior of the digital twin with the behavior of the physical twin under different operating conditions. This involves running simulations on the digital twin in real-time with the physical twin and comparing the results. The system was tested with pulsed loads and under different pulse lengths to confirm that the DT is capable of tracking the behavior of the physical twin in real-time.

Verifying a digital twin against its physical twin is an important step in ensuring that the digital twin accurately represents the behavior of the physical twin. Therefore, the system was tested under three different scenarios. Testing the system with these scenarios can provide several advantages when performing this verification:

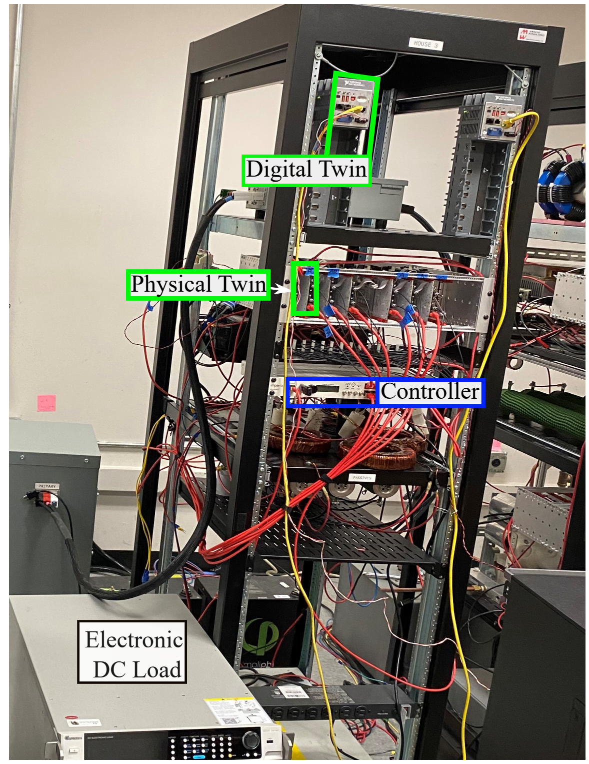

Fig. 4: Experimental hardware.

Assessing Dynamic Response: Pulsed loads can help assess the dynamic response of the system and show how quickly the system can respond to changes in the load. Testing under different pulse lengths can help evaluate the system ability to track rapid changes in the physical twin, which may be missed with steady-state tests.

Identifying Deviations: Testing under pulsed loads and different pulse lengths can help identify deviations between the digital twin and the physical twin that may not be apparent under steady-state conditions. This can help improve the accuracy of the digital twin and ensure that it can reliably predict the behavior of the physical twin.

Simulating Real-World Conditions: A pulsed load combined with a ramped load can simulate real-world conditions more accurately than steady-state loads. Many physical systems experience intermittent or transient loads in real-world applications, and testing under pulsed loads can help ensure that the digital twin accurately reflects these conditions.

Overall, testing the digital twin under pulsed loads and different pulse lengths and combining ramped loads is a crucial step in ensuring that the digital twin accurately represents the behavior of the physical twin and can reliably predict its performance under real-world conditions. Accordingly, different load scenarios were applied to the system to demonstrate the ability of the developed DT.

Scenario one: The system was subjected to a baseline load of a 1 A baseload and 2 A pulsed load with a period of 4 seconds and a pulse width of 50%. The inductor current and output voltage responses are shown in Fig. 5.

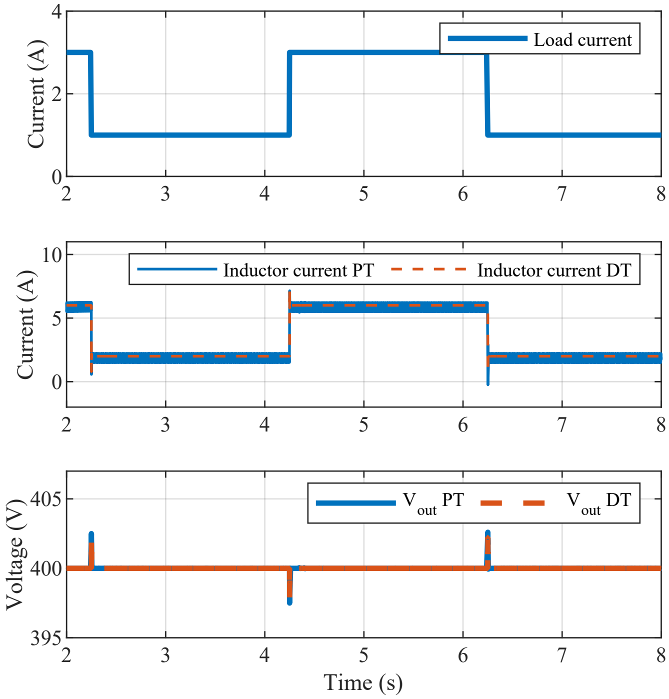

Fig. 5: Scenario one load.

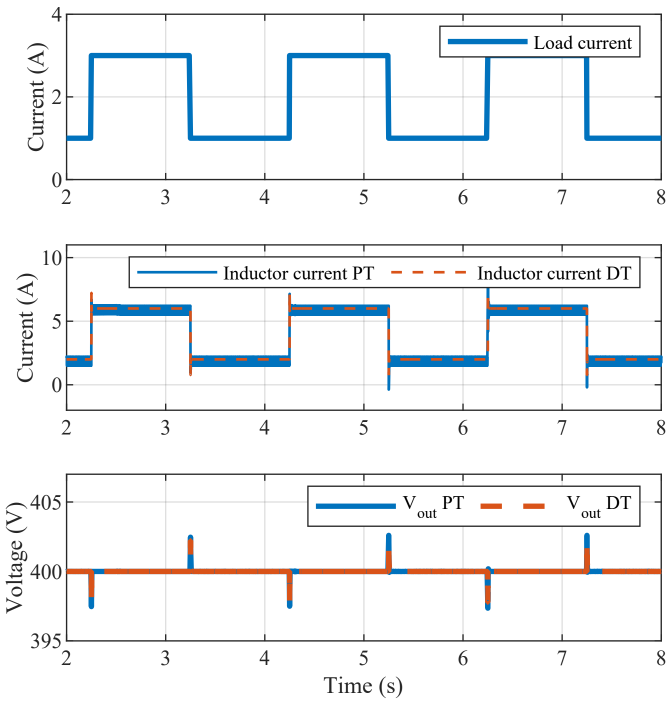

Fig. 6: Scenario two load.

Scenario two: The pulsed load was set with a period of 2 seconds and a pulse width of 50%. The responses of the inductor current and the output voltage are show in Fig. 6.

Scenario three: A combination of ramp and pulsed load was applied to the system. The responses of the inductor current and the output voltage are show in Fig. 7.

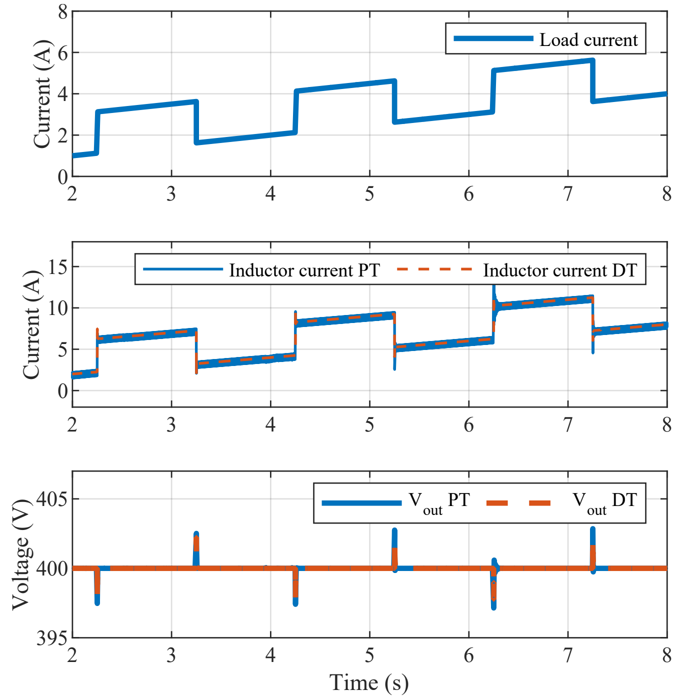

Fig. 7: Scenario three load.

The results of the study demonstrate the correlation between the real-time digital twin and its physical twin. The analysis of the inductor current in the physical twin reveals the presence of high-frequency noise, which is attributed to the sensitivity of the utilized sensors. This noise can be eliminated by filtering the inductor current. The maximum deviation between the digital twin and the physical twin was $\pm 2\%$.

While there are several advantages associated with the design of a real-time digital twin, it is important to acknowledge the limitations that exist within the design of such systems. Some of these limitations may include:

Latency: There is always a delay between the data generated by the physical twin and the data received by the digital twin due to communication delays. This can lead to discrepancies between the two twins. In this study, the communication delay was found to be within the range of 180 ms. The root cause of this delay was identified as the Ethernet switch that was used in the network setup.

Incomplete data: The digital twin relies on data from sensors and other sources to accurately represent the physical twin. If the sensors are not properly calibrated, or if they are not sensitive enough to capture all the relevant data, the digital twin may be incomplete or inaccurate.

Computational resources: The amount of computational resources required to simulate the physical twin in real-time can be significant. If the digital twin does not have access to sufficient computational resources, it may not be able to accurately represent the physical twin.

V CONCLUSIONS & FUTURE WORK

A real-time digital twin was developed for a DC-DC boost converter and verified experimentally under various load scenarios. The developed DT can be used to provide a comprehensive understanding of the system behavior and support improved decision-making and predictive maintenance. Real-time insights and analysis of the converter can be provided using the developed DT. The developed real-time digital twin had fast processing speeds and low-latency data transfer capabilities, enabling it to provide accurate and timely feedback on the behavior of the physical system. Furthermore, it can be integrated into larger digital twin models for the power system hardware, enabling comprehensive real-time modeling and analysis of the entire system. This allows for real-time scenario studies based on different load profiles. The evaluation of the physical twin against the DT confirms the readiness of the DT to be integrated into larger power system DT models. The maximum deviations observed between the DT and the hardware show that it is well aligned with the physical twin.

The developed DT in this work was limited to the electrical domain. Future development of this experiment leads to the consideration of expanding the DT to other domains with thermal modeling of the converter being the logical next step. The NI-cRIO will enable the multidomain DT with its additional data acquisition modules which will be able to integrate the digital and physical twins via the thermocouple modules.

Acknowledgments

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