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Electric Load Simulation for 48V DC Converter Using HIL Simulator

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Summary

A 48V DC converter on 48V power net is used to charge the 12V battery with electrical energy generated from an electrical drive system, such as a motor starter generator (MSG). The efficiency of the DC converter is influenced by the input voltage from 48V battery and the input voltage from 12V battery, and also depends on the load power level. A mode transition strategy for controlling the operating range of the DC converter in the efficiency section is proposed. This study also presents a practical method to simulate the real power conditions of the 48V converter through hardware-in-the-loop (HIL) simulator.

Keywords: Hardware-In-the-Loop(HIL), DC-DC Converter, 48V System, Electric Load Simulation

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1 Introduction

Due to the requirement of global environmental regulation and the rapid growth for automotive electrification, 48V power net including present 12V battery has been considered to be new alternative approach in order to meet regulatory fuel economy targets and adopt lower cost electrification systems.

The basic structure of the 48V power net architecture is to connect the two batteries, high voltage 48V battery and low voltage 12V battery, by the DC converter. This allows high power consumption to be switched to 48V battery, and all generated power from 48V drive system has to be converted through the converter.

The charging or discharging of the 48V battery is mainly governed by drive assist, power generation and regenerative braking control, which is determined by the optimal operating strategy of the hybrid control unit (HCU), rather than the power consumption by the auxiliary load.

The output power of the DC converter depends heavily on the auxiliary power and battery charge. DC converter needs to manage the state of the 12V battery while supplying the load power. Therefore, the output power should be controlled and optimized based on the 12V battery status, such as SOC, and in order to simplify the 12V battery management, intelligent battery sensor(IBS) can be utilized [1].

Numerous studies on 48V Mild HEV [2] have focused on developing a control strategy to obtain the fuel economy gain by efficiently distributing the power of the engine and the electric drive system. Efficient management of major power sources is a logical approach to maximize fuel efficiency improvement. DC converter is considered to have a relatively low contribution to fuel economy improvement. In that regard, the DC converter is mainly used to control the auxiliary load supply and 12V battery charging in given voltage or power control.

The motivation of this study is to investigate the efficiency operation of the DC converter considering the voltage and current of the input side and the output side of the DC converter with the driving condition of the vehicle.

Fig. 1 shows a simulation result for the torque distribution determined by hybrid control algorithm and the DC-DC converter input voltage in FTP75 driving cycle conditions. In a 48V power net, the two drive motors, which are mounted on the front and rear drivelines respectively, function to improve fuel economy through regenerative braking with torque assist of the engine, in which case the SOC of the 48V battery is reduced from the initial value [45%] to the minimum allowable value. Also, as the load increases, as shown in Fig. 1, it shows a property that the voltage of the 48V battery is relatively fast decelerated.

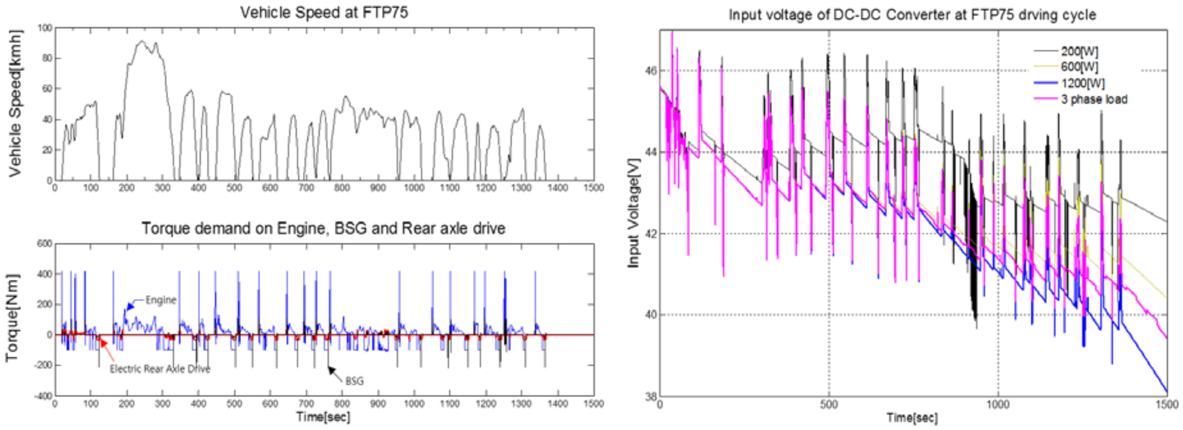


Figure1: Torque distribution and an input voltage of DC-DC converter at FTP75 driving cycle

In this paper, a method to test the converter at the actual power level is to utilize the HIL simulator which can provide the DC converter with the actual current and voltage calculated from the two battery models. Based on the 48V mild HEV model, the control logic that determines the DC converter output power is implemented in two types. The first control logic is the constant limit power control to follow the reference voltage regardless of the 12V battery status. The second is a mode transition control method that basically supplies the required load power corresponding to the measured load current and at the same time compares the voltage and SOC of the 12V battery with the reference value to add the charging power.

2 HIL Simulator at Electric Power Level

From Fig. 2, HIL Simulator consists specific hardware modules that implement the DC-DC Converter interface and the 48V mild HEV vehicle model. To realize the converter operating environment at a power level, HIL simulator is composed of the following major hardware modules (see Fig. 3), such as.

1) Power supply to replicate the 48V battery
2) Active electric load(DS5381) to replicate the charge and discharge modes for 12V battery
3) Sensor for measuring the input and output current of the converter
4) Wire harness for high-current interface between the converter and HIL simulator

The hybrid control unit (HCU) shall distribute the power of the engine, BSG and electric rear axle drive (eRAD [3]) to follow a FTP75 driving cycle, and the converter management unit model controls the operating range of output power to support the load power and simultaneously charge the 12V battery by considering a voltage condition of the high voltage battery and the low voltage battery. The converter management unit model is implemented with constant limit power control (CLC) and load adaptation control (LAC).

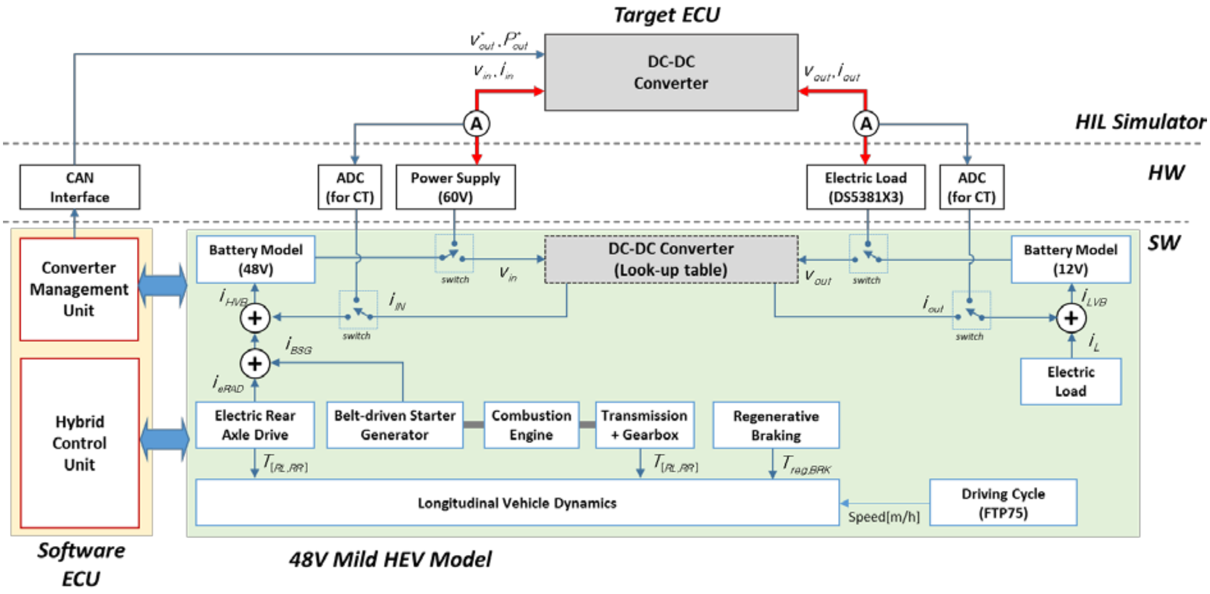


Figure2: HIL schematics based on 48V mild HEV model

The converter model implemented in Simulink consists of a look-up table that reflects the measured efficiency values by adjusting the output power while fixing the input voltage and output voltage of the actual hardware converter. The converter model basically receives each voltage calculated in the battery model as input, and provides the input current and output current calculated by the required output power and efficiency map as input to each battery model.

The switch block is capable of selectively connecting the battery model in real hardware converter and converter models. Regardless of whether the switch block is switched to the converter model or to the actual hardware, the converter management unit implements logic that determines the output power based on the voltage of high-voltage battery and the voltage and SOC of the low-voltage battery. It’s not guaranteed that the offline simulation results to include the converter model within a real-time simulation loop will work the same as the online simulation results with real hardware. However, offline and online test results are expected to be-held substantially the same characteristics, in that the experimental converter efficiency map is reflected and the power management logic that controls the required output power is commonly used.

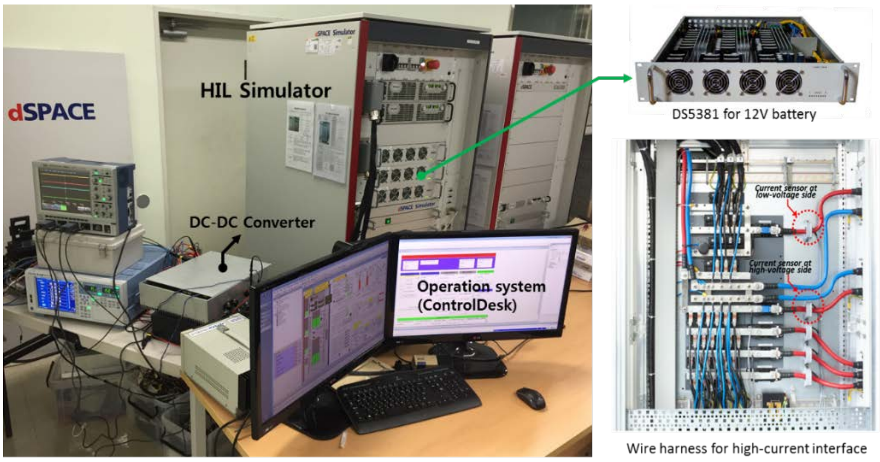


Figure3: HIL simulation setup

Fig. 3 shows the HIL simulator, DC-DC Converter, active electric load(DS5381), wire-harness and operation system. Since the DS5381 takes about 30.8μs to reach 100A in short circuit mode, the 12V battery model of the vehicle is updated in real time every 1ms inside HIL simulator, and the in-vehicle motorized module does not require around 1.2kW output within 30.8μs, the response characteristic of the electronic load is suitable for simulating the load on the vehicle.

3 Power Management Strategy for the Converter

3.1 Efficiency of the converter

Fig. 4 shows the results of efficiency test in accordance with the output power level based on the input and output voltage of the converter. In a load condition that deviates from a specific region of the load output, the efficiency of the converter is relatively low, and in particular, the efficiency is sharply reduced in the low load region.

The converter can minimize the energy dissipated from the 48V battery if it concentrates its operation in the efficiency section while supplying an auxiliary load. In this regard, as shown in Fig. 5, the lower and upper limits of the permissible operating range for a given input voltage and output voltage are determined. Further, the output power having the maximum efficiency exists in the efficiency operation region.

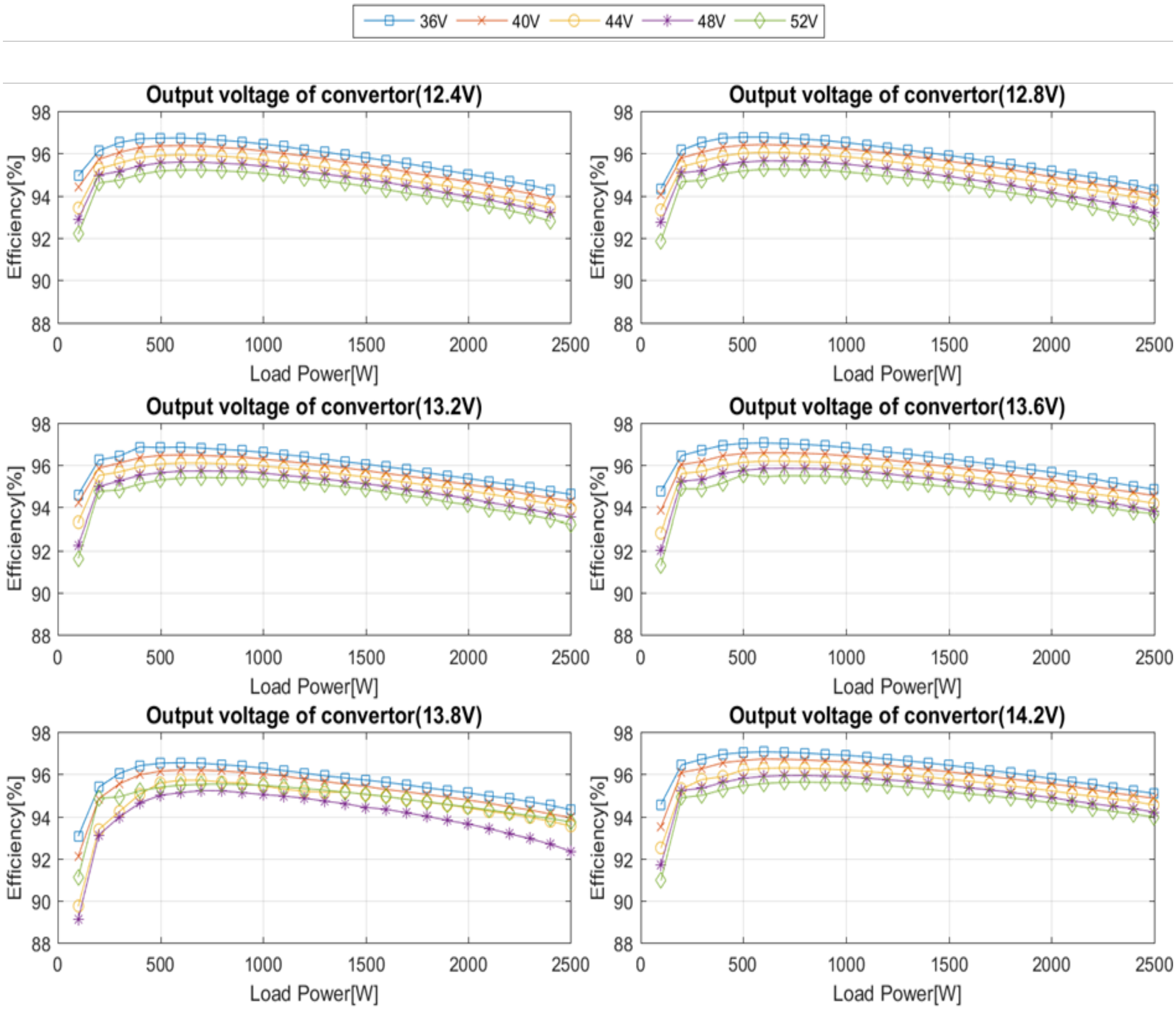
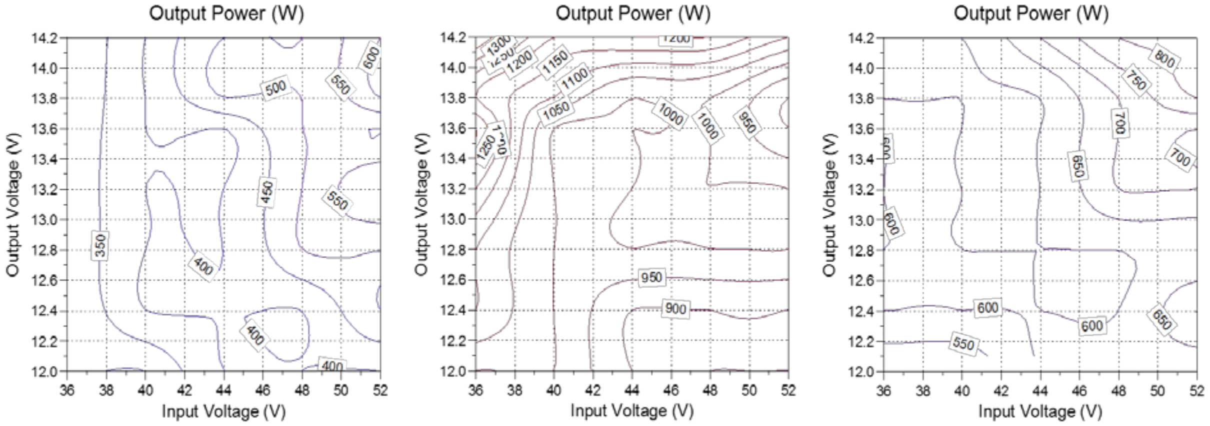


Figure4: Efficiency characteristics of the converter according to load power



(a) Lower limit power (b) Upper limit power (c) Optimal power

Figure5: Efficiency output of converter vs battery voltages

3.2 Control Strategy

Table1 shows the LAC(Load Adaptation Control) operation mode to determine output power, based on the state of the 12V battery voltage state and the SOC. The voltage state is set to High, If the 12V battery voltage is larger than the reference voltage by 0.1 V. The voltage state is set to Low, if the 12V battery voltage is less than the reference voltage by 0.2V. If the voltage is 0.1V less and 0.2V greater than the reference voltage, the voltage state is set to Normal. For conditions not considered in Table 1, the operation mode of the converter is defined as OFF.

Table1: Operation mode of LAC control to handle the power output

Operation Mode for Converter				
12V Battery		Load Power State[]		
SOC State[]	Voltage State[]	Low	Normal	High
Low	Normal	Load Shift Mode	Load Shift Mode	Load Shift Mode
Low	LOW	Load Shift Mode	Load Shift Mode	Load Shift Mode
Normal	LOW	Load Shift Mode	Load Shift Mode	Load Shift Mode
Normal	Normal	Efficiency Mode	Efficiency Mode	Efficiency Mode
Normal	LOW	Load Shift Mode	Load Shift Mode	Load Shift Mode
SOC State[] : Low[SOC <70%], Normal[70%≤SOC≤90], High[SOC>90%]				

If the converter's operating mode is Efficiency Mode, the output power of the converter is required to be set to the optimal power. Load Shift Mode controls the output power within the effective operating range. The efficiency of the lower limit power has almost the same value as the efficiency of the upper limit power in the efficiency operation region (see Fig. 5), and since the 12V battery charging takes priority, the output power required in the load shift mode is set to the upper limit power.

CLC(Constant Limit Power Control) does not take the efficiency interval into account, but basically it has a gain map depending on the difference between the reference voltage and 12V battery voltage. Therefore, when the CAC and the LAC are implemented, the characteristics of the 12V battery may be similar to each other.

At the mode transition, the desired output power jumps to a discontinuous value, so the first order dynamics with a time constant of 0.5 is applied to the final output power and the output power is controlled smoothly.

Fig. 6 shows a Simulink model that selects one of three operation modes, OFF, Load Shift Mode and Efficiency Mode, that determines the required output power based on input states. MODE block, a simulink subsystem model, receives 12V battery voltage state, SOC state, and state of load power, and finally determines DC converter operating mode.

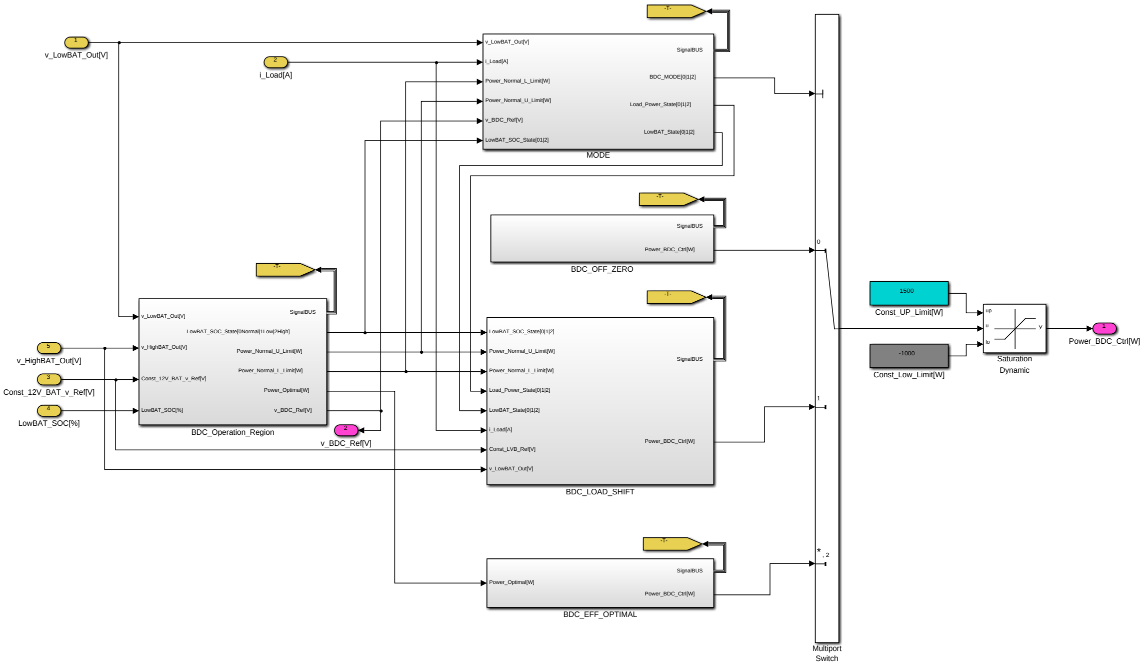


Figure6: Mode transition model constructed with Simulink

4 Off-line Simulation

Three DS5381s(see Fig. 3) inside HIL simulator can continuously simulate 150A current during 12V battery charge and discharge operation. Considering the load current limit simulated by the HIL simulator and 12V battery charging, the load power is divided into three types of static loads, light load[200W], medium load[600W] and heavy load[900W]. In addition, the 3-phase load is configured to change in order of 500 W, 1100 W, and 900 W every 30 seconds. The load power increase from 900W to 1100W, to account for 170 W estimated as an average of intermittent loads [4].

Fig. 7 shows the input and output energy of DC converter and the final SOC value of 12V battery under CLC and LAC control. In all simulation results, the initial SOC is 50%. The reference voltages are 13.0V, 13.5V and 13.8V. When the SOC of the 12V battery is less than 70%, the LAC (Load Adaptation Control) control enters the load shift mode and controls the output power to the upper limit power value of the efficiency operation section. Therefore, if the load power is 600W and 1200W in Fig. 7, the desired power of the DC converter will stay in the upper limit line for 1,500sec. From Fig. 8, it can be seen that the desired output power from LAC control is closely following the upper limit power line.

When the load output is 200W and the CLC control mode is implemented, the voltage difference gain in CLC decreases as the voltage difference decreases. For this reason, it can be seen that the energy consumed by the LAC control is relatively greater than the CLC. Under 3-phase load conditions, the output power determined by the CLC control is nearly fixed at the limit of 1,500 W. The output power required by the LAC control moves between the upper limit power value of the specified efficiency operating section and the limit value of 1,500 W. Since the open circuit voltage corresponding to the initial SOC 50% is 12.3 V, the time for setting the output power to the limit value(1,500W) becomes longer as the reference voltage increases.

Since the initial SOC 50% allows the output power to be controlled close to the power limit value, the efficiency calculated by the output energy versus the input energy of the DC converter is almost the same regardless of the CLC and LAC control modes.

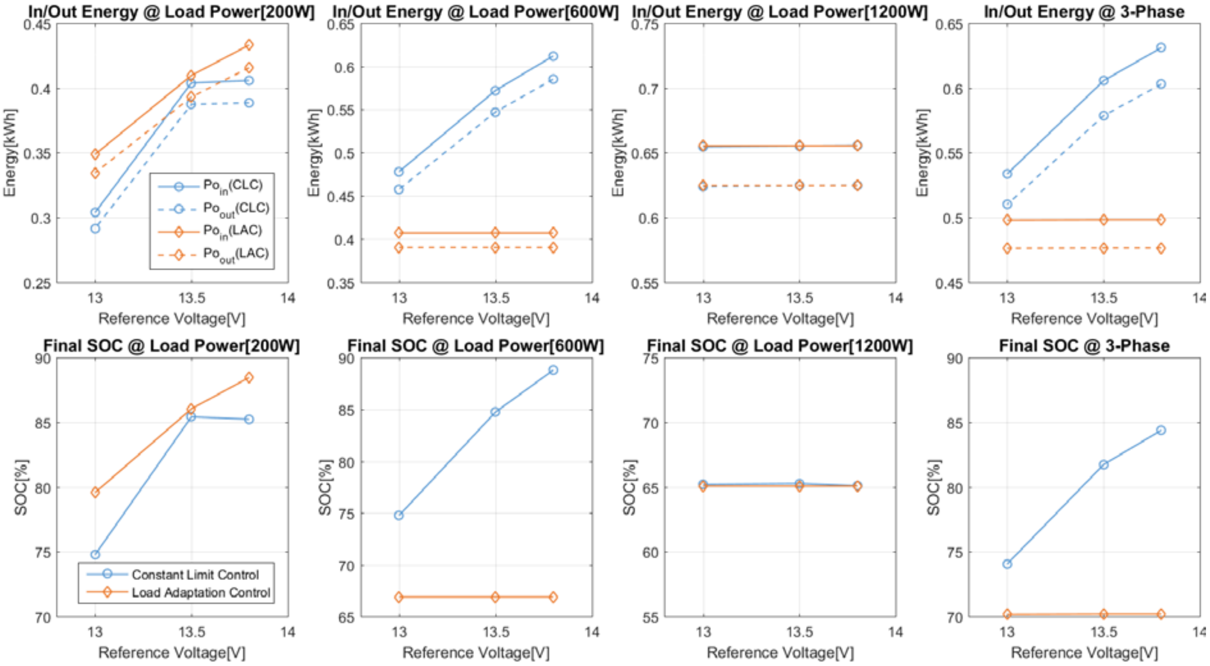


Figure7: The input and output energy[kWh] of the converter and the SOC of 12V battery

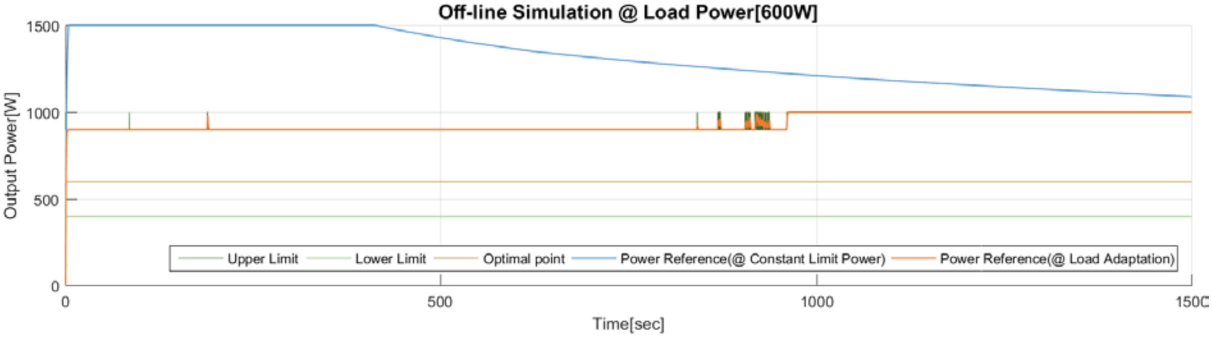


Figure8: Desired output power of the converter at load power 600W and reference voltage 13.5V

5 On-line Simulation

Fig. 9 shows the ControlDesk, one of the standard solutions from dSPACE, which is the operating environment for controlling, setting and monitoring the DC converter. Some specifications of the converter are shown in Table1.

In Fig. 10, compared with the off-line simulation results, the on-line simulation results show that the relative magnitudes are reversed at the reference voltages of 13.0V and 13.8V, respectively, when the load power is 200W. In other cases, there is a difference in the absolute value of the on-line simulation results, but the overall tendency is closely similar.

Such a phenomenon is expected to be caused by a partial difference in the operating characteristics of the DC converter model and the actual hardware, even though the CLC and LAC control logic are commonly used for off-line simulation and on-line simulation.

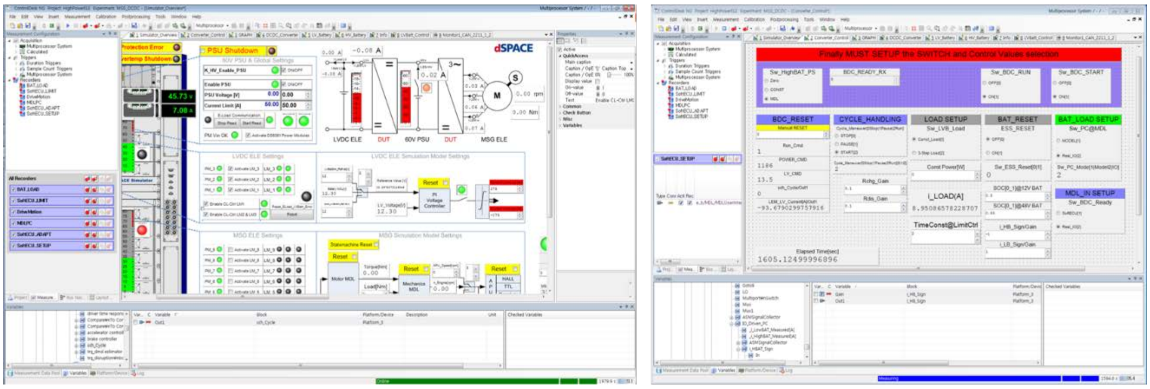


Figure9: ControlDesk to manage on-line simulation

Table2: Specific specification for DC converter

	Unit	Specification
Power ratings (max.)	[kW]	2.5
High side voltage(Min/Nominal/Max)	[V]	24/48/52
Low side Voltage(Min/Nominal/Max)	[V]	6.5/13.8/18
Current (Nominal/max.)	[A]	182/200
Control functions	[-]	Low side voltage (main control value)
cooling method	[-]	FAN operation(External)

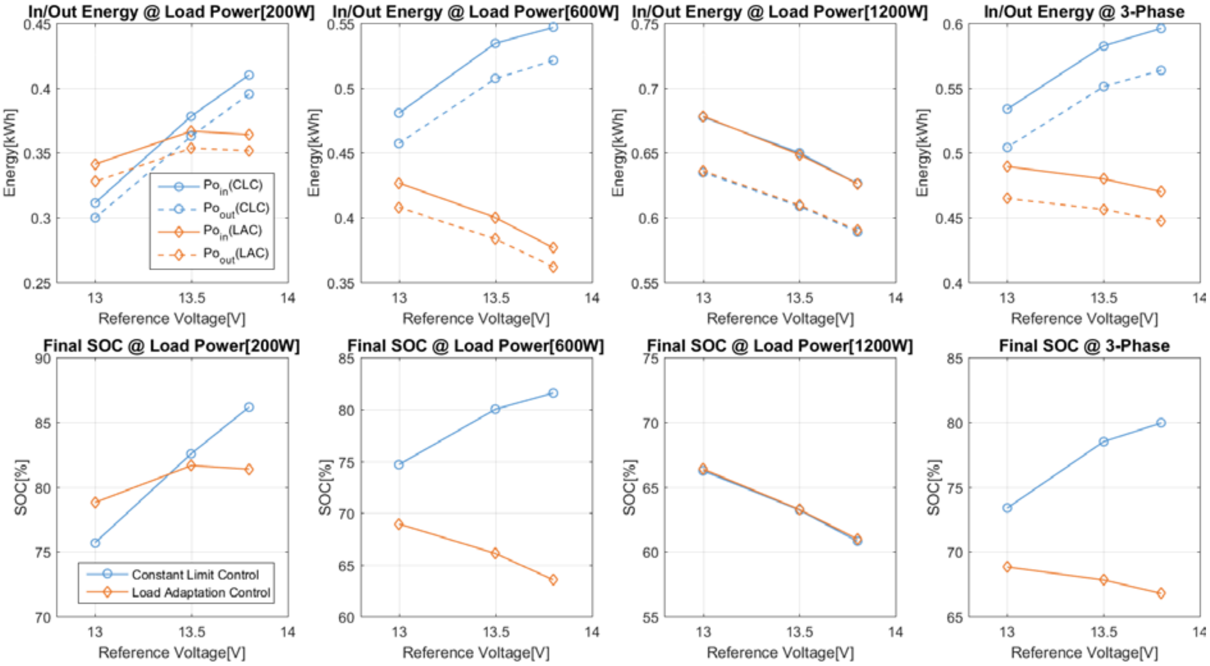


Figure10: Efficiency characteristics of the converter according to load power

Fig. 11 shows the desired output power by CLC and LAC control when the reference voltage is 13.5V and the load power is 600W. Compared with the result of Fig. 8, the output power to the DC converter is relatively small. Such a result can explain why on-line simulation results lead to differences in absolute amounts.

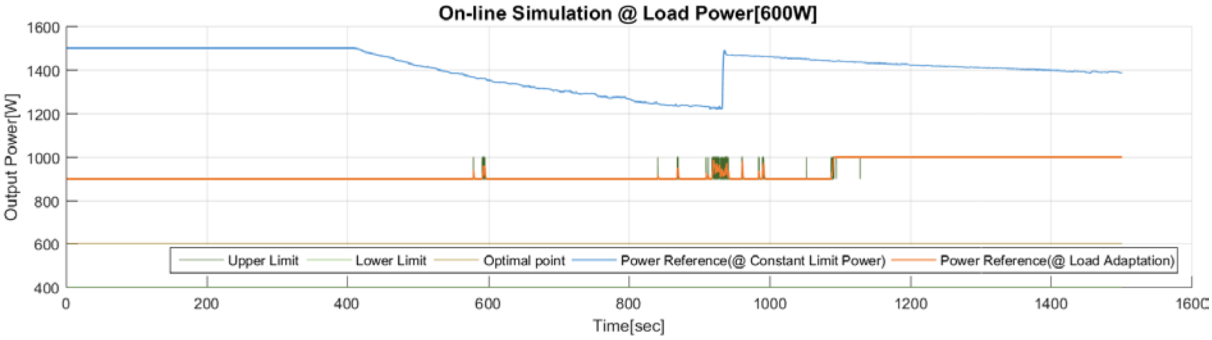


Figure11: Desired output power of the converter at load power 600W and reference voltage 13.5V

6 Comparison of Simulation Results in 3-phase Load

As shown in Fig. 7, when the initial SOC is as low as 50%, the CLC and LAC control modes tend to charge the 12V battery with high output power. When the SOC of the 12V battery is more than 70%, the CLA control mode is to supply the required output power to the DC converter within the efficient operation interval. The initial SOC is set to 65% in order to reach 70% faster than the initial SOC of 50%.

Fig. 12 through 15 show the online simulation results obtained using the HIL simulator and offline simulation results under the conditions of initial SOC 65% and 3-phase load. On-line simulation was initiated manually after confirming that the HIL simulator and DC converter operation was safe, since safety should be prioritized in real power simulation conditions. Due to such a manual start, a time shift occurs in on-line simulation results.

Overall, as the load power increases, the CLC and LAC control modes tend to require large output power.

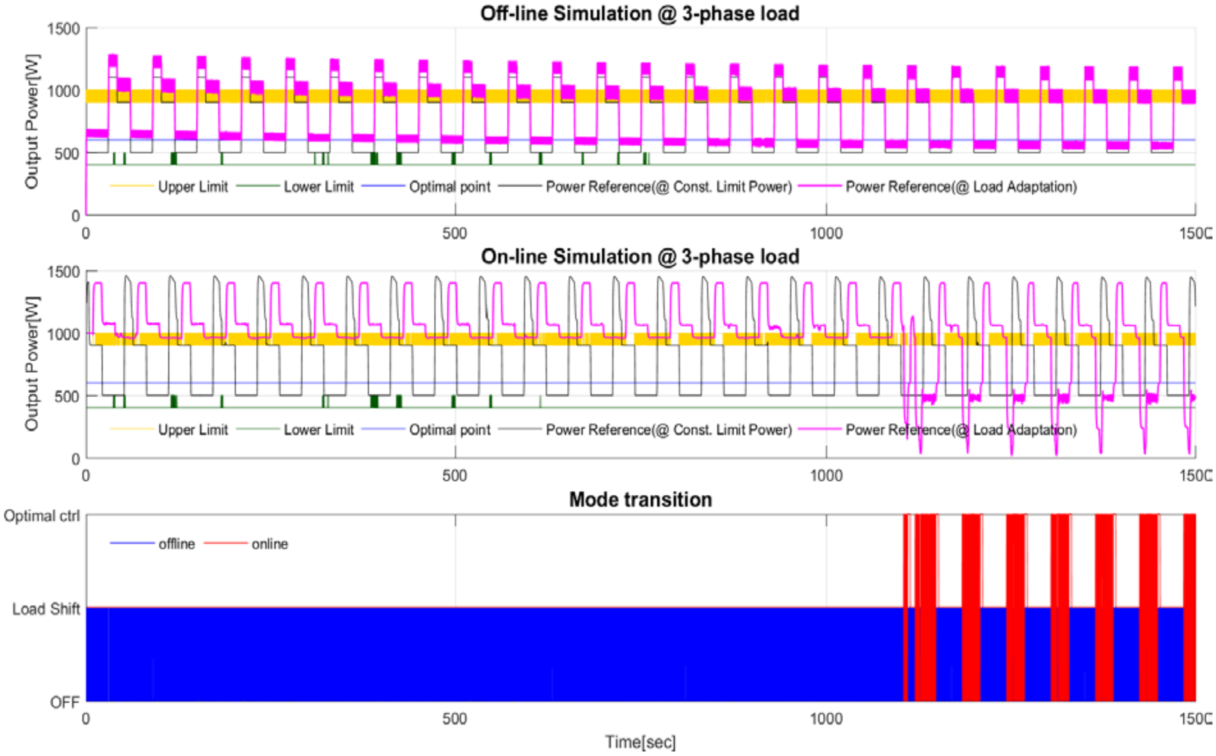


Figure12: Off-line and On-line simulation results at reference voltage 12.5V

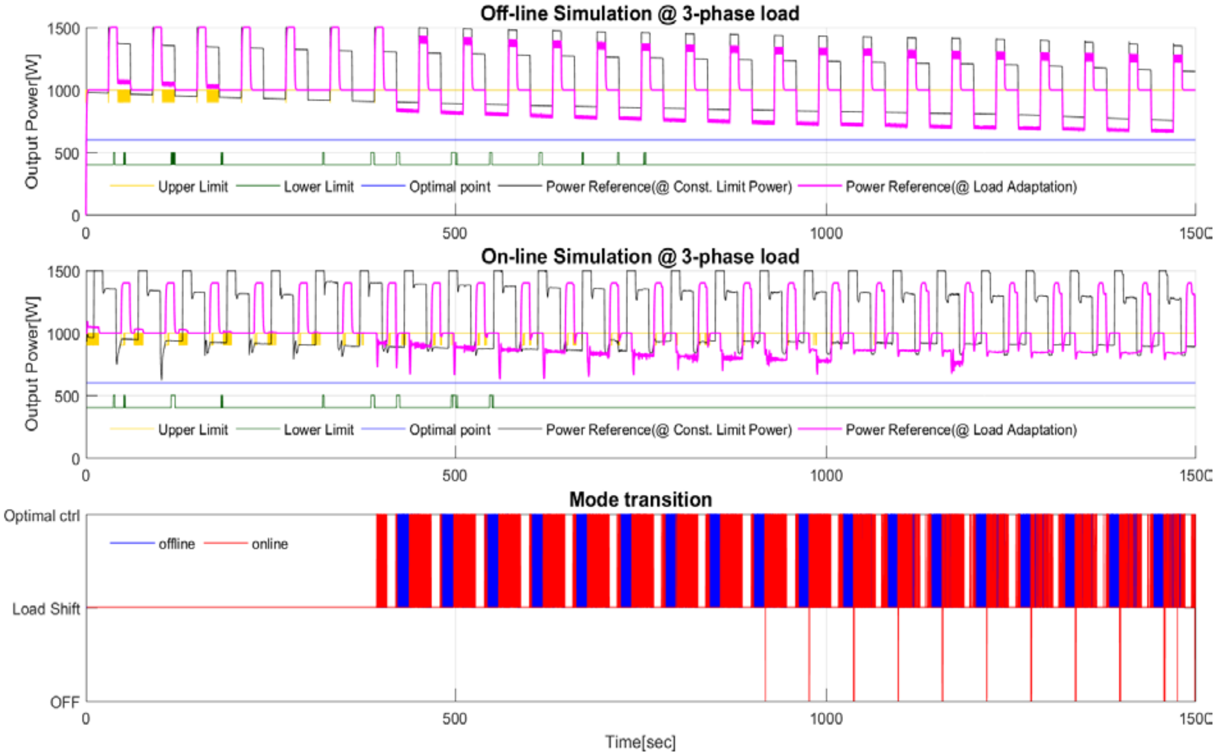


Figure13: Off-line and On-line simulation results at reference voltage 13.0V

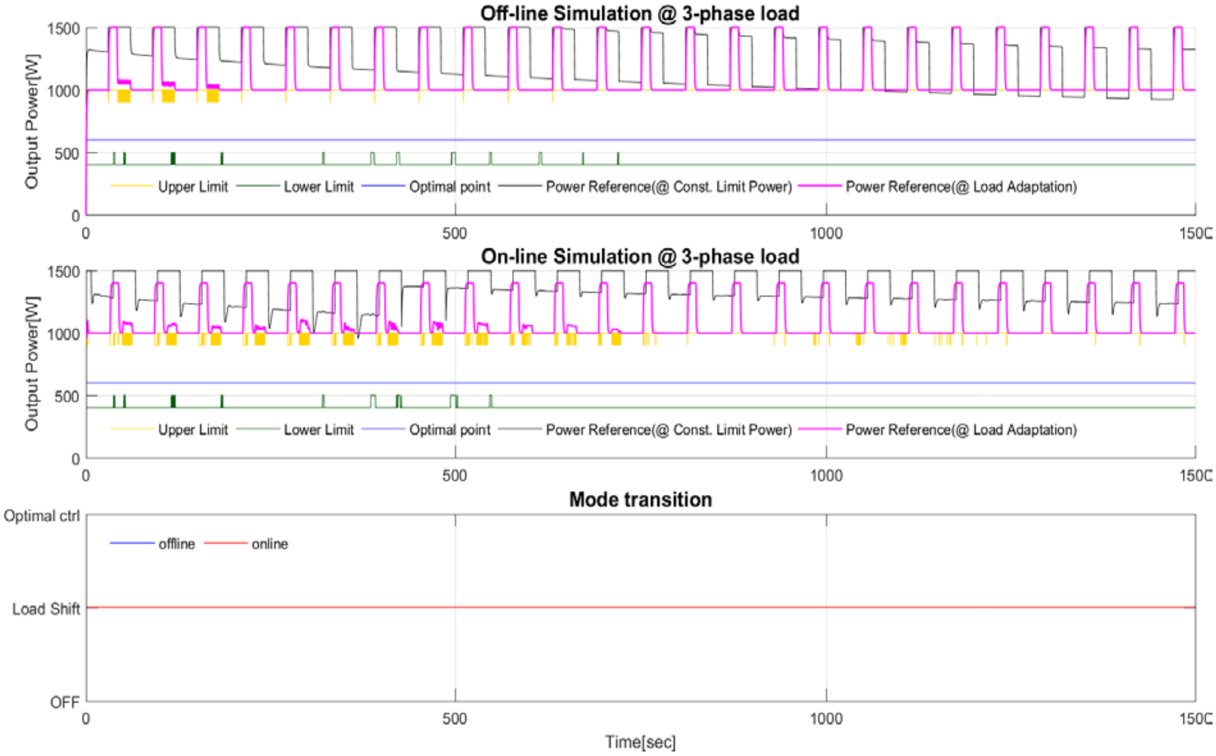


Figure14: Off-line and On-line simulation results at reference voltage 13.5

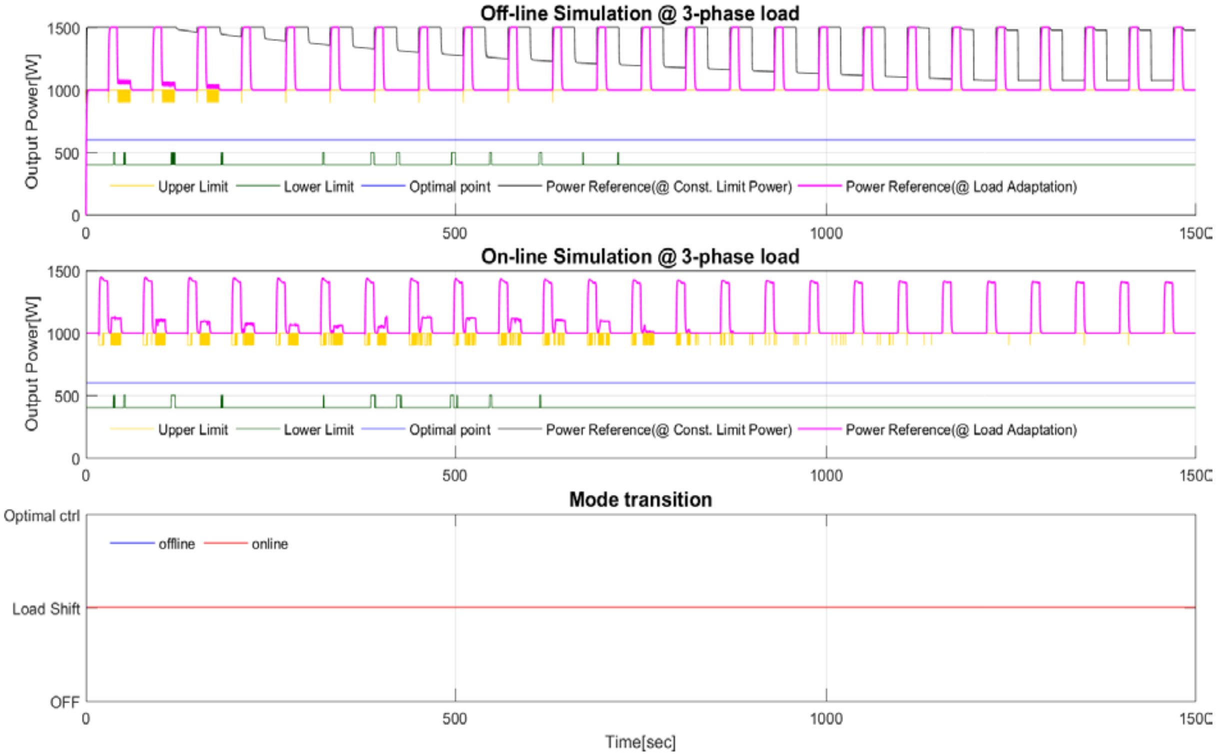


Figure15: Off-line and On-line simulation results at reference voltage 13.8V

7 Conclusion

The 48V mild HEV vehicle model includes a DC converter model with efficiency maps measured at input and output voltage conditions. Basically, it is necessary to control the DC converter in the efficiency region by supplying 48V battery voltage to the DC converter input when driving a vehicle.

From the off-line and on-line simulation results, it can be seen that there is no difference in DC converter efficiency between the reference voltages at the initial SOC 50% condition of 12V battery. However, the energy drawn from the 48V battery is relatively reduced by the LAC control. As the initial SOC decreases and the difference between the reference voltage and the open circuit voltage increases, the LAC control exhibits almost the same characteristics as the CLC control.

Since the operation of the DC converter is dependent on the 12V battery, the HIL simulator can be a very powerful tool in developing efficient operation logic in conjunction with various 12V batteries and DC converters.

The HIL simulator can electrically simulate the input and output operating conditions of the DC converter and proves to be an effective way to develop and evaluate the logic that controls the converter in the efficient operating region.

Acknowledgments

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