Applying Power Circulation Theory to More Accurately Measure Power Loss and Efficiency

Temesi Ernö, Sr. Development Engineer - Application & Test, Vincotech Kft.

Abstract

The race is on to push efficiency in power conversion beyond 99%. It is a contest with innovative new topologies running neck-on-neck with standard half-bridge solutions featuring SiC and GaN semiconductors. A wide range of applications requires bidirectional power conversion, and it has to be ultra efficient for everything from solar inverters to UPS and industrial drives that may have PFC built-in or added on. If that remaining 1% loss is to be eradicated, its composition will have to be analyzed in depth to learn why it occurs. The main causes are semiconductors' less-than-perfect static and switching properties. Semiconductors' have to be characterized accurately to quantify these loss factors, but new semiconductor technologies and topologies' unknown or undetected properties skew the data and therefore the accuracy of loss simulation and efficiency calculations. This is why a power converter's performance has to be verified using power conversion efficiency measurements. Direct measurement is by nature a rather more inaccurate method of detecting losses. However, there is a more accurate option, and it is cost-effective to boot. The answer – a way of measuring losses meaningfully so components can be optimized accordingly – is to be found in the theory behind power circulation.

1.   Introduction

Reports about switching power converters reaching or exceeding 99% efficiency have been in the news in recent years. [1][2][3][4]

Efficiency measurement is, by definition, quite inaccurate in determining loss quantity. [5][6]

$$\eta = \frac{Pout}{Pin} = \frac{Pin - Ploss}{Pin}$$

At an efficiency level of around 99 %, a *Pin* and *Pout* measurement that is just 0.1 % off will result in a 10 % error in *Ploss* losses. Such inaccuracy is unacceptable for an engineer seeking to analyze the composition of losses and improve overall efficiency.

Measuring DC power accurately under laboratory conditions is usually not a problem, but AC power measurement is not nearly as easy.

Efficiency and loss measurements in alternating current converters can be far more inaccurate. (Fig. 1)
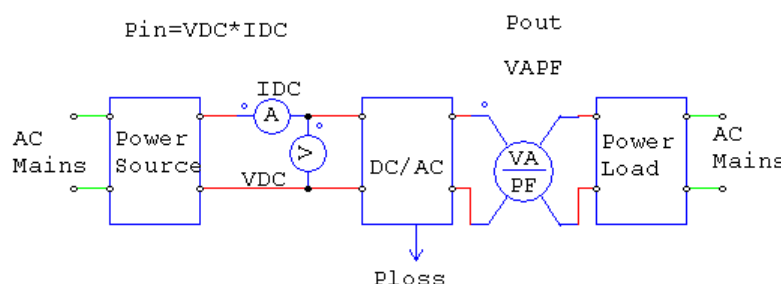

Figure 1:
Measuring power conversion efficiency

What's more, efficiency measurement under varying working conditions (VDC, Pout, and the like) requires a programmable power source and power load.

It gets even more complicated when **Q** reactive power is present in the AC network alongside **P** real power. **S** complex power is the vector sum of **Q** and **P**.

$$S = Q + P$$

P real power can approach zero, for example, when APFC or inverter operation at cosfi=0. In these cases, the definition of efficiency has to be extended so these power converters can be qualified.

$$\eta_S = \frac{S - Ploss}{S}$$

Where η_S is the apparent efficiency derived from the **S** apparent power.

Calorimetric measurements [7] can be accurate enough for *Ploss* losses at low power, but measuring equipment for high-power converters tends to be very expensive.

2.   Measuring loss with the power circulation theory

Ploss losses may be measured directly in a loopback configuration when the power conversion process consists of two stages and the input and output electrical quantities are alike as in this example of a UPS in operation. (Fig 2)
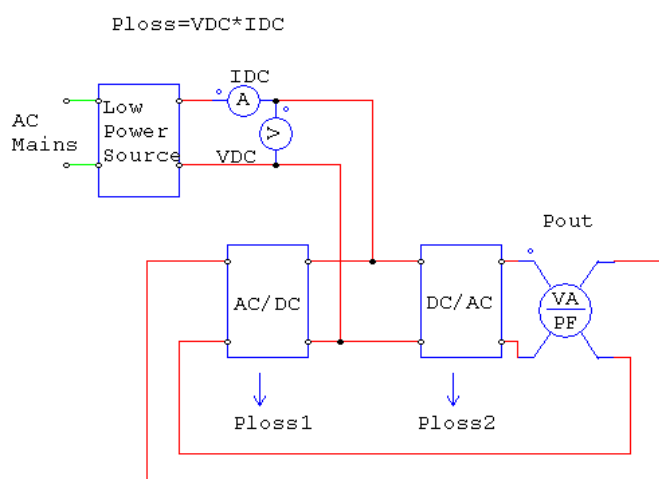

Figure 2:

Measuring power conversion efficiency in an online UPS

The equipment's DC link connects the DC sides of the PFC stage (AC/DC) and output inverter (DC/AC). The AC output side of the inverter is linked back to the input of the PFC stage. The output inverter can operate in AC voltage output mode, while the PFC stage can operate in AC input current regulation mode.

The amount of circulated power can therefore be controlled by the PFC stage. Overall UPS losses are *Ploss=Ploss1+Ploss2*. At a measurement accuracy of 0.1% at the low power source (VDC, IDC), this results 0.1%.loss measurement accuracy

Generally speaking, if one of the converters (AC/DC or DC/AC) has been precisely characterized then the other converter's losses can also be determined with the same accuracy.

The test setup needs a low-power supply to feed in the converters' losses and keep the power circulating in the loop. This method works for PFC, APFC, and inverter testing for single-phase and three-phase systems.

3. Controlling AC power circulation to measure semiconductor losses

In AC-to-AC conversion circuits, semiconductors losses' can be accurately measured and separated from passive components' losses using the AC inductor loopback method. (Fig 3)
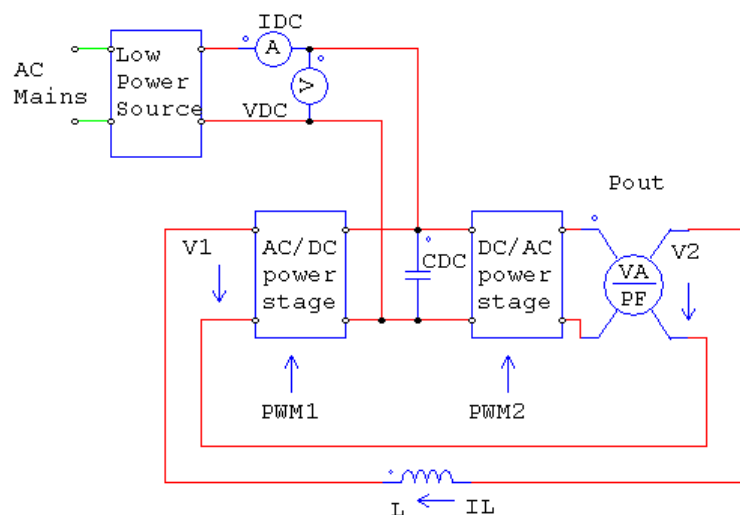

Figure 3:
Controlling the circulating power flow in AC converters

The AC/DC and DC/AC power stages are given PWM1 and PWM2 control signals and generate V1 and V2 voltages on the corresponding AC ports. Generally, the AC/DC and/or DC/AC stages can handle power that flows in one direction only.

If the power stages are both enabled for four-quadrant operation, than the direction of power flow is no longer a factor and any momentary IL current can be triggered with the help of an L control inductor.

In the simplest case, the two PWM signals share the same base and carrier frequencies. A small δ variance in the phase of the PWM base frequencies triggers a VL=V1-V2 voltage difference on the control inductor. Phasor diagrams are shown in Fig 4.
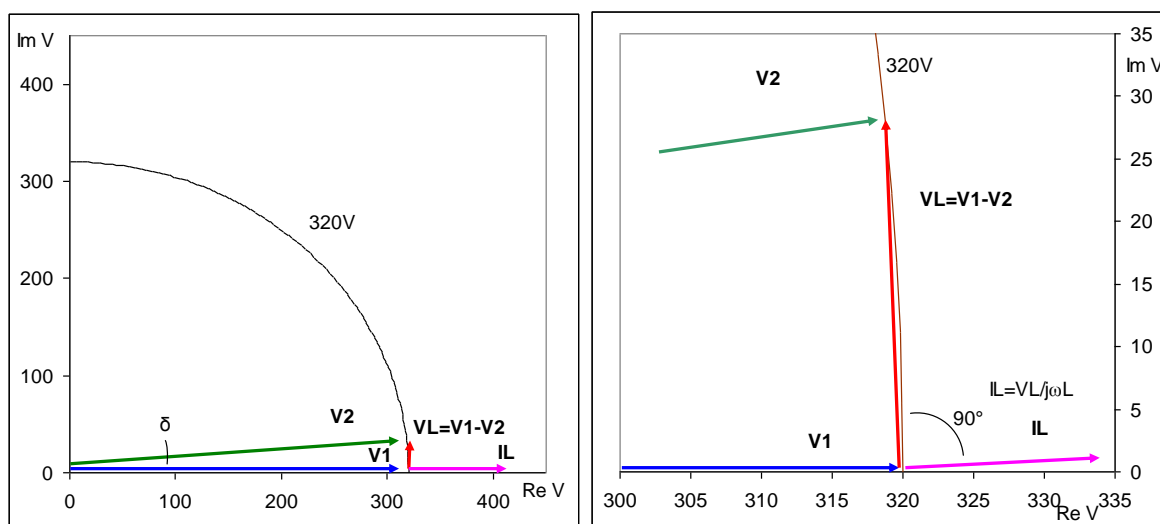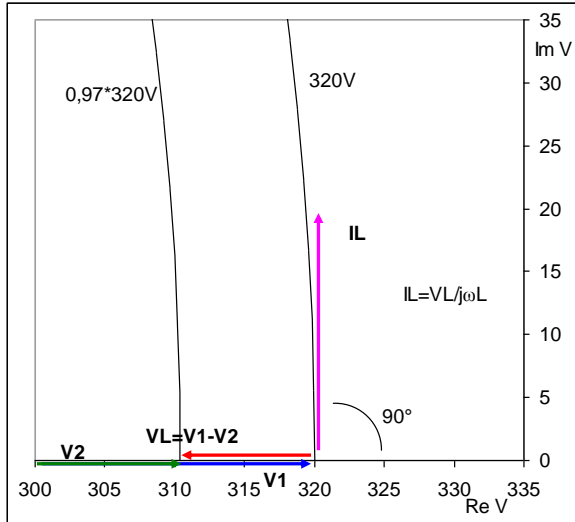

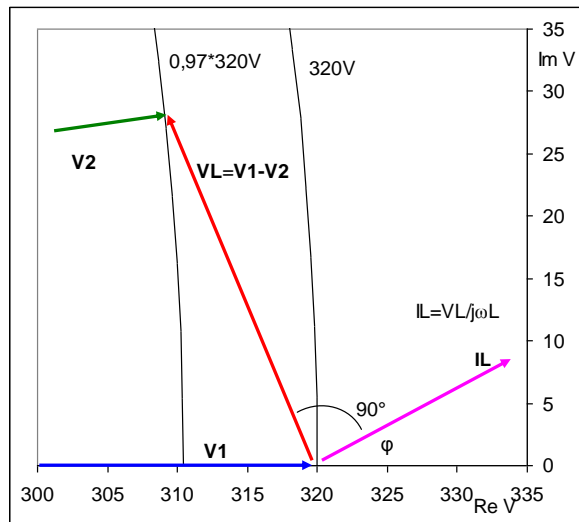Figure 4: Phasor diagrams of AC power circulator for real power flow (full and zoomed)

The VL voltage on the L inductor will develop a current with a value of $IL=VL/j\omega L$.

This current is a nearly resistive load for the first inverter (cosfi ~1) and close to regenerative (cosfi ~ − 1) for the second inverter. Negative δ reverses the power flow.

A minor difference in the amplitude of the base frequency results in a fully reactive current flow between inverters. The first will see inductive loading; the second capacitive loading as shown in Fig.6.

Figure 6: Phasor diagrams of AC power circulation for reactive power

Figure 7: Phasor diagrams of AC power circulation for a general case $(-1 \leq \cos{fi} \leq 1)$

Introducing a small delay in the phase and a small difference in the amplitude of the base frequency triggers a current flow with any $-1 \leq \cos{fi} \leq 1$ between inverters. (Fig.7)

If the PWM generators are synchronized and center-aligned, then the control inductor's current (IL) will be extremely smooth without significant carrier harmonics, and any losses in the inductor will be attributable strictly to copper conduction. Such losses are very easy to measure and calculate under varying load conditions. The DC link load is also significantly reduced, resulting in the graphs for online UPS PFC inverter synchronization shown in Fig.8.
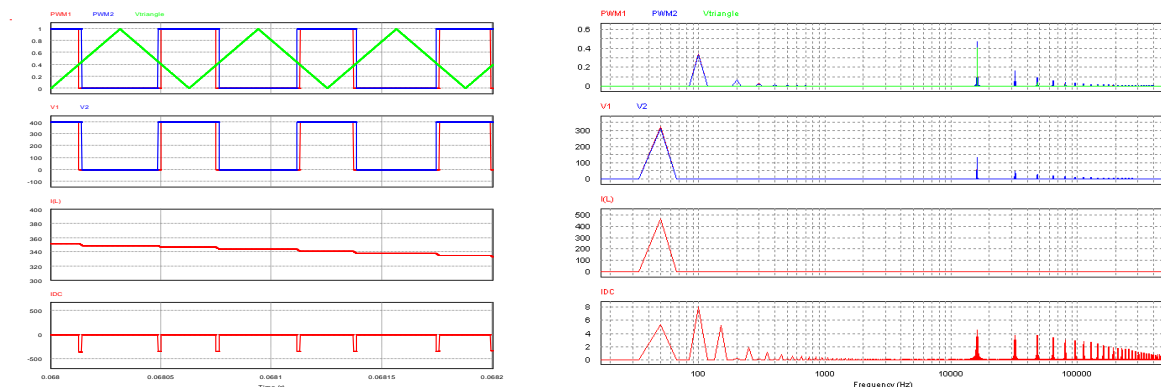

Figure 8: Current waveforms in a three-level inverter system at synchronized PWM (time and FFT diagrams)

4. Three-level power circulation using power modules

An AC power circulator with 2*M209 MNPC three-level, single-phase power modules was built to test this theory. Power modules were connected via a common DC link PCB and a loopback load inductor on the AC side. The test setup is pictured in Fig. 9.
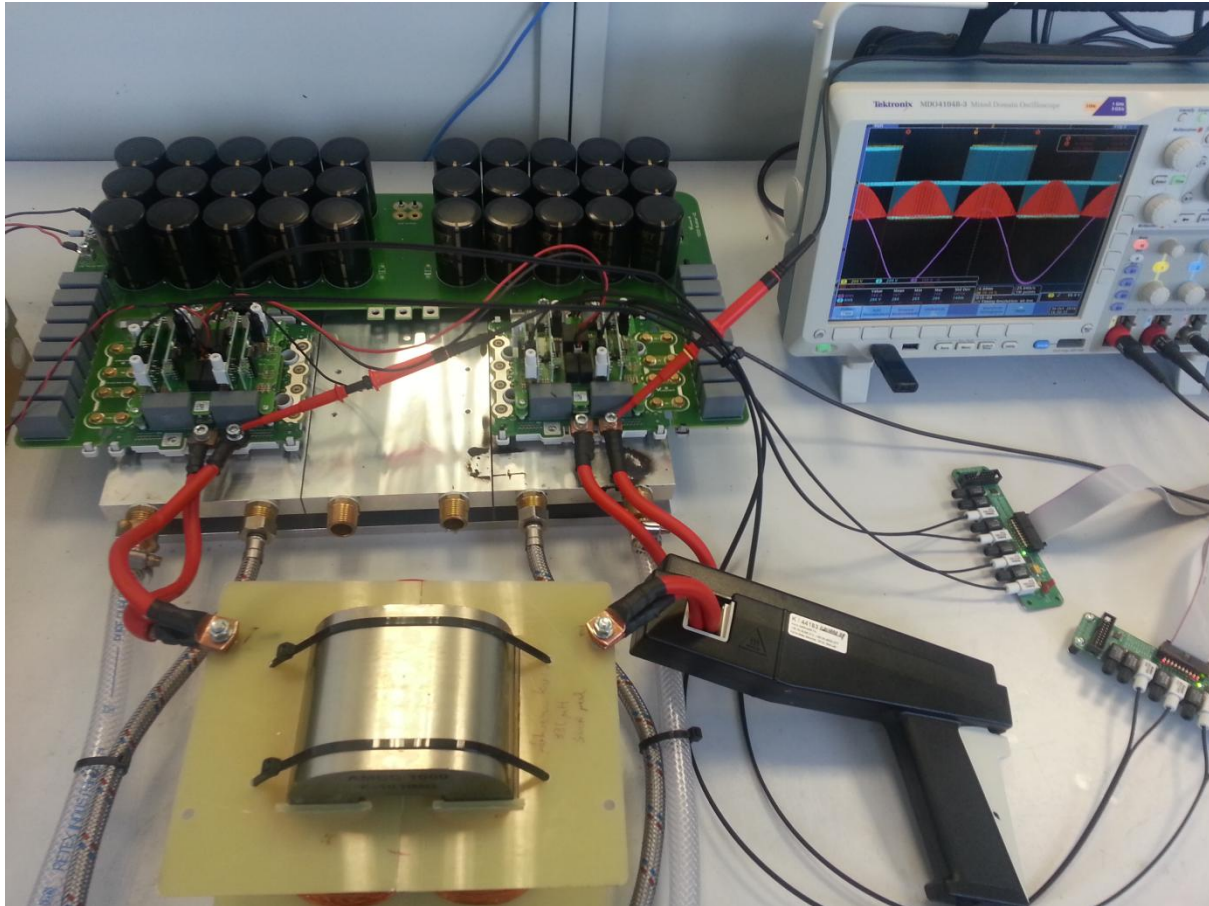

Figure 9: Test setup for AC power circulation

The modules were driven by center-aligned synchronized PWMs as shown in the schematic in Fig 10.
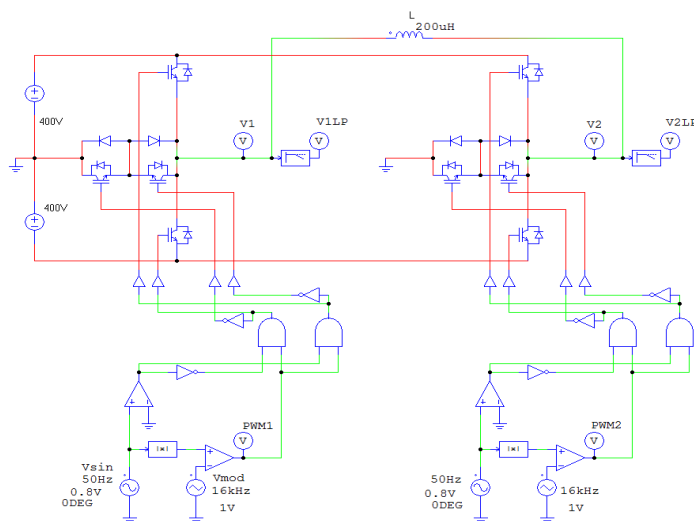

Figure 10: Schematic of the three-level power circulator
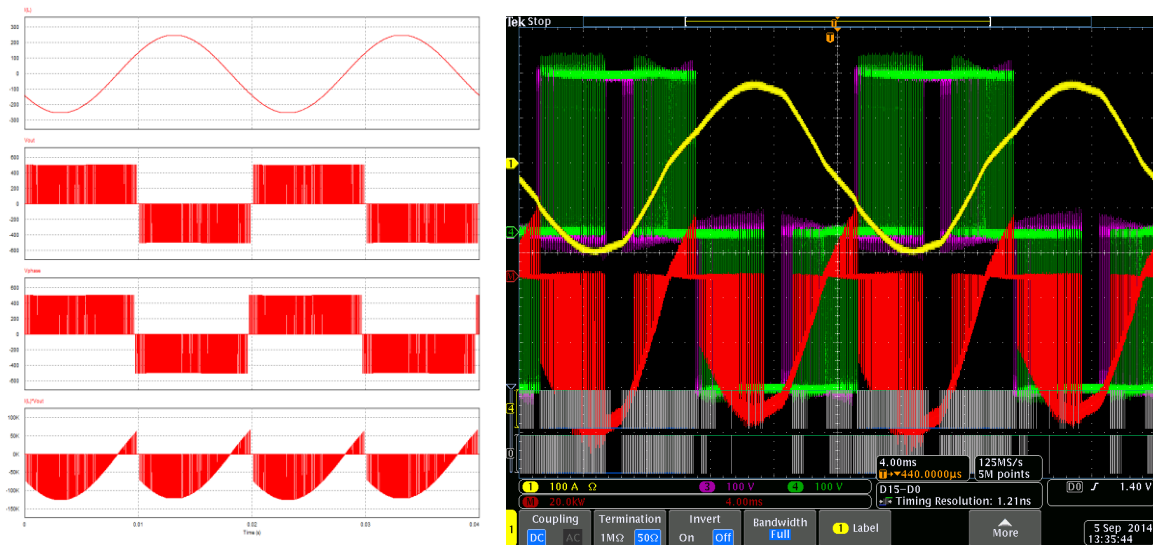
Fig.11 shows the simulated and measured signals.

Figure 11: Simulated and measured signals of the three-level AC circulator

Simulated	Measured
Inductor current	Load current 100A/DIV yellow
Phase voltages	Phase voltages 100V/DIV green, pink
Power	Power 20kW/DIV red

Conclusion:

The theory discussed in this paper was put into practice to measure the η_S apparent efficiency of the DC-AC-DC double conversion process with power flowing in different directions and at different φ voltage and current phase displacement values. The two modules circulated 35 kVA power at less than 1 kW total losses while switching at 16kHz . See Fig.12
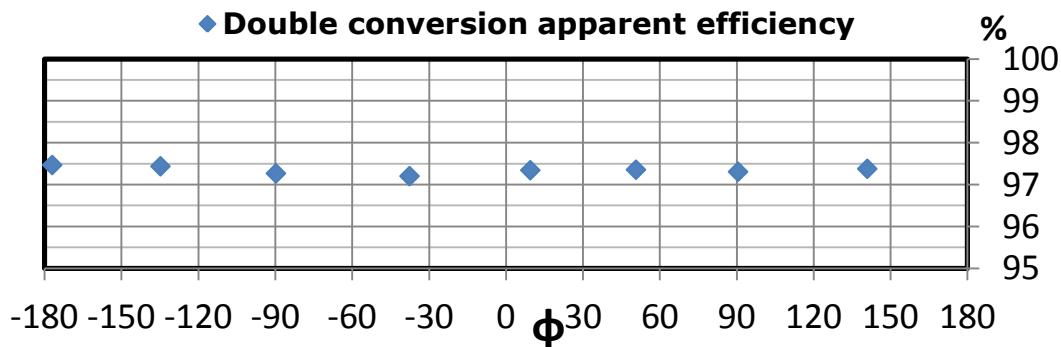

Figure 12: Measured apparent efficiency as a function of phase displacement circulator

Given equally rated components in each functional position of the three-level power modules, the η_S apparent efficiency proved to be independent of the direction of power flow and of the value of the φ phase displacement factor. No power meters were used for these measurements. Power was calculated using the mathematical functions of an oscilloscope equipped with standard probes rated for 2 % accuracy.

5.   References

[1] Fraunhofer claims 99.3 % efficiency inverters for solar PV systems.

http://www.renewableenergyfocus.com/view/2938

[2] The 99 % efficient string inverter has arrived

http://www.pv-magazine.com/services/press-releases/details/beitrag

[3] Optimal Design of a Compact 99.3 % Efficient Single-Phase PFC Rectifier

Biela, J. ; Power Electron. Syst. Lab., ETH Zurich, Zurich, Switzerland ; Kolar, J.W. ; Deboy, G

Applied Power Electronics Conference and Exposition (APEC), 2010 Twenty-Fifth Annual IEEE

[4] 99 % Efficiency True-Bridgeless Totem-Pole PFC Based on GaN HEMTs

 Liang Zhou, member IEEE and YiFeng Wu, member IEEE

Transphorm, Inc. 75 Castilian Dr., Goleta, CA, 93117 USA

[5] Measurement accuracy   Energy values and efficiency for PV Inverter Sunny Boy and Sunny Mini Central

SMA Technical information

[6] How to Accurately Measure Power Supply Efficiency TDK-LAMBDA

www.uk.tdk-lambda.com, March 2012.

[7] Calorimetric Power Loss Measurement for Highly Efficient Converters

D. Christen, U. Badstuebner, J. Biela, and J.W. Kolar

Power Electronic Systems Laboratory, ETH Zurich   IPEC 2010