Digital Twin Design and Experimental Validation of Step-Down DC/DC Converters in Power-to-Hydrogen Systems

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Abstract— **This paper presents the design of a digital twin of DC/DC step-down power converters in practical Power-to-Hydrogen applications. The motivation of the work arises from the increasing relevance of step-down DC/DC conversion in PtH systems, where the DC-link voltage obtained after rectification is often higher than the voltage level required by the electrolyzer stack, while low ripple and stable DC operation remain important for efficient and reliable operation. In this regard, the DC/DC buck converter is selected as a first and physically interpretable case study, since it captures the fundamental dynamics of step-down conversion and provides a suitable basis for later extension toward more advanced converter structures. The paper presents the converter structure, the main steady-state and dynamic relations and the development of a digital twin model. In addition, an experimental converter prototype is designed and built in order to compare the behavior of the digital twin model and the physical setup. The comparison indicates that the developed model is able to reproduce the main converter behavior with reasonable agreement, while also showing that parasitic elements and practical nonidealities have a clear influence on the compliance between the digital and physical systems. Based on the presented analysis, the paper further discusses how such a digital twin can provide a structured framework for future online monitoring, parameter adaptation, communication-assisted implementation and possible fault-oriented analysis in PtH power electronic systems.**

Keywords— Power-to-Hydrogen (PtH), DC–DC Power Converters, Digital Twin, Power Electronics, Buck Converter, Green Hydrogen, Renewable Energy.

I. INTRODUCTION

The advancement of sustainable, renewable and clean energy has increasingly appeared as an important topic in the worldwide energy technology revolution [1, 2]. The development of green hydrogen is necessary to accomplish sustainable and low-carbon technologies on a large scale [3]. In comparison with alternative hydrogen production technologies, hydrogen generation using water electrolysis in Power-to-X (PtX) plants shows substantial potential for integration with renewable energy and establishing a reliable and economical energy source [4, 5]. In the PtX plants, Power-to-Hydrogen (PtH) comprises an extremely important part as hydrogen is not only a direct energy carrier itself, but also the basis for downstream systems like Power-to-Methanol and Power-to-Ammonia production routes [6, 7]. In PtH systems, the electrolysis process requires a controlled DC supply and therefore the performance of the power-electronic conversion stage becomes highly important. In particular, the quality of the DC voltage and current applied to the electrolyzer stack has a direct influence on efficiency, ohmic losses and long-term stack degradation [8, 9]. Since the DC-link voltage obtained after rectification of a grid-connected ac supply is often significantly higher than the voltage required by the electrolyzer stack, a step-down DC/DC conversion stage becomes necessary in many practical PtH applications [10, 11]. For this reason, the development of reliable and well-understood step-down power converters is of clear interest in PtH-oriented power conversion systems [12, 13].

At the same time, DC/DC converters are increasingly used in modern electrified systems because of their high efficiency, controllability and suitability for compact power-conditioning applications [7, 14]. However, as the penetration of power electronics continues to increase, the requirements on reliability, safety and life-cycle performance also become more demanding [15, 16]. It has been widely reported that vulnerable components such as power semiconductors, capacitors and magnetic elements account for a significant share of failures in power converters and their degradation may gradually deteriorate converter performance before a severe malfunction occurs [17, 18]. In this regard, early monitoring of converter behavior and converter-parameter evolution is highly relevant not only from a condition-monitoring perspective but also from a system-performance point of view in applications where output voltage quality and operational stability are critical [19, 20].

Conventional condition-monitoring methods for DC/DC converters have often relied on direct measurement of component-related health indicators, such as on-state resistance or voltage for semiconductor devices, threshold-voltage- or gate-transient-based indicators, and equivalent-series-resistance- or capacitance-based indicators for capacitors [21, 22]. Although such approaches can provide useful degradation information, they typically require additional sensing circuits, higher sampling capability, dedicated signal-processing stages or access to internal converter quantities that are not always available in practical systems [22, 23]. Moreover, more hardware can increase both system complexity and cost and in some cases even reduce system reliability. Model-based parameter identification approaches have also been explored, for example through transfer-function-based estimation using recursive least squares, Kalman filtering or other optimization-based techniques [24, 25]. Nevertheless, many of these methods either focus primarily on controller tuning rather than converter monitoring, require injection of additional excitation signals or depend on access to controller variables such as the duty ratio in real time [21, 25].

In order to address these limitations, the concept of digital twin (DT) has emerged as a promising framework for the monitoring, analysis, and possible optimization of power-electronic systems [26, 27]. In general terms, a digital twin can be understood as a virtual replica of a physical system that runs in parallel with its physical counterpart, receives measured information from the real system and reproduces its behavior with sufficient fidelity to enable insight into its

internal condition and performance [28, 29]. For power converters, this concept is especially attractive because it provides a structured way to combine a digital model, measured data and a parameter-identification or data-analysis algorithm without necessarily requiring additional invasive hardware [30, 31]. This paper focuses on the development of a digital twin framework for step-down DC/DC power converters in green hydrogen production plants within large-scale PtX facilities. The fundamental step-down DC/DC power converter topology is investigated in order to capture the essential dynamics, parasitic effects and modeling challenges, while also providing a basis for future extension toward more advanced step-down converter structures in green hydrogen production plants. Accordingly, as shown in Fig.1, the paper develops a digital representation of the presented power converter and validates it against an experimental prototype, with particular attention to the comparison between digital and measured electrical quantities. In this way, the work aims to establish a practical and physically grounded basis for future digital-twin-assisted monitoring, parameter adaptation and possible control-oriented extensions in PtH DC/DC conversion.

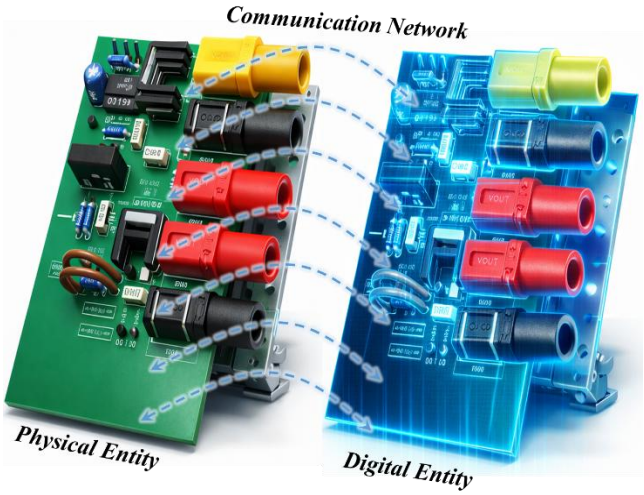


Fig. 1. Illustration of the Digital Twin concept

II. Proposed DC/DC Converter for PtX Systems

The water electrolysis process is an electrochemical process in which *H2O* is split into *H2* and *O2*. The detailed thermodynamic equations for different types of electrolysis are explained in [32, 33]. From the thermodynamic behavior of the electrolysis, it can be determined how much electrical DC power is needed, depending on the thermal energy provided. In the real PtX systems, because of the limitations associated with highly efficient hydrogen production at scale, green hydrogen plants use different water electrolysis stacks, where each stack is fed by an AC/DC power conversion system. The quality of the applied DC has a great influence on the efficiency and lifetime of the electrolyzer stacks. The DC voltage ripple and current ripple result in ohmic losses and also degradation of the electrolyzer stack. The voltage level applied to the electrolyzer stack depends on the number of cells connected in series in the actual stack. Across different electrolyzer technologies, the optimal voltage across each cell is approximately 1–2 V. The amplitude of the voltage from the source depends on the application; nevertheless, some connection to the electrical grid is often present. In Denmark, the electrical grid is a sinusoidal three-phase AC grid, where the phase-to-neutral voltage is approximately 230 V (RMS) and the phase-to-phase voltage is approximately 400 V (RMS), which leads to a DC-link voltage level of approximately 560 V after three-phase rectification. In most PtH applications, this voltage level is too high, even though multiple cells are placed in series. This leads to the necessity of step-down DC/DC power conversion.

A. Step-down DC/DC power converter

There are various topologies for step-down DC/DC power conversion. In broad terms, these topologies can be categorized into two types: non-isolated and isolated. Each topology has its own advantages and disadvantages compared with the others. Even though there are small differences in their design and control framework, many of them build upon the dynamics of the Buck converter. Some of the benefits of the buck converter topology are its simplicity, both in terms of hardware design and relatively simple control design compared to a topology like a full bridge converter, which has four switches and a transformer. The structure of the DC/DC buck converter is depicted in Fig. 2. The buck converter topology can be scaled employing various approaches. Although the component ratings can be increased to some extent, stacking may become necessary beyond a certain power level. In addition to stacking, interleaving can be utilized not only to distribute the power transfer among multiple switches but also to reduce current and voltage ripples. For PtH applications, stacked interleaved buck converters have been investigated and have demonstrated promising performance. When stacking and interleaving are applied to the buck converter, the complexity of the hardware and control framework increases. Nevertheless, from a modeling point of view, the same procedures and principles as those used for the buck converter remain applicable. As depicted in Fig.2, buck converter uses an inductance L as energy storage by turning the switch Q on and off. When Q is turned on, the voltage across the inductance is equal to:

$$V_L = V_{in} - V_{out} \tag{1}$$

where V_{in} is the input voltage and V_{out} is the output voltage. When Q is turned off, the inductance voltage is equal to:

$$V_L = -V_{out} \tag{2}$$

This means that there are two states, one where Q is turned on and one where Q is turned off. Common to the two states is the voltage across the inductance. In order to maintain the DC transfer function in Eq. (4), the differential equation for an inductor, in Eq. (3) and the volt-second balance law are as:

$$V_L = L \cdot \frac{di}{dt} \tag{3}$$

$$D = \frac{V_{out}}{V_{in}} \tag{4}$$

where D is the duty cycle. The dynamic model can be derived from the output filter as follows in the Laplace domain:

$$G_{Buck}(s) = \frac{\frac{1}{L \cdot C}}{s^2 + \left(\frac{1}{R_{Load} \cdot C}\right) \cdot s + \frac{1}{L \cdot C}} \tag{5}$$

$$G_{Buck-ESR+DSR}(s) = \frac{\frac{R_{Load} \cdot (R_{ESR} \cdot C \cdot s + 1)}{(R_{ESR} + R_{Load}) \cdot L \cdot C}}{s^2 + \left(\frac{R_{DSR}}{L} + \frac{R_L \cdot R_{ESR}}{(R_{ESR} + R_{Load}) \cdot L} + \frac{1}{(R_{ESR} + R_{Load}) \cdot C}\right) \cdot s + \frac{R_{DSR} + R_{Load}}{(R_{ESR} + R_{Load}) \cdot L \cdot C}} \tag{6}$$

When the inductor direct-current resistance (DCR) and the output capacitor equivalent series resistance (ESR) are included in the model, the transfer function becomes more complex. The corresponding transfer function is presented in Eq. (6). Besides the control-to-output transfer function, an input-to-output transfer function should also be derived. Parasitic inductances, capacitances and resistances can have varying importance depending on the application. Therefore, the desired accuracy of a system model should be considered depending on the intended application of the model and which parameters are most important [34, 35].

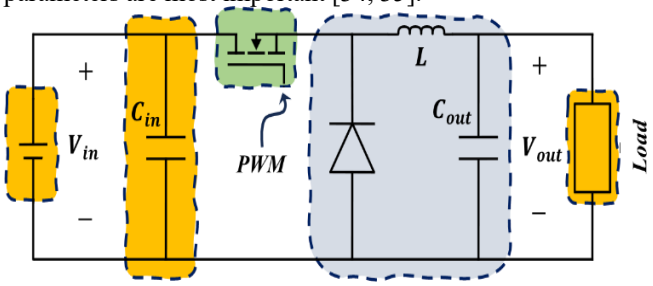


Fig. 2. Circuit topology of the proposed step-down DC/DC buck converter

For PtH, low ripple voltage and current, together with a stable DC output, are of great importance for, respectively, lifetime of the electrolyzer stack and optimal hydrogen production. Therefore, accuracy in the comparison of the output voltage between the model and the real application has been the primary focus when developing the DT of the buck power converter. When investigating the dynamic transfer function in (8), it can be seen that the load also has an important role in the system dynamics. A change in the load can potentially cause a transition between a stable and unstable system if the load characteristics are not well known. The load characteristics refer to the frequency response of the load. Depending on the application, these characteristics can vary widely, for example because of batch variations and degradation over time. If it were possible to estimate/ determine the load characteristics under operation, it could then be possible to adjust the control parameters and also detect developing degradation which could be addressed through planned maintenance instead of sudden breakdowns with expensive downtime/severe damage to the load.

III. The Digital Twin Framework for Green Hydrogen Production Systems

In recent years, the concept of the digital twin has gained considerable attention because of its usefulness across a broad range of applications [27, 30]. A digital twin can be utilized in several aspects of system analysis, development and operation. For example, it can be used for experimentation in a digital environment, where the test setup is easier to establish and where the risk of damaging expensive equipment is avoided. Before discussing the applications of a digital twin, its definition should first be clearly established [26, 32].

TABLE I
EXPERIMENTAL SETUP COMPONENTS/PARAMETER VALUES

Component/ Parameter	*Component/Parameter Value*		
	Description	*Value*	*Unit*
V_{in-max}	*Maximum input voltage*	*30*	*[V]*
V_{out}	*Desired output voltag*	*10*	*[V]*
f_s	*Switching frequency*	*25*	*[kHz]*
η	*Efficiency*	*0.9*	*[]*
ΔI	*Chosen ripple current*	*100*	*[mA]*
R	*Resistive Load*	*10*	*[Ω]*

The digital twin concept, as defined by Michael Grieves, comprises three fundamental components [32]: i) a physical entity in the real world, ii) a virtual replica of the physical object in a digital environment, and iii) a communication mechanism that enables information exchange between the real and virtual realms. Fig. 1 presents an illustration of the DT of the DC/DC buck converter for green hydrogen application. A DT can support the optimization of control procedures employing real measured data within a virtual environment to reduce the risk of damage to the physical setup. This framework can also boost online tuning efficiency of component parameters such as changes in capacitor ESR or variations in load impedance due to degradation. The DT framework can also be utilized for online pre-fault detection. For the DT concept, the binding component is the communication infrastructure, as shown in Fig. 1. Without the communication infrastructure connecting the loop between the virtual model and the physical entity, the concept would instead correspond more closely to a digital shadow [34].

As shown in Fig. 1, the communication infrastructure should be capable of transferring data not only internally between digital environments, but also between the physical and digital environments. In practice, this infrastructure has to be carefully configured in order to be both efficient and as fast as possible. The challenges can be related to the calculation time of the model and the data transfer time to potentially several different actuators in the system. Depending on the design choices, the infrastructure could include Serial Communication Interfaces (SCI) between a microcontroller (MCU) and a PC, CAN bus communication between various controller components, and other communication protocols. One of the challenges encountered when establishing such a communication infrastructure is the correct timing of transmission and reception in order to avoid data loss/overflows which could result in system malfunction. Based on the presented definition, functionality and the discussion of the same topic in [28, 30], a digital twin could provide a structured framework for linking measured data from the physical power system with a virtual model capable of analysis, prediction, and optimization. In the context of PtH power electronics, this enables continuous monitoring of critical components, estimation of component degradation, and evaluation of control strategies without interfering with the physical setup.

TABLE II
CALCULATED COMPONENT/PARAMETER VALUE

Component/ Parameter	*Component/Parameter Value*		
	Description	*Value*	*Unit*
C_{Out}	*Output capacitance*	*500*	*[nF]*
L_{Out}	*Inductance*	*2.666*	*[mH]*

IV. Experimental Test and Validation

In this section, the experimental validation of the proposed DC/DC power converter and its designed DT is presented. The choice of topology is based on the section II, where the presented buck converter is selected as a representative topology for investigating the fundamental behavior of step-down DC/DC conversion in the PtH application. By defining the design parameters listed in Table I, the values of the output capacitance and inductance are calculated, as shown in Table II. These values are used as the basis for both the physical realization of the converter and the development of the corresponding DT. In this way, the comparison between the physical and digital environments can be carried out on the

same design basis. The final hardware implementation of the presented power converter is shown in Fig. 3. Based on the calculations executed during the design stage, a detailed digital model is developed. During this process, to balance the computational time and the accuracy of the model, some of the components are simplified. For example, the MOSFET is modeled as a switch with a snubber circuit in parallel. Such simplifications are implemented with respect to maintaining a reasonable computation time during validation of the model quality, without compromising the accuracy of the variables of primary interest, here especially the output voltage. During the validation process, it can be seen that parameters such as parasitic impedances in the wires, ESR in the capacitor and DCR in the inductor have a considerable influence on the compliance between the model and the physical setup.

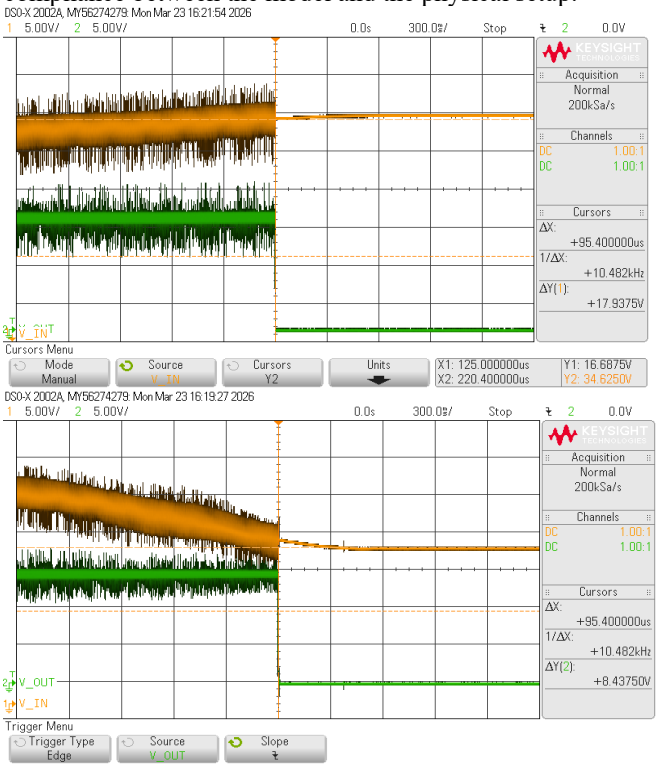


Fig. 4. Comparison between the expected duty cycle and actual duty cycle.

In particular, the parasitic impedance on the wires from the input source influences the model ability to imitate the input voltage noise and the ringing behavior seen at the switch node. This indicates that a physically representative DT cannot rely only on the ideal average dynamics if the purpose is to obtain a realistic comparison with experimental measurements.

TABLE III.
COMPONENT VALUE MODIFICATION

Component/ Parameter	*Component/Parameter Value*		
	Description	*Value*	*Unit*
C_{out}	*Output capacitance*	*470*	*[nF]*
L_{out}	*Inductance*	*1.7**	*[mH]*

*Due to inductance design the actual inductance became smaller.

Instead, a certain level of parasitic modeling is necessary in order to reproduce the measured transient behavior with acceptable accuracy. To illustrate one practical way of using the DT concept, the steady-state relation shown in Eq. (6) is employed to check for unexpected changes in input voltage in close-loop operation. Eq. (6) is used to estimate the expected duty cycle, and during operation the expected duty cycle is compared with the actual duty cycle. A maximum deviation can then be defined and if the deviation exceeds the defined value, the voltage reference is set to zero. The result of this

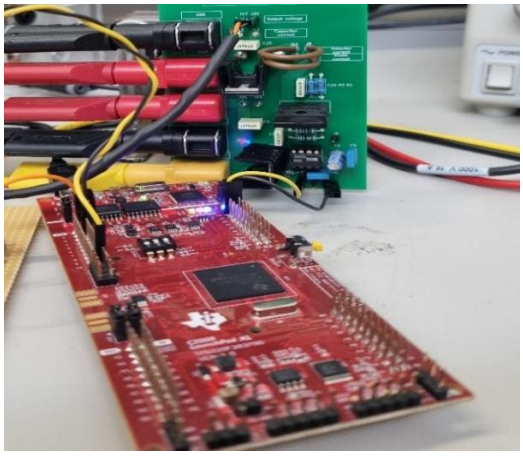


Fig. 3. Hardware setup of the proposed converter and its DT

principle is illustrated in Fig. 4. From the result it can be seen that the proposed comparison can react when the input voltage changes to a level corresponding to the maximum allowed deviation in duty cycle, for input voltages higher and lower than expected. In this way, DT is not only used as a passive model for comparison but also as an active part of a supervisory protection-oriented function. The open-loop experimental validations are summarized in Fig. 5-6.

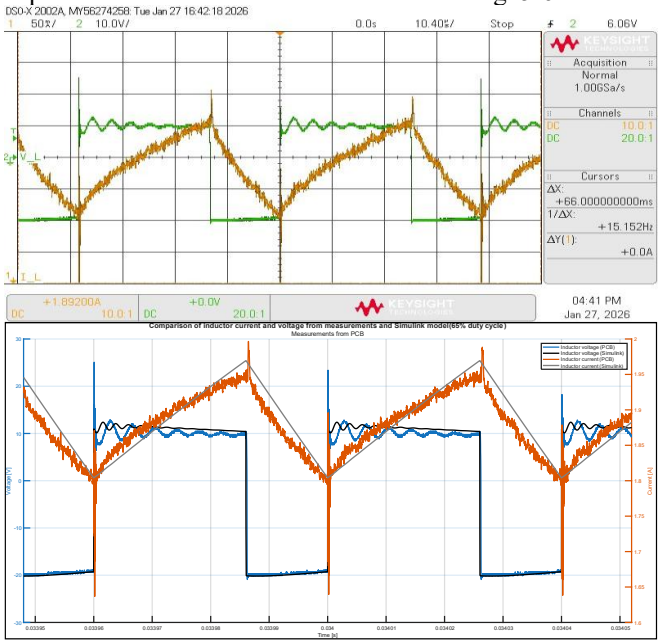


Fig.5. Comparison of the current through the inductance and the voltage across the inductance, where the black and gray curves represent the DT results-the red and blue curves represent the experimental measurements.

From these results it can be seen that the DT is capable of reproducing the main dynamic behavior of the physical power converter with reasonable agreement. In particular, the general waveform shape and the main operating tendencies are captured by the model which indicates that the selected model structure is suitable for representing the converter dynamics. At the same time, some deviation between the measured and simulated responses remains. This is expected, since the physical setup contains non-ideal effects that are difficult to model perfectly including parasitic impedances, switching-related noise and parameter uncertainty in the practical realization of the components. Regarding the output voltage comparison, the result shows that the DT can estimate the dominant output behavior with acceptable accuracy, which is of particular importance in the PtH context, where low ripple and stable DC operation are critical.

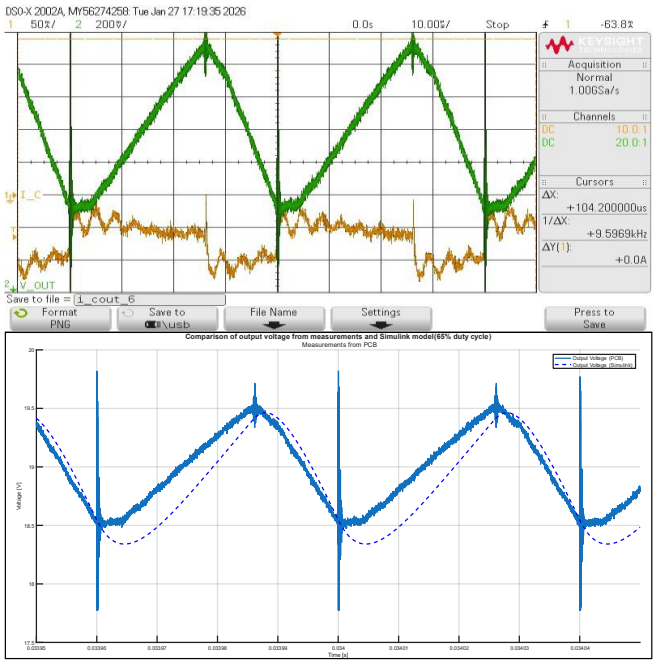


Fig. 6. Comparison of the output voltage where the dashed blue line is the DT result- the solid blue line is the experimental measurement.

Even if a complete overlap between simulation and experiment is not obtained, the model reproduces the output dynamics sufficiently well to be useful for monitoring, controller design and future supervisory functions. In the next step, a practical close-loop control framework with anti-windup based on back-calculation has been developed.

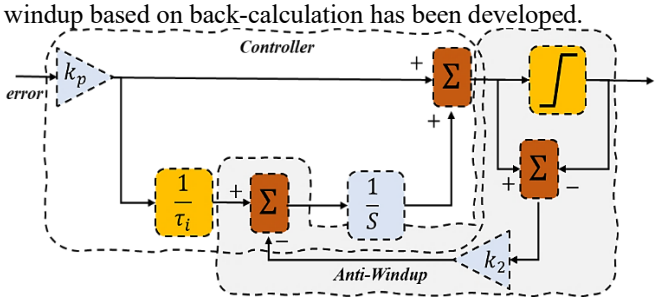


Fig. 7. Designed practical closed-loop control framework with anti-windup.

The controller architecture is shown in Fig. 7, while the controller dynamics are illustrated in Fig. 8.

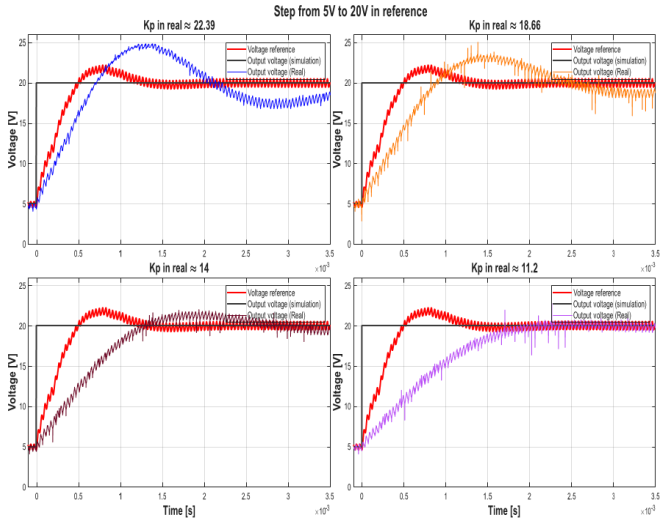


Fig. 8. Comparison of the output-voltage step response in the digital and physical environments for different gains of the designed controller.

The controller design process is based on the theory in [6, 34, 35] and the selected controller parameters are given in the controller parameter Table III. When validating the controller, a deviation between the digital and physical environments is observed. In particular, it could be seen that the physical setup was less damped than the digital setup. This indicates that some of the dynamics present in the real converter are not fully captured in the DT. Such deviation can originate from several practical factors, including unmodeled parasitic elements, uncertainties in the real component values, delay effects and switching-related nonlinearities. From a practical point of view, this level of agreement is sufficient to demonstrate the potential of the DT concept for PtH-related DC/DC converters. The results show that DT can be used for more than offline simulation. It can also support online monitoring, controller support and practical fault-oriented logics.

V. Conclusions

In this paper, the development of a digital twin of a DC/DC step-down power converter for green hydrogen production plants within PtX facilities is presented. The experimental demonstrations show that the proposed framework can provide a useful basis for linking the behavior of the physical converter with a corresponding digital representation. By comparing the developed digital model with the physical converter prototype, it is proved that the digital twin can reproduce the main converter behavior with acceptable agreement under the considered operating conditions. At the same time, the study highlights that practical nonidealities, including parasitic impedances, ESR, DCR, wiring effects, and implementation simplifications, have a noticeable impact on the consistency between the virtual and physical domains. In this sense, the presented work should be seen as a foundational step toward future PtX-oriented digital twin applications. For future work, the communication layer between the physical setup and the digital model will be implemented in a time-coordinated way for online operation. In addition, parameter-update mechanisms will be incorporated in to estimate the evolution of converter parameters during operation.

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