Leveraging renewable energy sources for sustainable traction vehicles

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ABSTRACT

In pursuit of sustainable transportation, green energy sources (GES) are taking center stage, propelling traction vehicles like tramways and trolley-buses towards a zero-emission future. Solar is the most prominent source among the available renewable sources and also for the transport system applications. To utilize photovoltaic (PV) source effectively, model predictive controller-based PV maximum power tracking algorithm is used to identify the PV parameters. Equipped with the smart energy storage system (SESS), light traction vehicles rely on the efficiency and reliability of brushless DC (BLDC) motors for smooth operation. However, BLDC motors operate at high voltages, which requires them to be connected to high voltage microgrids. Bridging the gap between ESS/SESS and the high-voltage microgrid with traditional DC-DC boost converters incurs efficiency losses and component stress. This paper tackles high-voltage needs in microgrids through innovative, efficient DC-DC boost converter designs. An innovative finite-control-set based model-predictive control (FCS MPC) controller tackles clean energy harnessing from PV and grid stability in traction applications, enabling optimized power sharing within microgrid constraints.

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1. INTRODUCTION

The pursuit of sustainable urban mobility solutions is central to addressing the growing environmental challenges and urbanization trends of the 21st century. Public transportation systems, including tramways and trolley-buses, play a pivotal role in shaping the sustainability of urban centers. Employing these alternative transportation options would significantly mitigate greenhouse gas emissions, air pollution, and traffic congestion. To unlock their full environmental potential, they must transition from traditional fossil fuel reliance to cleaner energy sources. One promising avenue for achieving this transition is the incorporation of green energy sources (GES) into the operation of traction vehicles [1]. In particular, solar energy has emerged as a leading candidate, offering an abundant and clean energy source to power urban transportation systems [2]. This paper explores control strategies, energy storage systems, and innovative microgrid integration approaches, providing a comprehensive framework for sustainable and efficient urban mobility.

The incorporation of GES into traction vehicles, such as tramways and trolley-buses, is a promising avenue for achieving sustainable urban mobility. Solar energy is the most promising renewable energy storage (RES) for transport applications due to its abundance and cleanliness [3], model predictive controller based photovoltaic (PV) maximum power point tracking (MPPT) algorithms can be used to effectively harness solar energy. An innovative algorithm employing fixed and adaptive step sizes has been devised to mitigate the cost constraints associated with standard model predictive controllers that rely on multiple voltage and current sensors.

Receding horizon model-predictive control (MPC)-based MPPT is a parametric identification technique that can adjust the optimal perturbation period for the perturb and observe (P&O) method [4]. Battery and super capacitor energy storage systems (ESS) are crucial for the stable operation of solar power, given its intermittent nature. Additionally, the combination of fuel cells and electrolysers can be used to create smart energy storage systems (SESS) [5].

Brushless DC (BLDC) motors are widely used in light traction vehicles due to their efficiency and reliability [6]. However, BLDC motors operate at high voltages, which requires them to be connected to high voltage microgrids. Integrating ESS and SESS into high voltage microgrids using conventional DC-DC boost converters can lead to increased stress and losses.

To attain voltage requirements of electric vehicles with a hybrid energy source system, a novel switched-capacitor bidirectional DC-DC converter [7] with a wide voltage gain range is proposed. By employing interleaved dual coupled inductors and a voltage multiplier cell [8], the converter effectively mitigates current ripple and alleviates voltage stress on the power devices. It is possible to use power flow controllers of modular multilevel converter, DC-DC boost converter topologies to attain high gain, high voltage levels [9] at higher efficiency. Additionally, finite-control-set based predictive current controller (FCS MPC) [10] can be used to guarantee equitable power distribution among the microgrid partakers within the operational constraints. This introduction elevates a comprehensive summary of the most recent advances in the integration of GES into traction vehicles. It highlights the key challenges and opportunities, and discusses the latest advancements in solar PV technology, MPPT algorithms, energy storage systems, and microgrid integration approaches.

2. THE PROPOSED METHOD

This paper proposed a solar system supported by ESS and SESS for grid connection and traction applications. The performance of the test system's PV source is enhanced by a hybrid ESS comprising a high-energy-density battery and a high-power-density super capacitor bank. Thus, the super capacitor bank handles high-frequency changes to relieve stress on the battery [11]. ESS's such as batteries and supercapacitor banks make the DC microgrid more reliable and stable [12].

The ESS stores excess energy from the shared busbar and discharges it when needed for the load. The battery is a high energy density device so it can store a high amount of energy, and super-capacitors have a high power-to-weight ratio, so it can respond within a fraction of seconds. Fuel cells offer a scalable and flexible backup solution for DC microgrids. Their modular design allows for easy integration and capacity adjustment based on specific needs, providing reliable power for critical loads [13]. The surplus energy available at the main busbar after the complete charging of ESS is used to generate the hydrogen fuel from the electrolyze. The hydrogen fuel is stored in the hydrogen tank to supply the fuel cell during an emergency condition. The synergistic pairing of a fuel cell and electrolyze creates a self-contained SESS [14], perfectly matched for high-voltage microgrids used by electric traction vehicles.

The integration of low voltage devices like ESS and fuel cells into high voltage microgrids using traditional converters can lead to increased stress and energy losses. To address this challenge, researchers have explored high-gain, high-efficiency converter topologies as a promising solution [15]. Additionally, advanced control techniques like receding horizon predictive control (RHPC) have been implemented for MPPT of solar and fuel cell stacks, ensuring optimal energy extraction from these sources.

However, fluctuations in irradiation and temperature can significantly impact the power quality and output of DC grid-connected systems, especially those incorporating solar power [16]. To mitigate this issue, dynamic power management algorithms have been developed to ensure balanced power sharing among microgrid participants and maintain system operation within defined limits [17]. Specifically for transportation applications, various optimized power management algorithms have been proposed, including MPC-based MPPT with minimized sensor requirements. Notably, MPC stands out as an optimal control strategy for constrained systems, offering superior performance compared to traditional sliding mode current controllers [18]–[20].

In the realm of DC microgrid control, FCS MPC has emerged as a preferred approach to address the limitations of conventional vector control strategies, such as complex PI parameter tuning and multi-objective optimization [21], [22]. This method not only enhances system operation during grid-connected scenarios but also proven effective in islanding mode by anticipating voltage responses for potential switching states within each sample period. By incorporating these innovative technologies, microgrids can achieve efficient and reliable operation, maximizing the utilization of low voltage resources while minimizing negative impacts on system stability and power quality. Test system with ESS and SESS for grid connection and traction applications is shown in Figure 1.

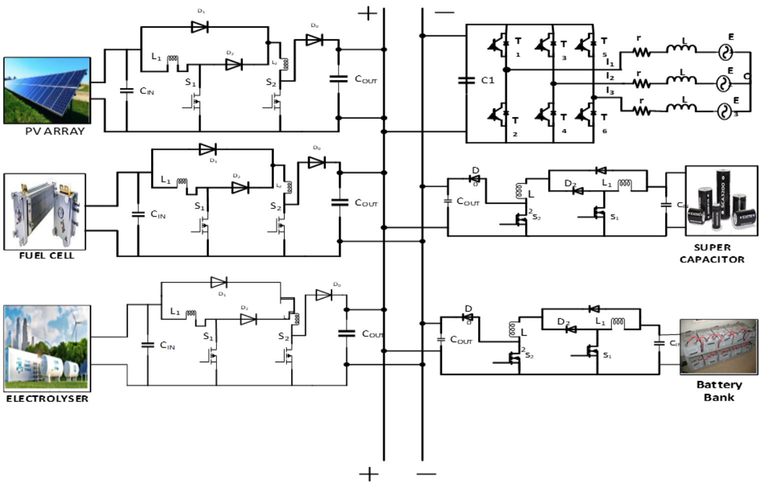


Figure 1. PV based microgrid system under study

3. METHOD

3.1. New high gain DC/DC converter designing equations

The high pulse signal triggers switches S1 and S2, diodes D2 and D0 are inoperative. L1 and L2 start charging from the DC power supply. The characteristic [23] for this process are shown in (1).

$$\left.\begin{aligned} U_{La}(t) &= U_{PV} \\ I_{PV}(t) &= C_{PV}\dot{U}_{PV} + 2I_{La} \\ U_{Lb}(t) &= U_{PV} \\ C_o\dot{U}_o &= I_{CO} = U_o/R \end{aligned}\right\} \quad (1)$$

Using inductor volt-second balance and capacitor charge-balance, (2) can be derived.

$$\left.\begin{aligned} < U_{La}(t) >&= 0 \\ < U_{Lb}(t) >&= 0 \\ < I_{CO}(t) >&= 0 \end{aligned}\right\} \quad (2)$$

The output voltage can be attained in terms of input voltage and the capacitors using (1), (2).

$$U_O = \left(\frac{1+\delta}{1-\delta}\right) U_{PV} \quad (3)$$

The (3) defines the voltage gain of the converter, where δ is the duty cycle. The (4) defines the inductor current ripple. The values of the inductors depend on the input voltage (U_{PV}), the duty cycle (δ), the sample time (T_S), and the inductor current ripple (ΔI_L).

$$2\Delta I_L = \left(\frac{U_{PV}}{L}\right)\delta T_S \rightleftarrows\rightleftarrows\rightleftarrows \quad (4)$$

The output capacitor C_0 shown in (5) can be designed based on capacitor capacity, output voltage ripple peak magnitude (ΔU_0), duty cycle (δ) and sample time (T_S).

$$C_o = \left[\frac{U_o}{2R\Delta U_o C_o}\right]\delta T_s \quad (5)$$

3.2. Proposed MPC based MPPT algorithm performance equations

In (6) and (7) show that for PV current forecasting, three sensors are essential. The sensors are: sampling time (Ts), inductance (L), PV voltage ($U_{pv}(n)$), PV current ($I_{pv}(n)$), output voltage (Uo). Using these sensors, the estimated value of PV current if the switch is inoperative $I'_{PV}(n+1)$ and the estimated PV current if the switch is in on position $I^{*}_{PV}(n+1)$ can be calculated [23].

$$I'_{PV}(n+1) = \left[\frac{2T_S}{L_a}\right] U_{PV}(n) + I_{PV}(n) \quad (6)$$

$$\dot{I}_{PV}(n+1) = \left[\frac{T_S}{2L}\right] [U_{PV}(n) - U_o] + I_{PV}(n) \quad (7)$$

Positive sequence and negative sequence voltage components are notated as U_{dq}^{+}, U_{dq}^{-}. The (8) discloses the two sequence components. The sequence components of current are notated as I_{dq}^{+}, I_{dq}^{-}.

$$\left.\begin{aligned} U &= e^{j\omega t} {U_{dq}}^{+} + e^{-j\omega t} {U_{dq}}^{-} \\ I &= e^{j\omega t} {I_{dq}}^{+} + e^{-j\omega t} {I_{dq}}^{-} \end{aligned}\right\} \quad (8)$$

Equations of instantaneous power in direct and quadrature axis coordinate system. The instantaneous real and reactive powers are shown by (9).

$$\left.\begin{aligned} P &= 1.5\, Re(I^{*}E) = P_o + P_{a1} \cos(2\omega t) + P_{a2} \sin(2\omega t) \\ Q &= 1.5\, Im(I^{*}E) = Q_0 + Q_{a1} \cos(2\omega t) + Q_{a2} \sin(2\omega t) \end{aligned}\right\} \quad (9)$$

3.3. Model predictive direct power control with a finite control set

New model predictive direct power control scheme [20] when compare to traditional power in dq coordinate system is more effective. In the αβ reference frame, e'_{α} and $e'_{\beta}$are the two-axis representation of E'. Based on the preceding equation the new instantaneous power's change rate is in (10).

$$\left.\begin{aligned} P &= 1.5\left(\dot{e_{\alpha}} i_{\alpha} + e_{\alpha} \dot{i_{\alpha}} + \dot{e_{\beta}} i_{\beta} + e_{\beta} \dot{i_{\beta}}\right) \\ Q &= 1.5\left(\dot{e_{\alpha}}' i_{\alpha} + 'e_{\alpha} \dot{i_{\alpha}} + \dot{e'}_{\beta} i_{\beta} + e'_{\beta} \dot{i_{\beta}}\right) \end{aligned}\right\} \quad (10)$$

The (11) expresses the rate of change of the new instantaneous power.

$$\begin{cases} \dot{P} = \frac{1.5}{L}\left(e_{\alpha}^{2} + e_{\beta}^{2} - e_{\alpha} u_{\alpha} - e_{\beta} u_{\beta}\right) - \frac{r}{L} P - \omega Q^{k} \\ \dot{Q}^{k} = \frac{1.5}{L}\left(e_{\alpha} e'_{\alpha} + e_{\beta} e'_{\beta} - u_{\alpha} e'_{\alpha} - u_{\beta} e'_{\beta}\right) - \frac{r}{L} Q^{k} - \omega P \end{cases} \quad (11)$$

4. RESULTS AND DISCUSSION

Traditional MPPT algorithms like incremental conductance (INC) [24] often struggle with rapid changes in environmental conditions, resulting in suboptimal power extraction and longer settling times. This drawback can be overcome by utilizing a receding horizon predictive control MPC-based MPPT algorithm [25]. Figure 2 shows the parameters of PV array and Figure 2(a) illustrates the variations in irradiance levels at distinct time intervals. In Figure 2(b), observed the output power generated under the MPC controller, which closely tracks the changes in irradiance. This close tracking indicates efficient power extraction across varying irradiance levels. In contrast, Figure 2(c) presents the output power generated by the INC method. Here, noticeable deviations from the ideal power curve, highlighting the limitations of the INC algorithm under such dynamic conditions. Figure 3, During the BLDC motor's regenerative braking period, it can be observed that real power is fed back to the grid. This feedback increases proportionally with both the load power and wind generation, demonstrating the system's ability to efficiently utilize excess energy.

Figure 4 highlights the crucial role of the fuel cell. When the battery state of charge (SOC) falls below a defined minimum threshold, the fuel cell actively supplies power to the system, ensuring continuous and reliable operation. Similarly, Figure 5 portrays the complementary function of the electrolyzer. When the battery SOC exceeds a pre-determined maximum limit, the surplus energy is directed towards the electrolyzer for hydrogen generation, optimizing energy storage capabilities. The BLDC motor parameters are shown in Figure 6 and the BLDC motor control system proves highly effective in maintaining constant speed, as shown in Figure 6(a). This stability is achieved even under varying torque loads, as illustrated in Figure 6(b). This robust performance demonstrates the controller's ability to adapt to dynamic operating conditions and ensure smooth motor operation. Furthermore, the dual-loop control strategy effectively maintains stable voltage at the grid terminals, even amidst fluctuations in solar irradiance and load torque. This key feature underscores the system's resilience and ability to provide reliable power delivery regardless of external disturbances.

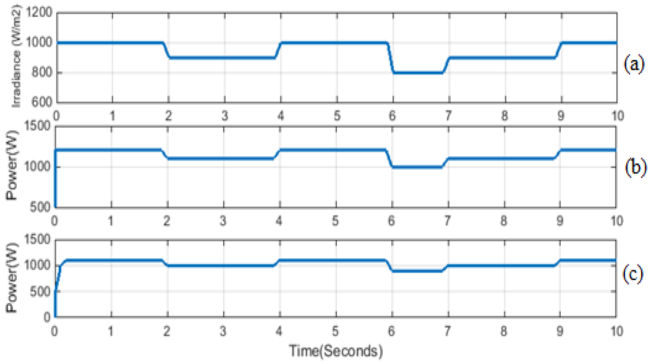


Figure 2. Parameters of PV array: (a) variation of irradiance (W/m^2), (b) receding horizon predictive MPPT output power (W), and (c) incremental conductance MPPT output power (W)

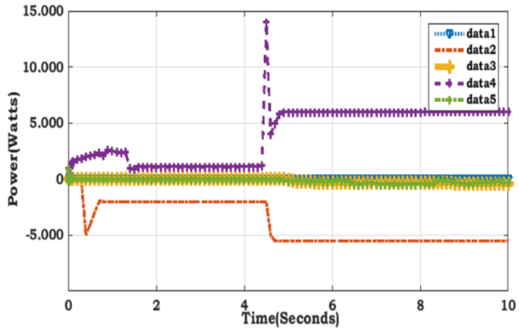


Figure 3. Real power imparting with the grid

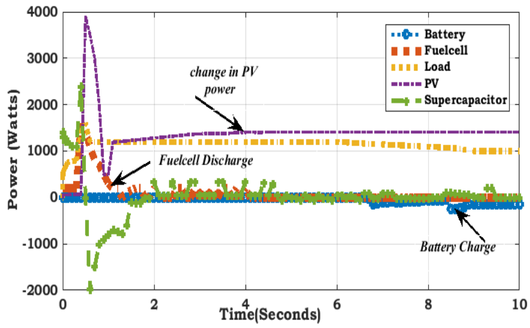


Figure 4. Real power imparting with the battery fuel cell

Figure 7 shows the DC bus parameters and the Figure 7(a) demonstrates that the DC bus voltage exhibits minimal overshoot and faster settling time, indicative of superior control performance. Additionally, Figure 7(b) reveals that the DC bus current waveform exhibits similar characteristics, showcasing the controller's effectiveness in regulating current flow and maintaining system stability. Overall, the presented system performance analysis provides strong evidence for its effectiveness and resilience. The system demonstrates efficient energy utilization, robust control performance, and stable operation under various dynamic conditions. These findings highlight the potential of this approach for future microgrid implementations.

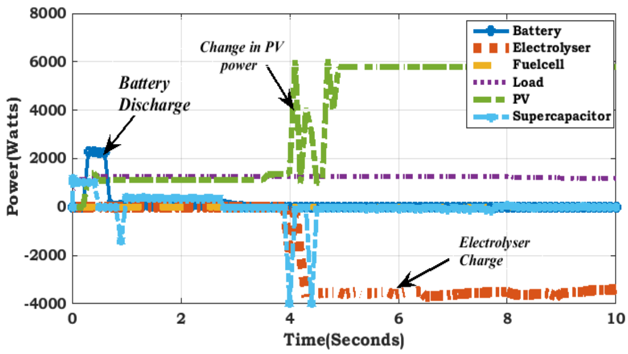
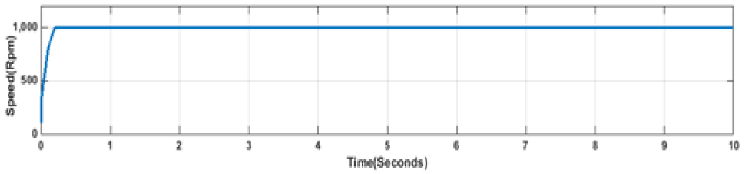
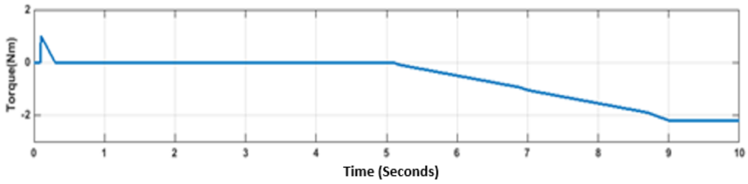


Figure 5. Real power imparting with the battery-electrolyze

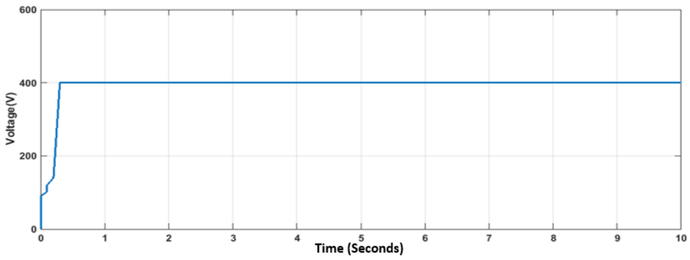


(a)

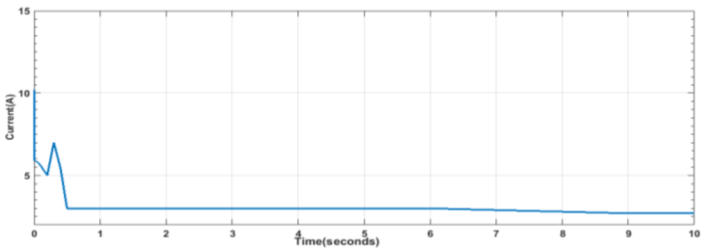


(b)

Figure 6. BLDC parameters (a) speed and (b) torque



(a)



(b)

Figure 7. DC bus parameters (a) voltage and (b) current

4.1. Hardware analysis

Table 1 shows hardware parameters [26] considered to test the proposed system in a real-time environment. Figure 8 shows the hardware test setup schematic arrangement, while Figure 9 shows a laboratory-scale microgrid test bench developed to evaluate the proposed controller. A simulated PV system (powered by the HULKON APS-3005) provides renewable energy, while the battery-super capacitor system seamlessly handles fluctuations and peak demands. The BLDC motor represents the microgrid's variable load, requiring efficient power conversion from the dedicated controllers. Sensor data is continuously fed to the field programmable gate array (FPGA) controller, which implements intelligent algorithms to optimize energy flow, ensuring reliable and stable operation of the simulated microgrid. A 12 V, 7 Ah battery and a 10-mF supercapacitor bank are used Figure 9. Dedicated ADC/DAC FPGA mezzanine cards (FMCs) interface to the FPGA device to transfer sensor signals and obtain converter switching pulses. Analyzing the performance with a constant 2 Nm load, Figure 10 reveals the resulting voltage and current waveforms. Figure 11 reveals how the BLDC motor’s performance changes under different load torques. Notice how the voltage and current waveforms evolve as the load increases from 1 Nm to 2 Nm.

Proposed controller shines in its ability to adapt pulse generation for the DC-DC converter’s output as shown in Figure 12. These dynamic pulses, tailored to the specific load conditions, ensure a constant load voltage regardless of the operating scenario. The programmed logic implementation in the FPGA kit incurs a typical total path delay of around 3.76 ns, allowing the controller to operate at 250 MHz, as opposed to the 100 MHz used in this analysis.

Table 1. Hardware parameters

Parameter	Specification
PV system voltage (V_{pv})	400 V
PV system current (I_{pv})	4 A
DC link voltage (V_{dc})	300 V
Grid voltage (L-L)	415 V
Grid current (L-L)	3 A
Grid inductor (L_f)	20 mH
Grid load (local)	0.5 kW (Max)

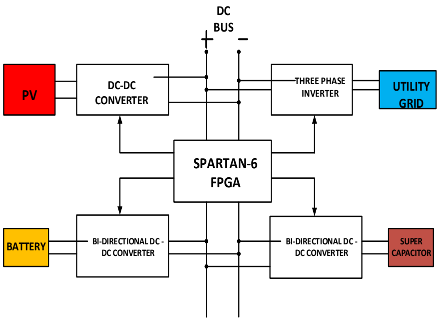


Figure 8. Schematic structure of hardware test setup

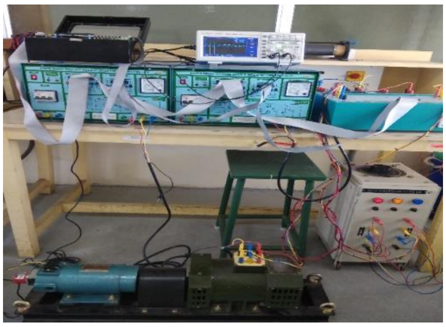


Figure 9. Hardware components setup for real time analysis

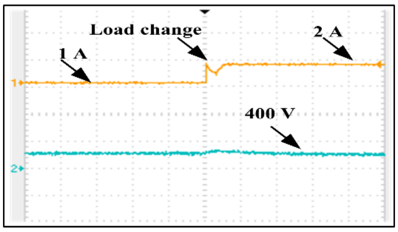


Figure 10. Current and voltage waveforms at variable load condition (Scale: Channel 1: x- axis: 1 A/div; y-axis: 0.5 s/div; CH 2 x- axis: 300 V/div; y-axis: 0.5 s/div)

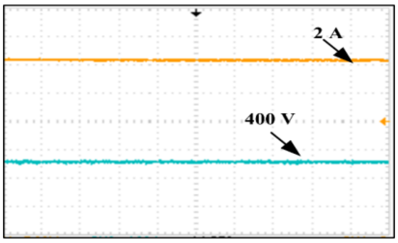


Figure 11. Current and voltage waveforms at constant load condition (Scale: CH 1: x- axis: 1 A/div; y-axis: 0.5 s/div; CH 2 x- axis: 300 V/div; y-axis: 0.5 s/div)

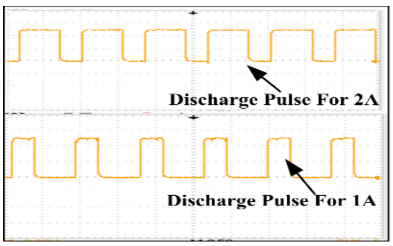


Figure 12. Discharge pulse of DC-DC converter (Scale: CH 1 and CH 2: x-axis: 1V/div; y-axis: 0.5 micro s/div)

5. CONCLUSION

In conclusion, the utilization of RES in traction vehicles provides an eco-friendly and sustainable transportation system. Solar energy is a prominent RES that can be effectively utilized in traction vehicles using a MPC based MPPT algorithm. ESS like batteries and super capacitors play a crucial role in balancing the intermittent nature of solar energy. Additionally, SESS, such as fuel cells and electrolyzers, can be used to enhance the performance of the microgrid. BLDC motors are widely used in traction vehicles due to their efficiency and reliability. However, BLDC motors operate at high voltages, which requires them to be connected to high voltage microgrids. High-gain high-efficient DC-DC boost converter topologies can be used to achieve high voltage levels with improved efficiency. Both simulation and hardware results shown that the designed system is efficient for traction vehicles. Additionally, a model MPC can be used to ensure proper power distribution among the microgrid partakers within the operational constraints. The integration of RES, ESS, SESS, and high-performance power converters enables the development of efficient and sustainable traction vehicles.

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