Power Source / Sink Inverters for high efficient EV Battery Charging and Solar Energy Generation on Three-Phase Utility

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1 Abstract

The race for power conversion efficiency over 99% continues. New innovative topologies are competing with the standard half-bridge topology using SiC and GaN semiconductor technologies. Requirements for high-efficient power conversion both unidirectional and bidirectional are getting standard in the wide field of applications ranging from EV battery chargers, solar inverters and UPS to industrial drives with built-in or separate PFC. In order to be able to make further cutting on the remaining losses of the power conversion, the process requires deep analyses on the loss composition. The main sources of the losses originate from the non-ideal static and switching characteristics of the power semiconductors. The second highest contribution to losses comes from the parasitic of passive components like inductors, transformers and capacitors. Finally, but not with less importance, the applied control strategy plays a definitive role in the overall efficiency of the whole conversion process.

The strategy of Power Sink / Source Inverter (PSI) control shows improvement compared to Voltage Source Inverter (VSI) and Current Source Inverter (CSI) solutions widely used in three-phase systems.

2 State of the art

With more conversion steps in the applications - like EV battery charging - the total efficiency at full load is hardly reaching an overall efficiency of 95.5 %.

Typical distribution of losses in state of the art VSI PFC + LLC three-phase AC to the isolated DC converter for a EV charger using advanced SiC components (*Fig. 1*) looks like 2.9% semiconductor losses (97.1% semiconductor efficiency) and 4.5% total losses (95.5% total efficiency) including the losses of passive components for the three conversions. (P=22.5 kW, ACin=400 V , DCout=450 V)

PFC semiconductor losses	1.3% (0.75% conduction + 0.55% switching)
PFC passive losses	0.6%
LLC semiconductor losses	1.6% (1.3% conduction + 0.3% switching)
LLC passive losses	1%

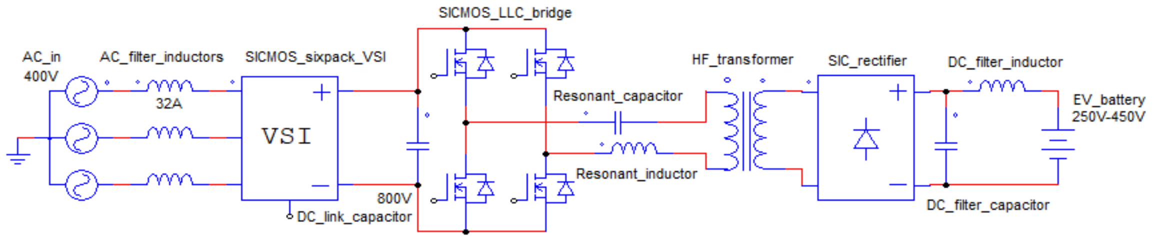


Figure 1: VSI PFC + LLC SiCMOS EV charger

The analysis of losses in the three conversion stages of VSI PFC, LLC resonant inverter and LLC resonant rectifier shows that for higher efficiency both the conduction and switching losses of the VSI PFC and the conduction losses of the LLC stage need to be improved.

The major technical barrier against higher efficiency in PWM systems is the fact that a tradeoff must be made between conduction and switching performance of the used semiconductors, which will lead to a minimized loss at the optimal switching frequency only. However, with extra components and/or control efforts the tradeoff limits can be extended and the way for higher efficiencies can be widened.

Such examples are the single-phase totem pole PFC for low power supplies or the three-phase ANPC topologies for high-power high-voltage solar inverters, in which a mixture of semiconductor technologies allows single-stage switching power converters to reach or exceed the efficiency of 99%.

3 AutoPFC and SRC in SRTE mode

The minimum configuration for three-phase AC to HF isolated DC conversion for an EV charger application should include a rectifier, an HF inverter and a HF rectifier. The simplest control is no control for the rectifier (called autoPFC) and a fix frequency control with 25% fix duty cycle for the SRC (*Fig 2*).

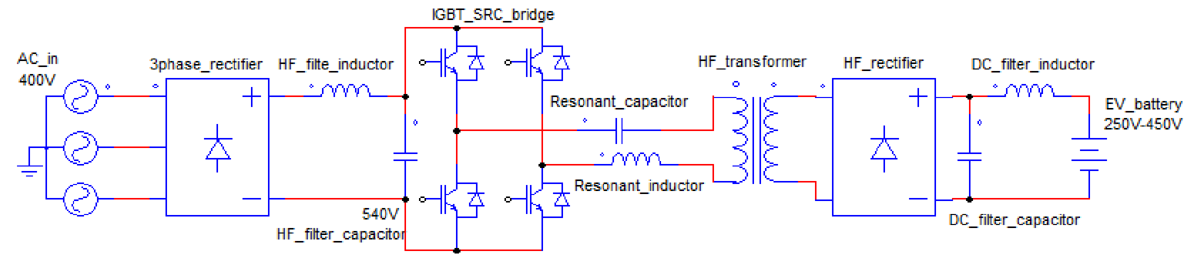


Figure 2: AutoPFC + SRC IGBT

The frequency of the control is selected to be half of the self-resonance of the SRC, so that the converter is working in ZCS (mode SRTE). This allows the selection of low drop semiconductors for both the IGBT and the output rectifier. The input three-phase rectifier bridge is handling 50Hz only, so also standard rectifiers with low drop can be used. The expected efficiency can be calculated from the losses.

As both the input rectifier and the SRC are free from hard-switching, the switching losses on the first estimation can be considered close to zero. Efficiency can be estimated by static losses.

The drop of rectifiers (1 V+1 V) while losses of the IGBTs (1.3 V+1.3 V) are to be related to the same 540V DC average voltage on the HF filter capacitor. The drop of output HF rectifier (1.1 V+1.1 V) are to be related to battery voltage (450 V).

autoPFC (rectifier) semiconductor losses	0.37%
autoPFC passive losses	0.2%
SRC semiconductor losses	0.97%+ (0.48% IGBT + 0.49% HF rectifier)
SRC passive losses	0.8%

The three conversion steps come to > 98.6% semiconductor and > 97.6% total efficiency.

The SRC in fix frequency mode delivers an output current proportional to the input DC voltage.

The three-phase mains rectified voltage has about 15% fluctuation, so the output PF will be close to 1.

The input PF will be limited to about PF>0.95 due to the fact that the three-phase rectifier current can flow in two phases at a time only. This conforms to the PF>0.9 requirement of the standards, but it conforms to THD requirement only under specific conditions of the three-phase net (IEC 61000-3-12).

The system has no energy storage, but the HF ripple of SRC have to be filtered both towards the three-phase input and towards the battery.

If the frequency of the SRC is modulated inversely to the input voltage of the SRC (HF filter capacitor voltage), the current into the battery will be constant in time, so the constant power mode results PF=1 for the battery and PF>0.95 for the three-phase input.

4 CSPFC in EV charger and solar applications

The THD can be significantly improved by injecting a regulated current into at least one phase of the three phases. The idea is based on two laws of physics. The first is the Kirchhoff's law and the second is the law of conservation of energy.

According to Kirchhoff's law the sum of currents of the three-phase mains must be equal to zero in each moment. I1(t)+I2(t)+I3(t) = 0 where I1,I2,I3 are the phase currents of the three-phase system.

On the other hand according to the law of energy conservation, if there is no significant energy storage in the power converter, then the energy entering or leaving the three-phase AC must follow the energy leaving or entering on the DC side. For the battery charger:

U1(t)*I1(t)+U2(t)*I2(t)+U3(t)*I3(t)=VBATT*IBATT(t)=P(t)=VBATT*IBATT=P

where U1, U2, U3 are the phase voltages of the three-phase system.

By controlling the output current so that it is constant in time, that is IBATT(t)=IBATT, the three-phase input power has to be also constant in time. So in case of a symmetric three-phase network it is enough to control the current in one of the input phases at a time. The other two phase currents will follow for a symmetric load. This type of inverter is called Power Sink / Source Inverter (PSI).

There are several methods to select one from the three phase currents to control.

The simplest control can be realized by a single PWM current controller, so that its current is multiplexed into the phase always with the smallest amplitude. The multiplexing is done at 50Hz repetition rate.

The phase currents are synthesized from the controlled current by the half-bridge through the IGBT multiplexer and from the indirectly controlled currents of the rectifiers. The topology for EV charging results in a Current Synthesizing PFC (CSPFC) followed by an SRC controlled for constant power. (*Fig 3*)

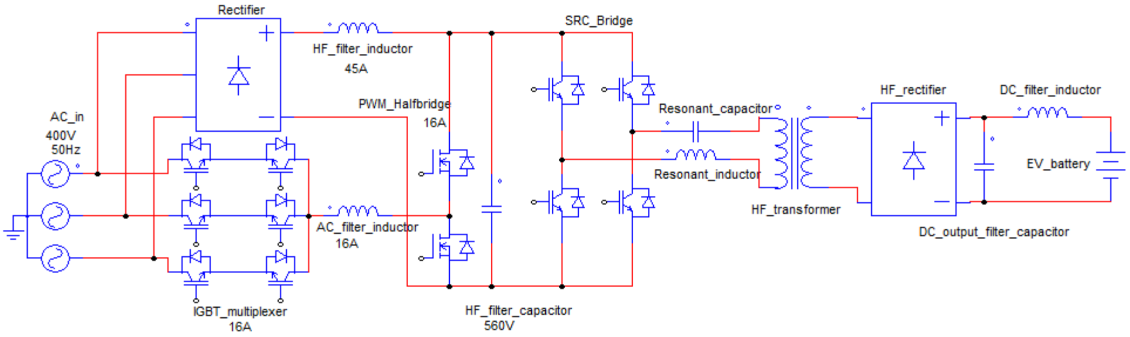


Figure 3: CSPFC + SRC

As the PWM control leg has only ½ of the three-phase currents in amplitude and as the control per phase must be done in only 1/3 of the total time (2* -30 DEG to +30 DEG), the power to be handled by the half-bridge is only 1/6 of the total power through the converter, so the losses associated to the PWM stage are also only about 1/6 compared to traditional three-phase VSI inverter losses.

Distribution of losses:

PFC rectifier semiconductor losses	5/6*0.37%=	0.31%
PFC passive losses	5/6*0.2%=	0.17%
IGBT multiplexer losses	1/6*1%=	0.17%
PWM inverter losses	1/6*1.9%=	0.32%
SRC semiconductor losses		0.97%+ (0.48% IGBT + 0.49% HF rectifier)
SRC passive losses		0.8%

Total losses will come to 2.74% (0.97% PFC and 1.77% SRC), that is, the expected power efficiency is about 97.26% for the three conversion steps. Compared to autoPFC that has a poor THD on the AC side, even though the effort to reach PF=1 on both ports is relative high (8 additional gate control), the overall efficiency is only about 0.4% lower.

It can be stated that the PWM current shaping and multiplexing stage is bidirectional, so if the direct power path through the rectifier is extended to a CSI type IGBT sixpack with LF switching, only then the power flow can be opposite as well. A typical solar energy regeneration system with a boost MPP can be seen on *Fig 4*. The MPP can be of any type of buck, boost or buck-boost hard-switched or resonant, but it must be controlled for constant power. This will ensure PF=1 on both AC and DC ports and close to 100% MPP efficiency. Total power efficiency of the system will be about 99%, as semiconductor efficiency will be dominated by the IGBT sixpack static efficiency and the MPP stage efficiency.

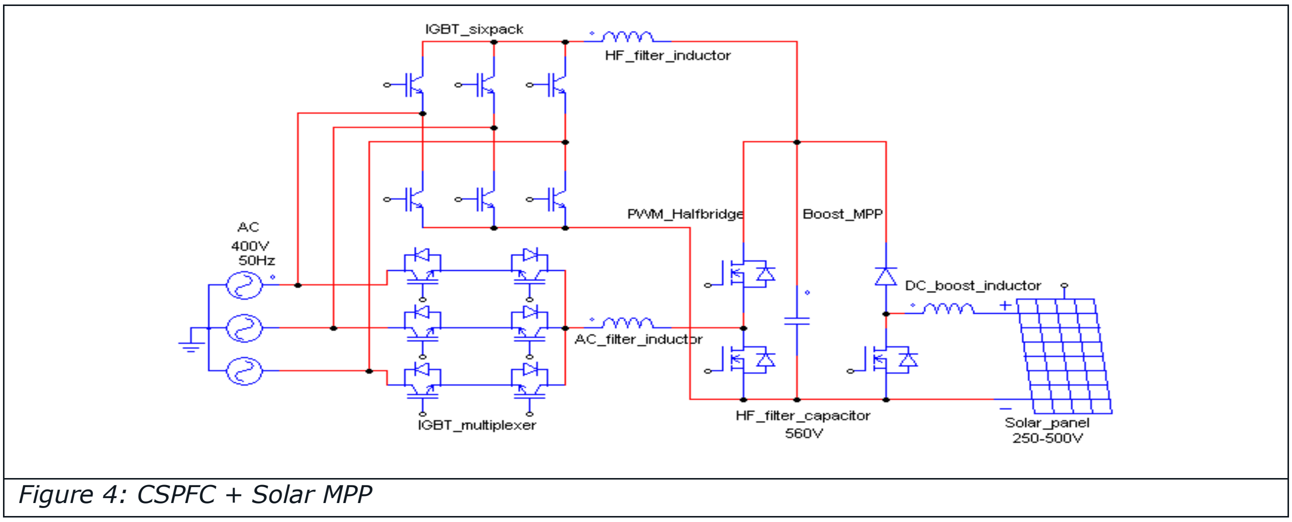


Figure 4: CSPFC + Solar MPP

5 UHPFC in EV charger and Solar applications

There is another option to inject the sine wave PWM control currents into the appropriate phases through a three-phase VSI inverter. In this solution a standard VSI sixpack (MOS1-MOS6) is driving the current control signals into the three-phase utility. As discussed before the sixpack is sized for 1/6 times of the full power only. The rectifiers will take the majority of the currents at a very high efficiency, dominating the losses. This is for the name of Ultra High Efficient PFC (UHPFC). (*Fig 5*)

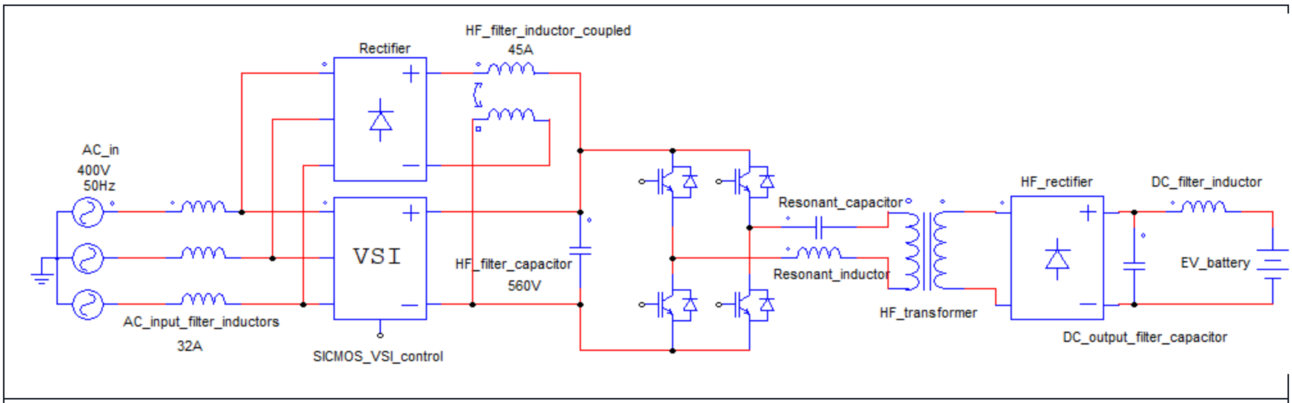


Figure 5: UHPFC + SRC

Because of the missing IGBT multiplexer the UHPFC will reach about 0.2% higher efficiency (99.2%) than CSPFC solution (99%) and so it finally results in an overall efficiency of about 97.45% for the three conversion steps of the UHPFC+SRC battery charger. The UHPFC can handle limited reactive power without significant distortion in the input currents. This can be an extra benefit for solar inverters without DC link energy storage capacitors.

The same way as CSPFC of Chapter 4, the UHPFC can also be used for solar energy generation applications as shown on *Fig* 6.

In this solution only one phase of the HF sixpack is operating at a time and only for the -30DEG to +30DEG and 150DEG to 210DEG parts of the sine-waves. Approximately 5/6 of the power passes through the LF Six-pack without chopping, thus, resulting in very high efficiency.

The power sourcing feature is added by the Flying Capacitor Buck converter.

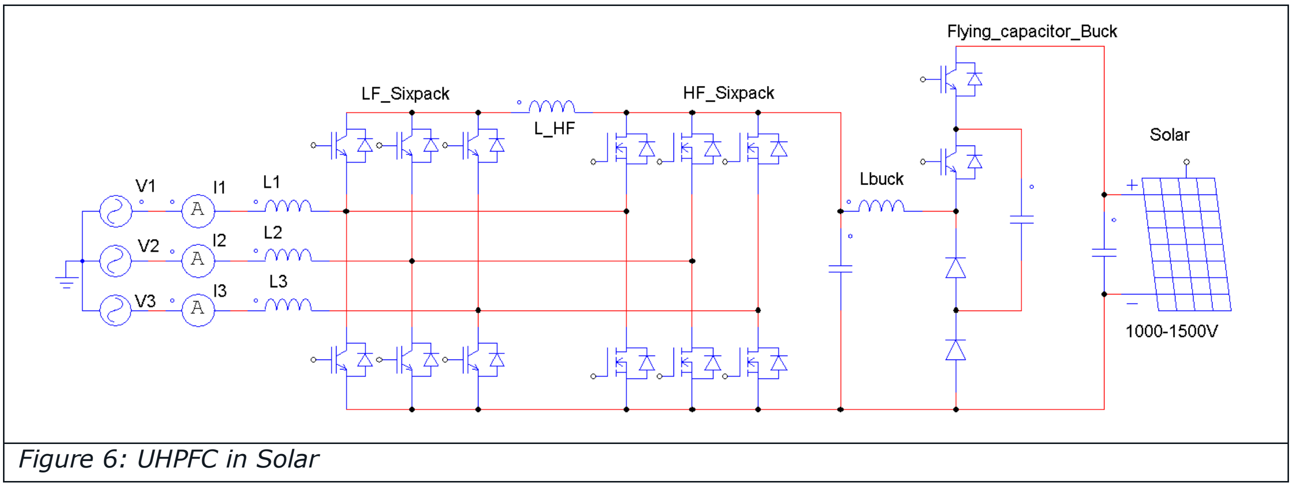


Figure 6: UHPFC in Solar

6 Three-phase autoPFC-Solar-EV charger Triport

Solar energy is often used for EV charging. For the best efficiency and the minimum cost the power conversion steps in this case should be kept at minimum.

However, solar energy generation and EV charging require different control methodologies. Solar energy generation should be kept at Maximum Power Point (MPP) whenever solar energy is available. On the other hand EVs need electricity for charging in a controlled manner dependent on the state of the EV battery and independent from solar power availability.

It is evident to use the AC utility net for backup of the electrical energy to serve best for both needs. Symmetric three-phase net is preferred, as it is capable for sourcing or sinking constant power in time. However, DC-AC and AC-DC conversions are always less efficient than DC-DC conversions.

Furthermore, charging the EV battery and generating solar energy at the same time requires two conversion steps involving one DC-AC conversion for the energy flow from the solar panels to the three-phase net, and one AC-DC conversion for the energy flow from the three-phase net to the EV batteries. Direct DC-DC conversions should be used in this case.

The Power Source/Sink Triport of *Fig* 7 allows the optimum power flow at all conversion cases.

- from the three-phase net to the EV battery (isolated AC>DC)
- from solar panels to the three-phase net (non-isolated DC>AC)
- from solar panels to the EV battery (isolated DC>DC)

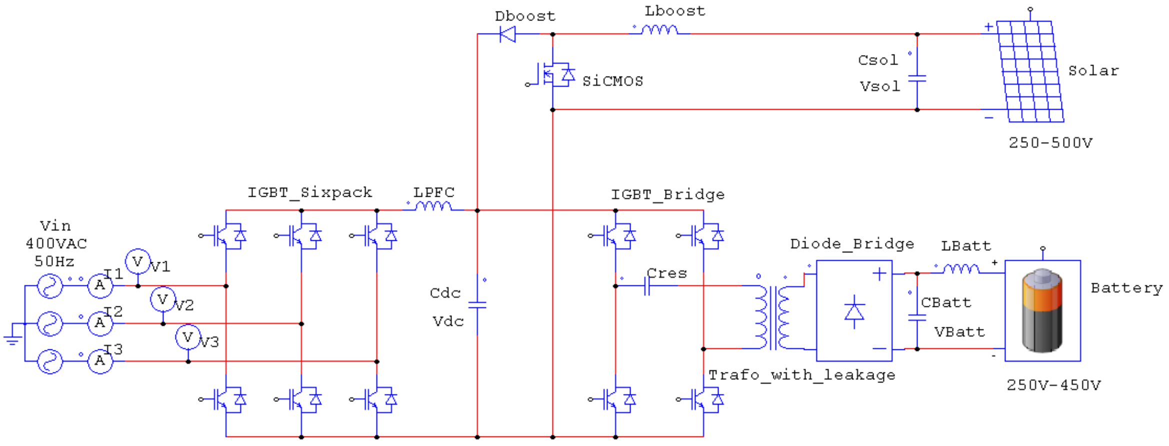


Figure 7: AutoPFC + Solar + EV charger Triport

The three-phase net is used to sum up the powers of the sourcing solar panel and of the sinking EV battery charger on a virtual power junction of Vdc.

The bidirectional IGBT sixpack ensures that Vdc for low frequency is the difference of the most positive and most negative phase voltages independent from the direction of the power flow through it.

As the Cdc is of a low capacitance value (only for HF filtering of the solar boost output current the EV charger input current), it does not store significant energy. Therefore, the power sourcing/sinking of the net is equal to the difference of the power sourcing of the solar panel and power sinking of the EV battery charger.

Each of the power flows are set independently by their controllers (Solar MPP and EV Battery Charge). The power that have to be sunk by the three-phase net through the IGBT sixpack will be the maximal power of the solar source. The power that have to be sourced by the three-phase net will be the maximal power of the EV battery charger.

If the solar panel power is higher than the EV battery charging power necessity, then the Triport will transmit the difference of power to the three-phase net automatically. If the required EV battery charging power is higher than the solar panel power, then the Triport will take the difference from the three-phase net automatically. The transition between sourcing and sinking is also automatic in both directions.

7 Three-phase Solar-EV charger Triport with bidirectional Current Synthesizing PFC (CSPFC)

As discussed in Chapter 4 the THD on the three-phase line can be significantly improved by injecting a regulated current into at least one phase of the three phases. The power factor can be adjusted to unity (PF=1).

As the injection of the PF=1 control current is bidirectional, the current injecting PWM halfbridge of *Fig* 3 is inherently suitable for both AC>DC and DC>AC power conversions. This Triport can be seen on *Fig*. 8.

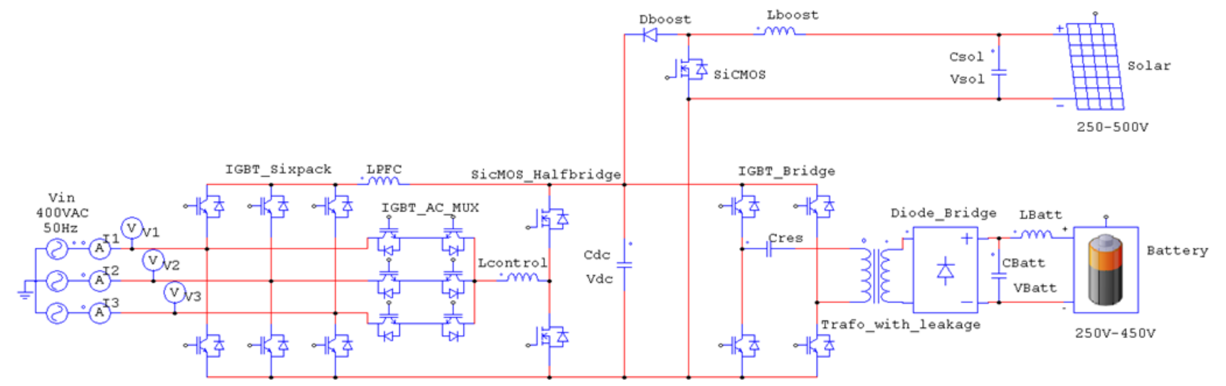


Figure 8: CSPFC + Solar + EV charger Triport

It has all the advantages as Triport of *Fig.* 7, but with undistorted sine-wave currents on the three-phase net for both directions of power flow.

Distribution of losses:

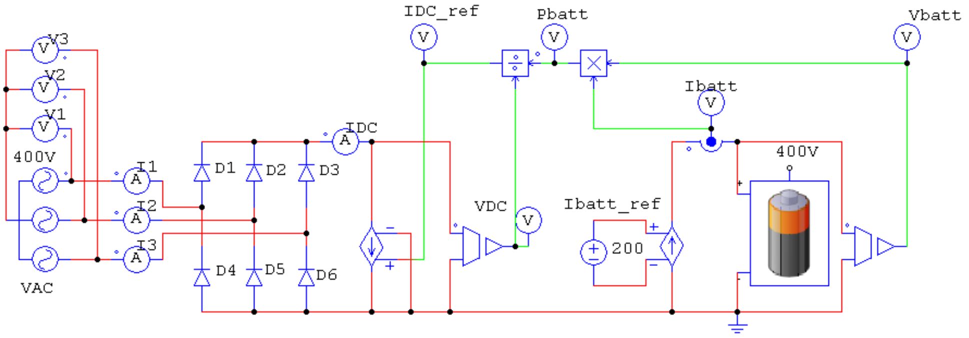
Solar boost losses (boost switch, diode, inductor)		0.8 %
PFC rectifier semiconductor losses	5/6*0.37%=	0.31 %
PFC passive losses	5/6*0.2%=	0.17 %
IGBT sixpack semiconductor losses	5/6*0.48%=	0.4 %
IGBT multiplexer losses	1/6*1%=	0.17 %
PWM inverter losses	1/6*1.9%=	0.32 %
SRC semiconductor losses		0.97 %+ (0.48% IGBT + 0.49% HF rectifier)
SRC passive losses		0.8 %

Total charging losses will come to 2.74 % (0.97% PFC and 1.77 % SRC) resulting in 97.26 % efficiency.

Total solar generation losses 1.86 % (0.8% booster and 1.06% PFC) resulting in 98.14 % efficiency.

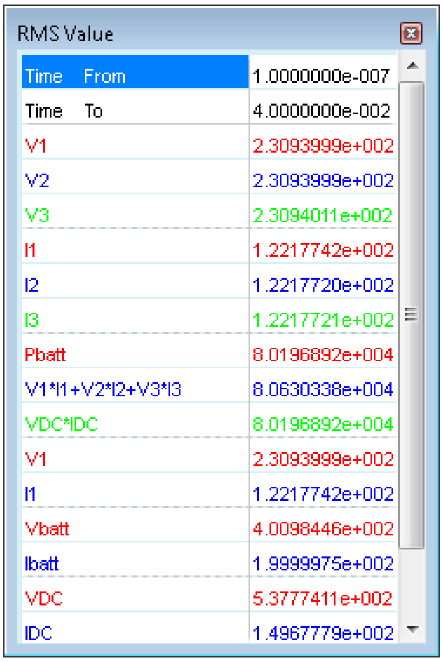
However, if EV charging is needed when solar power is also present, then a DC-DC direct conversion with 2.57 % losses (0.8% booster +1.77% SRC) will improve the efficiency of Triport to 97.43 % in respect of solar power utilized for battery charging.

Appendix 1. AutoPFC at constant power load (400 V, 200 A) simulation

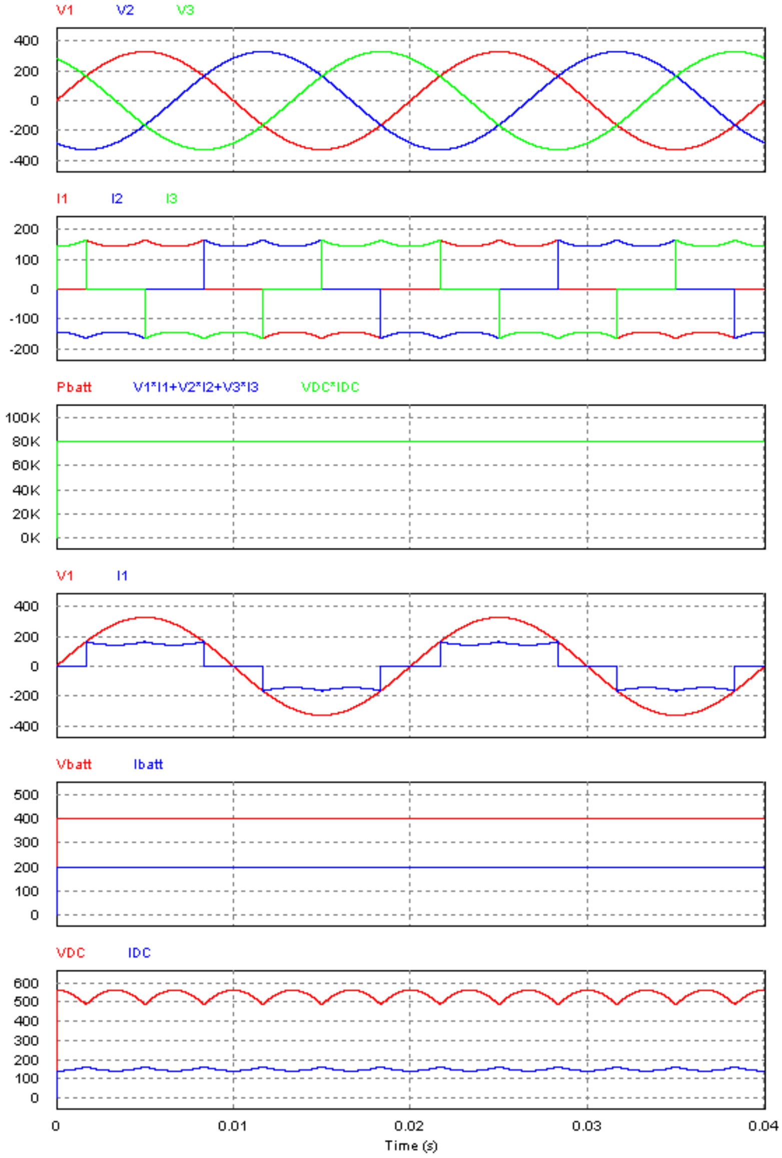


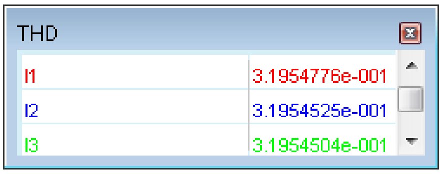
- V1,V2,V3 AC phase voltages
- I1,I2,I3 AC phase currents
- Pbatt measured battery power
- Vbatt measured battery voltage
- Ibatt_ref required charge current to battery
- Ibatt   measured battery current
- VDC measured virtual DC voltage
- IDC_ref   required DC current
- IDC measured DC current

Pin(t)=V1(t)*I1(t)+V2(t)*I2(t)+V3(t)*I3(t)=PDC(t)=VDC(t)*IDC(t)=Pout(t)=Vbatt(t)*Ibatt(t) =Pbatt(t)=Pbatt=80kW


RMS Value

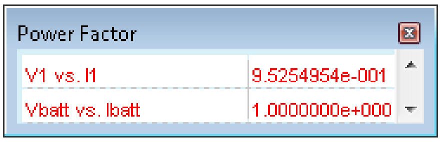
Time From	1.0000000e-007
Time To	4.0000000e-002
V1	2.3093999e+002
V2	2.3093999e+002
V3	2.3094011e+002
I1	1.2217742e+002
I2	1.2217720e+002
I3	1.2217721e+002
Pbatt	8.0196892e+004
V1*I1+V2*I2+V3*I3	8.0630338e+004
VDC*IDC	8.0196892e+004
V1	2.3093999e+002
I1	1.2217742e+002
Vbatt	4.0098446e+002
Ibatt	1.9999975e+002
VDC	5.3777411e+002
IDC	1.4967779e+002




THD

I1	3.1954776e-001
I2	3.1954525e-001
I3	3.1954504e-001

THD input current= 31.9%

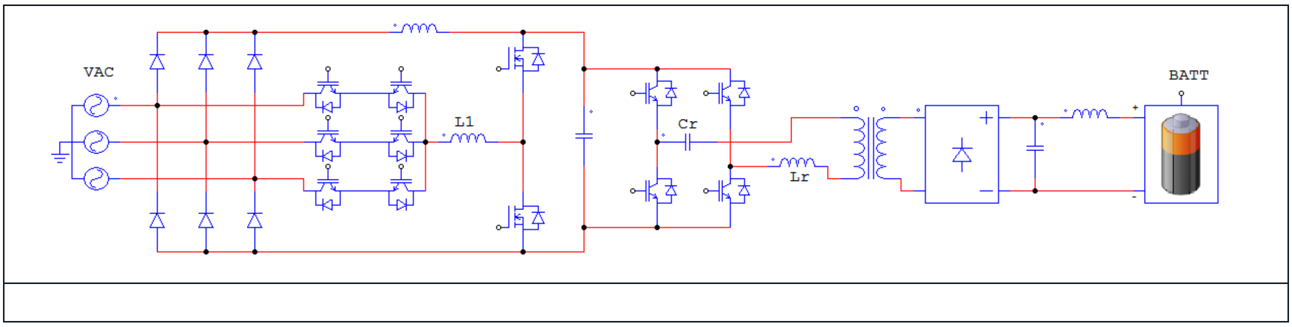

Power Factor

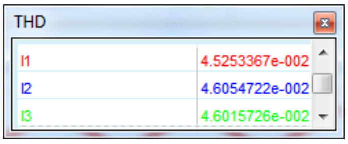
V1 vs. I1	9.5254954e-001
Vbatt vs. Ibatt	1.0000000e+000

PF AC= 0.952

PF Batt= 1

Appendix 2. CSPFC and SRC simulation





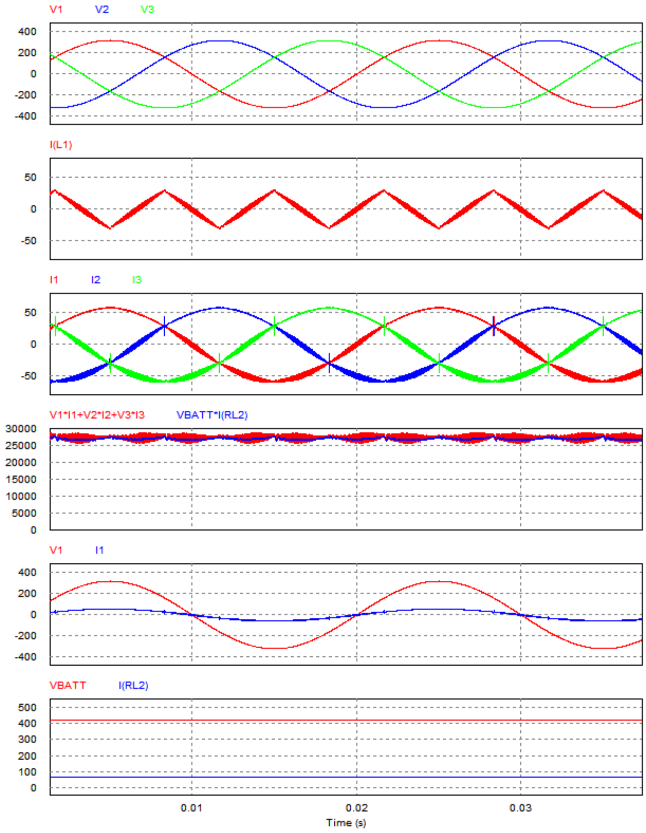
I1	4.5253367e-002
I2	4.6054722e-002
I3	4.6015726e-002

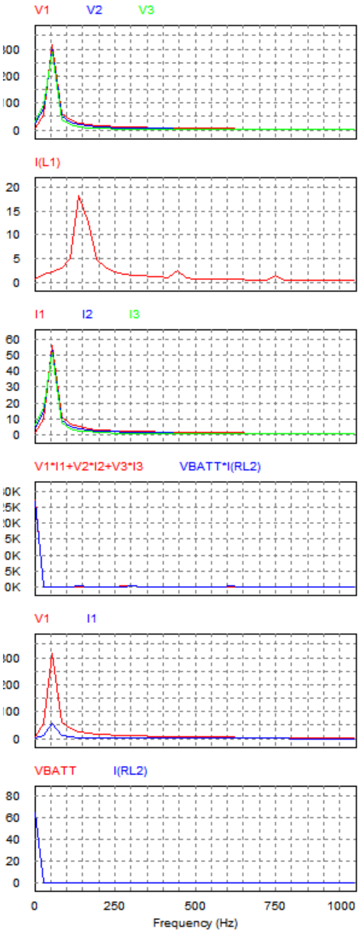
THD input current < 5%

V1 vs. I1	9.9904635e-001
VBATT vs. I(RL2)	9.9994692e-001

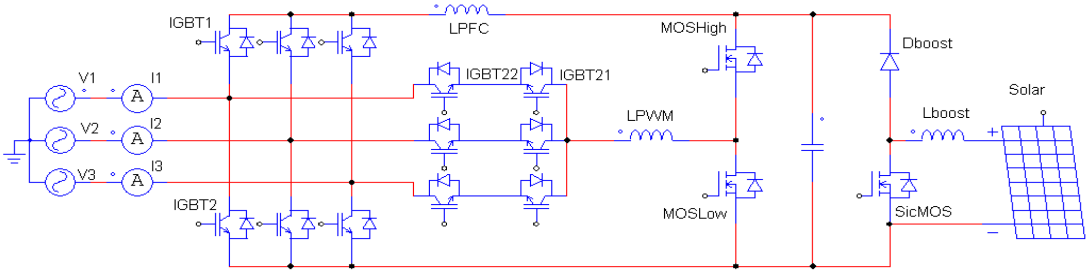
PF AC > 0.999

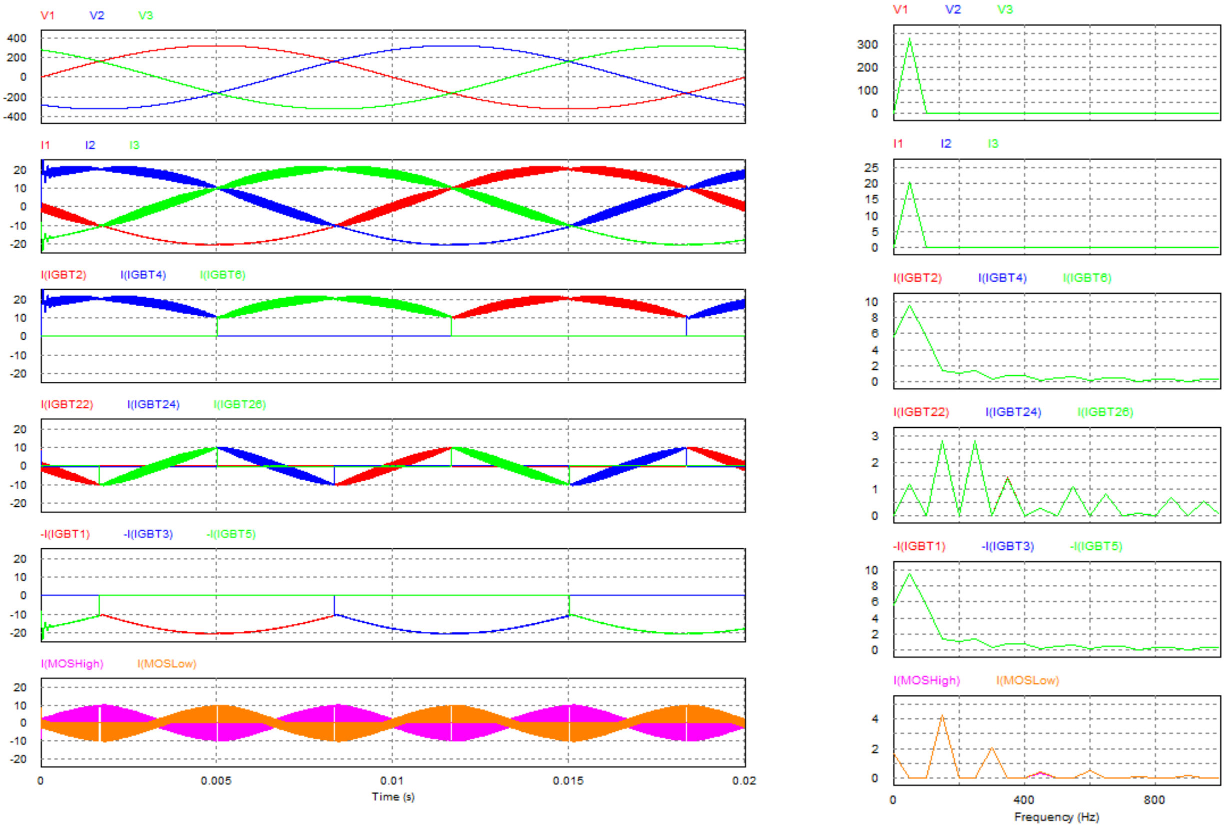
PF Batt > 0.999





Appendix 3. CSPFC and Solar simulation





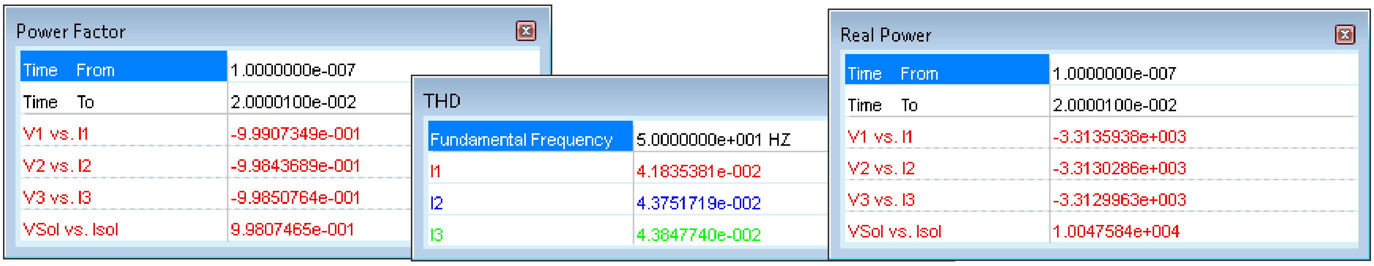
PF AC > 0.998

PF Batt > 0.998

THD input current < 5%

Static Efficiency = 98.9%

335V DC -> 3ph 400V AC



Power Factor

Time From	1.0000000e-007
Time To	2.0000100e-002
V1 vs. I1	-9.9907349e-001
V2 vs. I2	-9.9843689e-001
V3 vs. I3	-9.9850764e-001
VSol vs. Isol	9.9807465e-001

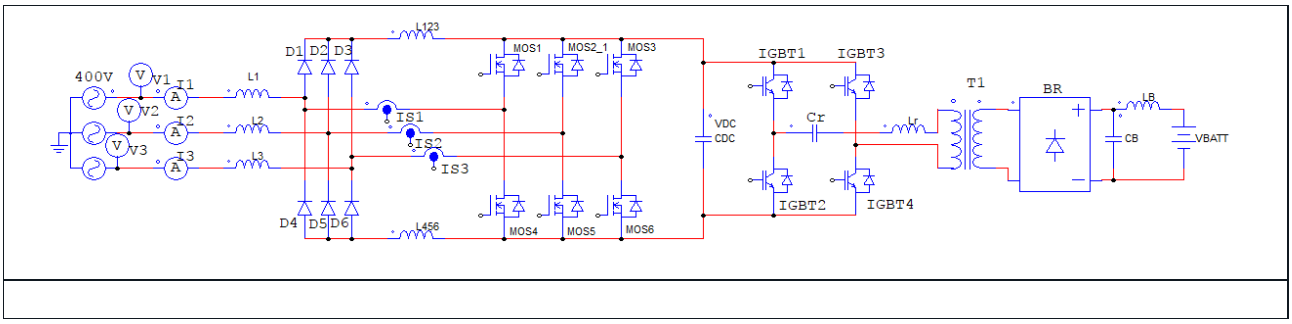
THD

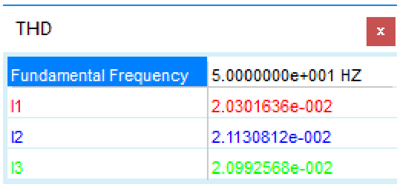
Fundamental Frequency	5.0000000e+001 HZ
I1	4.1835381e-002
I2	4.3751719e-002
I3	4.3847740e-002

Real Power

Time From	1.0000000e-007
Time To	2.0000100e-002
V1 vs. I1	-3.3135938e+003
V2 vs. I2	-3.3130286e+003
V3 vs. I3	-3.3129963e+003
VSol vs. Isol	1.0047584e+004

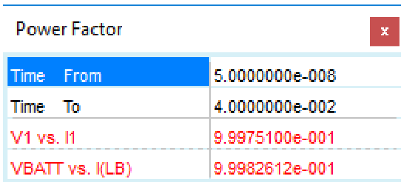
Appendix 4. UHPFC and SRC simulation





Fundamental Frequency	5.0000000e+001 HZ
I1	2.0301636e-002
I2	2.1130812e-002
I3	2.0992568e-002

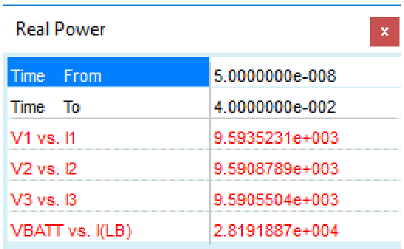
THD input current < 3 %



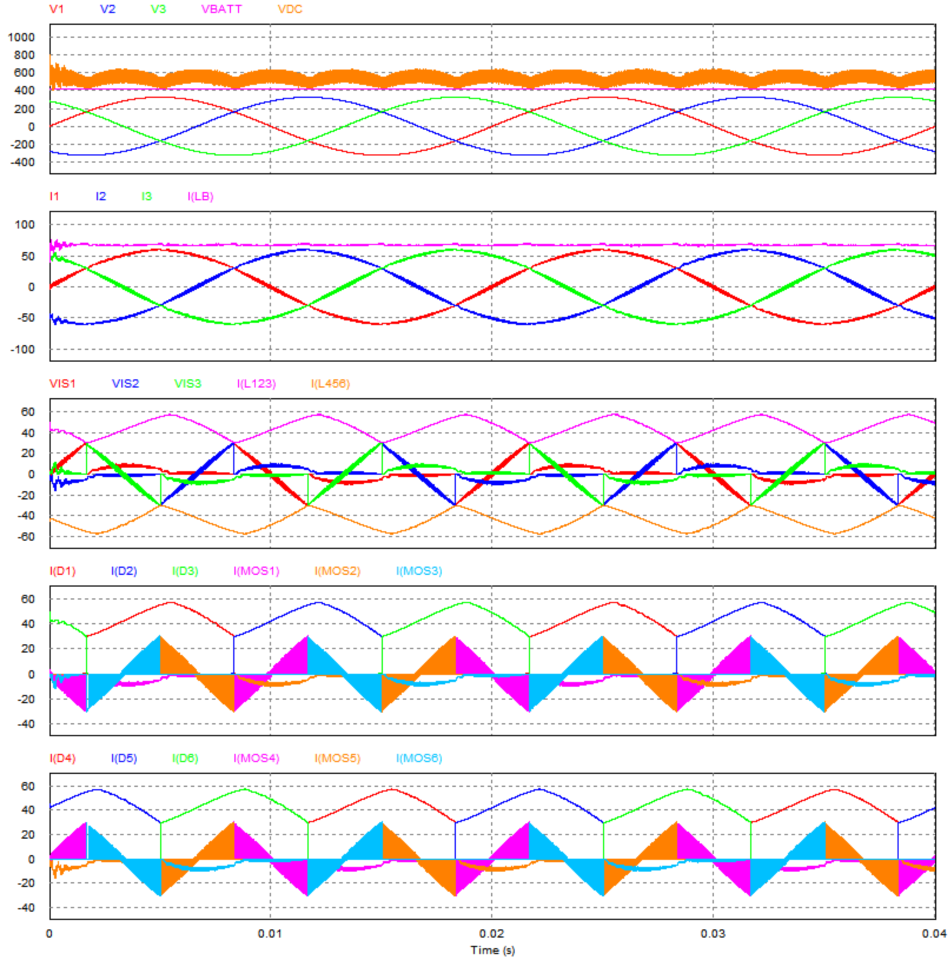
Time From	5.0000000e-008
Time To	4.0000000e-002
V1 vs. I1	9.9975100e-001
VBATT vs. I(LB)	9.9982612e-001

PF input > 0.999

PF output > 0.999



Time From	5.0000000e-008
Time To	4.0000000e-002
V1 vs. I1	9.5935231e+003
V2 vs. I2	9.5908789e+003
V3 vs. I3	9.5905504e+003
VBATT vs. I(LB)	2.8191887e+004



Static Efficiency = 98%

3ph 400 V AC -> isolated 450 V DC