EVALUATION OF THE HILLCREST HIGH EFFICIENCY INVERTER AND IMPLICATIONS OF ITS USE IN A DRIVE SYSTEM

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1 HILLCREST BACKGROUND

Hillcrest Energy Technologies Ltd. (“Hillcrest”) is a Canadian-based clean technology company developing high value, high performance power conversion technologies and digital control systems for next-generation powertrains and grid-connected renewable energy systems.

Through its technology portfolio, Hillcrest seeks to optimize overall system performance with a wide variety of potential applications, including electric vehicles, grid-tied renewables, charging and storage systems, and high voltage/high power applications such as utility-scale grid.

Systematec GmbH (“Systematec”) is a privately-owned German power electronics engineering and electromechanical component design company servicing the German automotive industry. The company specializes in the development, production, integration and testing of power electronics and electromechanical components for hybrid and electric vehicles. The Systematec team has over 25 years of experience in powertrain component engineering for hybrid and electric vehicles – from discovery and definition phase, through design and manufacturing, to integration, testing and validation.

Hillcrest and Systematec are partners in a Technology Collaboration Agreement with combined technical teams on both continents jointly managing technology development activities that leverage Hillcrest’s electric machine control software and Systematec’s design capabilities to develop high-value power electronics and electromechanical IP for commercialization.

All products and IP developed through this collaboration are owned by Hillcrest.

2 EXECUTIVE SUMMARY

Power converters are a critical component found in nearly every electrical application, including industrial drives, renewable energy conversion systems, and energy storage systems. As global efforts to reduce greenhouse gas emissions accelerate, there is an increasing urgency to electrify systems historically powered from the combustion of fossil fuels. As the world transitions to the use of electric systems powered by clean energy, the efficiency and performance of converters as the main building block of these systems is becoming more important.

In this paper the Hillcrest high efficiency inverter technology (“Hillcrest inverter technology” and “Hillcrest inverter”) is discussed and evaluated. The Hillcrest inverter technology is a new class of Zero Voltage Switching (ZVS) inverter. As experimental results show, in a 3-phase 2-level inverter, the Hillcrest inverter technology reduces inverter losses by up to 70%. This results in a significant reduction in cooling requirements. Since the Hillcrest inverter technology materially eliminates switching losses, it makes higher switching frequencies feasible, which results in better output power quality and lower total harmonic distortion (THD) and smaller DC-link capacitor size. Moreover, the oscillating current on the DC-link is lower, which results in a further reduction of required capacitance on the DC-link and increased power density.

Hillcrest inverter technology also reduces the dV/dt of the main power switches without adversely affecting losses, which helps to protect motor windings and cabling from insulation breakdown and decreases problems traditionally caused by EMI.

These benefits offer valuable system-level advantages, such as increasing drive system efficiency up to 13% as our lab experiments demonstrate, potentially reducing motor size and its cooling requirements, lower torque ripple and increased lifetime of mechanical parts in traction applications, as well as better power quality and reduced sizing and cost for both CAPEX and OPEX. These system-level advantages open a wide range of possibilities and broaden the potential field of applications.

3 INTRODUCTION TO POWER CONVERSION AND LOSSES

A single leg of the most common industry topology, a conventional two-level converter, is shown in *Figure 1*. This converter synthesizes reference output voltage by switching between -$V_{DC}/2$ and +$V_{DC}/2$, as illustrated in *Figure 2.*

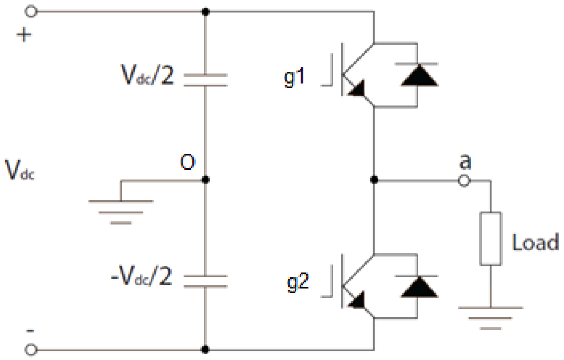


Figure 1. A leg of a converter

If the switches were ideal, there would be no losses, and the output power would be equal to the power drawn from the DC-link. However, power switches are not ideal, they have some conduction resistance, and they cannot switch instantly from one state to another. The conduction resistance creates conduction losses when a switch is on. The transition overlap between voltage and current generates switching losses. *Figure 2* shows these losses on the waveform.

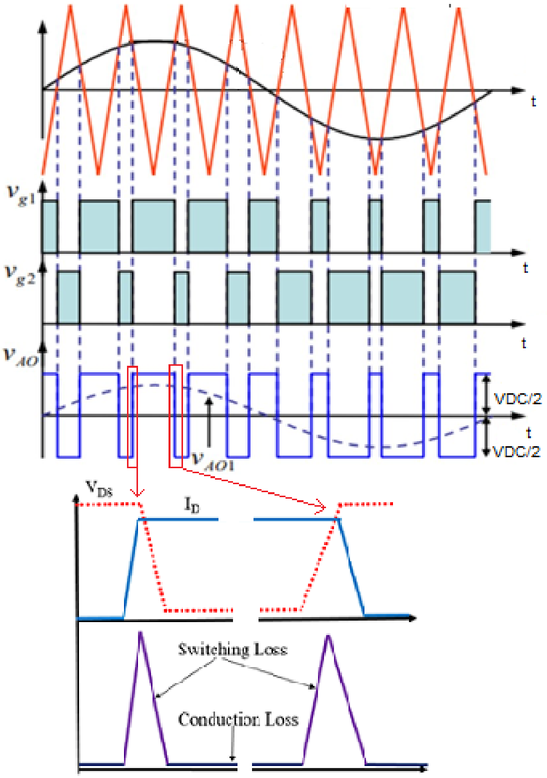


Figure 2. Operation principal of a half-bridge converter and generated losses

To address conduction losses, technologies based on Si, such as super junction MOSFETs, have been developed. In recent years, low conducting resistance switches have also been introduced using the wide-band gap materials SiC and GaN. Wide-band gap devices also reduce switching losses by reducing the transition time, but this in turn has created issues with EMI and dV/dt.

The other way to reduce/eliminate switching losses is by eliminating the current and voltage transition overlap. The well-known approach based on the above theory is Zero Voltage Switching (ZVS). The existing ZVS methods are not suitable for traction applications, as they suffer from issues such as temperature- and load-dependent performance, sensitivity to circuit parameters, and narrow operating range. The Hillcrest inverter technology implements the ZVS method controlled by novel control software algorithms. These algorithms solve the issues found in existing ZVS inverters and enable a wide operating range while maintaining the Safe Operating Area (SOA). These algorithms can be implemented using commonly used microcontrollers. This sophisticated software enables soft switching and materially eliminates switching losses. Therefore, with eliminated switching losses, switching frequency of the converter can be increased and the system can enjoy the benefits of high switching frequency e.g., better performance, lower cost, smaller size and weight.

4 EXPERIMENTAL RESULTS AND COMPARISON

The Hillcrest inverter technology was evaluated through a proof-of-concept (POC) setup. The setup is shown in *Figure 3*. The control system is implemented on a TI C2000 microcontroller. However, it can be implemented on any other micro-controller. The power section is built using a 17A, 1200V Rohm SiC MOSFET, SCT3160KW which has 160mΩ conduction resistance. This switch can also be used to build hard switching converters that produce low dynamic losses because it can be switched very quickly and cleanly.

Each inverter is connected to a 3-phase R-L load with 2.9 Ω resistance and 3.7mH inductance on each phase. The inverters are operated on a controlled cold plate. The cold plate temperature is maintained at 25.6°C. The input voltage and current, as well as the phase voltages and currents are measured using a Teledyne LeCroy Motor Analyzer (MDA8108HD). The efficiency and losses are measured using a Yokogawa Power Analyzer (WT5000).

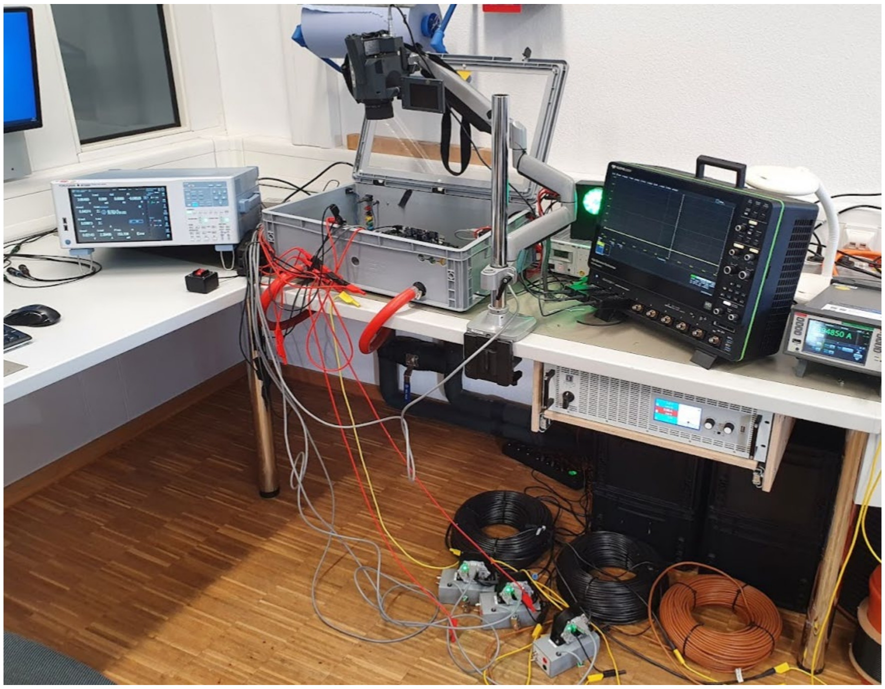
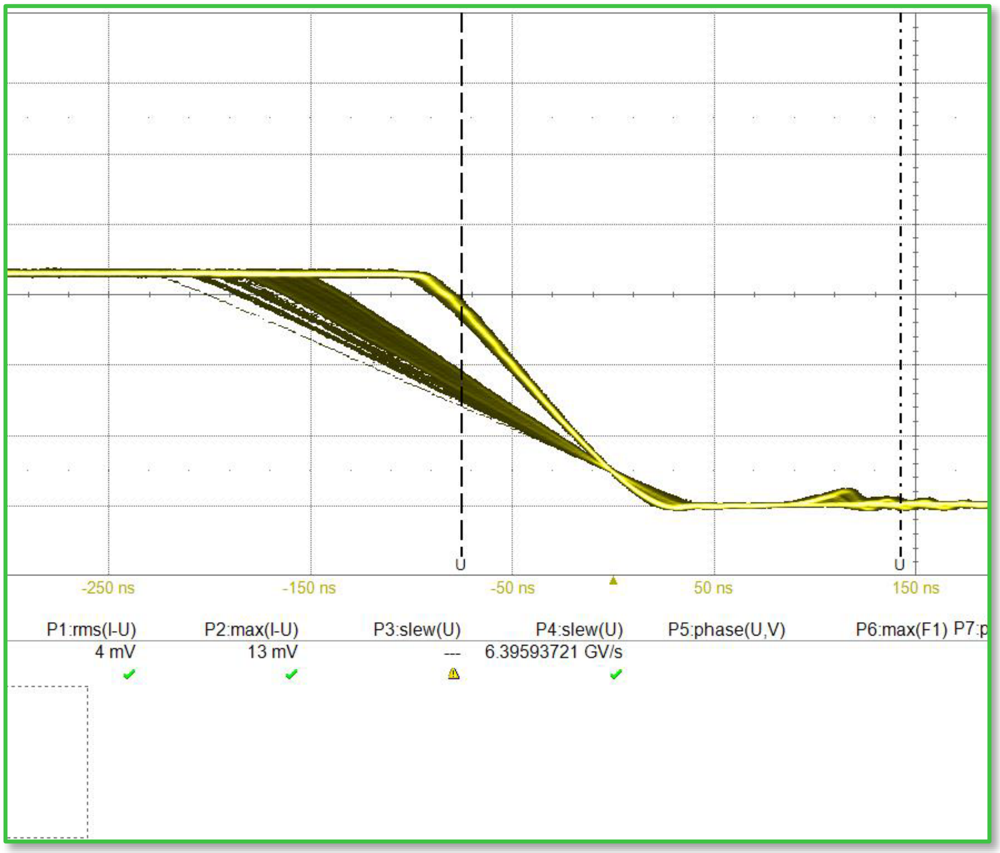


Figure 3. Proof of Concept Test Setup

4.1 SOFT SWITCHING BEHAVIOR

Figures 4 and 5 demonstrate infinite capturing of the switching performance of the Hillcrest inverter, V_{DC}=670V and I_L=10A, turn-on and turn-off. As illustrated, the voltage transition is very smooth without overshoot or oscillation. As the figures show, there are no hard-switching events. The main benefits are:

1. Material elimination of diode reverse recovery current spikes.
2. Reduction of overshoot which results in the protection of devices and reduces ringing significantly and hence EMI.
3. Material elimination of risk associated with Miller Effect.



P1:rms(I-U)	P2:max(I-U)	P3:slew(U)	P4:slew(U)	P5:phase(U,V)	P6:max(F1)	P7:p
4 mV	13 mV	---	6.39593721 GV/s			
✓	✓	⚠	✓			

Figure 4. Hillcrest inverter - soft switching turn-on

Max dV/dt = 6.4 kV/µs

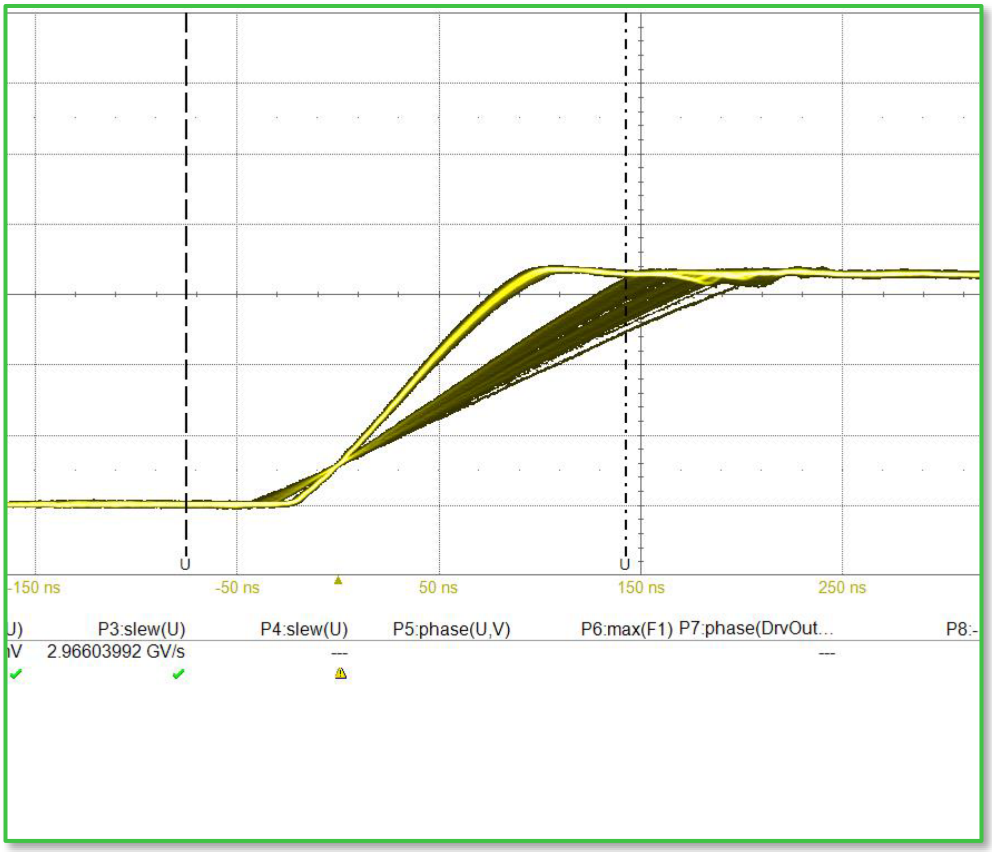


Figure 5. Hillcrest inverter - soft switching turn-off

Max dV/dt = 3 kV/µs

4.2 COMPARISON OF SWITCHING LOSSES

A comparison of switching losses is calculated based on the instantaneous measured switch voltage (VDS) and current through the switch (IS) by multiplying them using the Teledyne LeCroy Motor Analyzer. The system is tested with 470V DC-link voltage under 5A load with 20kHz switching frequency.

In the *Figures 6 through 9* below, “VDS” is the drain-source voltage of the low-side switch, “IS” is the source current of the low-side switch, “IL” is the load current, “GateL” is the gate signal (Vgs) of the low-side switch, “GateH” is the high-side switch gate signal (Vgs), and “Power” is the math function calculating power on the low-side switch by Power=VDS*IS. The utilized FETs (SCT3160KW, single FET per switch) have kelvin connection, hence the gate current is not included in IS.

Figures 6 and 7 depict results for turn-off transition under 5A current toward the converter (negative direction). In the hard switching scheme approximately 65 µJ is dissipated in the switch with peak power of 1.5kW. In this scheme the dV/dt is around 13kV/µs which is quite high and can damage cables and motors. On the other hand, the losses of the soft-switching scheme during transition is amazingly low at approximately 2 µJ. The dV/dt value in this scheme is 1.1kV/µs, which results in longer life of the motor and cables, lower EMI, and lower shielding requirements.

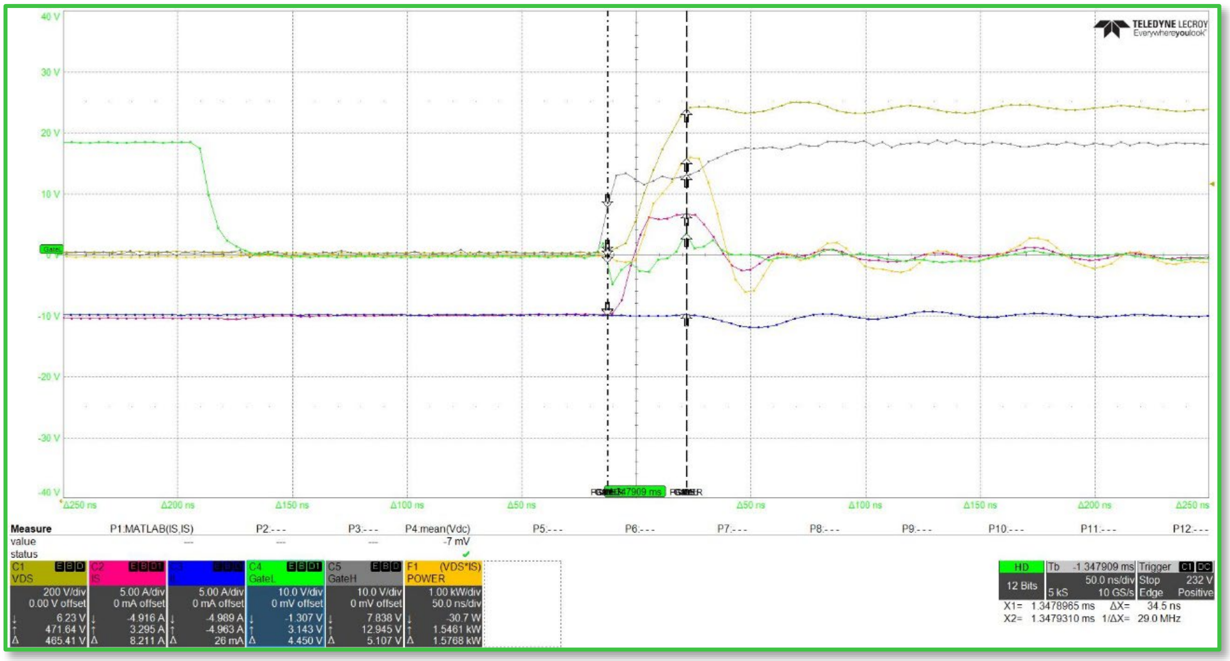
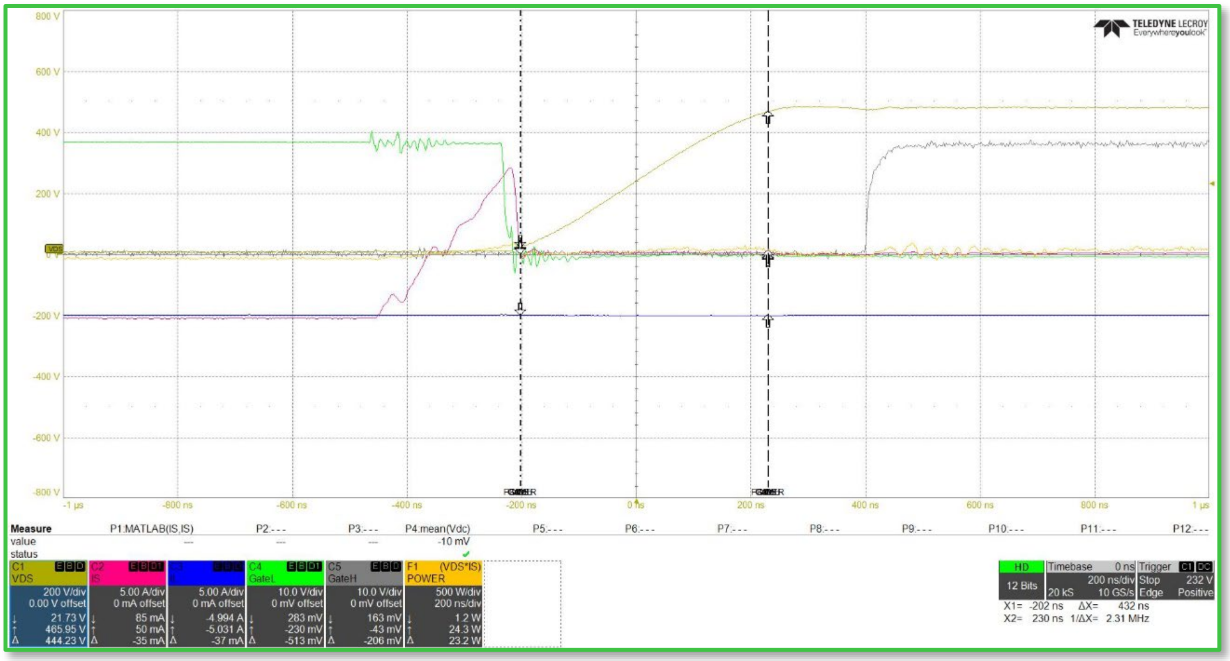


Figure 6 – Hard switching turn-off under 5A inward load current



Measure	P1:MATLAB(IS,IS)	P2:---	P3:---	P4:mean(Vdc)	P5:---	P6:---	P7:---	P8:---	P9:---	P10:---	P11:---	P12:---
value	---	---	---	-10 mV								
status				✓								

C1 VDS	C2 IS	C3 IL	C4 GateL	C5 GateH	F1 (VDS*IS) POWER
200 V/div	5.00 A/div	5.00 A/div	10.0 V/div	10.0 V/div	500 W/div
0.00 V offset	0 mA offset	0 mA offset	0 mV offset	0 mV offset	200 ns/div
↓ 21.73 V	↓ 85 mA	↓ -4.994 A	↓ 283 mV	↓ 163 mV	↓ 1.2 W
↑ 465.95 V	↑ 50 mA	↑ -5.031 A	↑ -230 mV	↑ -43 mV	↑ 24.3 W
Δ 444.23 V	Δ -35 mA	Δ -37 mA	Δ -513 mV	Δ -206 mV	Δ 23.2 W

HD	Timebase 0 ns	Trigger C1 DC
12 Bits	200 ns/div	Stop 232 V
	20 kS 10 GS/s	Edge Positive

X1= -202 ns ΔX= 432 ns
X2= 230 ns 1/ΔX= 2.31 MHz

Figure 7 – Soft switching turn-off under 5A inward load current

Figures 8 and 9 show the performance of hard- and soft- switching schemes in turn-on transition. In the hard-switching scheme, approximately 14 µJ is dissipated in the switch with peak power of 500W. In this scheme the dV/dt is around 15kV/µs. On the other hand, in the soft-switching scheme the losses are lower at approximately 3 µJ. In addition, in this scheme the dV/dt value is 1.1kV/µs.

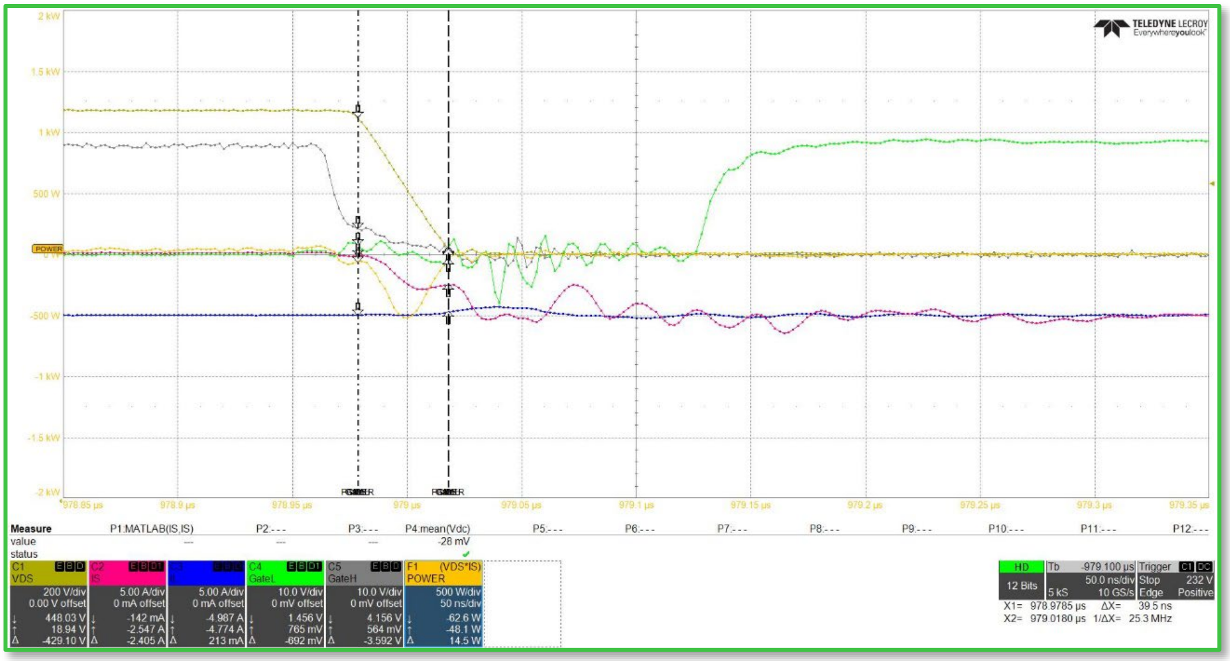


Figure 8 – Hard switching turn-on under 5A inward current

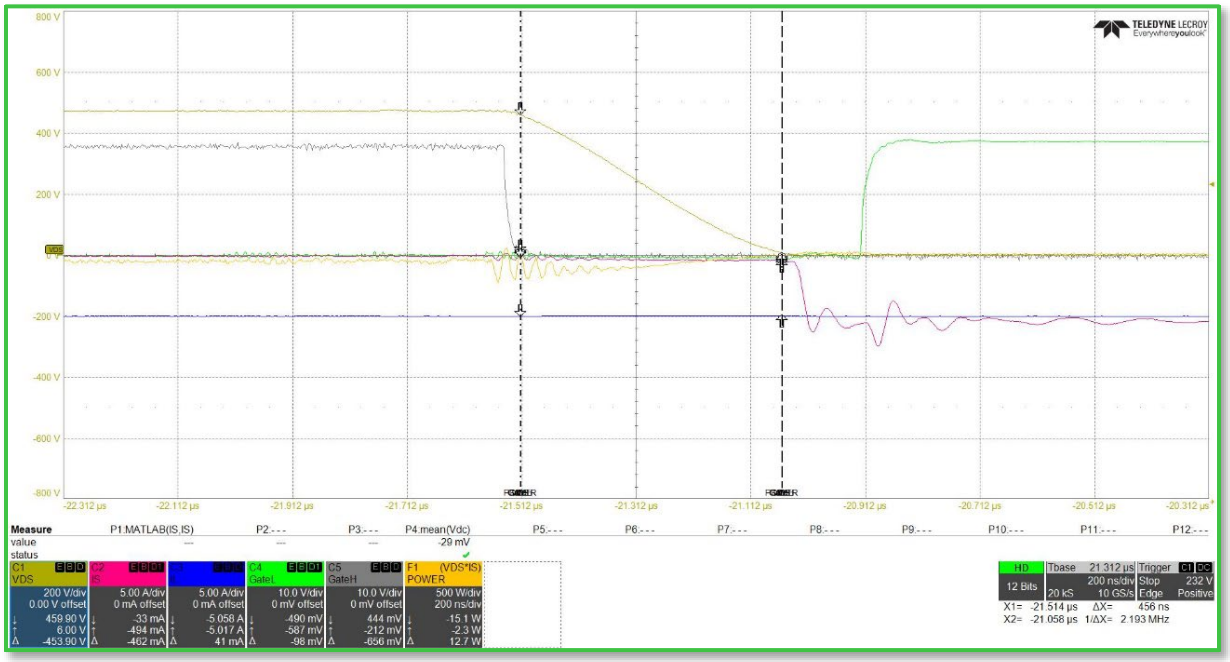


Figure 9 – Soft switching turn-on under 5A inward current

Table I summarizes the comparison of switching losses and dV/dt calculated based on the instantaneous measured switch voltage (VDS) and current through the switch (IS) with 470V DC-link voltage under 5A load with 20kHz switching frequency. The Hillcrest inverter achieves an average of more than 90% fewer switching losses and a roughly 90% reduction in dV/dt compared to a conventional, hard switched inverter.

Table I: Performance of a motor drive based on Hillcrest inverter technology at different switching frequencies

	Hard Switching	***Soft Switching***
Switching Losses	Average 37 µJ	Average 3 µJ
dV/dt	Between 10kV/µs - 18kV/µs	Approximately 1.1 kV/µs

4.3 COMPARISON OF TOTAL INVERTER LOSSES

A comparison of the total inverter losses of the Hillcrest inverter and a conventional inverter with the same power components under various working voltages and 10A load are illustrated in *Figures 10 through 12*. As can be seen from these charts, losses from the Hillcrest inverter change a small amount with frequency. Furthermore, the losses remain nearly constant with voltage increases, generating an additional benefit. *Figures 13 through 15* show loss comparisons under the same voltages with a 5A load. From these results, we can conclude that the remaining losses are mainly conduction losses. Note that the losses shown do not include householding power, which is the same in both cases.

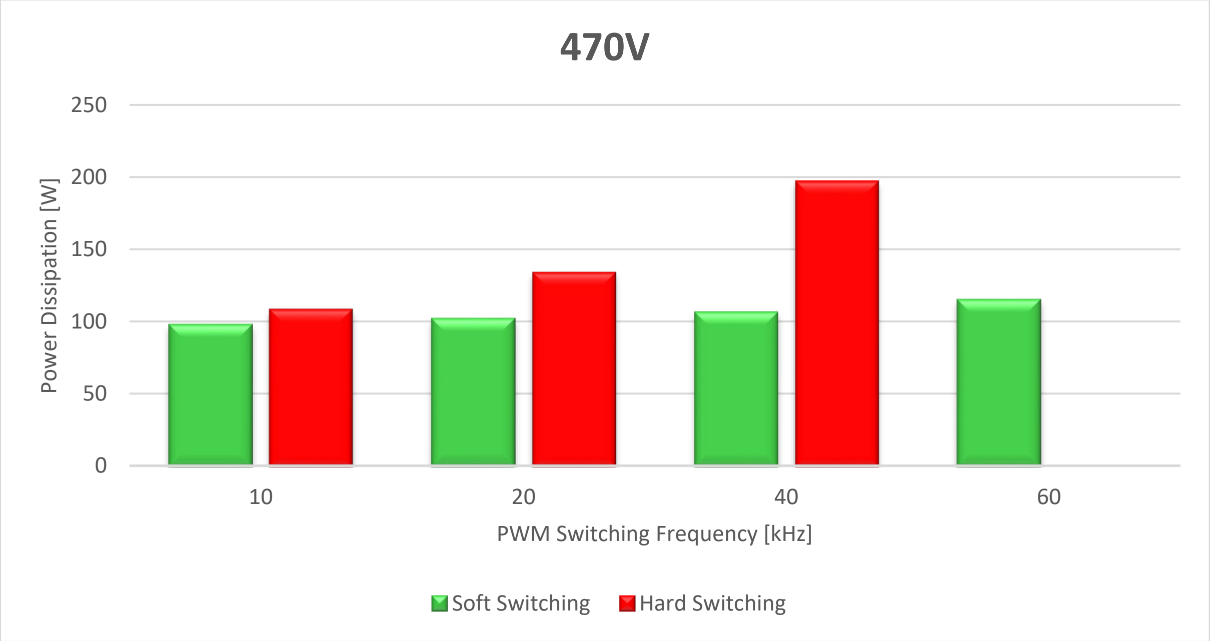


Figure 10. Loss comparison of Hillcrest inverter and conventional inverter in V_{DC}=470V and I_L=10A

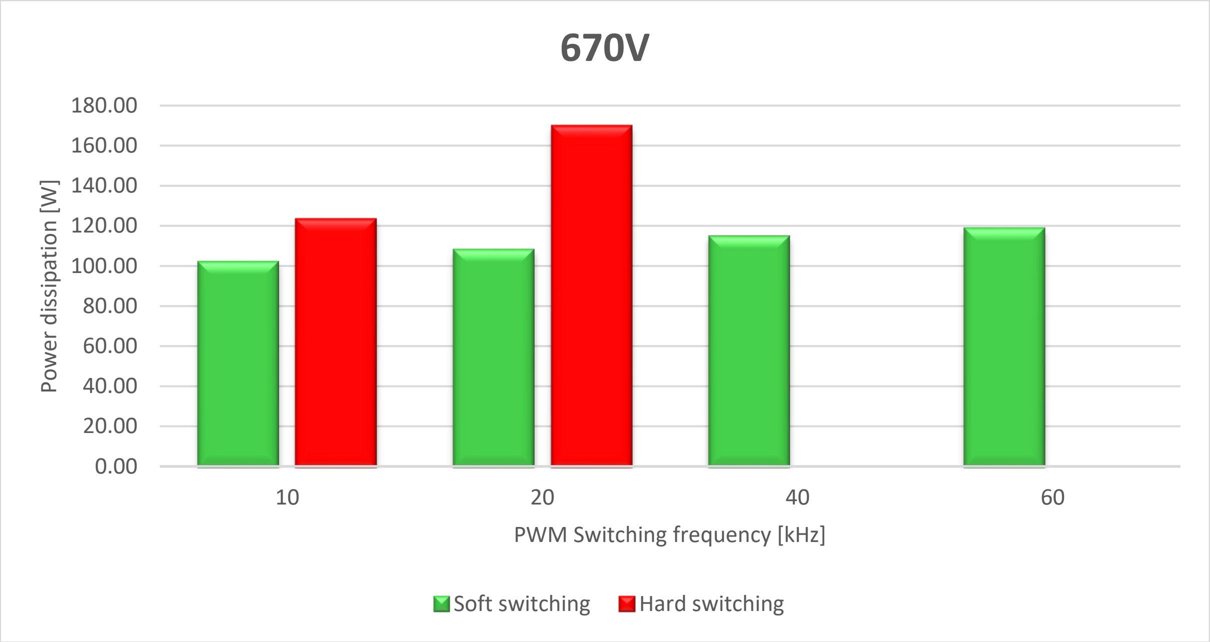


Figure 11. Loss comparison of Hillcrest inverter and conventional inverter in V_{DC}=670V and I_L=10A

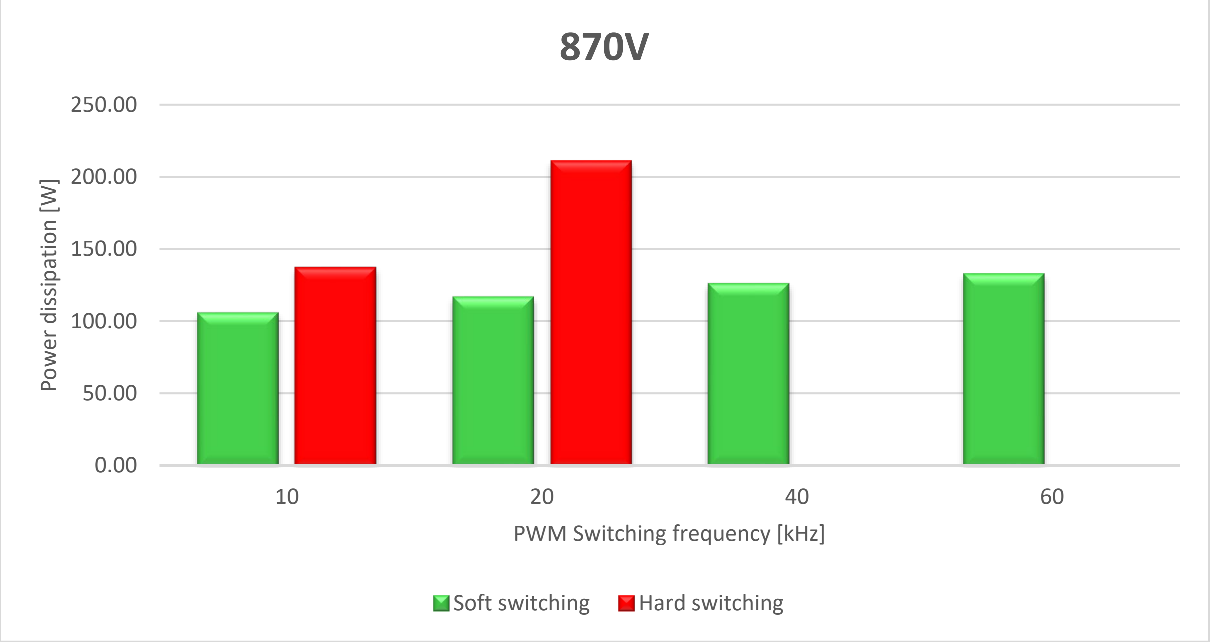


Figure 12. Loss comparison of Hillcrest inverter and conventional inverter in V_{DC}=870V and I_L=10A

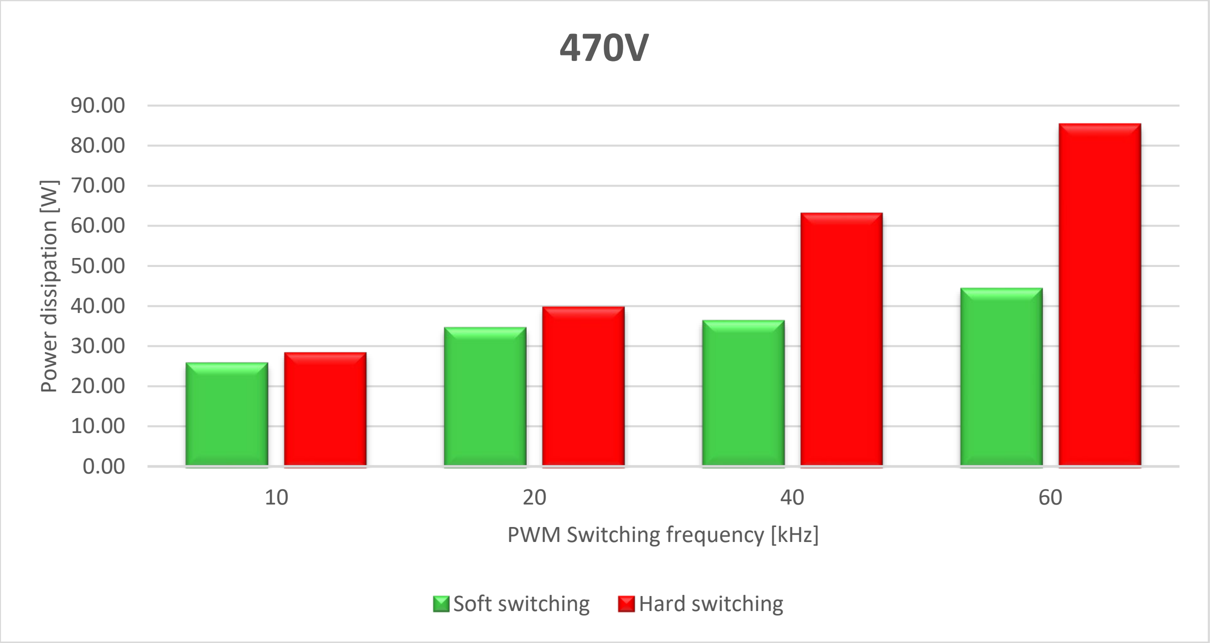


Figure 13. Loss comparison of Hillcrest inverter and conventional inverter in V_{DC}=470V and I_L=5A

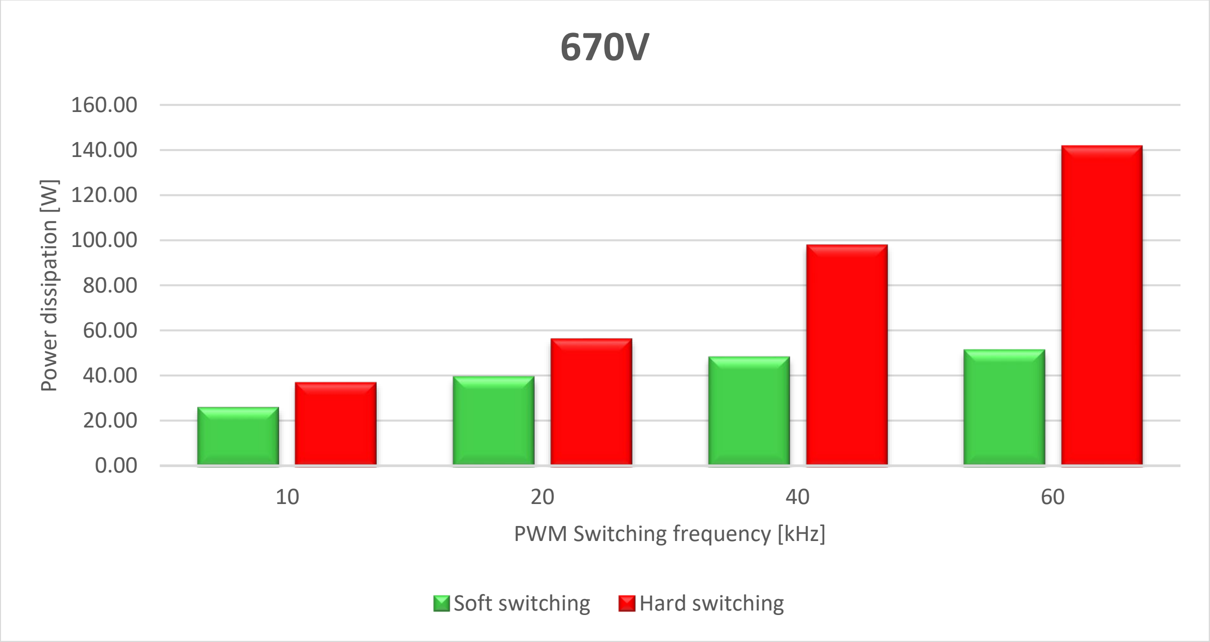


Figure 14. Loss comparison of Hillcrest inverter and conventional inverter in V_{DC}*=670V and* I_L*=5A*

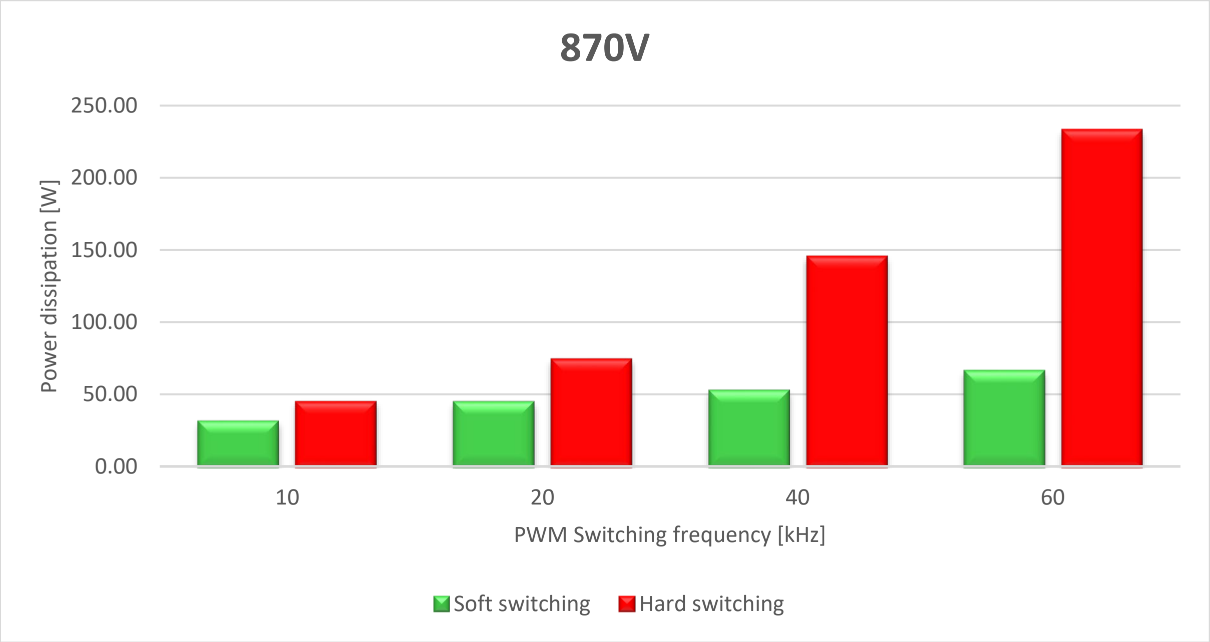


Figure 15. Loss comparison of Hillcrest inverter and conventional inverter in V_{DC}*=870V and* I_L*=5A*

Table II summarizes the results achieved under V_{DC}=870V, I_L=5A. As illustrated, at this condition, the Hillcrest inverter achieves 70% fewer losses when the switching frequency is 60kHz.

Table II: Losses comparison of Hillcrest inverter and conventional inverter @870V, 5A

	10kHz	*20kHz*	*40kHz*	*60kHz*
Conventional inverter losses [W]	44	74	145	232
Hillcrest inverter losses [W]	31	44	52	65
Hillcrest inverter improvement	***30%***	***40%***	***65%***	***70%***

Table III summarizes results achieved under V_{DC}=870V, I_L=10A. It should be mentioned that the Hillcrest inverter was able to perform at a 60kHz switching frequency while it was not achievable with the conventional inverter due to excessive heat. Thus, this information is not included in the table. As demonstrated, at 10A, 20kHz, the Hillcrest inverter produces 44% fewer losses.

Table III: Comparison of inverter losses between Hillcrest inverter and conventional inverter @870V, 10A

	10kHz	*20kHz*
Conventional Inverter losses [W]	*136*	*210*
Hillcrest inverter losses [W]	*105*	*116*
Hillcrest inverter improvement	***22%***	***44%***

The efficiency of the Hillcrest inverter and a conventional inverter are compared in *Figure 16*. As shown, the Hillcrest inverter performance exceeds that of the conventional inverter. The higher efficiency and lower losses achieved by the Hillcrest inverter allows for a smaller cooling system which in turn increases the power density of the inverter. Alternatively, at a same size, the Hillcrest inverter offers a lower junction temperature which leads to increased reliability and lifecycle of the inverter.

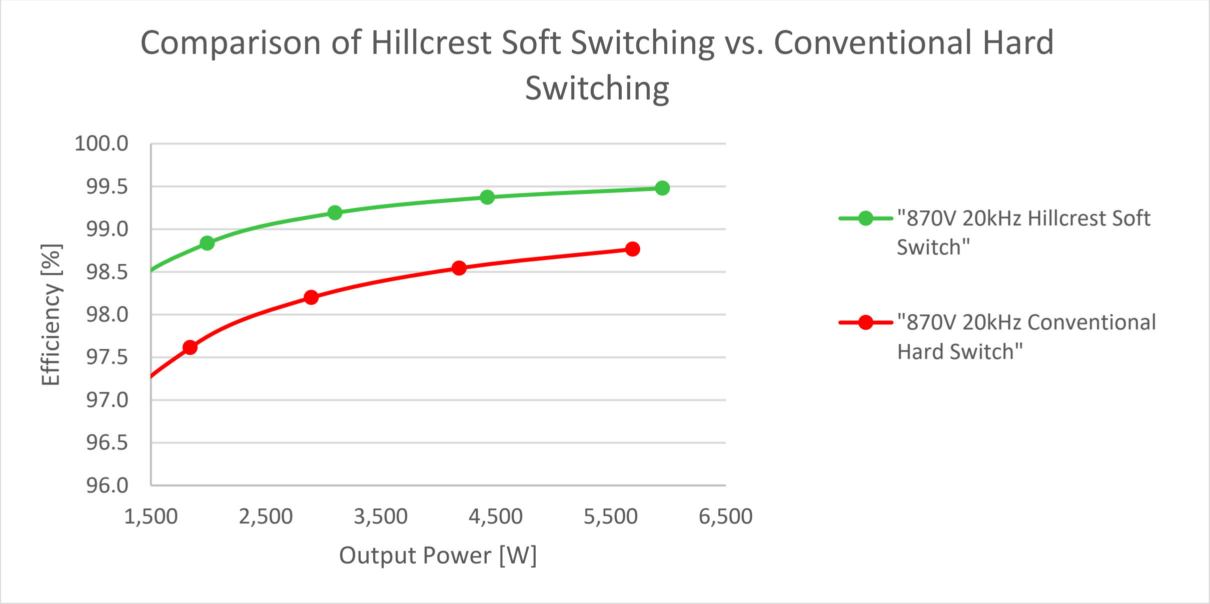


Figure 16. Efficiency comparison of Hillcrest HEI and conventional inverter over various loads.

5 TESTING INVERTER IMPACT ON DRIVE SYSTEM EFFICIENCY

With increasing switching frequency, iron losses of the motor are reduced [1], and pulsating torque will also be reduced which leads to better motor performance. The key means of achieving these advantages is a converter with high-switching frequency and high efficiency capabilities, both of which are offered by the Hillcrest inverter technology. The efficiency measurements of the Hillcrest inverter as a stand-alone unit are shown in the *Figure 17*. As these results demonstrate, the Hillcrest inverter possesses the capability to operate at high switching frequencies and at high efficiency.

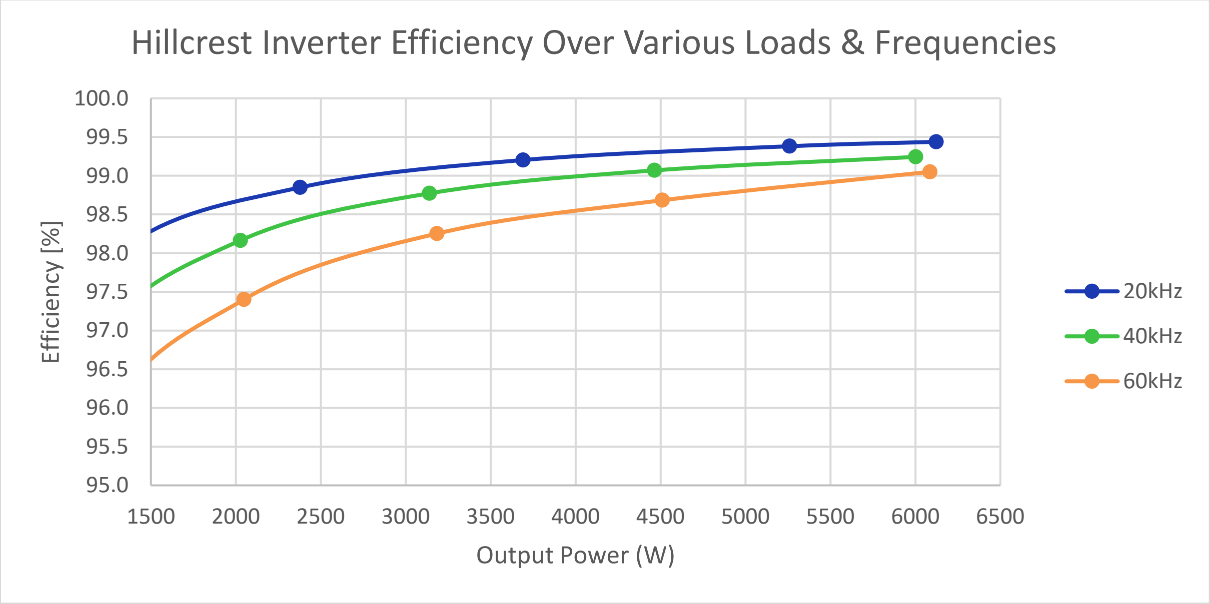


Figure 17. Efficiency of Hillcrest inverter over various loads and switching frequencies.

To demonstrate the effect on the drive system, an experiment is conducted. In this experiment, the test setup is comprised of a mechanically coupled electric machine configuration, which is shown in *Figure 18*. In this configuration, one of the machines acts as a motor, and the other machine acts as a generator. The Hillcrest inverter is used to control a commercial 80kW EV-type machine, manufactured by Renault.

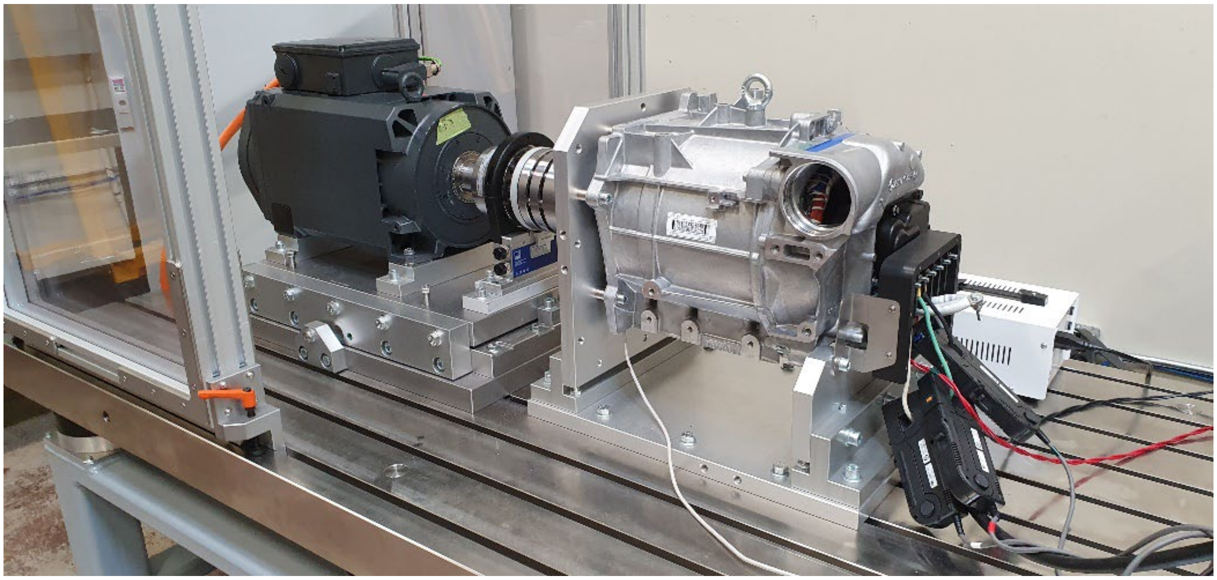


Figure 18. Testbench with coupled electric machines to test traction drive system performance. The right hand-side machine is an EV-type manufactured by Renault

In the test the 10kW PoC hardware with the proprietary Hillcrest inverter technology is used to control the 80kW EV-type machine at a partial-load operating point of 7kW, which is a common operating point when, for example, cruising in an EV at low speed in the city. At this operating point, the efficiency of the machine is lower than the efficiency at the nominal power operating point (80kW), allowing for significant efficiency improvement. Efficiency tests were conducted on the motor to establish a performance baseline at the industry-standard 10kHz switching frequency. The same tests were conducted at 20kHz, 40kHz and 60kHz. Results show a 7% drive system efficiency improvement at 20 kHz and nearly 14% drive system efficiency improvement at 60 kHz. The results are summarized in *Table IV.*

Table IV: Performance of a motor drive based on Hillcrest inverter technology at different switching frequencies

	AC CURRENT RIPPLE ($A_{PK\text{-}PK}$)	***DC CURRENT RIPPLE ($A_{PK\text{-}PK}$)***	***EFFICIENCY IMPROVEMENT COMPARED TO 10kHz***
10kHz	15	7	-
20kHz	8	2	***7.39%***
40kHz	5	1.2	***13.31%***
60kHz	3.2	0.9	***13.9%***

With increased switching frequency enabled by the Hillcrest inverter technology, the overall efficiency of the drive system is increased considerably. Reduced output current distortion is another advantage of switching at higher frequencies. With better output AC current quality, the generated torque is smoother which leads to higher efficiency and longer mechanical life. Furthermore, with higher switching frequency, the current ripple on the DC-link is lower, which results in lower losses on the DC-link, longer life of the DC-link capacitors, and/or reduced size of the DC-link capacitor bank, which results in higher power density, lower cost and extended lifetime.

The full quantitative drive system benefits that can be achieved with the Hillcrest inverter technology are dependent on the specific application, power level, operating voltage and current, as well as customer requirements. Additional testing focused on the drive-system effects of the Hillcrest inverter technology across a variety of applications will be completed as progress is made on the Hillcrest inverter commercial prototypes, aimed at 250kW, 800V. These prototypes are expected to be available for internal testing in the summer of 2022.

6 CONCLUSION

The design methodology of an inverter is iterative. There are several system-level parameters that must be taken into consideration, such as cooling method and architecture, switching frequency, EMI, etc. These parameters are usually opposing, and thus create trade-offs in the final design.

With the Hillcrest inverter technology, we eliminate two major hindering factors - switching frequency and excessive dV/dt. Being able to increase switching frequency without compromising losses on the inverter, the Hillcrest inverter technology allows for reduced losses in electric machines, such as motors and generators, the ability to reduce the size of line filters and DC-link capacitors and improve overall system-level performance.

The impact of the increased switching frequency is studied in a drive system, and it is shown that system efficiency can be increased considerably, and its size can be further reduced by the ability to use a smaller sized DC-link capacitor bank and cooling system. With the material elimination of switching losses and lower dV/dt offered by the Hillcrest inverter technology, switches optimized for lower conduction losses can be utilized. Thus, the Hillcrest inverter technology indirectly helps reduce conduction losses as well. Moreover, being able to reduce dV/dt without compromising losses, enables a reduction in EMI and an increase in the life of motors and cables.

With the Hillcrest inverter technology, a system with high power density, lower cost and weight with better power quality and performance can be realized.

7 REFERENCES

[1] A. Balamurali, et. al "Improved Harmonic Iron Loss and Stator Current Vector Determination for Maximum Efficiency Control of PMSM in EV Applications," IEEE Trans. Ind Electron., vol. 57, no.1, Jan. 2021.