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Hardware-in-the-loop Simulation of Closed Loop Buck Converter using Virtual Typhoon HIL Simulator

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Abstract: Over the past two decades, universally useful PC has gotten both progressively powerful and affordable. This has prompted the rise of exceptionally advanced applications that not just empower high-fidelity simulation of dynamic frameworks yet also has automatic code generation for testing and implementation of real-time controllers. Because of the progression of software like MATLAB/SIMULINK real-time simulator systems are utilized broadly in engineering fields, for example, industry, research establishments, and academics. The main objective of this paper is to simulate a closed-loop buck converter using a virtual typhoon HIL simulator and verify the design and modeling using MATLAB/SIMULINK. The brief steps of HIL implementation of a closed-loop buck converter using virtual typhoon HIL are discussed.

Keywords: Buck Converter, Closed-loop Control, Typhoon HIL, Hardware-in-the-loop Simulation (HILS)

I. INTRODUCTION

Hardware-In-the-Loop Simulation (HILS) based testing of controllers has become an essential part of the embedded programming validation and verification process. In particular, controller programming is tried by running the actual controller with a real-time signal of the physical system that it is intended to control, with real signals traded between the controller and test system[1]. This innovation is broadly utilized in aviation, car, and rail transportation ventures. The advantages of utilizing HILS testing are four folds: first, the controller can be tried even before the actual plant that it will control (for instance, a motor, engine or transmission) is fabricated or accessible; second, the danger of harming the plant is reduced in this manner decreasing expense and hazard; third, faulty conditions can be tested without any cost or resource expense; and fourth, the field condition can be recreated with given field parameters with which we can understand and analyze the anomalies. HILS testing has been effectively utilized for testing mechanical as well as electrical frameworks that require lower test rates. Be that as it may, HILS systems for testing controllers for electric drives, power electronics, which are by and large progressively utilized in cars and airplanes, modern applications, need to recreate a lot of dynamic elements. Recreating these dynamic elements requires the advancement of elite equipment, programming, and models. The capacity to run complex constant models in time steps going from the sub-microsecond level to the 10 millisecond level on a solitary stage is basic for HILS recreation. HILS innovation has progressed to meet these necessities utilizing commercial FPGAs and multi-core CPUs combined with fast analog and computerized interface. The objective of the hardware-in-the-loop (HIL) technique is to utilize a simulation model of the procedure, techniques, and the real target hardware equipment. The simulation model gives all the system signals continuously that are next changed over by D/A modules and are provided to the controller as voltages. The control signals are delivered by the controller and provided using A/D converters to the simulation model. It is the motivation behind this arrangement to cause the hardware equipment part to carry on as intently as conceivable to these that would be experienced in the actual real system framework.

II. LITERATURE SURVEY

As per the [2], the simulation software platforms based on existing techniques are discussed and proposes a general-purpose personal computer-based platform real-time simulation techniques. Its merits and execution of procedure are explained in detail. Personal computers have gotten both progressively powerful and affordable. This has prompted the rise of profoundly advanced applications that not just empower high-constancy simulation of dynamic system frameworks yet also programmed code for the continuous control of electric machine-drives. Today, electric drives, power electronic system frameworks, and their controls which have become increasingly mind-boggling, and their utilization is generally expanding in all parts, for example, power drive train, distributed power generation, hybrid vehicles, industrial and consumer electronics, marine, and aviation systems, and so forth. Power Semiconductor devices have had a colossal effect on the performance of the electric drives. Because of the progressive advancement of the software products like MATLAB/SIMULINK, real-time systems platforms for the simulation are utilized broadly in many engineering fields, for example, industry, training, and extensively in research areas. Thus, incorporation of the real-time simulation applications in present-day engineering gives incredible assistance to the researcher and academicians.

As presented in [3], modelling of network incorporated for photovoltaic framework utilizing Typhoon HIL is utilized. Sustainable power sources, essentially wind and sun based are generally utilized for power generation. Solar energy can be utilized in two modes, standalone system mode, and grid-tied application. The photovoltaic framework comprises of Photovoltaic panels through DC to DC converter alongside MPPT algorithm and DC to AC inverter to transfer the generated energy to the grid. Here MPPT algorithms are utilized for extricating the point where maximum power obtained in different environmental conditions and factors. Besides, for the control of the inverter, PWM technique control is used. Three-phase voltage sources are associated at the grid side to supply the load.

As per the work proposed in [4], modeling and simulation of a buck converter are picked, because it is the most crucial of all switch mode based DC-DC converter. There are different ways to deal with the model of the buck converter. From the operating principle, circuit analysis, and converter performance, mathematical and hardware modeling are usually utilized. For system response and control procedure, transfer function, and state-space model representation are more suitable.

As per the author in [5], investigation for appropriateness of the real-time simulation test platform by building up a HIL arrangement where a switching converter with a large power system framework is recreated on an FPGA utilizing Latency-Based Linear Multi-step Compound Method (LB-LMC) and is controlled remotely in a closed-loop cycle by a microcontroller working at frequencies of 100kHz. First, the overview of the real-time simulation method is presented, trailed by how this technique is actualized on an FPGA. At that point, then the system framework test model utilized in the real-time experimental simulation is discussed. A HIL platform and execution rates of the developed models are discussed in detail.

As per the author in [6], general methodologies and consequences of real-time hardware-in-the-loop simulation (HILS) testing for power hardware controllers are discussed. A wide range of power electronic controllers can be simulated and tested by interfacing them to a real-time-digital-system (RTDS) for closed-loop HIL testing in real-time. Two HIL computerized controller tests are introduced as examples of the low-level sign interface in the closed-loop simulation of power electronic controllers that are dealt with in detail. In the HIL tests, the power system framework and the power electronic hardware equipment are modelled in the RTDS. The necessary control elements of the power electronic equipment are excluded from the RTDS. Rather, the control algorithms are coded utilizing the local C code and downloaded to the devoted advanced digital signal processor (DSP)/microcontrollers. The two exploratory applications delineate the viability of the HIL controller testing. Consequences of the HIL tests and equipment validation are introduced to represent the real-time HIL simulation testing strategy for power electronic controllers.

III.HARDWARE IN THE LOOP SIMULATION

By utilizing a few simulations, serious faults which could degrade the converter equipment, for example, cut off, or overcurrent can be observed on the monitor. In light of these conditions, there was a test interfaced to give quick information exchange. Hardware-in-the-loop (HIL) is a strategy that as of late mainstream technique that is used to test the intricate complex installed system framework in real-time. HIL is done between the accessible equipment to the models of that equipment which are not accessible. By and large, the HIL procedure or interface permits the model of the system framework researched under sensible conditions more than once, securely and monetarily. The benefits of utilizing this procedure are to try to replicate the field conditions of the entire system framework, even a portion of the equipment segments is not accessible. Second is the HIL simulation could help to test the power electronic equipment before executing it in the real field condition. The third is to give a powerful stage for creating and testing ongoing implanted frameworks, which is frequently in close correspondence with the improvement of the equipment. Typically, a researcher or a designer invests a ton of energy concentrated on creating and testing of electronic control devices, at that point move to experimentation utilizing actual hardware simulation is not feasible. By utilizing HIL, the experimentation can be done in real-time with the actual model of the system and decrease the cost and effectively investigate any shortcomings. The scientist or system designer no longer needs to wait for that quite a while to test the whole system framework at once. In any case, these HIL system frameworks are restricted being used on account of the costly ongoing equipment controller. Fig 1 represents the block diagram of HIL.

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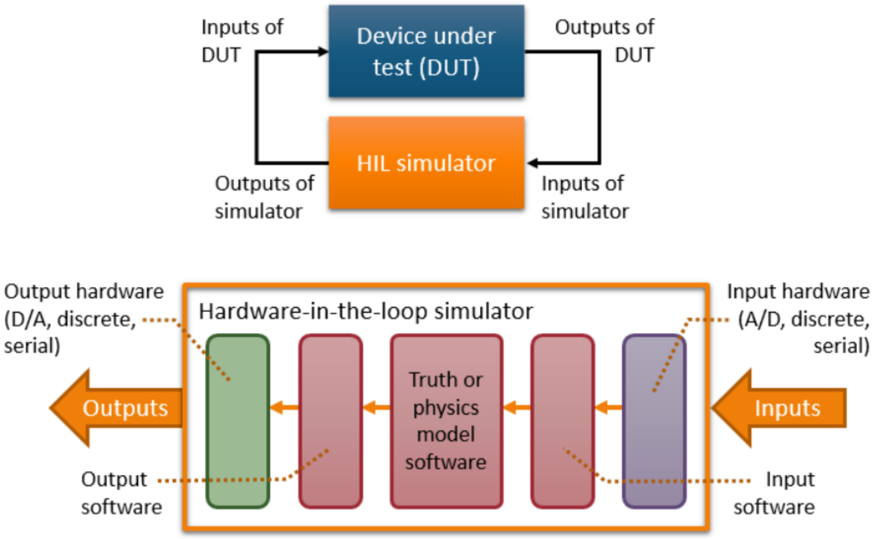

Figure1. Block diagram representation of Hardware-In-Loop (HIL) simulation

IV. MODELLING OF BUCK CONVERTER

Mathematical modelling is the most crucial methodology of modelling and simulation. The mathematical modelling approach can be used as long as the laws of physics are applied. Mathematical modelling is on a very basic level, dependent on the first rule where calculus is broadly applied. The Mathematical model is formed from the circuit design of the buck converter dependent on circuit analysis. Fig. 2 shows the conventional buck converter circuit that is used for modelling and, is implemented in close loop operation with the implementation of an integral controller. The buck converter comprises of two energy storage elements and two switching power electronic components, they are n-channel MOSFET transistor and Schottky diode. During switching activity, power electronic components complement one another in ON state, and the other in OFF state at a given period and the other way around. Fig 3 represents the modelling of the closed-loop buck converter in SIMULINK.

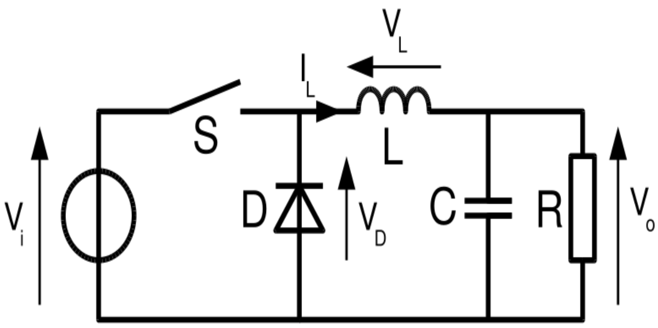

Figure 2. Conventional buck converter circuit diagram

At the point when the MOSFET is turned ON, the voltage V_{in} is applied backward over the diode. In this manner, the diode must remain OFF as long as MOSFET stays ON. The ON territory of MOSFET consistently infers the off condition of the diode. With the MOSFET turned ON, current I_L beings to develop. The development of IL happens exponentially because of the inductance L. The MOSFET is kept ON for a period stretch T_{ON}, and OFF for the span T_{OFF}. At the moment when MOSFET is off, I_L has a limited value (I_{P1}), which is the pinnacle estimation of the yield current during the chopper cycle. This maximum current flows at the moment when the MOSFET is turned off. The presence of the inductance L forestalls the abrupt drop of I_L to zero. The decay of I_L causes an induced voltage $L\ diL/dt$ to show up over the inductance. As a result of this voltage, the diode becomes forward-biased and makes the current flow and decay exponentially. The expression "Free-Wheeling" is normally used to depict the progression of current as such without the guide of a voltage source, yet exclusively because of the put-away vitality in the inductance. The reason for the diode is to give the free-wheeling way to the MOSFET when it is turned off. Consequently, the diode

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naturally turns ON at the moment the MOSFET turns off because of the presence of an inductance. The decay of I_L proceeds as long as MOSFET stays OFF, that is, for a term T_{OFF}. The most minimal incentive to which the present falls toward the finish of the primary chopper cycle is marked as the valley extent I_{V1}. The subsequent chopper switching cycle begins when MOSFET turned ON again towards the finish of the T_{OFF}, and the current again begins to develop. Because of the underlying current I_{V1}, the second pinnacle $_{IP2}$ will be bigger than I_{P1}. Subsequently, the extent I_{V2} toward the finish of the subsequent cycle will likewise be bigger than I_{V1}. Along these lines, as the switching advances, both the maximum and minimum extents have dynamic increments. After a few cycles, the contrast between progressive cycles turns out to be irrelevant. By that time, the state that the circuit conditions have arrived is called a steady-state. Few parameters of the duty cycle, duty ratio based on input and output currents are mentioned as below:

The equation obtained: $t_{ON} \times (V_{IN} - V_{OUT}) = t_{OFF} \times V_{Out}$ ………………………………(1)

Rearranging: $V_{OUT}/(V_{IN} - V_{OUT}) = t_{ON}/t_{OFF}$ ……………………………………....(2)

Adding 1 to both sides and collecting terms: $V_{OUT}/V_{IN} = t_{ON}/(t_{ON} + t_{OFF})$…………(3)

Because the duty ratio is D: $t_{ON}/(t_{ON} + t_{OFF}) = D$………………………………....(4)

For the buck circuit: $D = V_{OUT}/V_{IN}$ .... (5)

Where, V_{in}: Input voltage

V_{out}: Output Voltage

t_{on}: Turn on period

t_{off}: Turn off period

D: Duty ratio

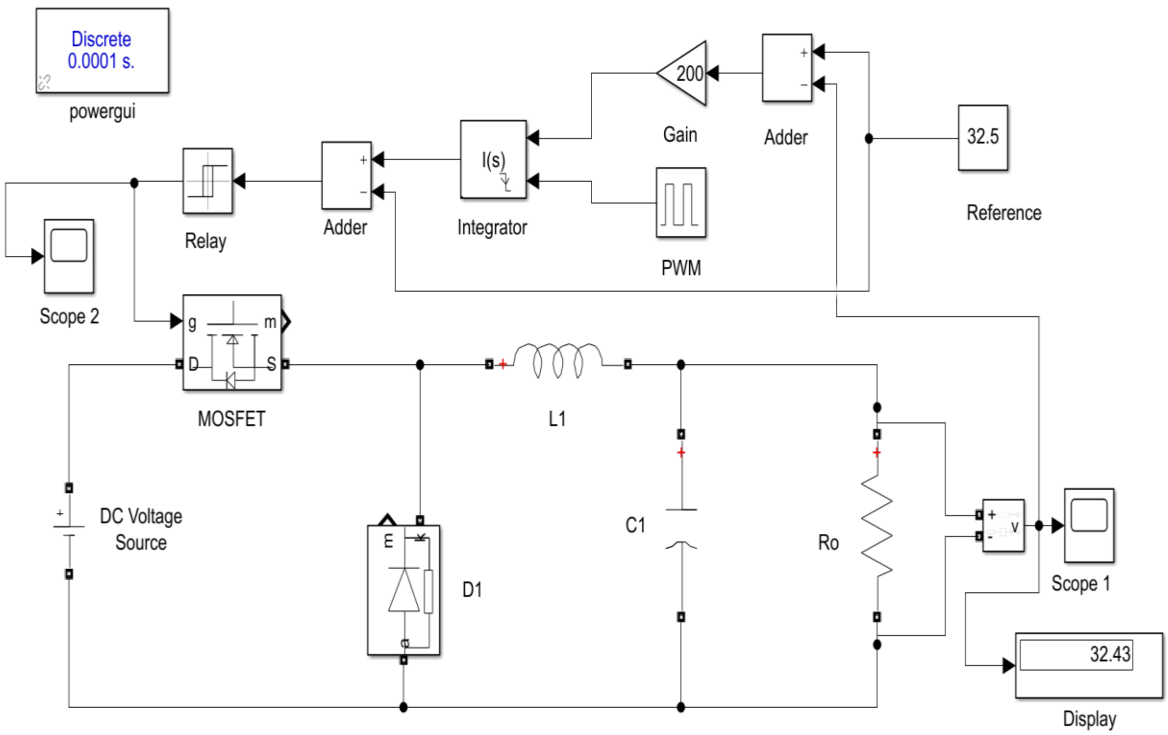

Figure 3. SIMULINK model of closed loop operation of buck converter

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V. BUCK CONVERTER MODEL IN TYPHOON HIL

A. HIL Wizard Setup

Typhoon HIL software is initialized, the new schematic wizard is set up by selecting the Hardware settings and simulation settings as shown in the fig. 4. For the present simulation of buck converter, HIL402 is selected as a hardware product and hardware configuration ID is set to 5. As shown in fig. 6, the parameters of configuration ID 5 are shown in detail. Based on the requirements of the simulation the hardware configuration ID is chosen. The simulation of buck converter does involve time-varying elements and converter losses calculations; hence converter losses are taken into to simulate actual real-time hardware simulation using a virtual HIL environment. The simulation method is set to exact to get the actual simulation results and simulation setup time is fixed to auto to enable automatic scheduling of time for the simulation based on the computer system configuration as shown in fig. 5. After the completed setup of the schematic wizard, the schematic editor is initialized.

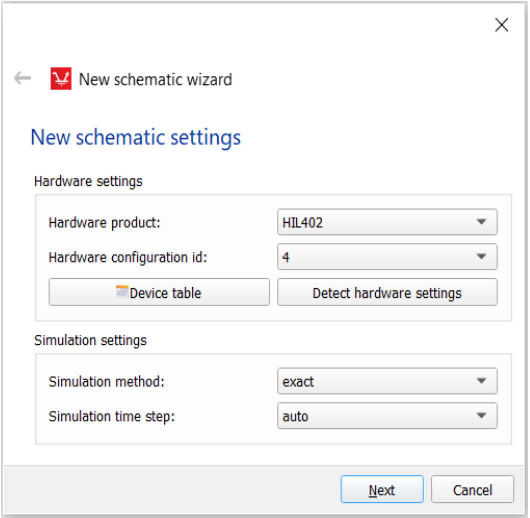

Figure 4. Dialog box of new schematic wizard in Typhoon HIL control centre

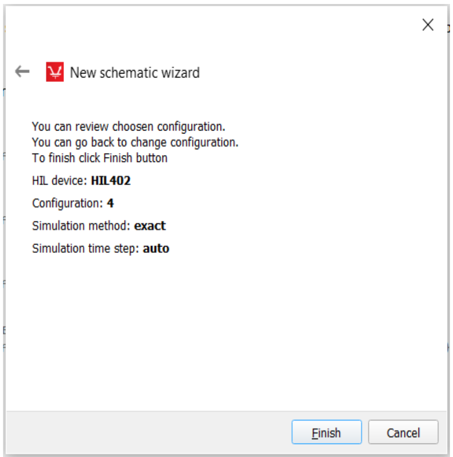

Figure 5. Configuration details of new schematic wizard in Typhoon HIL control centre for the simulation

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Device Configuration Table

HIL Device HIL402

	Configuration 1	Configuration 2	Configuration 3	Configuration 4	Configuration 5	Configuration 6
Number of SPCs	3	4	2	2	2	2
Machine solvers	1	0	0	1	2	1
Signal generators	12	12	12	12	12	12
Look Up Tables	8	8	8	8	8	8
PWM channels	12	12	12	12	12	12
SPC peak processing power [GMACS]	0.64	0.64	1.28	0.64	0.64	0.64
SPC matrix memory [KWords]	16.0	16.0	16.0	16.0	16.0	16.0
SPC output memory size [variables]	256	256	512	512	256	256
Max converter weight (ideal switches) / SPC	3	3	3	3	3	3
Contactors (ideal switches) / SPC	6	6	6	6	6	6
Non-ideal switches / SPC	0	0	32	32	0	0
Time varying elements / SPC	0	0	16	16	0	0
GDS oversampling	yes	yes	yes	yes	yes	yes
Nonlinear machine support	no	no	no	no	no	yes
Switching delay	yes	yes	yes	yes	yes	yes
Converter power loss calculation	no	no	no	yes	no	no

Close

Figure 6. Device configuration table in Typhoon HIL control centre

B. HIL Schematic Editor

HIL Schematic Editor is the user interface wherein the exact circuit can be realized with the help of the elements block obtained from the library explorer. The different components of power electronics such as diode leg, buck, boost, and passive elements can be selected and placed on the editor, and connections are to be made as per the circuit diagram. The buck converter is modelled as per the circuit diagram as shown in fig. 7. The signal processing part is different and can be indicated in blue connecting lines. The electrical part is compiled in C code after the circuit validation is completed. The execution time for the components can be initialized in the python script editor for the given schematic.

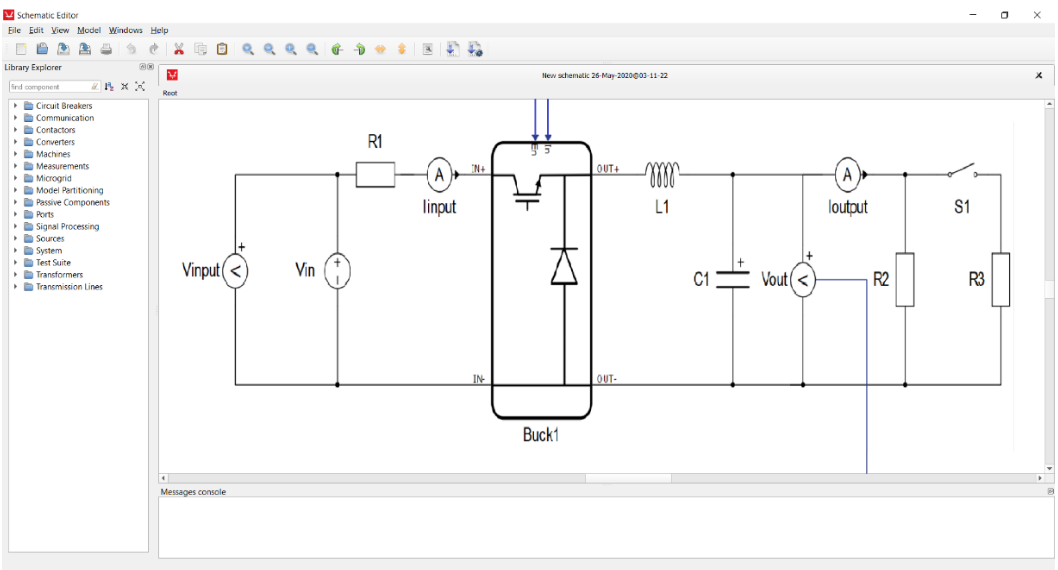

Figure 7. Schematic editor in Typhoon HIL

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For the present simulation, simulation time is chosen to be Ts=100e-6 s. After the successful validation of the circuit and C code compilation, the code is imported to HIL SCADA. The new HIL SCADA panel is designed and loaded in Virtual HIL mode to simulate real-time calculations; all thought there are differences between actual HIL 402 device simulation and Virtual HIL simulation.

C. HIL SCADA

HIL SCADA is an interactive environment with supervisory control and data acquisition. The SCADA panel has to be designed as per the circuit parameters and controller design. Different widgets are available on the left of the SCADA editor in the library, such as a knob, slider, display, scope/capture, and combo box, etc. On the right of the SCADA editor, we have the model settings which consist of the model input and output control. As per the buck converter circuit, the gauge widget is used to measure the voltage and current on input and as well as output. A display widget is used to indicate the measured voltage on input as well as an output terminal. The reference is to set the help of a slider to vary the input voltage. The contactor state is displayed with the help of the combo box and indicated as “open” and “closed”. LED is connected to the feedback signal of the contactor to display the state, “open” and “close” as off and on respectively. The controller is designed using the group widget; it contains the reference signal knob through which the reference signal can be changed to obtain the desired output voltage. The enable signal can be turned on or off with the help of the combo box designed for the enable signal with two modes being indicated as “Enable” and “Disable”. The SCADA panel is locked and activated. The Run button is pressed to compile the SCADA widget functions and the SCADA panel becomes interactive, with all functions accessible as per the designed. The output waveforms can be seen using the scope/capture tool. The signal sampling rate can be set as per the requirement; the capture is triggered at 30V DC output voltage.

The closeup view of the HIL SCADA panel is as shown in fig 8. The HIL SCADA panel has different widgets namely, gauge, scope/capture, combo box, slider, display, group, knob, LEDs. The operation of each SCADA widget is as intended. The gauge is used to display the digital as well as analog voltage and currents values of both input and output terminals. The digital display is used to display the finite, two decimal voltage, or current value. The slider widget is used to change the input voltage which has a minimum of 16V and a maximum of 72V with 0.8 P.U and 1.2 P.U being the lower and upper P.U values. The step rate of the slider is set to 0.02 P.U. The group widget is used to design and implement the controller, which has a combo box that displays the state of the enable signal given to the buck converter. The knob inside the group widget is used to set the reference voltage to facilitate the closed-loop operation. The capture/scope widget is used to observe the output waveform. The scope function is used only to observe the voltage, current, and PWM signals, but the capture tool is used to freeze the waveform values at a particular time duration with a required sampling rate. The trigger function is set at the required level to capture the desired signal. Thus, the scope/capture tool is an important tool to observe and study the targeted waveform. The different HIL SCADA widgets are represented in the red box as shown in fig 9.

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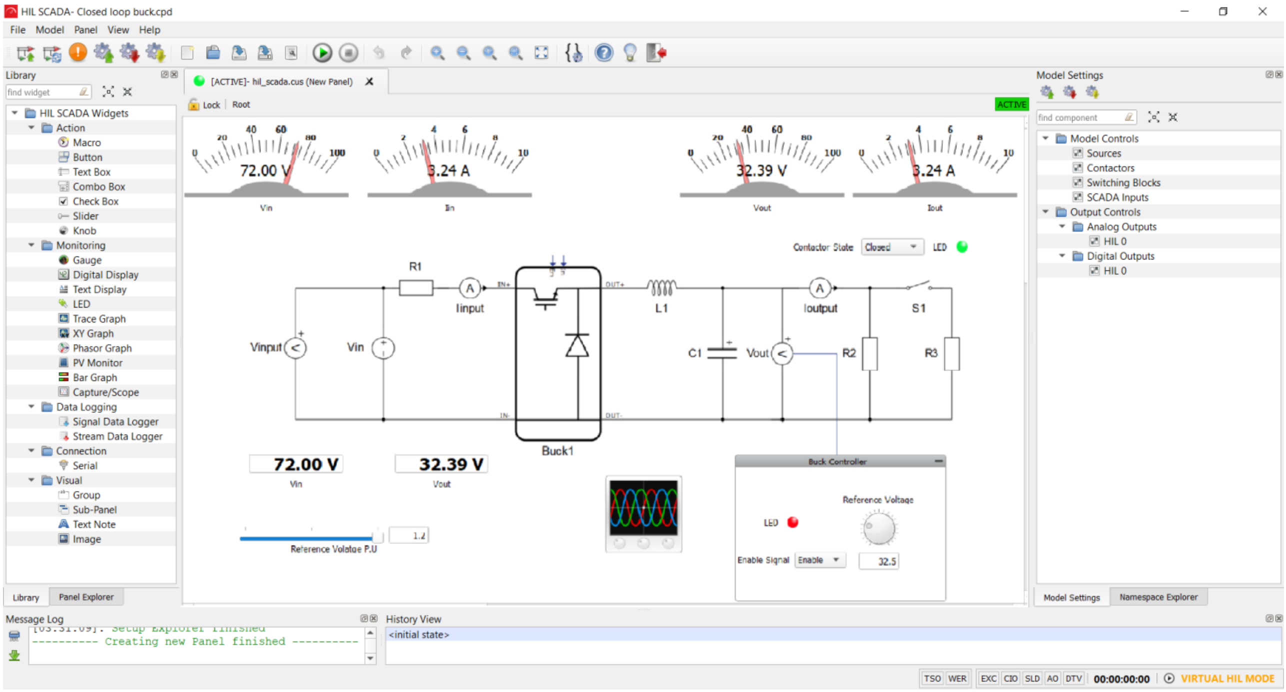

Figure 8. HIL SCADA panel view in Typhoon HIL

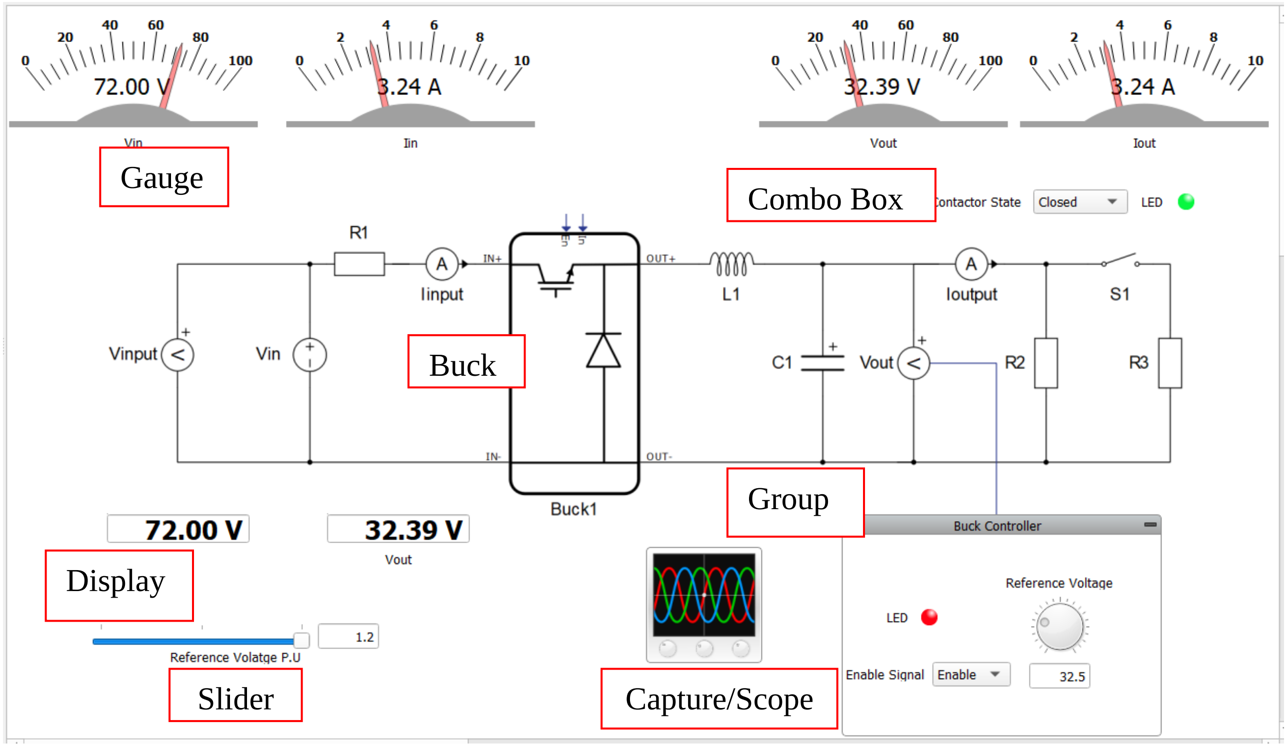

Figure 9. Close up view of closed buck converter in HIL SCADA

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VI. SIMULATION RESULTS

Fig. 10, represents the PWM signal obtained from the closed-loop controller implemented using the Integral controller. The amplitude is 1V and the frequency is set to be 10kHz. The duty cycle depends on the input voltage and the output voltage required. For this simulation, the input voltage was considered to be 72V and the reference voltage was set to 32.5V which translates into output voltage being 32.43V in MATLAB/SIMULINK simulation. Fig. 11 represents the output voltage waveform obtained from the buck converter with the mentioned reference.

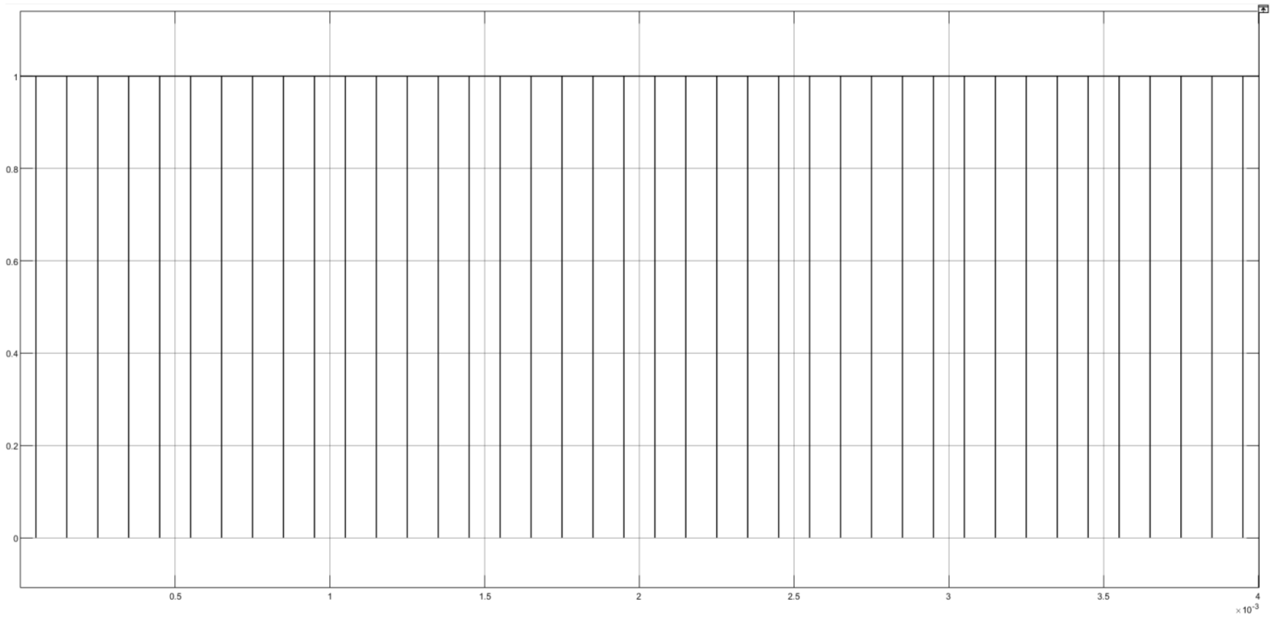

Figure 10. Waveform of Pulse width modulated signal for closed loop operation of buck converter (Voltage in V vs Time in s)

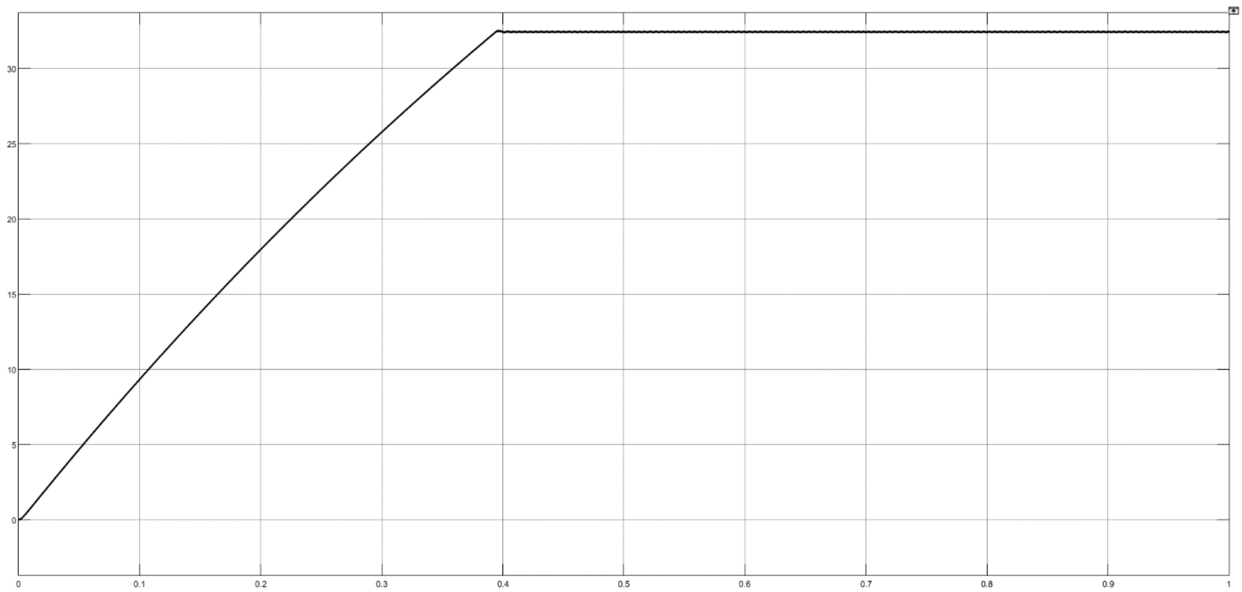

Figure 11. Output waveform of closed loop operated buck converter (Voltage in V vs Time in s)

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The fig. 12 represents the scope waveform of the hardware-in-loop simulated closed-loop buck converter. The left has the side of the graph represents the input and output voltage (top to bottom) and the right side of the graph represents the input and current waveform (top to bottom). The waveform obtained in scope is based on the virtual simulation and cannot notice properly. Hence the capture tool was used to capture the output waveforms as shown in fig. 13, the triggering function was set to 30V and input voltage was considered to be 72V and the output voltage obtained was 32.39V. The duty ratio is dependent on the input voltage and the reference voltage is given. With the variation of the contractor switch, different loads were simulated. With enable engaged and did engaged the waveforms were analyzed.

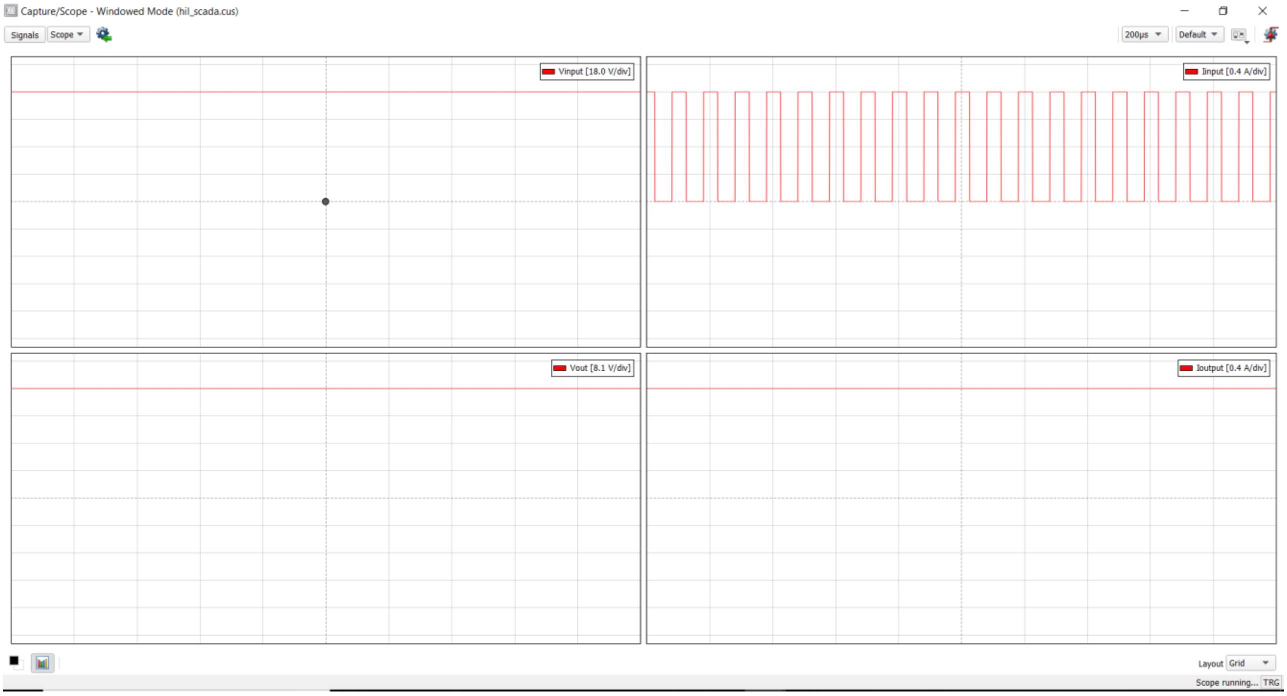

Figure 12. Output Wave from of the buck converter simulated in virtual Typhoon HIL (Scope Waveform)

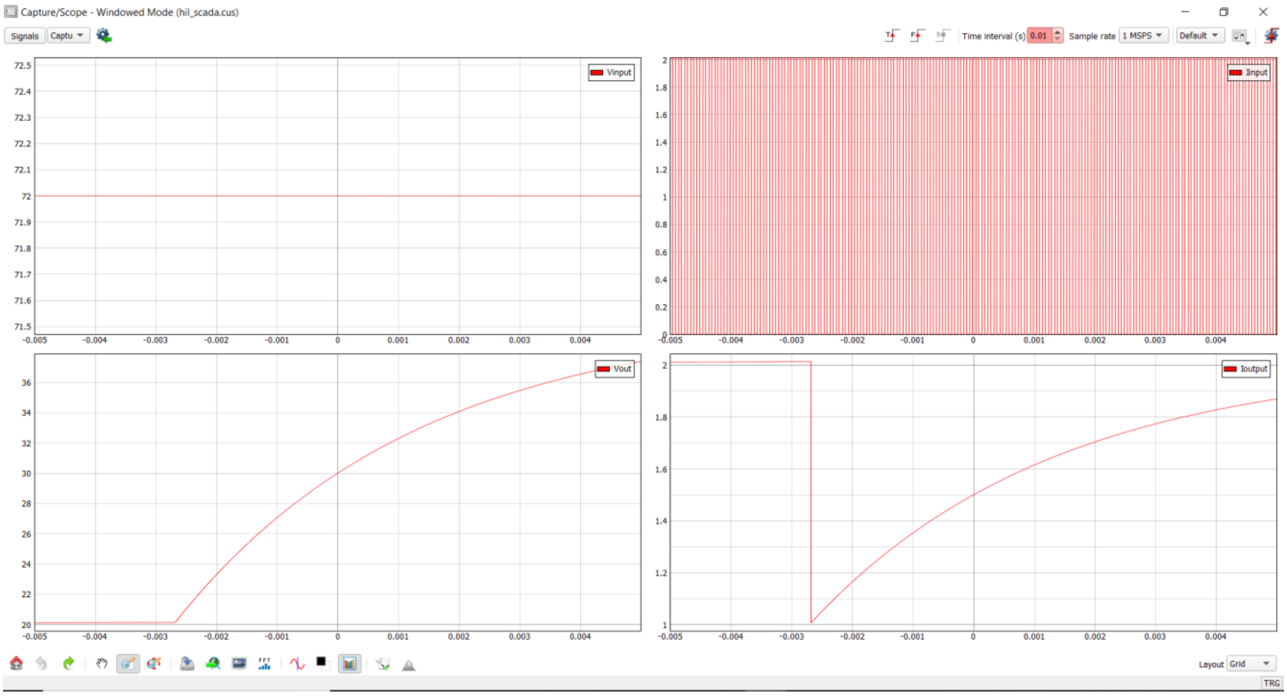

Figure 13. Output Wave from of the buck converter simulated in virtual Typhoon HIL (Capture Waveform)

VII. CONCLUSION

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The closed-loop buck converter was simulated in a virtual Typhoon HIL simulator. The closed-loop buck converter was modelled in MATLAB/SIMULINK as well and the reference voltage given to both the models was the same. But the output voltage obtained from the SIMULINK model was 32.43V whereas it was 32.39 from the virtual Typhoon HIL simulator. The Typhoon HIL simulator is a powerful tool to simulate complex controllers and complicated power system design and calculations. The Typhoon HIL offers better interactive features as compared to MATLAB. With the use of the HIL 402 kit, more accurate simulation results can be obtained. The ease of operation of library files and SCADA widgets is observed in Typhoon HIL. The HIL can be used as a test for microgrid simulations which brings a revolutionary change in the real-time simulation platform. Thus, to conclude, the closed-loop buck converter was simulated in the virtual Typhoon HIL environment and the obtained results were compared with the SIMULINK result values.

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BIOGRAPHY

Mr. Vishnu. S is currently pursuing his final year of Bachelor's Degree in Electrical and Electronics Engineering at BNM Institute of Technology, Bangalore. He is interested in the field of power electronics, unmanned vehicles and defense robotic systems. He is passionate about electronic projects and technical article writing.