Technical White Paper

How Cycloconverters With GaN Help Optimize Micro Inverter and Portable Power Station Designs

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ABSTRACT

Micro inverters and portable power stations continue to grow in popularity, partly driven by the demand for more sustainable and flexible power solutions. The prevalence of both technologies could increase even more with the recent introduction of balcony-based inverters, which combine micro inverters with a small battery storage system.

This technical white paper outlines a new single-stage converter, known as a "cycloconverter," that makes implementation of the micro inverter and portable power station more efficient and smaller in size while also reducing cost.

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Trademarks

1 Introduction

Power conversion systems in micro inverters are typically designed using a two-stage approach, as shown in Figure 1-1.

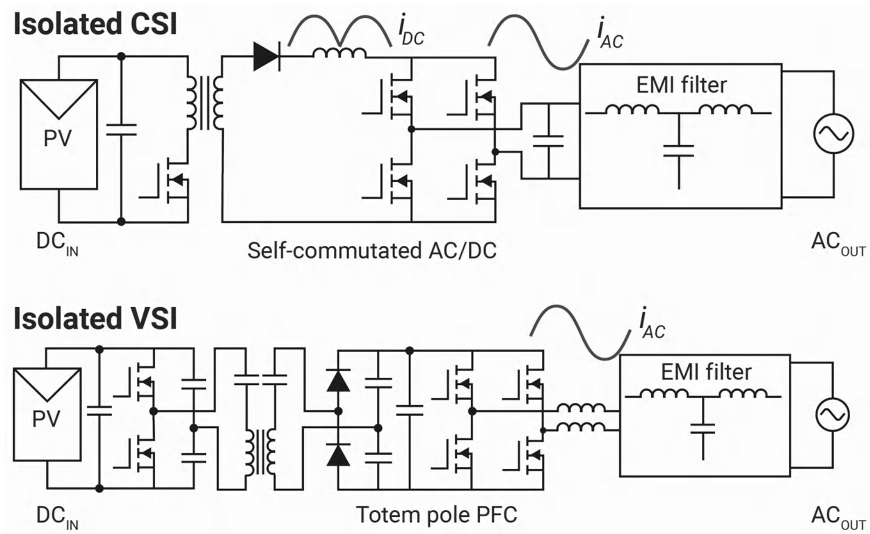

Figure 1-1. Micro Inverter Two-Stage Topologies

In this approach, there is a first DC/DC stage (flyback or push-pull boost stage) followed by another AC/DC-stage (self-commuted AC/DC or totem pole PFC) to convert DC-power available from a PV-panel to an interim DC-Bus very often around $400V_{DC}$. This DC-Bus is then converted to an AC-voltage ($110V_{AC}$..$230V_{AC}$), depending on the grid available in a country or region. Power levels used to be often between 300-400W, however, there are recent implementations with up to 600W per input as well as multi input systems. Micro inverters were traditionally built as unidirectional converters since power flows from thePV panel to AC-grid. Mainly two implementations can be found: isolated current source inverter (CSI) and Isolated Voltage Source Inverter (VSI). The VSI is slightly more complex, but provides better efficiency at comparable power levels. An isolation barrier is needed to isolate the PV-panel from high-voltage AC-connections to avoid electrical hazard when someone touches the panel. Additionally, an isolation barrier is needed to isolate the capacitive behavior of a PV panel from the AC-connections to avoid residual current.

The changes needed to make the isolated DC/DC-stage bi-directional for usage in an energy storage system are to replace the push-pull or flyback stages with bi-directional converters like CLLLC or dual active bridge (DAB) as shown in Figure 1-2. The AC/DC stage remains the same. Either a totem pole PFC/Inverter or a full bridge running in unipolar or bi-polar operation. The differences of AC/DC stages can be studied in the design guide for TIDA-010938 (configurable AC/DC stage).

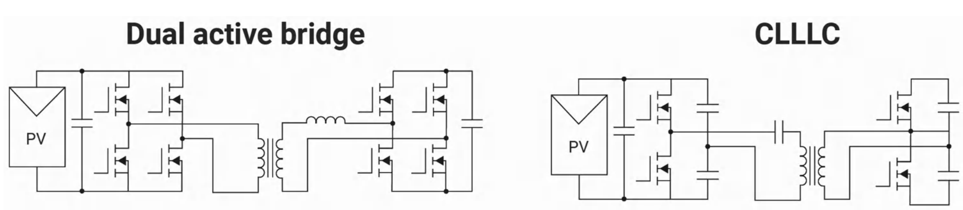

Figure 1-2. Bi-Directional Power Stage Topologies for Portable Power Stations

The operating principle of a dual active bridge is described in reference design TIDA-010054 and for the LLC or CLLLC converter in reference design TIDA-010933. The CLLLC is a resonant converter where the control MCU uses frequency modulation to control the output power. A resonant controller shows good efficiency when operated in a narrow range near the resonant frequency. A dual active bridge is running typically at a fixed frequency and power flow is controlled by the phase shift between the input and output bridges on each side.

Both have advantages and disadvantages. Which one is finally selected depends on the requirements for the system, like input and output voltage ranges.

Two-stage converters are often limited to power efficiencies in the range of up to 96% from DC to AC, especially when operated uni-directional with diodes on rectification stage. From a pure power switch count perspective, two-stage converters can easily end up in 10-12 high-voltage switching elements.

This article presents a new single-stage converter reference design TIDA-010954 that makes implementation of the above end equipment more efficient and smaller in size while reducing cost. The power conversion control algorithm is based on extended-phase shift which lowers the requirements on MCU speed and software complexity.

2 Cycloconverter Fundamentals

A cycloconverter or a cyclo inverter converts a constant amplitude and frequency AC waveform to another AC waveform of a lower frequency by synthesizing the output waveform from segments of the AC supply without an intermediate DC link. For the use case of a micro inverter or portable power station, the input waveform is pure DC. The output is the AC-grid connection. Figure 2-1 visualizes a possible implementation.

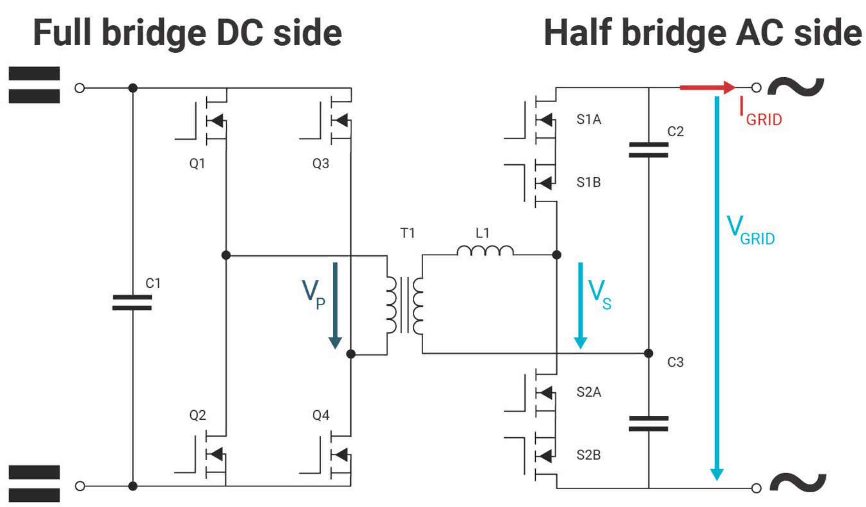

Figure 2-1. Cycloconverter With Full Bride on DC and Half Bridge on AC side

In this example, a full bridge is implemented on the DC side to create the input signal V_P on the primary side of the transformer T1. A half bridge configuration is implemented on the AC side (with capacitive divider) to resemble the segments V_S on the secondary side for AC output V_{GRID}.

For positive output signals, the switches S1B and S2B are permanently turned on. The converter can be seen as a dual active bridge operated in phase shift. Applying PWM to S1A and complementary to S2A, the output voltage and current are resembled. The amount of power transferred is defined by phase shift between V_P and V_S. For negative output voltages, S1A and S2A are permanently turned on. Again, the switches S1B and S2B are forming a phase shifted dual active bridge for negative output voltage and current.

In the reference design TIDA-010954, GaN devices from TI are used to operate the converter at fast switching frequencies to make all magnetic components as small as possible, while not sacrificing efficiency.

Why GaN?

- A cycloconverter is a soft switching topology, which means turn-on losses can be neglected.
- GaN FETs have significant lower turn-off losses compared to SiC or SiFET.
- A GaN device's output capacitance COSS is lower than SiFET. This helps to achieve a wider zero voltage switching range.
- The conduction losses are caused by the device's R_{DSON}. This defines how much loss the converter will finally have.

The devices used on the primary side are the 100V GaN half bridge LMG2100R026 (with R_{DSON} 2.6mΩ). For the secondary side of the 650V GaN device with integrated gate driver: the LMG3650R035 (with R_{DSON} 35mΩ).

3 Design Considerations and Results

Phased shifted dual active bridge converters have good efficiency as long as switches are operating in soft switching. This is difficult to achieve when secondary side voltage is changing, such as a sinus on the AC-side. In TIDA-010954, two methods for phase shift control have been implemented. The control method is explained in following IEEE paper. For heavy power, “Mode II” is implemented around the AC-peak. For light power (AC-slopes & 0-cross of AC signal), “Mode III” has been used. The differences in phase shift control of Mode II and III can be seen in Figure 3-1.

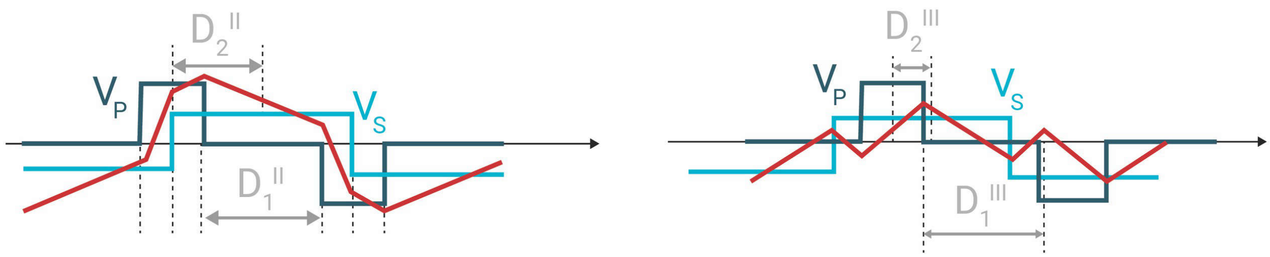

Figure 3-1. Phase Shift Modes and Control Variables

The control variables D_1 and D_2 are used to control power flow and are calculated in the microcontroller (TMS320F28P550), depending on which mode the converter is operating in. It is important to point out that in Mode II the primary voltage V_P is always leading secondary voltage V_S for positive power transfer. For reverse power transfer V_P is always lagging V_S. This is needed to keep the converter in soft switching for heavy power transfer. In Mode III, the primary voltage pulse V_P is fully included inside the second voltage pulse V_S. This is needed to reduce RMS-currents in the transformer and to reduce conduction losses in the switches. In addition to the phase shift control, a frequency control has been implemented to keep the RMS current in the transformer small while the converter is operated in light load. The operating frequency of the converter is varying between 300kHz and 600kHz.

The extended phase shift control with variable frequency modulation runs in a 20kHz (50us) interrupt service routine on the TMS320F28P550 core (150MHz clock speed) and requires less than 40% MCU utilization. This allows to add additional housekeeping routines and run control on a single MCU. Such a low utilization is only possible because the micro controller has advanced features like "configurable logic block (CLB)" to run time critical code in hardware instead of loading the MCU. Additionally, the TMS320P550 has very good peripherals that allow to update PWM in very short time simultaneously for phase shift and frequency modulation. To achieve this on traditional MCUs often an additional FPGA or an ASIC implementation was needed to perform such combined control algorithms.

Using PLEXIM simulator, the design has been simulated to predict proper functionality of the control before HW has been built.

Figure 3-2 shows simulation results for a $40V_{DC}$ input and a $230V_{AC}$ output under two different load conditions (300W and 600W).

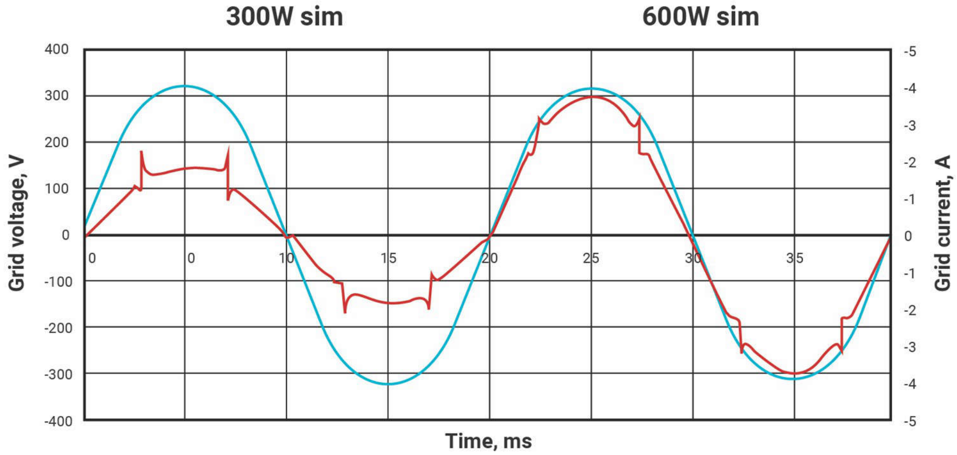

Figure 3-2. Simulation Results for 300W and 600W Load Condition

In the simulation, the mode changes can be seen as little spikes on the current waveform (in red) when the converter changes the mode operation.

The TIDA-010954 has been fabricated on a standard 6-layer PCB. All GaN devices are bottom side cooled and dissipate the power into the PCB without the need for an additional heat sink. Figure 3-3 shows a picture of the converter. The design has a power density of approximately 600W/L. This is about 2x higher than commercial two stage micro inverters available with same power rating today.

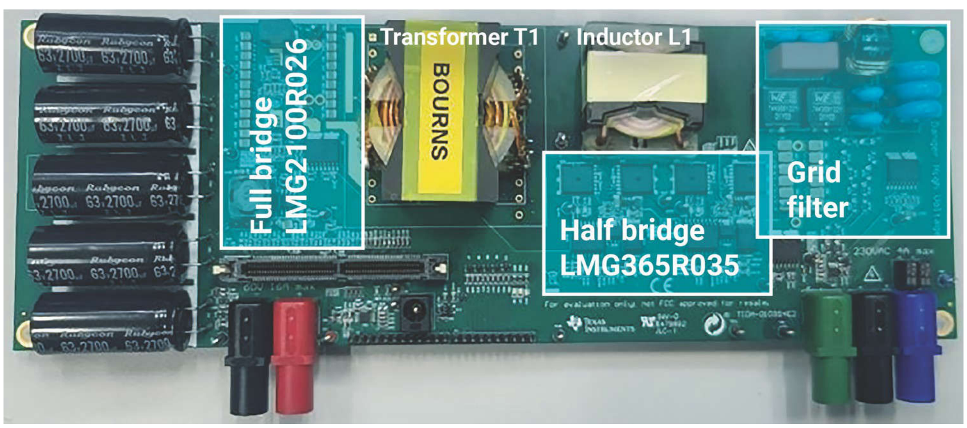

Figure 3-3. Photography of Cycloconverter TIDA-010954

The converter was measured under various load conditions in the lab. Figure 3-4 shows the time domain measurements on the AC-output of the converter.

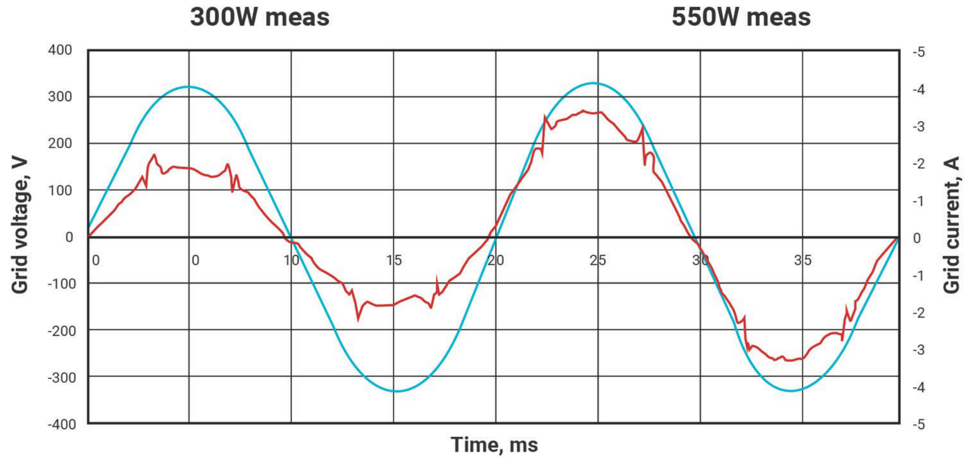

Figure 3-4. Measurement Results for 300W and 600W Load Condition

An excellent match between simulation and measurement is shown inFigure 3-2). The total harmonic distortion measured for full load condition of 600W is only 2.6% and is well below 3% requirement for grid connected micro inverters.

The test under different load conditions is an important performance parameter. The converter needs to achieve high efficiency in full load as well as 50% condition, but also at lighter load. The measured efficiency curve is given in Figure 3-5. The peak efficiency is around 97%.

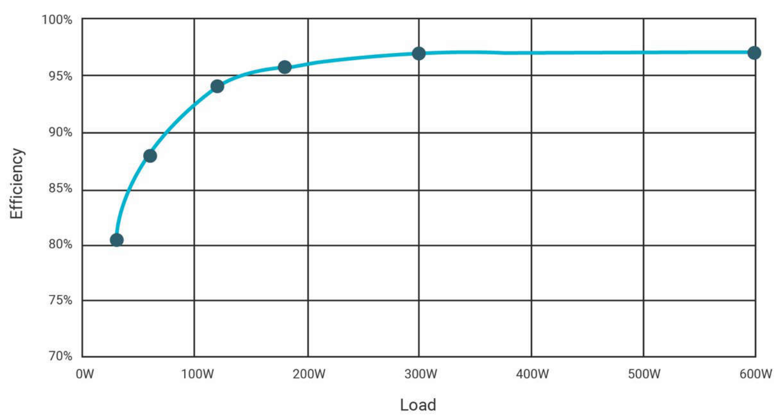

Figure 3-5. Measurement Efficiency Versus Load Condition

To compare different micro inverter designs, a weighted efficiency has been defined. The most common definitions are Euro and CEC Efficiency. The above curve represents η_{EURO} approximately 95.4% and η_{CEC} of approximately 96.4%. This is very high compared to solutions available in the market that are based on traditional two stage topologies.

4 Cost Optimization

System cost is an important consideration for a micro inverter or portable power station. This section gives some insights into how system cost is positively impacted by moving from a SiFET-based two stage converter to a GaN-based single stage converter. The amount of power switches can be reduced in a cycloconverter. The switches used on the DC side need to be rated 170V for push-pull and flyback converters, whereas on the cycloconverter they can be rated 100V for a single panel input. The operating frequency of this new cycloconverters is in the range between 300kHz and 600kHz. That means the magnetic design (transformer and inductors) is much smaller compared to two stage converters. 'Two stage' converters typically operate below 100kHz in order to keep switching losses in the SiFETs small. In addition, the EMI filter to the grid is much smaller for a cycloconverter compared to a full bridge AC/DC. This results in an overall cost reduction. Figure 4-1 illustrates a cost comparison. A push-pull converter is used as 100% reference for relative comparison.

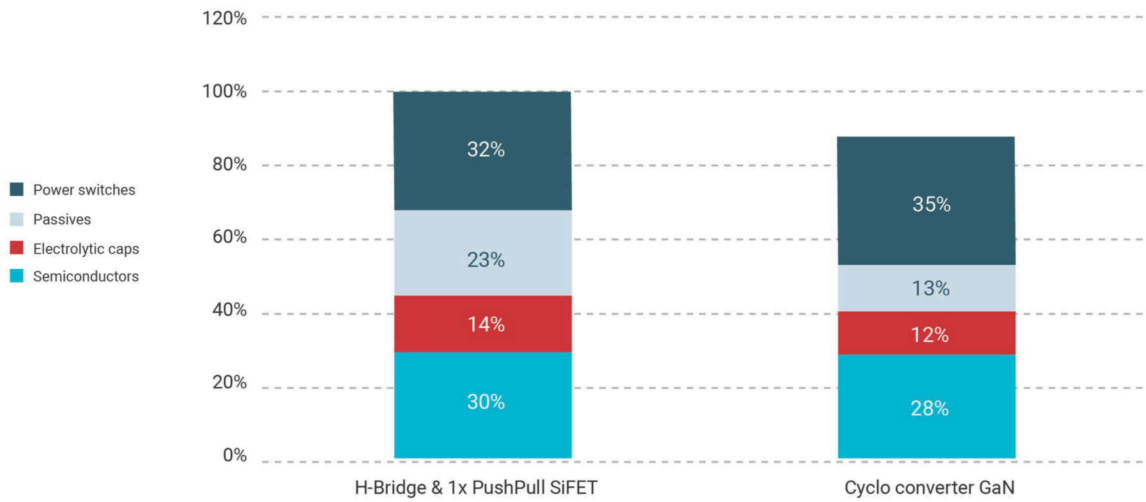

Figure 4-1. Cost Comparison

Cost on power switches increases slightly, whereas the cost on magnetics goes down significantly. As a result, the overall solution cost is down by 12%.

5 Conclusion

This technical white paper outlined a new single stage converter (cycloconverter) that makes implementation of the micro inverter and portable power station more efficient, smaller in size while reducing cost at the same time. The power conversion control algorithm is based on extended-phase shift with additional frequency modulation. This increases the efficiency on mid- and low-output power levels. By using a novel real-time C2000™ MCU the control algorithm can be run with out the need for external FPGA or need for a dedicated ASIC.

6 References

- Q. Yang, J. Yang and R. Li, "Analysis of grid current distortion and waveform improvement methods of dual-active-bridge microinverter", *IEEE Trans. Power Electron.*, vol. 38, no. 4, pp. 4345-4359, Apr. 2023.

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