# STARplug™
## Efficient Low Power supply with the TEA152x

Version 1.0
AN00055

Philips
Semiconductors

PHILIPS

Let's make things better.

# APPLICATION NOTE

# STARplug$^{TM}$
## Efficient Low Power supply with the TEA152x

**Version 1.0**
**AN00055**

**Philips**
**Semiconductors**

PHILIPS

*Abstract*

*This Application Note provides simple guidelines for creating an efficient AC/DC conversion function using the TEA152x fly-back controller IC. This document describes the basic operation of a standard fly-back or Buck converter. Furthermore a general description of TEA152x (STARplug) controller is given.*
*In this document can also be found a step-by-step design procedure for a fly-back and Buck converter.*
*Finally, the performance of the small demo board (5V/3W) is included.*

# APPLICATION NOTE

# STARplug$^{TM}$
## Efficient Low Power supply with the TEA152x

**Version 1.0**
**AN00055**

**Author:**

**Vincent van den Broek**
**Design & Application Power Control Ics**
**The Netherlands**

**Keywords**

Portable Products
AC/DC Conversion
DC/DC Conversion
High Efficiency
TEA152x
STARplug
Fly-back Converter
Standby Supply
Low Power Standby
Cellular Phones
GSM Chargers

**September 2000**

### Summary

The first part of this report contains basic information about the operation of a standard fly-back and Buck converter. The report continues with a functional description of the STARplug (TEA152x). In this chapter, the basic operation and features of the STARplug are explained.

The second part covers the application of a standard fly-back and Buck converter in detail. With the "step-by-step" design procedure, a working application is guaranteed.

The last part of this application note shows the results of the small demo board, a 5V/3W application.

## Contents

# 1 Introduction

This document gives insight into the operation and application of the STARplug fly-back converter. It has been written for anyone who is interested in this product and fly-back converters.

This introductory chapter describes the contents of this Application Note and the purpose of each chapter. Every chapter is a piece of information in itself, most of it can be read without going through the previous chapter(s) first. Specific references to other sections are included which contribute to an even better comprehension of the subjects.

The first part of this application note is background information about fly-back converters using a transformer with only one output, the non-isolated Buck converter and especially about the STARplug itself. The second part illustrates the STARplug reference design.

In Chapter 2 "Fly-back and Buck topology; Theory and Operation" the basic operation of a fly-back converter is clarified in brief. Since the STARplug is also able to operate in a Buck converter configuration, this type of topology is highlighted also. More details of the exact operation of fly-back or Buck converters can readily be found in electronic reference books.

Chapter 3 "Functional Description" serves as background information about the STARplug features in general.

The actual application design is covered by chapter 4 "General step-by-step design procedure" which guides you through the design. With this chapter it is easy to realize a successful fly-back or Buck converter design.

The last chapter highlights the performance of the reference design; a small 5V/3W output voltage supply for the universal mains.

## 2 Fly-back and buck topology; theory and operation

To clarify the operation of the isolated fly-back converter and the non-isolated Buck (Down) converter, the following paragraph

### 2.1 Fly-Back Converter

In many applications isolation from the mains is necessary for safety reasons. The fly-back converter does not need an additional inductive element for mains isolation because the inductor itself can be provided with an additional winding for that purpose. In comparison with the push-pull and the forward converter the fly-back converter is the least expensive and the simplest system since it is the sole circuit needing only one inductive element.

Figure 1 shows a simplified application diagram of an isolated fly-back converter, connected to a supply and a load. The polarity of some relevant voltages and currents is also included in this diagram. For basic understanding of the application, $V_{in}$ and $V_o$ should be considered to be DC like. In a practical application, a MOSFET or Bipolar transistor replaces the switch S1 while a diode replaces the switch S2.

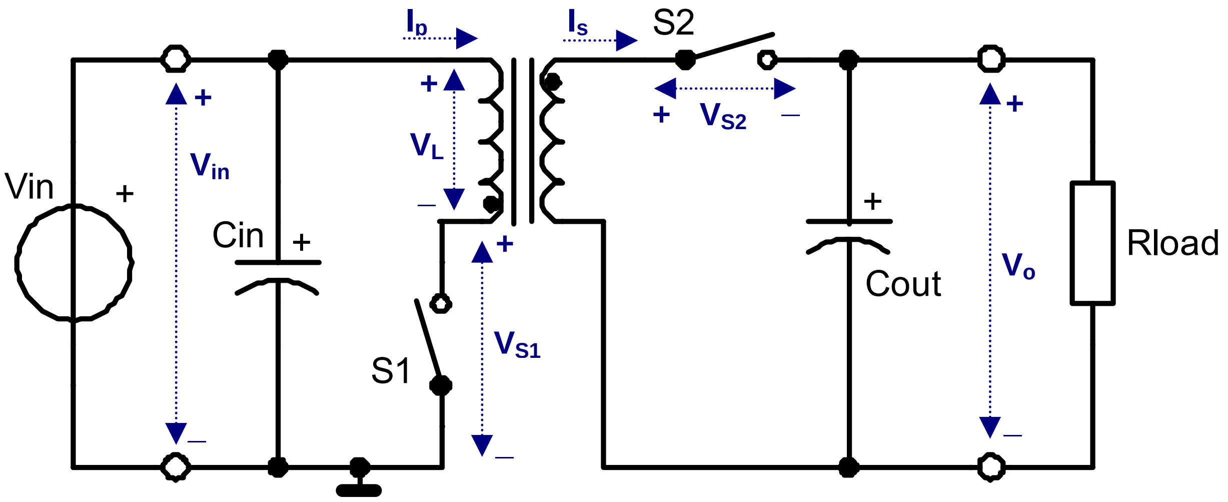


*Figure 1: Basic fly-back converter*

The circuit is defined by the state of the switches. With two switches there are four modes but not all of them are applicable. Modes 1 and 2 are the most important and nearly always present while mode 3 is only present for discontinuous conduction mode (mode 4 must be prevented). The state of the switches in the different modes is displayed in Table 1.

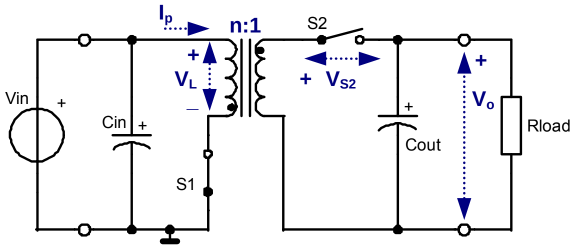
| Mode | S1 | S2 | Duration |
|---|---|---|---|
| **1** | On | Off | $\delta_1 \cdot T$ |
| **2** | Off | On | $\delta_2 \cdot T$ |
| **3** | Off | Off | $\delta_3 \cdot T$ |
| **4** | On | On | NA |

*Table 1: Table of possible modes*

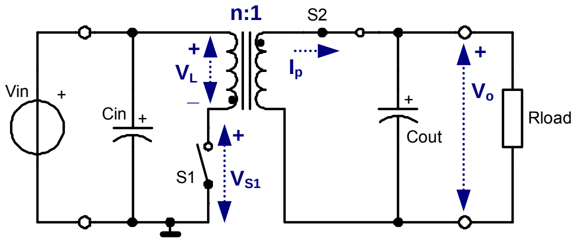
Operation of the fly-back converter is briefly explained on the next page. The figures show the equivalent circuit diagrams for the tree applicable modes. Simplified waveforms for one complete switching cycle are shown also.

Exact operation can readily be found in electronic reference books.

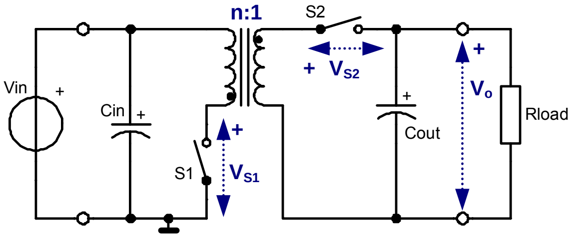
| Interval | $\delta_1$·T | $\delta_2$·T | $\delta_3$·T |
|---|---|---|---|
| Switch 1 | Closed | Open | Open |
| Switch 2 | Open | Closed | Open |



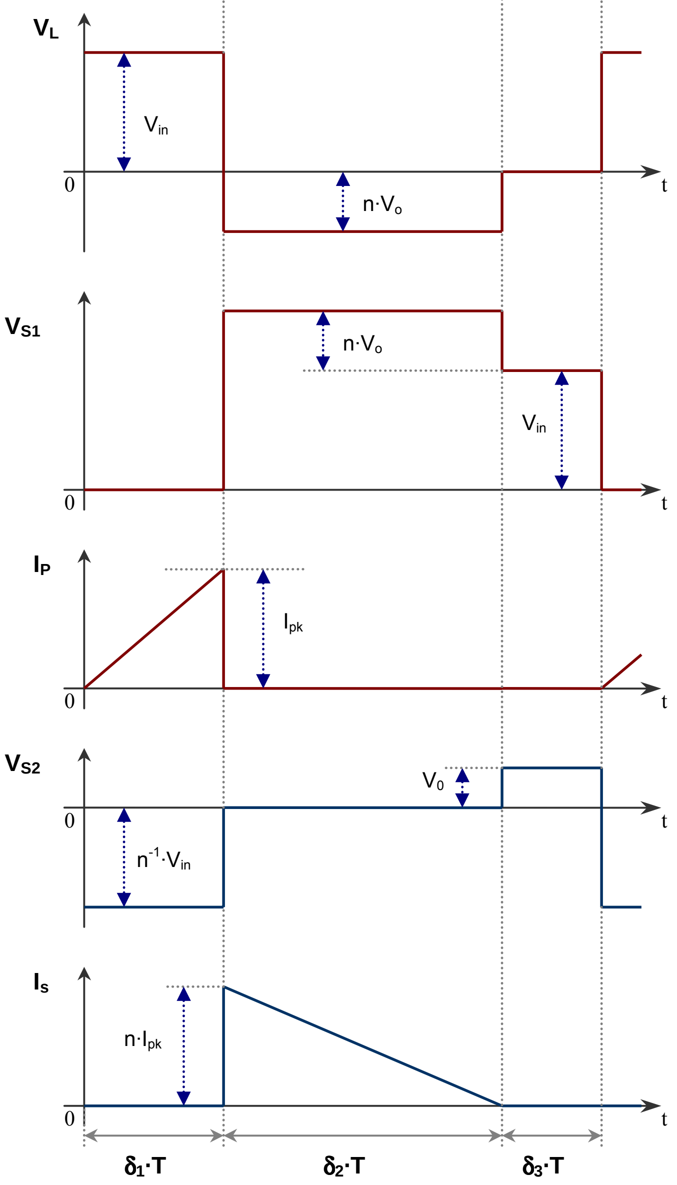
Mode 1 ($\delta_1$·T)



Mode 2 ($\delta_2$·T)



Mode 3 ($\delta_3$·T)



During the time $\delta_1$·T (mode 1) switch S1 is switched on and a current starts to flow through the primary winding of the transformer. At the moment switch S1 is switched off the secondary switch S2 is closed and a current starts to flow towards the output. The peak value of this current is equal to the transformers turns ratio ($N_p/N_s$) multiplied by the primary peak current at the moment of switching off the switch S1. During the conduction time of switch S2, the output voltage is reflected to the primary side of the transformer. Mode 3 is entered as soon as the current through switch S2 has decreased to zero.

The mode of operating just described is called "discontinuous conduction mode". The border between discontinuous conduction mode and continuous conduction mode is reached when the time $\delta_3$·T has become zero seconds.

## 2.2 Buck Converter

Not all applications need to have an output that is isolated from the mains. In this case the Buck (down) converter is a good alternative. The converter requires only one inductive element in stead of transformer with (at least) two windings as used in the fly-back converter.

Figure 2 shows a simplified application diagram of the non-isolated Buck converter, connected to a supply and a load. This converter type will take an unregulated input voltage and produce a lower regulated output voltage.

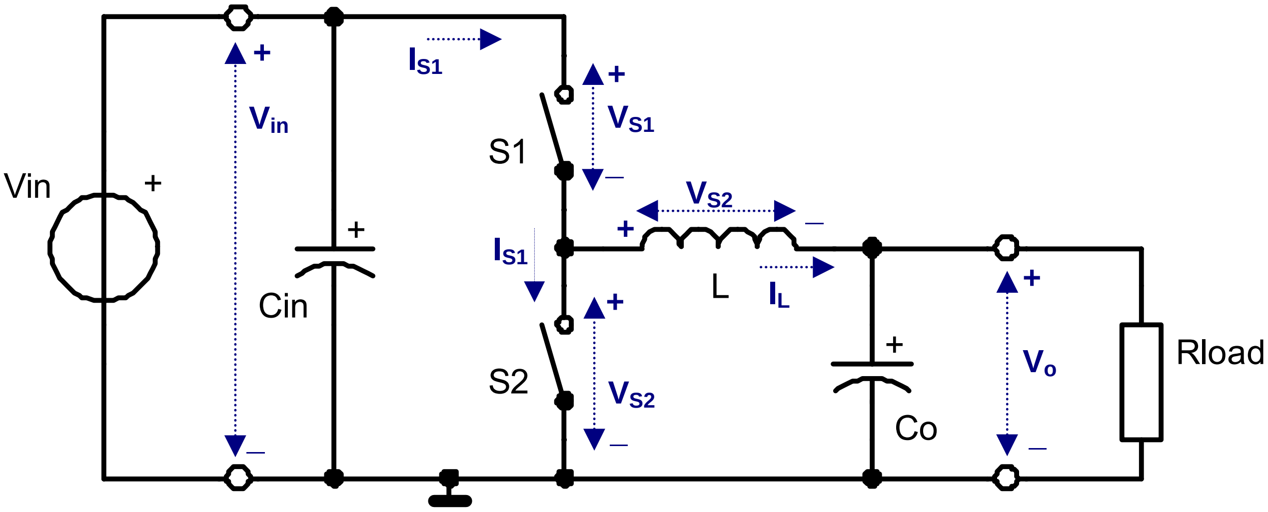


*Figure 2: Basic Buck converter*

The polarity of some relevant voltages and currents is also included in this diagram. For basic understanding of the application, Vin and Vo should be considered to be DC like. In a practical application, a MOSFET or Bipolar transistor replaces the switch S1 while a diode replaces the switch S2.

The circuit is defined by the state of the switches. With two switches there are four modes but not all of them are applicable. Modes 1 and 2 are the most important and nearly always present while mode 3 is only present for discontinuous conduction mode (mode 4 must be prevented). The state of the switches in the different modes is displayed in Table 2.

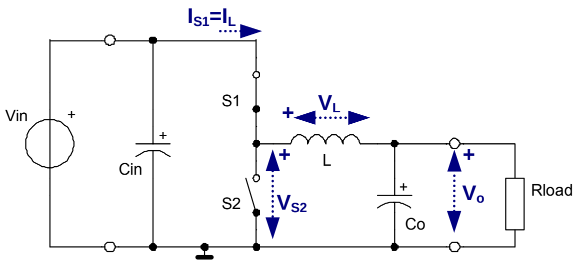
| **Mode** | **S1** | **S2** | **Duration** |
|---|---|---|---|
| **1** | On | Off | $\delta_1 \cdot T$ |
| **2** | Off | On | $\delta_2 \cdot T$ |
| **3** | Off | Off | $\delta_3 \cdot T$ |
| **4** | On | On | NA |

*Table 2: Table of possible modes*

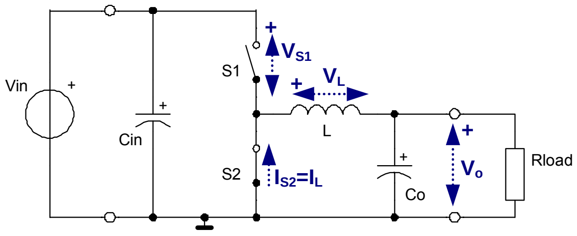
Operation of the fly-back converter is briefly explained on the next page. The figures show the equivalent circuit diagrams for the tree applicable modes. Simplified waveforms for one complete switching cycle are shown also.

Exact operation can readily be found in electronic reference books.

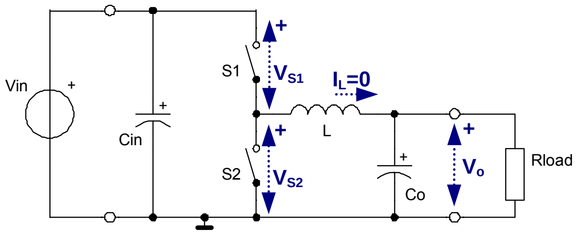
| Interval | $\delta_1 \cdot T$ | $\delta_2 \cdot T$ | $\delta_3 \cdot T$ |
|---|---|---|---|
| Switch 1 | Closed | Open | Open |
| Switch 2 | Open | Closed | Open |



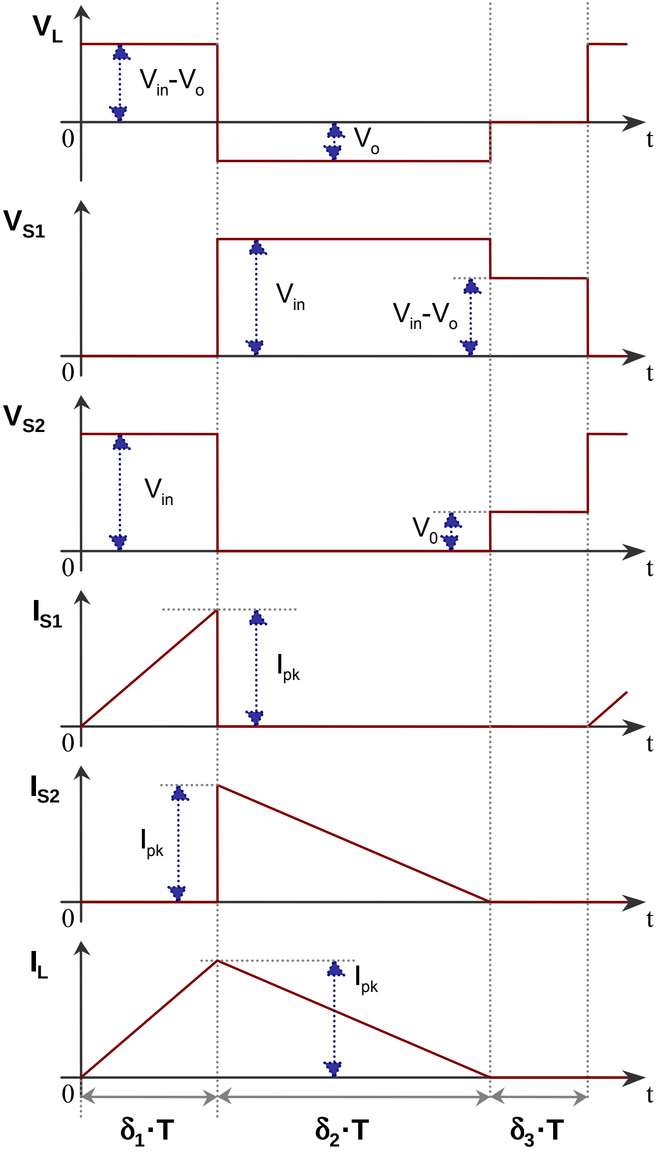
Mode 1 ($\delta_1 \cdot T$)



Mode 2 ($\delta_2 \cdot T$)



Mode 3 ($\delta_3 \cdot T$)



During the time $\delta_1 \cdot T$ (mode 1) switch S1 is switched on and an increasing current starts to flow trough the inductor towards the output. At the moment switch S1 is switched off, the inductor current flows through the switch S2. The inductor current decreases due to a negative voltage ($V_o$) across the coil. Mode 3 is entered as soon as the current through inductor has decreased to zero.

The mode of operating just described is called "discontinuous conduction mode". The border between discontinuous conduction mode and continuous conduction mode is reached when the time $\delta_3 \cdot T$ has become zero seconds.

# 3 General description

This chapter serves as background information. It describes the features and control mechanism of the STARplug. Most features can be identified in the simplified block diagram below, figure 3.

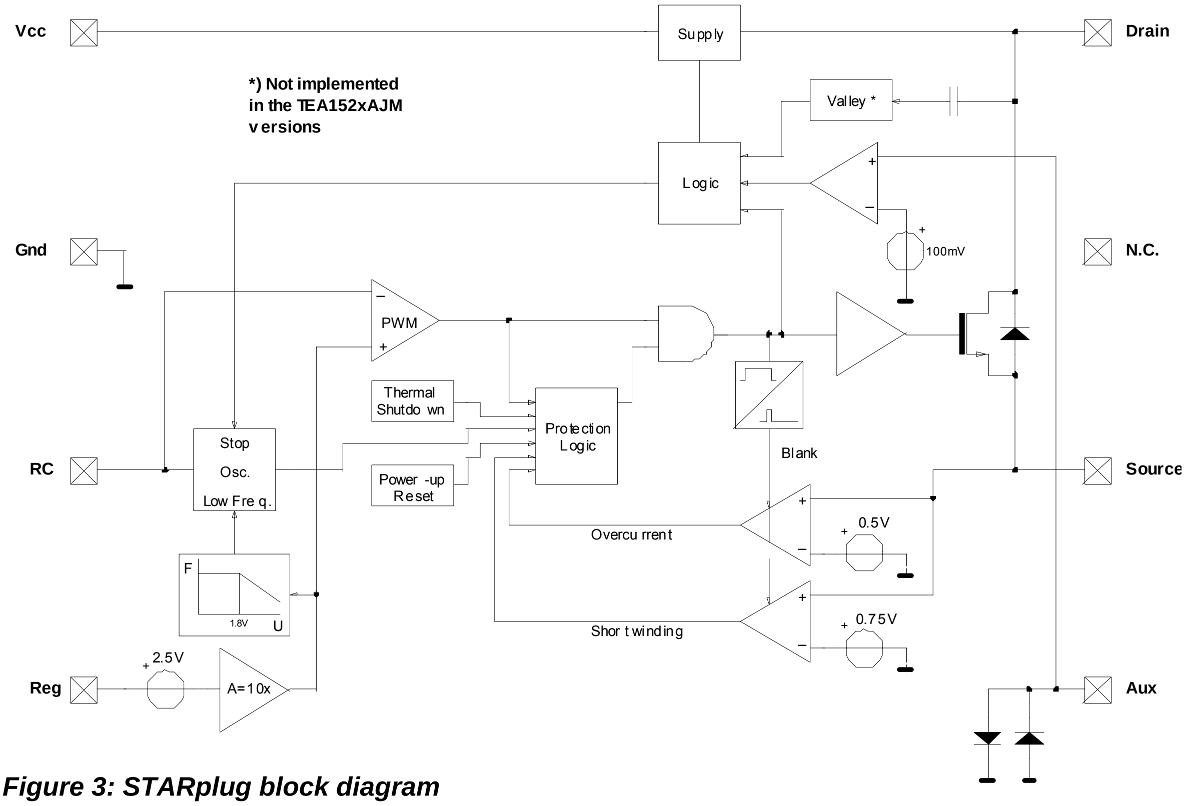


*Figure 3: STARplug block diagram*

## 3.1 Start-up and under voltage lockout

The start-up is realized with an accurate high voltage start-up current source instead of a dissipative bleeder resistor as commonly used by low voltage control ICs. When the voltage on the drain pin is high enough, a start-up current will flow towards the Vcc pin. The STARplug starts switching as soon as the voltage on the Vcc pin passes the $V_{CC\text{-start}}$ level.

The supply drawn from the drain pin of the IC is, for high efficiency operation, stopt and taken over by the auxillary winding of the transformer as soon as the Vcc voltage is high enough.

When for some reason the auxillary supply is not sufficient, the internal high voltage supply will also supply the IC. As soon as the voltage on the Vcc pin drops below the $V_{UVLO}$ level, the IC will stop switching and will restart from the rectified mains voltage.

## 3.2 Power MOS transistor

The STARplug has an on-board power switch. The switch is capable to withstand 650V on the drain. The devices are not avalanche rugged, thus sufficient measures need to be taken to prevent a breakdown of the device. The on-state resistance ($R_{ds\text{-}on}$) of the MOS transistor depends on the type of STARplug that is chosen. See the specification for detailed information.

### *3.3 Oscillator*

A parallel connection of a capacitor and a resistor to the RC pin set the switching frequency of the STARplug. The capacitor is charged rapidly to the $V_{RC\text{-}max}$ level and, starting from a new primary stroke, it will be dischaged by the resitor to the $V_{RC\text{-}min}$ level. At the moment the $V_{RC\text{-}min}$ level has been reached, the capacitor is charged again. The switching frequency is calculated with equation 1.

$$\frac{1}{f_{sw}} = t_{charge} + R_{osc} \cdot C_{osc} \cdot \ln\left(\frac{V_{RC-max}}{V_{RC-min}}\right) \qquad \textbf{Equ. 1}$$

The frequency is reduced as soon as the switching duty cycle drops be low a certain value. The reduction in frequency is accomplished by increasing the oscillator's charge time.

### *3.4 Control mechanism*

The STARplug uses voltage mode control. The conduction time of the internal MOS transistor is modulated and thus also the primary peak current through the transformer (= converted power). This method of controlling the primary peak current is called **P**ulse **W**idth **M**odulation (PWM). The implementation is shown in figure 4.

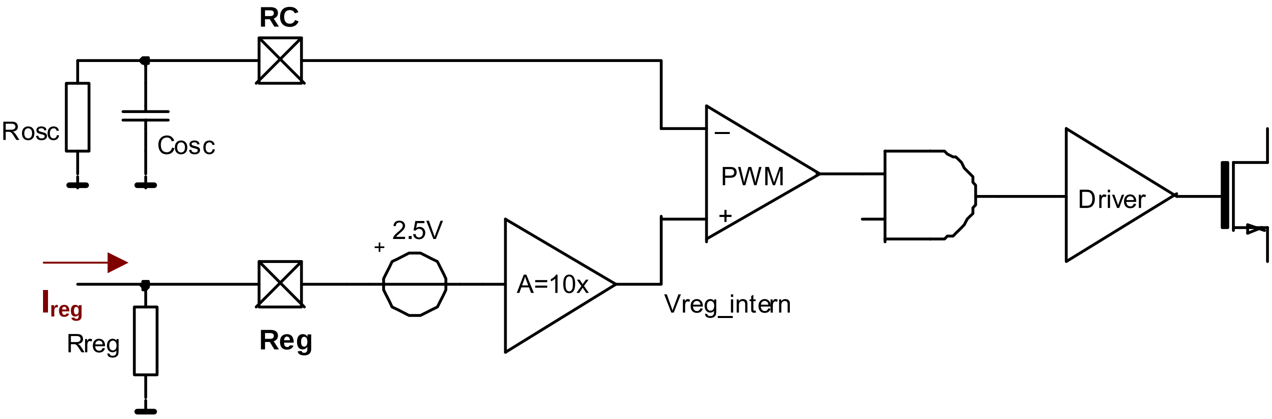


*Figure 4: STARplug regulation mechanism*

### 3.4.1 PWM Control

The internal regulation voltage (Vreg_intern) is equal to the difference between the external regulation voltage and the internal voltage source (2.5V) multiplied by a factor 10. This internal regulation voltage is compared with the voltage of the oscillator. As soon as the oscillator voltage is lower than the internal regulation voltage, the power MOS transistor is turned off. The higher the external regulation voltage, the lower the conduction time of the MOST transistor. Figure 5 visualizes this mechanism of controlling the MOST's conduction time.

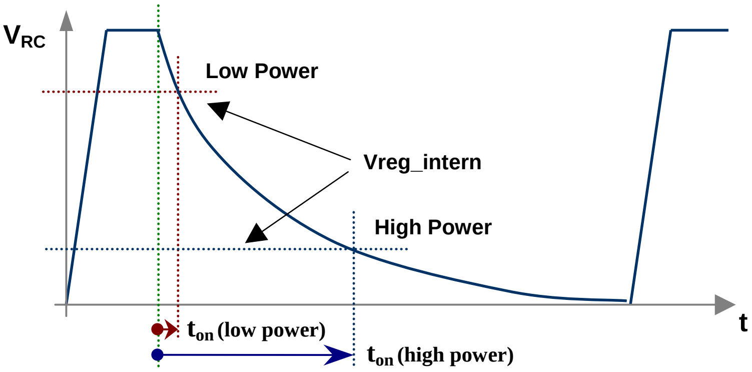


*Figure 5: Regulation mechanism*

### 3.4.2 Maximum duty cycle

The power MOS transistor will always be switched off as soon as the oscillator voltage is decreased below the $V_{RC\text{-}Dmax}$ level (typical 140mV). The maximum conduction time of the power MOS transistor is calculated with equation 2.

$$t_{on-max} = R_{osc} \cdot C_{osc} \cdot \ln\left(\frac{V_{RC-max}}{V_{RC-Dmax}}\right) \qquad \textbf{Equ. 2}$$

### 3.4.3 Minimum duty cycle

The minimum duty cycle is equal to 0%. This is achieved when the internal regulation voltage is equal to (or higher than) the maximum oscillator voltage. In this case the power MOS transistor is not switched on.

### 3.4.4 Advantage exponential oscillator

The use of an exponential oscillator has the advantage that the relative sensitivity of the duty cycle to the regulation voltage at low duty cycles, is almost equal to the relative sensitivity at high duty cycles. This results in a more constant gain over the duty cycle range compared to a PWM system with a linear sawtooth oscillator.

A small variation in the regulation voltage, see Figure 6, results in a variation of the MOS transistor's conduction time. This variation is smaller at low duty cycle levels than at high duty cycle levels. For a sawtooth oscillator, the variation is equal over the full duty cycle range.

The variation in the conduction time of the MOS transistor results in a variation of transferred power. For an exponential oscillator the variation in transferred power, at a low duty cycle level, is lower with respect to the linear oscillator. This guarantees stable operation at low duty cycle levels.

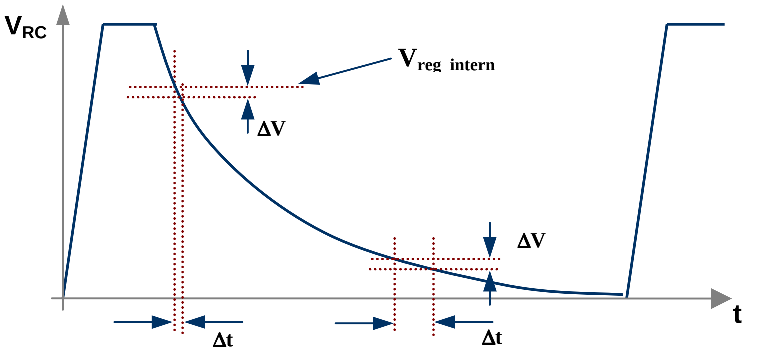


*Figure 6: Regulation mechanism*

## 3.5 De-magnetisation

The STARplug will allways operate in discontinous conduction mode.

The auxiliary winding of the transformer is connected to the STARplug's AUX pin via a resistor. Via the two anti parallel diodes, a current will flow into (or out of) the AUX pin. Whether this current flows into, or out of

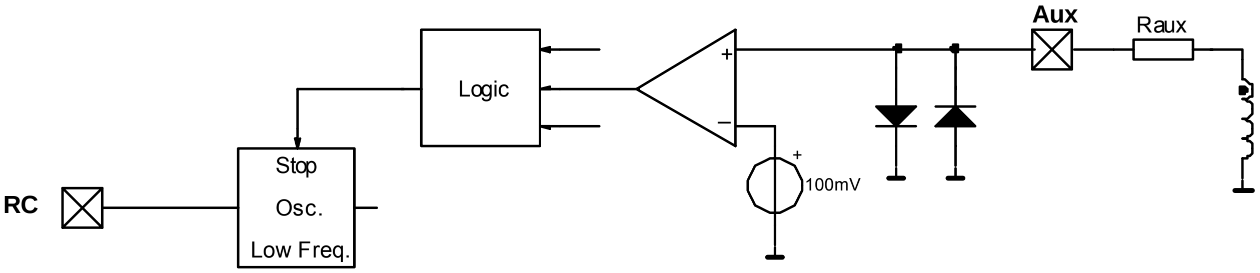


*Figure 7: Demag circuit*

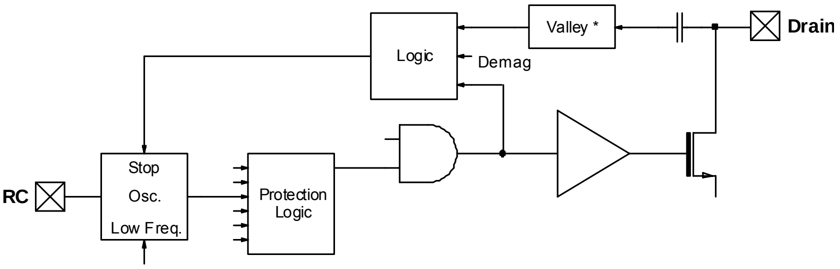
the AUX pin depend on the transformer's auxilairy winding voltage.

As long as the secondairy diode is conducting, the voltage of the auxiliary winding is positive. This injects a current in the AUX pin. As a result, the AUX pin voltage is clamped to a positive diode voltage. As long as the AUX-pin voltage is higher than 100mV, the oscillator will not start a new primary stroke.

Demagnetisation recognition is suppressed during the $t_{suppr}$ time. This time start at the moment of switching off the intergrated power MOS transistor. Specially for application with low output voltages and transformers with a large leakage induction, this might be necessary to prevent a false demagnetisation detection. The $t_{suppr}$ time starts at the moment of switching off the power MOS transistor.

## *3.6 Valley switching*

In order to increase the efficiency of a STARplug converter, dedicated valley switching circuitry is build in.



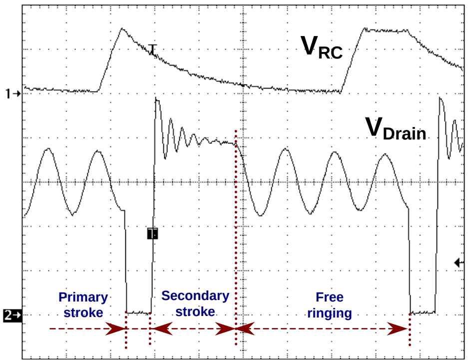


***Figure 8: Valley switch circuit***

Minimizing the power MOS transistor's switch-on losses increases the efficiency of the converter. See both Figures 8 and 9. When the internal power MOS transistor is switched-on, a new primary stroke is started. After a certain time, determined by the oscillator voltage ($V_{RC}$) and the internal regulation voltage ($V_{reg\_intern}$), the power switch is turned off (see paragraph PWM Control). At this moment, the secondary stroke is started. The duration of the secondary stroke is determined by the energy stored in the transformer and the output voltage. The STARplug detects the secondary stroke with the De-magnetization function. Due to the primary transformer's inductance and a parasitic capacitance on the drain pin, the voltage on the drain pin shows an oscillation. The frequency of this oscillation is calculated with equation 3.

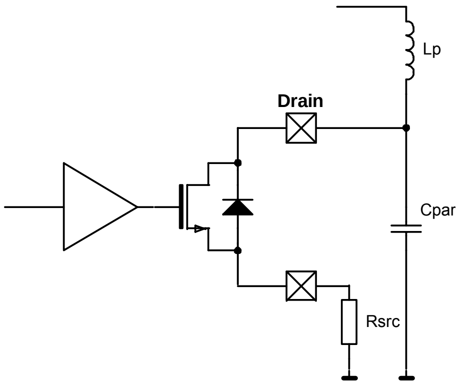


***Figure 9: Components at the drain pin***

$$f_{ringing} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_p \cdot C_{par}}}$$ **Equ. 3**

$$P_{switch-on} = \frac{1}{2} \cdot C_{par} \cdot V_{Drain}^2 \cdot f_{Switching}$$ **Equ. 4**

As soon as the oscillator is ready ($V_{RC}$=$V_{RC-max}$) and the secondary stroke has ended ($V_{Aux}$<100mV), the oscillator waits for a low drain voltage before a new primary stroke is started. The voltage, the value of the parasitic capacitor and the switching frequency determine the switch-on losses (see equation 4)

Actually, the power MOS transistor can be switched on just before the actual valley (at low ringing frequencies) or just after it at high ringing frequencies. For a fly-back application with a reflected output voltage (nVout) of 80 Volt, a typical curve is drawn in figure 10.

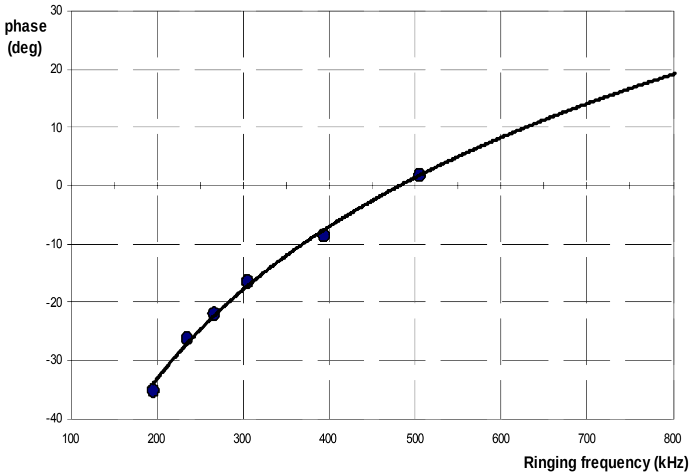


***Figure 10: Typical switch-on angle (@ nVout=80V)***

The figure shows that for a ringing frequency of 480 kHz, the power MOS transistor is switched-on exactly in the valley, thus at the minimum drain voltage. This reduces the switch-on losses to its minimum. At a ringing frequency of 200 kHz the MOS transistor is switched-on at about 33° before the actual valley. Still the switch-on losses are reduced significantly.

The valley-switching feature is disabled for STARplug types in a DBS9P envelope (TEA152xAJM version).

## *3.7 Current protections*

Via the external source resistor, the current through the internal power MOS transistor is converted into a voltage and supplied to two comperators. With these two comperators two type of current protections are implemented in the STARplug. Both protections will be discussed in the following two paragraphs.

### 3.7.1 Over current protection (OCP))

Cycle by cycle, the voltage on the source pin is measured and compared to the $V_{src\text{-}max}$ max level.
The power MOS transistor is switched off as soon the voltage on the source pin exceeds the $V_{src\text{-}max}$ level (typical 0.5V). To prevent a false OCP detection at switching on the power MOS transistor, the comperator is disabled during the $t_{LEB}$ time (typical 350ns)

### 3.7.2 Short Winding Protection (SWP)

If for some reason (i.e. short circuit of the output diode) the voltage on the source pin exceeds the $V_{SWP}$ level, the circuit will stop switching. Only a power-on reset will restart the STARplug to normal operation. Of course, to prevent a false detection also this comperator is disabled for the first $t_{LEB}$ time.

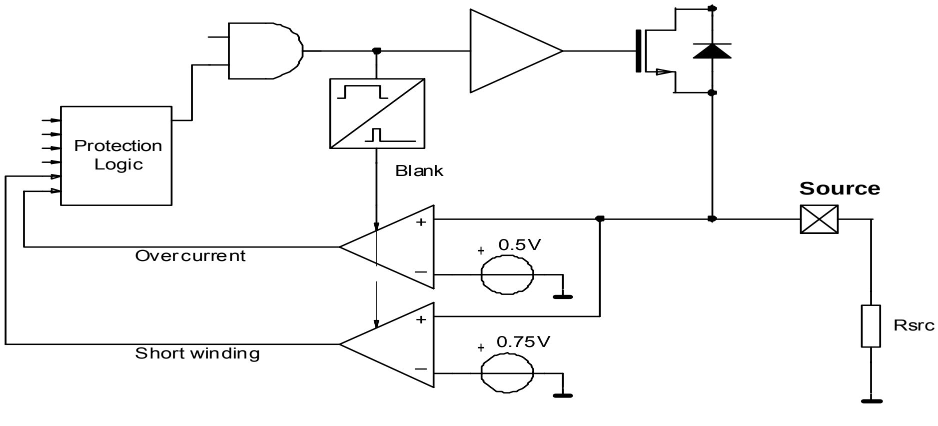


***Figure 11: Current protections***

### 3.8 Over temperature protection (OTP)

An accurate temperature protection is provided with the STARplug. When the junction temperature exceeds the thermal shutdown temperature ($T_{prot(max)}$), the IC will stop switching and the supply current is lowered to the start-up current level. As a result, the internal junction temperature will decrease. The STARplug resumes operation as soon as the temperature has dropped sufficient ($T_{prot(max)}$-$T_{prot(hys)}$). Should the temperature rise higher than the $T_{prot(max)}$ level again, switching is stopped and the supply current is lowered. So low frequent cycling between on and off state occurs.

# 4 General Step-by-step design procedure

This chapter guides you through the procedure for designing a basic fly-back or Buck converter with the STARplug.

## *4.1 Designing the basic STARplug application*

Below in Figure 12, the most basic application using the STARplug is shown. This application behaves like a primary regulated voltage source.

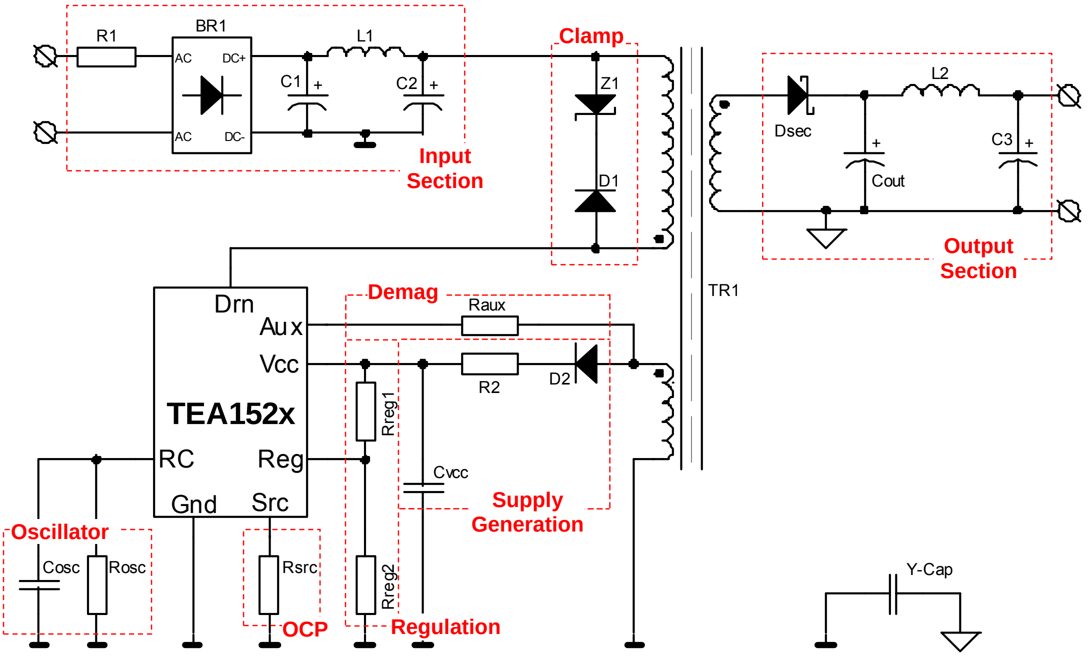


*Figure 12: Basic STARplug application*

The mains voltage is rectified, buffered and filtered in the input section and connected to the primary winding of the transformer. Around the STARplug (TEA152x), the following blocks can be identified:

- Oscillator
- OCP (**O**ver **C**urrent **P**rotection and also **S**hort **W**inding **P**rotection)
- Regulation
- Demag (demagnetization detection)
- Supply generation

In the output section, the transferred energy is stored in a capacitor and filtered before it will be available on the output pins.

A clamp is added across the primary winding of the transformer to prevent a to high voltage overshoot on the drain pin of the STARplug, at the moment the internal power MOS transistor is switched off.

### 4.1.1 Input section

**Determine system requirements**

In order to calculate the input section, the following system parameters must be identified:

***a) Minimum and maximum AC input voltage***

Select the minimum and maximum AC mains voltages from table 3.

| Input Voltage Range | $V_{AC\text{-}min}$ | $V_{AC\text{-}max}$ |
|---|---|---|
| 110V | $80V_{AC}$ | $135\ V_{AC}$ |
| 230V | $195\ V_{AC}$ | $276\ V_{AC}$ |
| Universal Mains | $80\ V_{AC}$ | $276\ V_{AC}$ |

***Table 3: Input voltage ranges***

***b) Frequency of the mains***

The frequency mentioned is the minimum line frequency possible, thus tolerances included.

***c) Required output Power and Voltage***

***d) Estimated efficiency***

Efficiency loss due to output diode:

The voltage drop across the output diode effects the efficiency of the whole converter. The higher the voltage drop across the output diode, the lower the converter's efficiency.

If the output voltage is below about 7 Volts and high efficiency is required, use a Schottky Barrier diode else a Fast PN diode can be used.

$$P_{loss,Dout}(\%) = \frac{V_{f,Dout}}{V_o} \cdot 100\%$$

PN diode : $V_{f,Dout} = 0.7$ Volt
Schottky diode : $V_{f,Dout} = 0.5$ Volt

**Equ. 5**

The efficiency loss due to the output diode is calculated with equation 5.

Efficiency loss due to snubber/clamp circuit:

A snubber network on the drain pin or a clamp circuit across the transformer's primary winding is required in order to keep the drain voltage below the breakdown voltage of the integrated MOS transistor. The estimated efficiency loss due to a snubber or clamp circuit is displayed in Table 4.

| | Power Range | Efficiency loss |
|---|---|---|
| RC snubber | $P_o < 3$ Watt | 20% |
| RCD clamp | Full range | 15% |
| Zener clamp | Full range | 10% |

***Table 4: Clamp/Snubber efficiency loss***

Efficiency loss due to others:

Efficiency loss due to other components in the application is estimated to be about 5%.

**Efficiency of the whole converter**

The estimated efficiency of the whole converter is calculated with equation 6.

$$\eta = \frac{100 - P_{loss,diode} - P_{loss,clamp} - P_{loss,additional}}{100}$$

**Equ. 6**

Remark: 1) For a practical application these estimated values can be different.
2) The peak clamp might not be necessary for the 110V range.

### Calculate the inrush resistor (R1)

The inrush resistor limits the maximum peak current through the diode bridge rectifier. The minimum value for this resistor is calculated with equation. For almost all diode bridge rectifiers, the $I_{FSM}$ parameter is about 20A.

$$R_{inrush} = \frac{\sqrt{2} \cdot V_{AC,max}}{I_{FSM}} \qquad \textbf{Equ. 7}$$

### Calculate the minimum DC voltage.

Before the minimum DC bus voltage can be calculated two additional parameters have to be defined.

**a)** ***The total buffer capacitance***

Select the $C_{Buf}$ multiplicator from table 5 and determine the total input capacitance $C_{Buf,tot}$

| Input Voltage Range | $C_{Buf}$ (µF/Watt) |
|---|---|
| 110V | 3 |
| 230V | 1 |
| Universal Mains | 3 |

$$C_{Buf,tot} = \frac{P_o}{\eta} \cdot C_{Buf} \qquad \textbf{Equ. 8}$$

***Table 5: $C_{buf}$ multiplicators***

**b)** ***The conduction time ($t_c$) of the diode bridge rectifier.***

The conduction time of the diode bridge rectifier depends on the value of the inrush resistor (R1), the output power and the total capacitance of the buffer capacitors. A good practical value is a conduction time of 3ms

The minimum DC voltage can now be calculated with equation 9.

$$V_{DC,min} = \sqrt{2 \cdot V_{AC-min}^2 - \frac{2 \cdot P_o \cdot \left( \frac{1}{2 \cdot f_{mains}} - t_c \right)}{\eta \cdot C_{Buf,tot}}} \qquad \textbf{Equ. 9}$$

### Calculate the maximum DC voltage.

The maximum DC bus voltage is built up out of two components; the peak voltage of the mains ($V_{pk,mains}$) and some additional voltage increase due to mains transients ($\Delta V_{transient}$).

a) The first part is easily defined by equation 10.

$$V_{pk,mains} = \sqrt{2} \cdot V_{ac,max} \qquad \textbf{Equ. 10}$$

b) The second part is more difficult to determine, see equation 11.

$$\Delta V_{transient} = V_{tran,pk} \cdot \frac{\alpha}{\alpha - \beta} \cdot \left( e^{-\frac{\beta}{\alpha-\beta} \cdot \ln\left(\frac{\alpha}{\beta}\right)} - e^{-\frac{\alpha}{\alpha-\beta} \cdot \ln\left(\frac{\alpha}{\beta}\right)} \right) \qquad \textbf{Equ. 11}$$

$$\alpha = \frac{1}{R_{inrush} \cdot C_{Buf,tot}}$$

$$\beta = \frac{1}{t_{tran}}$$

The equations for calculating the voltage increase due to a transient are not practical. A more convenient method is applying figure 13. This figure shows the increase in DC supply voltage as a function of the input filter time constant ($R_{inrush} \cdot C_{Buf,tot}$) for a high energy mains transient (1kv/50µs).

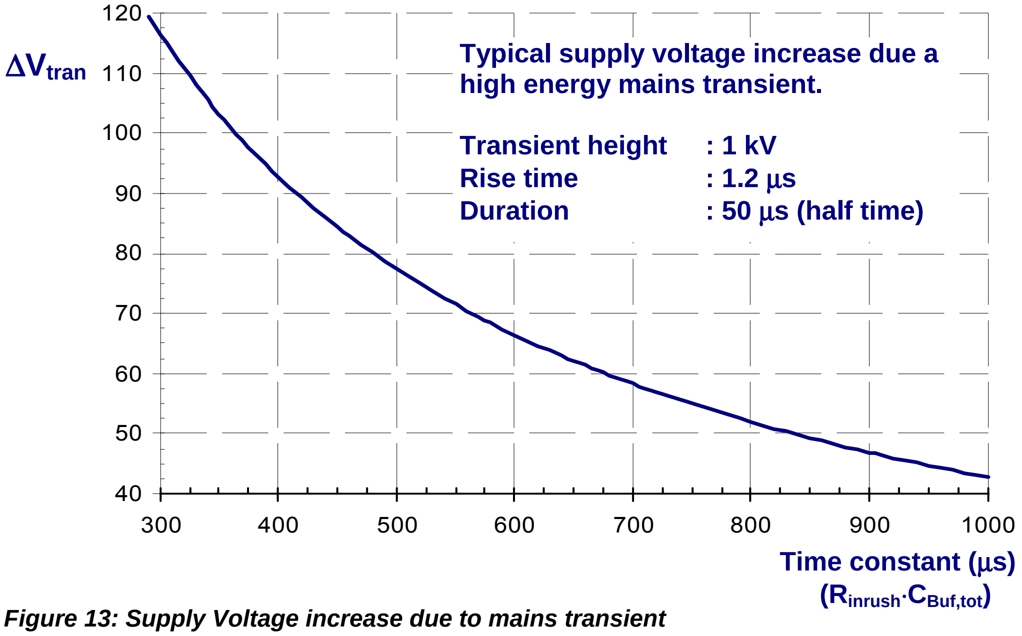


*Figure 13: Supply Voltage increase due to mains transient*

The maximum DC bus voltage can now be determined with equation 12.

$$V_{DC,max} = V_{pk,mains} + \Delta V_{tran}$$ **Equ. 12**

Check whether the maximum DC bus voltage exceeds the 475V. If this is the case, it is recommended to reduce the effect of the mains transient by increasing the resistance value for $R_{inrush}$ (R1).

**example**: $V_{pk,mains}$ = 390V, thus $\Delta V_{tran} \leq$ 85V (475V - 390V) gives an $R_{inrush} \cdot C_{buf,tot}$ time constant of 450µs. If the total buffer capacitance is 11.5µF (6.8µF + 4.7µF), the value of the inrush resistor needs to be at least 39Ω.

### 4.1.2 Clamp

The maximum clamping voltage can be found if equation 13 is applied. In this equation $BV_{DSS}$ is the breakdown voltage of the STARplug's integrated power MOS transistor. Since the power MOS transistor is not avalanche rugged, a small safety margin is added (a $V_{margin}$ of 25V is sufficient).

$$V_{Clamp,max} = BV_{DSS} - V_{DC,max} - V_{margin}$$ **Equ. 13**

### 4.1.3 Oscillator

Before the oscillator components can be calculated, the operating frequency has to be chosen. The switching frequency of the STARplug can be set between 10kHz and 200kHz. Common used switching frequencies are 40-50kHz and 100kHz.

The oscillator frequency is set by two parallel components, a resistor ($R_{osc}$) and a capacitor ($C_{osc}$).

The capacitor is rapidly charged to the $V_{RC\text{-}max}$ (typical 2.5 V) level and discharged via the resistor to the $V_{RC\text{-}min}$ level (typical 75 mV). The discharge takes 3.5 RC times (RC = oscillator time constant = $R_{osc} \cdot C_{osc}$).

The oscillator time constant is calculated with equation 14.
The oscillator charge time is derived from the STARplug specification ($t_{charge}$ = 1µs).

$$RC = \frac{1}{3.5} \cdot \left( \frac{1}{f_{switch}} - t_{charge} \right) \qquad \textbf{Equ. 14}$$

The values for both $R_{osc}$ and $C_{osc}$ can now easily be extracted from the RC time constant.
Using an oscillator capacitor less than 220pF is not recommended. The drain voltage might distort the oscillator voltage in this case. From efficiency point of view, a large $C_{osc}$ capacitor is not preferred at high operating frequencies (at 200kHz and $C_{osc}$=10nF a power 12.5mWatt is dissipated in the oscillator)

**example**: for an switching frequency of 100kHz, a oscillator time constant of 2.57µs is required. This time constant is made with the parallel connection of a 7.5kΩ resistor and a 330pF capacitor.

### 4.1.4 OCP resistor

The OCP resistor ($R_{src}$) set's the transformer's primary peak current and thus also the maximum transferred output power. The maximum required transformer's peak current is calculated with equation 15.

$$I_p = f_{switch} \cdot \left( \frac{2 \cdot P_o}{\eta \cdot f_{switch}} \cdot \left( \frac{1}{V_{DC,min}} + \frac{1}{nVout} \right) + \pi \cdot \sqrt{\frac{2 \cdot Po \cdot C_{par}}{\eta \cdot f_{switch}}} \right) \qquad \textbf{Equ. 15}$$

In this equation the new variable nVout represents the reflected output voltage. At this moment, no transformer parameters are available. A suitable value for nVout can be found when the clamp voltage, calculated with equation 13, is divided by approximately 1.5. In practical situations a nVout of 80V up to 120V is often used.
The capacitor $C_{par}$ is represents the parasitic drain capacitance. A typical value for $C_{par}$ is 100pF.

Equation 16 is used to calculate the value of the OCP resistor.
The typical value for $V_{src\text{-}max}$ is 0.5 Volt

$$R_{src} \le \frac{V_{src-max}}{I_p} \qquad \textbf{Equ. 16}$$

**example**: For a 3 Watt application running at a switching frequency of 100kHz and a efficiency of 75%, the primary peak current through the transformer will be 230mA (case $V_{DC,min}$ = nVout = 80V). The $R_{src}$ resistor is set to 2Ω, limiting the peak current to 250mA.

### 4.1.5 Transformer

A STARplug application requires a 3-winding transformer. The main winding is called $N_p$, the output winding $N_s$ and the auxiliary winding $N_a$. For all three windings, the number of turns will be calculated. Also included are equations for the inductance value of $N_p$ and the airgap in the center leg of an E-core.

**Calculate the primary inductance.**

The inductance value ($L_p$) of the primary winding ($N_p$) is calculated with equation 17.

$$L_p = \frac{2 \cdot P_o}{\eta \cdot I_p^2 \cdot f_{switch}} \qquad \textbf{Equ. 17}$$

### Selecting the core type.

If a core fits the application, is determined by the maximum stored energy in the transformer together with the required airgap. A core with a large airgap can store more energy in its ferried material than a core with a small airgap. Also the spread on the transformer's primary inductance ($L_p$) will be lower for wide airgaps. The disadvantage of a wide airgap is the high leakage inductance of the transformer. A trade off has to be made between high storable energy levels, low leakage inductance and small tolerances on the inductance. In practical situations, the airgap for a fly-back transformer is about 100µm up to 300µm.

With equation 18 the maximum energy stored in the transformer is calculated.

$$E_{core} = I^2L = I_p^2 \cdot L_p$$ **Equ. 18**

Select a suitable core from the table below or use the $I^2L$ characteristic in appendix 1. Use equation 19 as selection criteria.

$$E_{core(100\mu)} \leq E_{core} \leq E_{core(300\mu)}$$ **Equ. 19**

| Maximum $E_{core}$ (mJ) for $l_{gap}$ = 100µm | Maximum $E_{core}$ (mJ) for $l_{gap}$ = 300µm | Core type | Effective Core Area $A_e$ ($mm^2$) |
|---|---|---|---|
| 0.10 | 0.23 | E13/7/4 | 12.40 |
| 0.13 | 0.33 | E16/12/5 | 19.40 |
| 0.14 | 0.34 | E16/8/5 | 20.10 |
| 0.15 | 0.35 | E13/6/6 | 20.20 |
| 0.20 | 0.45 | E19/8/5 | 22.60 |
| 0.21 | 0.50 | E20/10/5 | 31.20 |
| 0.27 | 0.62 | E20/10/6 | 32.00 |
| 0.33 | 0.78 | E25/9/6 | 38.40 |
| 0.33 | 0.78 | E25/10/6 | 37.00 |
| 0.38 | 0.88 | E19/8/9 | 41.30 |
| 0.45 | 1.00 | E25/13/7 | 52.00 |
| 0.64 | 1.40 | E30/15/7 | 60.00 |
| 0.74 | 1.80 | E31/13/9 | 83.20 |
| 0.74 | 1.80 | E32/16/9 | 83.00 |
| 0.74 | 1.80 | E34/14/9 | 80.70 |

***Table 6: Core selection table***

The table contains only some values for E-cores. Other core types may also fit the application. See the corresponding data books for detailed information.

**example**: If the maximum peak current through the transformer is 330mA (Equ. 15) and the primary inductance equals 1.5mH (Equ. 17), the maximum stored energy $E_{core}$ = 0.163mJ.
The following E-cores can be used: E13 and E16 types

### Determine the airgap.

The length of the required airgap can be calculated with equation 20 .

$$l_{gap}(mm) = \frac{4 \cdot \pi \cdot L_p \cdot I_p^2 \cdot 10^8}{A_e \cdot B_{max}^2} \qquad \textbf{Equ. 20}$$

In this equation the parameter $A_e$ represents the effective core area in $mm^2$ and $B_{max}$ represents the maximum flux density in mTesla. For most ferried materials a $B_{max}$ value of 275mT is low enough to prevent saturation.

**example**: Core type: E13/7/4 ($A_e$=12.4$mm^2$)
$I_p$ : 330mA $L_p$ = 1.5mH $B_{max}$ = 275mT
The airgap length will be 0.1mm = 100µm

### Primary winding count.

Determine the number of primary winding with equation 21.

$$N_p = \frac{B_{max} \cdot l_g}{4 \cdot \pi \cdot I_p} \cdot 10^4 \qquad \textbf{Equ. 21}$$

Obtain a practical value for $N_p$ by rounding the calculated value to its nearest integer.

### Secondary winding count.

Apply equation 22 for the number of secondary windings.

$$N_s = N_p \cdot \frac{V_o + V_{f,Dsec}}{nVout} \qquad \textbf{Equ. 22}$$

The values for nVout and $V_{f,Dsec}$ have been identified earlier (see § 4.1.1 and § 4.1.4).
Obtain a practical value for $N_s$ by rounding the calculated value to its nearest integer.

### Auxiliary winding count.

The number of windings for the transformer's auxiliary output depends on the supply voltage of the STARplug. Initially the STARplug is self-supplying until supply is taken over by the Auxiliary winding. The maximum supply voltage ($V_{CC}$) for the STARplug is 40V. To prevent the internal high voltage supply from supplying the IC a minimum $V_{CC}$ voltage of 13V is acceptable. A practical $V_{CC}$ value is 20 Volts.

After the $V_{CC}$ voltage is chosen, the number of auxiliary winding turns can be determined (equation 23).

$$N_a = N_s \cdot \frac{V_{CC} + V_{f,Daux}}{V_o + V_{f,Dsec}} \qquad \textbf{Equ. 23}$$

Normally the auxiliary diode is a General Purpose PN-diode. The voltage drop across the PN diode is 0.7V
Obtain a practical value for $N_s$ by rounding the calculated value to its nearest integer.

### 4.1.6 Regulation components

Easy interfacing with both primary and secondary regulation is possible. In case of secondary regulation, additional secondary electronics drives the photo diode of an opto coupler. In this case, the resistor $R_{reg1}$ is replaced by the opto coupler's transistor.

The other method (less accurate one) is called primary regulation. In this case the output voltage is controlled on the primary side of the fly-back converter. Due to the fact that all windings of the transformer have the same flux variation, the secondary voltage and the auxiliary voltage ($V_{CC}$) are related via the transformer's turn ratio $N_a/N_s$. The supply voltage is calculated with equation 24.

$$V_{cc} = \frac{N_a}{N_s} \cdot \left(V_o + V_{f,Dsec}\right) - V_{f,Daux}$$ **Equ. 24**

The $V_{CC}$ voltage information is provided to the REG pin via a resistive divider. The STARplug directly regulates the $V_{CC}$ output voltage and indirectly the output voltage.

The ratio between the two resistors is defined by equation 25.

$$R_{reg1} = \left(\frac{V_{CC}}{V_{duty-DC}} - 1\right) \cdot R_{reg2}$$ **Equ. 25**

To prevent distortion on the regulator pin due to in coupling of high voltage signals it is recommended to keep the lower regulator resistor ($R_{reg2}$) below 10kΩ.

### 4.1.7 Demag

The auxiliary resistor ($R_{aux}$) limits the current in the Aux pin of the STARplug. According the specification, the maximum current into or out of the Aux pin is respectively 5mA and 10mA. These values are far beyond the current that is really needed for detecting demagnetization. A good approximation for the resistance value for $R_{aux}$ is given in equation 26.

$$R_{aux} \approx 7 \cdot nVout \left(k\Omega\right)$$ **Equ. 26**

### 4.1.8 Supply Generation

Due to the fact that the integrated start-up current source is only switched-off when the auxiliary winding provides enough energy to supply the IC, only a small supply capacitor ($C_{Vcc}$) less than 1µF is required (470nF will fit practically all applications).

The diode which connects the supply to the auxiliary winding is of the General Purpose PN type. The required breakdown voltage of this diode is calculated with equation 27.

$$V_{br,Daux} = \frac{N_a}{N_p} \cdot V_{dc,max}$$ **Equ. 27**

The transformer parameters $N_a$ and $N_p$ are determined in § 4.1.4 and the maximum DC voltage in § 4.1.1.

A resistor is placed in series with the diode. The function of this resistor is to prevent peak rectification. The exact value for this resistor has to be defined empirically. A good value to start with is 100Ω to 560Ω.

### 4.1.9 Output Section

**Output diode.**

The output section starts with the output diode. What kind of diode will be used (PN or Schottky) is decided in § 4.1.1d. Equation 28 can be used to determine the minimum breakdown voltage for the diode.

$$I_{pk,Dsec} = \frac{N_p}{N_a} \cdot I_p \qquad \textbf{Equ. 28}$$

$$I_{pk,Dsec} = \frac{N_p}{N_a} \cdot I_p \qquad \text{See } \textbf{Equ. 15} \text{ for } I_p \qquad \textbf{Equ. 29}$$

Calculate the average output current with the following equations and select an output diode with a higher rating.

$$t_{fb} = \frac{N_s \cdot L_p}{N_p \cdot (V_o + V_{f,Dsec})} \cdot I_{pk,Dsec} \qquad \textbf{Equ. 30}$$

$$I_{avg,Dsec} = \frac{N_p}{N_s} \cdot I_p \cdot t_{fb} \cdot f_{switch} \qquad \textbf{Equ. 31}$$

**Output Capacitor.**

Select an output capacitor with low ESR characteristics and a ripple current rating ($I_{RMS}$) of at least the value as determined by equation 32.

$$I_{C,RMS} = \sqrt{\left(\frac{N_p}{N_s} \cdot I_p\right)^2 \cdot \frac{t_{fb} \cdot f_{switch}}{3} - I_o^2} \qquad \textbf{Equ. 32}$$

**Output filter.**

The resonance frequency of the output filter must be set to a frequency below the minimum operating frequency. The minimum operating frequency of the STARplug application can be as low as 0 Hz, but this is not a practical value. With the following equations, an output filter section can be calculated which has a resonance frequency of 1/20th of the switching frequency.

$$LC = \frac{100}{(\pi \cdot f_{switch})^2} \qquad \textbf{Equ. 33}$$

$$L_{filter} = \frac{LC}{C_{filter}} \qquad \textbf{Equ. 34}$$

## 4.1.10 Fly-back converter Formula Overview

- **Select input voltage range**

| Input Voltage Range | $V_{AC\text{-}min}$ | $V_{AC\text{-}max}$ | $C_{Buf}$ (µF/Watt) |
|---|---|---|---|
| 110V | $80V_{AC}$ | $135\ V_{AC}$ | 3 |
| 230V | $195\ V_{AC}$ | $276\ V_{AC}$ | 1 |
| Universal Mains | $80\ V_{AC}$ | $276\ V_{AC}$ | 3 |

| | | |
|---|---|---|
| (1) | $V_{ac,max}$ | |
| (2) | $V_{ac,min}$ | |
| (3) | $C_{Buf}$ | |

- **Mains frequency**

Line frequency ($f_{line}$) : .......... Hz
Tolerance (tol) : .......... %

$$f_{mains} = \left(1 - \frac{tol}{100}\right) \cdot f_{line}$$

| | | |
|---|---|---|
| (4) | $f_{mains}$ | |

- **Output**

Voltage ($V_o$) : .......... V
Power ($P_o$) : .......... W

$$I_o = \frac{P_o}{V_o}$$

| | | |
|---|---|---|
| (5) | $P_o$ | |
| (6) | $V_o$ | |
| (7) | $I_o$ | |

- **Estimate Efficiency**

1) Output diode voltage drop
($V_{f,Dout}$) : .......... V

$$P_{loss,Dout}(\%) = \frac{V_{f,Dout}}{V_o}$$

2) Snubber / Clamp losses

| | Power Range | $P_{loss,clamp}$ (%) |
|---|---|---|
| RC snubber | $P_o < 3$ Watt | 20 |
| RCD clamp | Full range | 15 |
| Zener clamp | Full range | 10 |

3) Additional losses are about 5%

4) Calculate system efficiency

$$\eta = \frac{100 - P_{loss,Dout} - P_{loss,clamp} - P_{loss,additional}}{100}$$

| | | |
|---|---|---|
| (8) | $\eta$ | |
| (9) | $C_{buf,tot}$ | |

- **Total buffer capacitance**

$$C_{buf,tot} = \frac{P_o\ (5)}{\eta\,(8)} \cdot C_{buf}\ (3)$$

- **Minimum DC supply voltage**

Set conduction time bridge rectifier
$t_c$ = 3 ms

$$V_{DC,min} = \sqrt{2 \cdot V^2_{ac,min}(2) - \frac{2 \cdot P_o(5)}{\eta(8) \cdot C_{buf,tot}(9)} \cdot \left(\frac{1}{2 \cdot f_{mains}(4)} - t_c\right)}$$

| | | |
|---|---|---|
| (10) | $V_{DC,min}$ | |

- **Inrush resistor**

Get the non-repetitive peak forward Current rating ($I_{FSM}$) of the bridge Rectifier diodes (commonly used 20A)

$$R_{inrush} = \frac{\sqrt{2}\cdot V_{ac,max}(1)}{I_{FSM}}$$

(11) | $R_{inrush}$ |

- **Maximum DC voltage**

a) Peak mains voltage

$$V_{pk,mains} = \sqrt{2}\cdot V_{ac,max}(1)$$

b) Transient influence

A typical transient is defined as:

Height : $V_{tran}$ = 1 kV

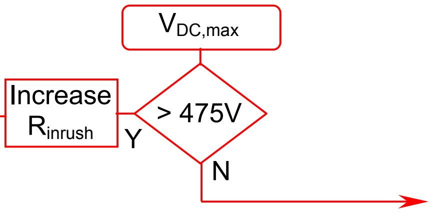
Half-time : $t_{tran}$= 50 µs

$$\begin{cases}\Delta V_{transient} = V_{tran,pk}\cdot\frac{\alpha}{\alpha-\beta}\cdot\left(e^{-\frac{\beta}{\alpha-\beta}\cdot\ln\left(\frac{\alpha}{\beta}\right)} - e^{-\frac{\alpha}{\alpha-\beta}\cdot\ln\left(\frac{\alpha}{\beta}\right)}\right)\\ \alpha = \frac{1}{R_{inrush}\cdot C_{Buf,tot}}\\ \beta = \frac{1}{t_{tran}}\end{cases}$$

c) Calculate $V_{dc,max}$

$$V_{DC,max} = V_{pk,mains} + \Delta V_{transient}$$

d) Check $V_{DC,max}$



(12) | $R_{inrush}$ |
(13) | $V_{DC,max}$ |

- **Maximum peak clamp voltage**

Breakdown voltage ($BV_{DSS}$) = 650V

Marge ($V_{margin}$) = 25V

$$V_{cl,max} = BV_{DSS} - V_{DC,max} - V_{margin}$$

(14) | $V_{cl,max}$ |

- **Oscillator**

Select a maximum operating frequency between 10 kHz and 200 kHz.

$f_{switch}$ : .......... kHz

$$RC_{osc} = \frac{1}{3.5}\cdot\left(\frac{1}{f_{switch}} - 1\mu\right)$$

Select an oscillator capacitor between 220pF and 1000pF and calculate the oscillator resistor

$C_{osc}$ : .......... pF

$$R_{osc} = \frac{RC_{osc}}{C_{osc}}$$

(15) | $R_{osc}$ |
(16) | $C_{osc}$ |

Recalculate the maximum switching frequency

$$f_{switch} = \frac{1}{3.5\cdot R_{osc}(15)\cdot C_{osc}(16) + 1\mu}$$

(17) | $f_{switch}$ |

- **Reflected output voltage**

  Typical values for nVout:

  80V ≤ nVout ≤ 120V

$$\mathrm{nVout} \approx \frac{\mathrm{Vclamp}}{1.5}$$

(18) nVout

- **Primary peak current**

  $C_{par}$ represents the paracitic capacitor on the drain node (typical value 100 pF)

$$I_p = f_{switch}(17)\cdot\left(\frac{2\cdot P_o(5)}{\eta(8)\cdot f_{switch}(17)}\cdot\left(\frac{1}{V_{DC,min}(10)}+\frac{1}{\mathrm{nVout}(18)}\right)+\pi\cdot\sqrt{\frac{2\cdot P_o(5)\cdot C_{par}}{\eta(8)\cdot f_{switch}(17)}}\right)$$

(19) $I_p$

- **Source Resistor**

$$R_{src} = \frac{0.5}{I_p(19)}$$

(20) $R_{src}$

- **Primary inductance**

$$L_p = \frac{2\cdot P_o(5)}{\eta(8)\cdot I_p^2(19)\cdot f_{switch}(17)}$$

(21) $L_p$

- **Transformer's Airgap**

  Effective core area ($A_e$) : .......... mm²

  Maximum flux density ($B_{max}$) : .......... mTesla

  (Typical value for $B_{max}$ = 275 mT)

$$l_{gap}(\mathrm{mm}) = \frac{4\cdot\pi\cdot L_p(21)\cdot I_p^2(19)\cdot 10^8}{A_e\cdot B_{max}^2}$$

(22) $l_{gap}$

- **Primary winding**

$$N_p = \frac{B_{max}\cdot l_g(22)}{4\cdot\pi\cdot I_p(19)}\cdot 10^4$$

(23) $N_p$

- **Secondary winding**

$$N_s = N_p(23)\cdot\frac{V_o(6)+V_{f,Dsec}}{\mathrm{nVout}(18)}$$

(24) $N_s$

- **Auxiliary winding**

  Set $V_{CC}$ to 20 Volts

  Set $V_{f,Daux}$ to 0.7V

$$N_a = N_s(24)\cdot\frac{V_{CC}+V_{f,Daux}}{V_o(6)+V_{f,Dsec}}$$

(25) $N_a$

- **Recalculate supply voltage**

$$V_{CC} = \frac{N_a(25)}{N_s(24)}\cdot\left(V_o(6)+V_{f,Dsec}\right)-V_{f,Daux}$$

(26) $V_{CC}$

- **Regulator resistors**

  Set $R_{reg2}$ between 1kΩ and 10kΩ

$$R_{reg1} = \left(\frac{V_{CC}(26)}{2.5}-1\right)\cdot R_{reg2}$$

(27) $R_{reg1}$

(28) $R_{reg2}$

- **Auxilary resistor**

$$R_{aux}(\mathrm{k}\Omega) \approx 7\cdot\mathrm{nVout}(18)$$

(29) $R_{aux}$

- **Auxilary Supply**
  Set supply capacitor 470nF

$$V_{\mathrm{br,Daux}} = \frac{N_a(25)}{N_p(23)} \cdot V_{\mathrm{DC,max}}(13)$$

(30) | $V_{\mathrm{BR,Daux}}$ |

- **Output diode**
  Minimum required breakdown voltage

$$V_{\mathrm{br,Dsec}} = \frac{N_s(24)}{N_p(23)} \cdot V_{\mathrm{DC,max}}(13)$$

(31) | $V_{\mathrm{BR,Dsec}}$ |

  Minimum required average current

$$\mathrm{tfb} = \frac{N_s(24) \cdot L_p(21) \cdot I_p(19)}{N_p(23) \cdot (V_o(6) + V_{\mathrm{f,Dsec}})}$$

$$I_{\mathrm{avg,Dsec}} = \frac{N_p(23)}{N_s(24)} \cdot I_p(19) \cdot t_{\mathrm{fb}} \cdot f_{\mathrm{switch}}(17)$$

(32) | $I_{\mathrm{avg,Dsec}}$ |

- **Output capacitor**
  Select a low ESR capacitor with
  a high ripple current specification.

$$I_{\mathrm{C,RMS}} = \sqrt{\left(\frac{N_p(23)}{N_s(24)} \cdot I_p(19)\right)^2 \cdot \frac{t_{\mathrm{fb}} \cdot f_{\mathrm{switch}}(17)}{3} - I_o^2(7)}$$

(33) | $I_{\mathrm{,C,RMS}}$ |

- **Output filter**

$$LC = \frac{100}{(\pi \cdot f_{\mathrm{switch}}(17))^2}$$

  Select a filter capacitor and determine
  the filter inductance
  Filter Capacitor ($A_e$) : .......... µF

$$L_{\mathrm{filter}} = \frac{LC}{C_{\mathrm{filter}}}$$

(34) | $C_{\mathrm{filter}}$ |
(35) | $L_{\mathrm{filter}}$ |

## *4.2 Designing the Buck application*

Below in figure 14, the application diagram of a Buck converter build up around the STARplug. This circuit is capable to produce a regulated output voltage (13V up to 40V) directly from the rectified mains voltage. How the different blocks need to be dimensioned is explained in the next paragraphs.

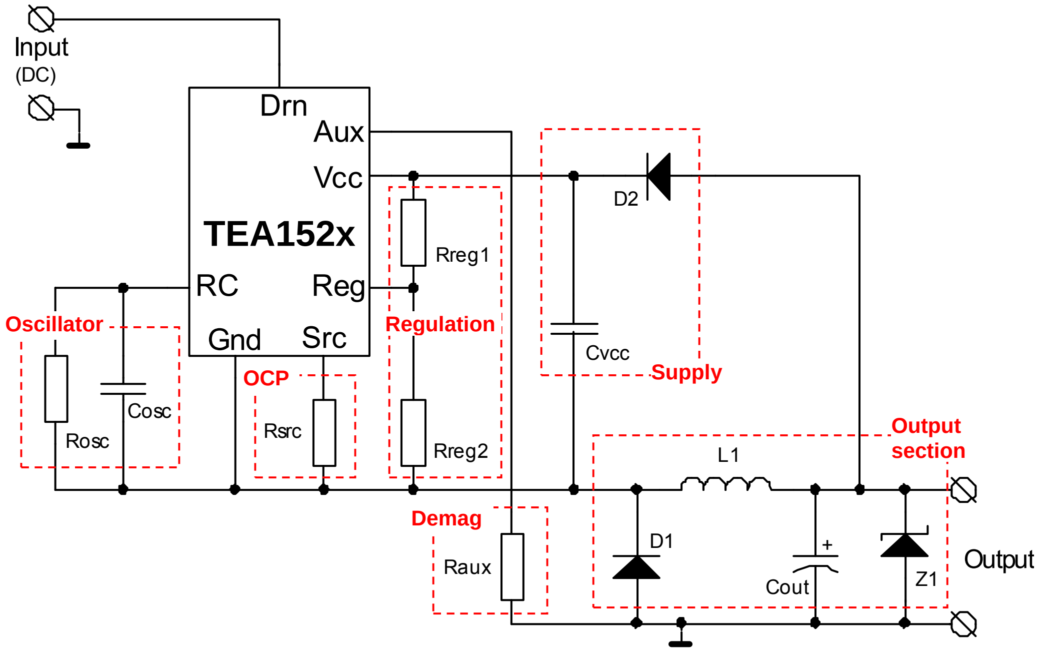


*Figure 14: STARplug Buck converter*

### 4.2.1 OCP

The resistor $R_{src}$ limits the maximum peak current through the inductor. Due to the fact that the STARplug Buck converter operates in discontinuous conduction mode, this resistor also limits the maximum output current in overload conditions. The value of the resistor can easily be defined by equation 35.

$$R_{src} = \frac{V_{src-max} \cdot V_o}{2 \cdot P_{o,max}}$$ **Equ. 35**

The $V_{src-max}$ parameter represents the OCP detection level (typical value is 0.5V).

### 4.2.2 Output section

- **Determine the inductor**

If the output is short-circuited, the source resistor limits the output current. This is only true if the voltage across the source resistor ($R_{src}$) does not exceed the OCP threshold ($V_{src-mar}$) level before the leading edge blanking time ($t_{LEB}$) has been expired.
To prevent an increasing short circuit output current, a minimum value for L1 is required. This minimum value can be calculated with equation 36. For the STARplug, the maximum leading edge blanking time ($t_{LEB}$) is 450ns.

$$L_{min} = \frac{\left(V_{DC,max} - V_0\right) \cdot V_o \cdot t_{LEB,max}}{2 \cdot P_{o,max}}$$ **Equ. 36**

At full output power, the circuit operates on the edge of continuos and discontinuous mode. As a result, the switching frequency depends on the input voltage. The minimum inductance value which is calculated in equation 36, sets the maximum possible switching frequency.

$$f_{\text{switch,max}} \approx \frac{\left(V_{\text{DC,max}} - V_o\right)}{V_{\text{DC,max}}} \cdot \frac{V_0^2}{2 \cdot P_o \cdot L_{\min}} \quad \textbf{Equ. 37}$$

If the maximum switching frequency is beyond the limit of the STARplug (200 kHz) or beyond the design criteria (maximum allowed switching frequency), the inductance value of L1 should be increased. In this case, the inductance value for L1 can be calculated with the next equation.

$$L_{\min} \approx \frac{\left(V_{\text{DC,max}} - V_o\right)}{V_{\text{DC,max}}} \cdot \frac{V_0^2}{2 \cdot P_o \cdot f_{\text{switch,max}}} \quad \textbf{Equ. 38}$$

**example**: Buck converter with $V_0$=15V and $P_o$=5W
Input voltage range: 80$V_{DC}$ to 400$V_{DC}$ and a maximum switching frequency of 50kHz.
For an accurate OCP on the output, the minimum value for L1 is 270µH (Equ. 36). This value gives a maximum switching of 80kHz (Equ. 37). The inductance value for L1 needs to be increased to 430µH (Equ. 38) in order to achieve a maximum switching frequency of 50kHz.

- **Output Capacitor requirements**

The limiting value for the output capacitor is the ripple current. This maximum RMS ripple current is equal to the maximum output current of the converter.
For a low output voltage ripple, a low ESR type electrolytic capacitor should be used.

- **Freewheeling diode.**

Every time the STARplug's integrated power MOS transistor is switched-on, the voltage across the freewheeling diode (D1) is equal to the maximum DC input voltage. The minimum breakdown voltage of the diode must be higher than the maximum DC input voltage. The maximum average current through the diode is calculated with equation 39.

$$I_{\text{D,avg}} = \frac{2 \cdot P_o^2}{V_o^3} \cdot L \cdot f_{\text{switch,max}} \quad \textbf{Equ. 39}$$

A fast recovery diode is required since the voltage across the diode is applied instantaneously.

- **OVP zener.**

In normal operation, the output voltage is regulated via the supply voltage of the IC. A small error is made due to the fact that the regulator resistors and the supply of the IC discharge the supply capacitor of the IC. The supply voltage is not a one to one presentation of the output voltage anymore. At low output power levels, this effect results in a transfer of too much power, resulting in an increasing output voltage. The zener diode prevents the output of reaching unacceptable high voltages.

### 4.2.3 Oscillator

The oscillator must be set to the maximum frequency on which the converter can operate. This frequency is calculated with equation 37.

The oscillator frequency is set by two parallel components, a resistor ($R_{osc}$) and a capacitor ($C_{osc}$).

The capacitor is rapidly charged to the $V_{RC\text{-}max}$ (typical 2.5 V) level and discharged via the resistor to the $V_{RC\text{-}min}$ level (typical 75 mV). The discharge takes 3.5 RC times (RC = oscillator time constant = $R_{osc} \cdot C_{osc}$).

The oscillator time constant is calculated with equation 40. The oscillator charge time is derived from the STARplug specification ($t_{charge}$ = 1µs).

$$RC = \frac{1}{3.5} \cdot \left( \frac{1}{f_{switch,max}} - t_{charge} \right) \qquad \textbf{Equ. 40}$$

The values for both $R_{osc}$ and $C_{osc}$ can now easily be extracted from the RC time constant.

Using an oscillator capacitor less than 220pF is not recommended. The drain voltage might distort the oscillator voltage in this case. From efficiency point of view, a large $C_{osc}$ capacitor is not preferred at high operating frequencies (at 200kHz and $C_{osc}$=10nF a power 12.5mWatt is dissipated in the oscillator)

### 4.2.4 Demag

Via the demag resistor ($R_{aux}$) which is connected to the AUX-pin of the STARplug, the circuit detects whether the freewheeling diode is still conduction. As long as this diode is conducting, a new switching cycle is not started. This limits the maximum output current, in short circuit condition.

The AUX-pin is internally connected to the STARplug's Gnd pin via two anti-parallel diodes. Due to these diodes, a current can flow into or out of the IC. The Raux resistor limits this current. As long as the integrated MOS transistor is conducting, a current will flow out of the AUX-pin. The maximum current allowed is 10mA.

The minimum value for this resistor can be calculated with equation 42 and with equation 41, the losses in this resistor can be calculated.

$$R_{aux} = \frac{V_{DC,max}}{I_{aux,max}} \qquad \textbf{Equ. 42}$$

$$P_{loss,Raux} = \frac{V_{DC,max}^2}{R_{aux}} \cdot \frac{2 \cdot P_o \cdot L}{V_o \cdot \left(V_{DC,max} - V_o\right)} \cdot f_{switch,max} \qquad \textbf{Equ. 41}$$

If the minimum resistor is applied, the losses in this component can be high and thus the efficiency of the converter low. However, the value for the $R_{aux}$ resistor is not critical and a resistance value of 220kΩ will perform well. This will increase the efficiency of the converter.

### 4.2.5 Regulation

If the Buck converter is in regulation, the supply voltage of the STARplug is equal to the output voltage. Via a resistor divider, the supply voltage is provided to the STARplug's REG pin. In this case, the supply voltage of the STARplug (and output voltage) is regulated. The ratio between the two resistors is defined by equation 43 ($V_{duty\text{-}DC}$ = 2.5V)

$$R_{reg1} = \left( \frac{V_o}{V_{duty-DC}} - 1 \right) \cdot R_{reg2}$$ **Equ. 43**

To prevent distortion on the regulator pin due to in coupling of high voltage signals it is recommended to keep the lower regulator resistor ($R_{reg2}$) below 10kΩ.

### 4.2.6 Buck converter formula overview

- **OCP resistor**

Get output requirements:

$V_o$ : ………. V

$P_o$ : ………. W

$$I_{pk} = \frac{2 \cdot P_o}{V_o}$$

$$R_{src} = \frac{0.5}{I_{pk}}$$

| | | |
|---|---|---|
| (1) | $V_o$ | |
| (2) | $P_o$ | |
| (3) | $I_{pk}$ | |
| (4) | $R_{src}$ | |

- **Minimum inductance**

Get maximum DC voltage:

$V_{DC,max}$ : ………. V

$t_{LEB,max}$ = 450 ns

$$L = \frac{\left(V_{DC,max} - V_o(1)\right) \cdot V_o(1)}{2 \cdot P_o(2)} \cdot t_{LEB,max}$$

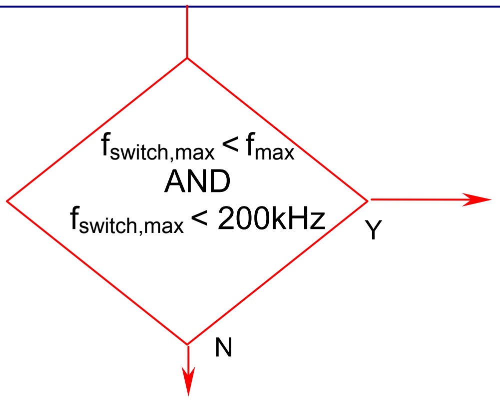
| | | |
|---|---|---|
| (5) | $V_{DC,max}$ | |
| (6) | L | |

- **Maximum frequency**

Set maximum frequency

$f_{max}$ : ………. V

$$f_{switch,max} \approx \frac{\left(V_{DC,max}(5) - V_o(1)\right)}{V_{DC,max}(5)} \cdot \frac{V_0^2(1)}{2 \cdot P_o(2) \cdot L(6)}$$



| | | |
|---|---|---|
| (7) | $f_{switch,max}$ | |

$$L \approx \frac{\left(V_{DC,max}(5) - V_o(1)\right)}{V_{DC,max}(5)} \cdot \frac{V_0^2(1)}{2 \cdot P_o(2) \cdot f_{max}(8)}$$

| | | |
|---|---|---|
| (7) | $f_{max}$ | |
| (6) | L | |

- **Output capacitor**

$$I_{ripple,RMS} = \frac{P_o(2)}{V_o(1)}$$

| | | |
|---|---|---|
| (8) | $I_{Cout,RMS}$ | |

- **Freewheeling diode.**

$$I_{D,avg} = \frac{2 \cdot P_o^2(2)}{V_o^3(1)} \cdot L(6) \cdot f_{switch}(7)$$

$$V_{br,min} = V_{DC,max}(5)$$

| | | |
|---|---|---|
| (9) | $I_{D,avg}$ | |
| (10) | $V_{br,min}$ | |

- **Oscillator**

$$\boxed{RC_{osc} = \frac{1}{3.5} \cdot \left( \frac{1}{f_{switch}(7)} - 1\mu \right)}$$

Select an oscillator capacitor between 220pF and 1000pF
and calculate the oscillator resistor

$C_{osc}$ : ………. pF

$$\boxed{R_{osc} = \frac{RC_{osc}}{C_{osc}}}$$

| | | |
|---|---|---|
| (11) | $R_{osc}$ | |
| (12) | $C_{osc}$ | |

- **Demag**

Set the auxilairy resistor to 220kΩ

| | | |
|---|---|---|
| (13) | $R_{aux}$ | |

- **Regulation**

Set $R_{reg2}$ between 1kΩ and 10kΩ

$$\boxed{R_{reg1} = \left( \frac{V_o(1)}{2.5} - 1 \right) \cdot R_{reg2}}$$

| | | |
|---|---|---|
| (14) | $R_{reg1}$ | |
| (15) | $R_{reg2}$ | |

- **Supply**

Set the supply capacitor to 470nF.

The breakdown voltage for the diode is equal to the maximum DC voltage (5)

| | | |
|---|---|---|
| (14) | $C_{Vcc}$ | |
| (15) | $V_{br,Dvcc}$ | |

# 5 Demo board

A small demo board is build in order to demonstrate the basic operation of the STARplug controller. The requirements for this application are:

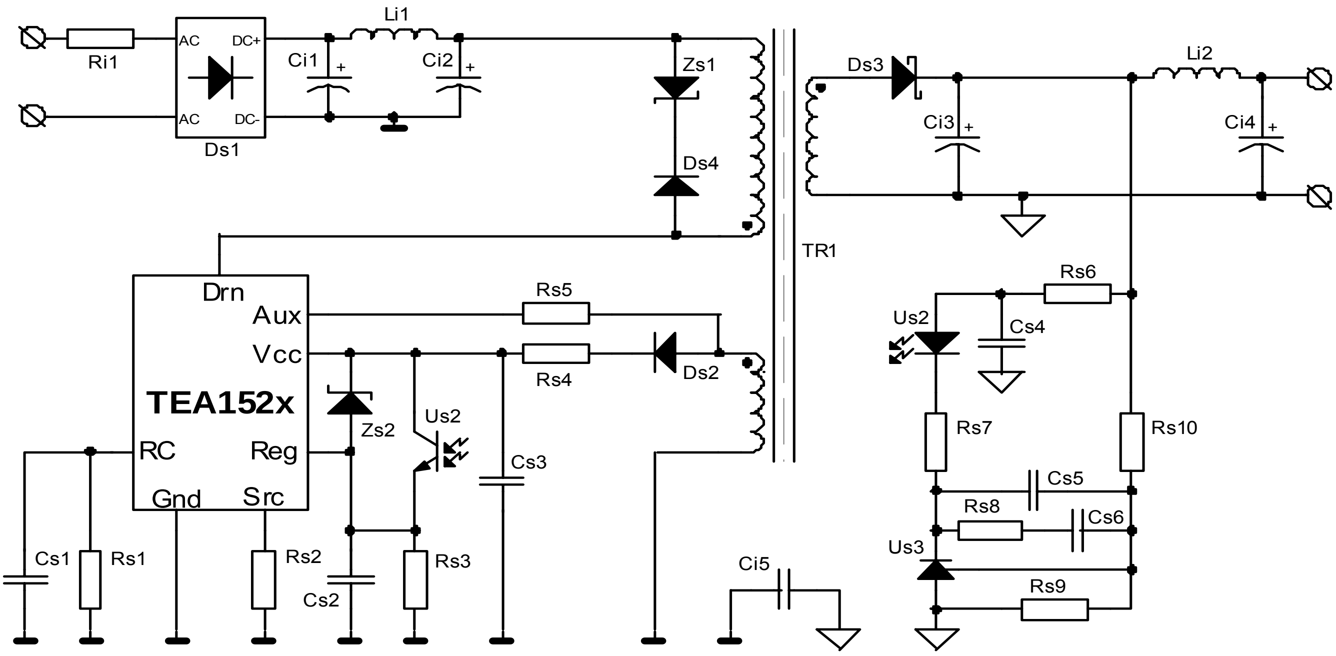
**Input**
Voltage range : Universal mains ($80V_{AC}$…$276V_{AC}$)
Frequency : 50 / 60Hz ± 10%
Standby power : < 100mW (full range)
Net transients : High-energy transient (1kV/50µs)

**Output**
Voltage : 5V / ± 2%
Current : 600 mA
Power : 3 Watt

The narrow output voltage tolerance requires a secondary regulated (TL431) system.
Furthermore, the maximum switching frequency of the converter is set to approximately 100kHz.
The efficiency of the whole converter must be as high as possible. This makes the use of a schottky diode on the secondary side necessary.

## 5.1 Schematic

Below, the electrical circuit diagram of the STARplug demo board is shown, a secondary regulated voltage source.



In the left upper corner, the mains input section is found. This part of the circuit rectifies and filters the mains voltage. The output section is found in the right upper corner. Below the output section, the regulation part can be found. This circuit measures the output voltage and compares it with the reference voltage of Us3. If there is an error, this is communicated to the primary side of the circuit via the opto-coupler. The STARplug with the control components is placed on the left lower corner.

An **O**ver **V**oltage **P**rotection is built in by the zener diode Zs2. In case the opto-coupler fails, the output voltage of the converter increases. Via the turns ratio $N_a/N_s$ of the transformer, this can be seen on the supply voltage of the IC. In case the supply voltage is too high (= high output voltage), the zener diode will take over the regulation.

A list of all used components is shown below.

### Odd components

| Ref. | Describion | Value | Ordering Code | Manufacture | Internet |
|---|---|---|---|---|---|
| Ri1 | Fusistor | KNP 1W 5% 47E | C152M43Y5UQYFSP | TyOhm | www.tyohm.com.tw |
| Ci1 | Elco | 6,8uF / 400V / 105°C / BXA | 400 BXA 6E8 M 10x16 | Rubycon | www.rubycon.co.jp |
| Ci2 | Elco | 4,7uF / 400V / 105°C / YXA | 400YXA 4E7 M 10x16 | Rubycon | |
| Ci3 | Elco | 330uF / 16V / 20% / 105°C / ZA | 16 ZA 330 M 10x12.5 | Rubycon | |
| Ci4 | Elco | 120uF / 16V / 20% / 105°C / JXA | 16 JXA 120 M 6.3x11 | Rubycon | |
| CI5 | Y1-cap | Y1-Cap / 2.2n / 20% / 250V | 2251 837 51227 | Philips | www.bccomponents.com |
| Li1 | Inductor | SP0508 / 1mH / 10% / 190mA | SPT0508A-102KR19 | TDK | www.tdk.com |
| Li2 | Inductor | SP0508 / 10uH / 10% / 1900 mA | SPT0508A-100K1R9 | TDK | |
| Con1 | Connector | MTA-100 / 3 pins | 640454-3 | AMP | connect.amp.com |
| Con2 | Connector | MTA-100 / 2 pins | 640454-2 | AMP | |
| Tr1 | Transformer | CE133t or CE135t (E13/7/4) $L_p$=1.8mH / $N_p$=134 / $N_s$=8 / $N_a$=22 | Custom made transformer | Philips Ovar (Portugal) | |

### SMD components

| Ref. | Describion | Value | Ordering Code | Manufacture | |
|---|---|---|---|---|---|
| Rs1 | Resistor | RC11 / 7.5k / 2% | 2322 730 31752 | Philips | www.acm.components.philips.com |
| Rs2 | Resistor | RC11 / 2.0E / 2% | 2322 730 31208 | Philips | |
| Rs3 | Resistor | RC11 / 5.1k / 5% | 2322 730 61512 | Philips | |
| Rs4 | Resistor | RC11 / 10E / 5% | 2322 730 61109 | Philips | |
| Rs5 | Resistor | RC11 / 75k / 5% | 2322 730 61753 | Philips | |
| Rs6 | Resistor | RC11 / 1k / 5% | 2322 730 61102 | Philips | |
| Rs7 | | | | | |
| Rs8 | Resistor | RC11 / 22k / 5% | 2322 730 61223 | Philips | |
| Rs9 | Resistor | RC11 / 2.4k / 2% | 2322 730 31242 | Philips | |
| Rs10 | | | | | |
| Jp1 | Jumper | RC01 / Jumper 0E | 2322 711 91032 | Philips | |
| Cs1 | Capacitor | NP0 / 330p / 2% / 50V / 0805 | 2238 861 14331 | Philips | www.acm.components.philips.com |
| Cs2 | Capacitor | X7R / 100n / 20% / 16V / 0805 | 2222 780 15749 | Philips | |
| Cs3 | Capacitor | Y5V / 470n / 20% / 50V / 1206 | 2238 581 19716 | Philips | |
| Cs4 | Capacitor | X7R / 47n / 20% / 16V / 0805 | 2222 780 15745 | Philips | |
| Cs6 | | | | | |
| Cs5 | Capacitor | X7R / 10n / 20% / 25V / 0805 | 2222 910 15736 | Philips | |
| Ds1 | Diode | Diode bridge 600V / 1A | S1ZB60 | Shindengen | www.shindengen.co.uk |
| Ds2 | Diode | BAV101 / SOD80C | 9336 993 40115 | Philips | www..philips.semiconductors.com |
| Ds3 | Diode | STPS340U / 40V / 3A / DO-214AA | STPS340U | Stmicroelectronics | us.st.com |
| Ds4[1] | Diode | BYD37J / SOD87 | 9338 123 00115 | Philips | www.philips.semiconductors.com |
| Zs1[1] | Zener | BZD27-C160 / SOD87 | 9338 677 60115 | Philips | |
| Zs2 | Zener | Zenerdiode / 22V / 2% / 500mW | 9339 317 70115 | Philips | |
| Us1 | STARplug | TEA152x | | Philips | www.STARplug.com |
| Us2 | Optocoupler | SFH6106-2 option 9 | SFH6106-2 X009T | Siemens | www.infineon.com |
| Us3 | Reference | Voltage Reference TL431/SOD89 | TL431CPK | Texas Intruments | www.ti.com |

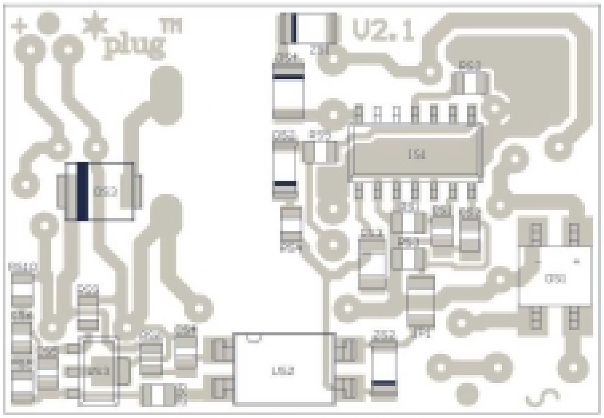
---

[1] Philips has developed a special SMD device, which is called ZENBLOCK. This device contains an anti-series connection of a high voltage blocking diode and a high voltage zener diode. This device can replace the two components ZS1 and DS4.

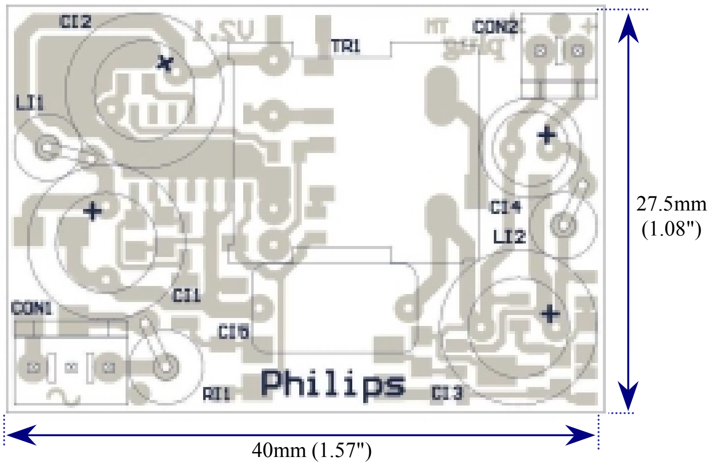
## 5.2 PCB

In order to fit the whole application on a small PCB, both SMD and trough hole components are used. The layout and component positions are shown on the next pictures.

**Bottom side**



**Top side**



## 5.3 Measurements

### No load performance

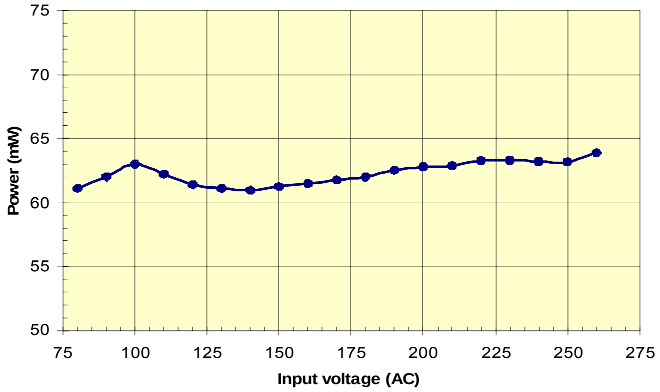


*Figure 16: No load input power consumption*

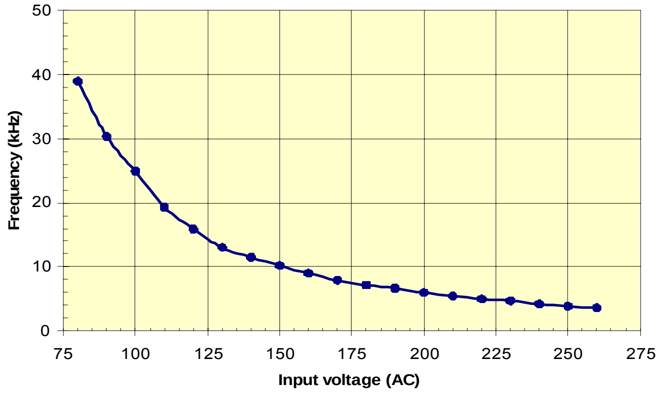


*Figure 15: No load switching frequency*

### Efficiency

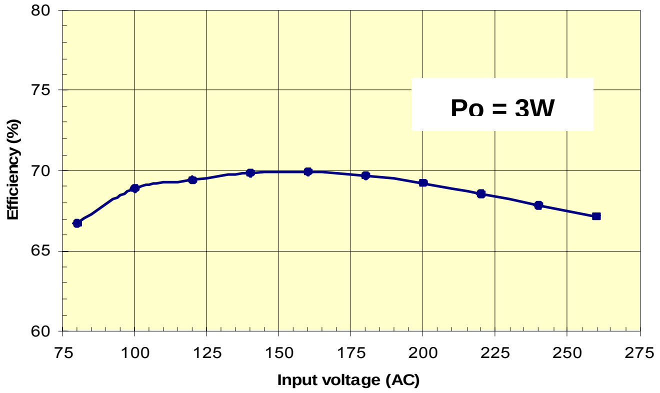


*Figure 17: Efficiency versus input voltage ($P_o$=3W)*

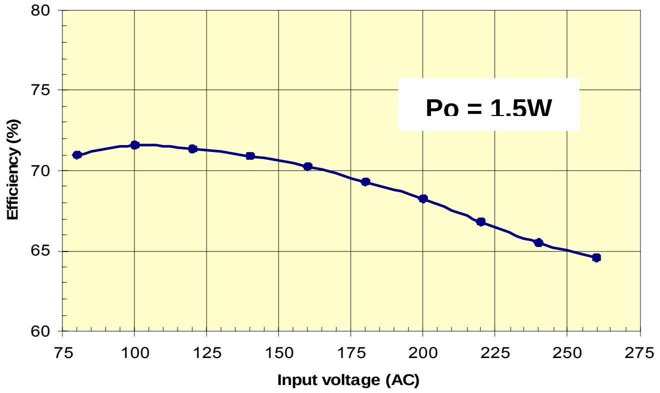


*Figure 18: Efficiency versus input voltage ($P_o$=1.5W)*

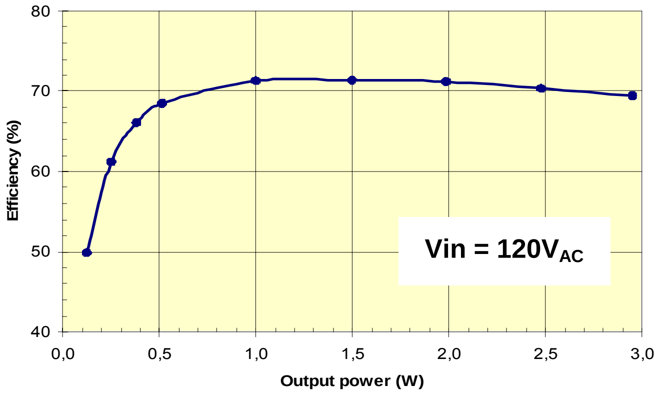


*Figure 19: Efficiency versus output power ($V_{in}$=120$V_{AC}$)*

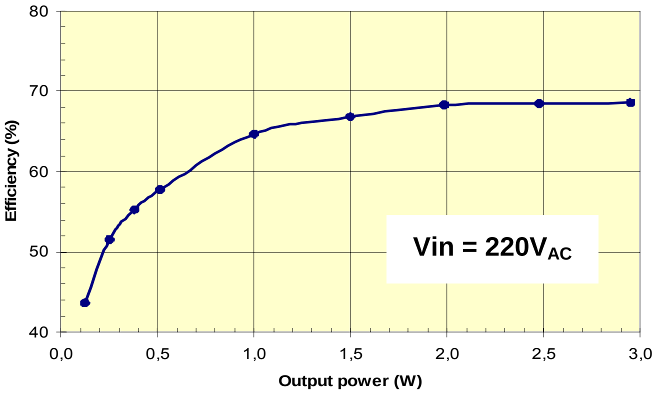


*Figure 20: Efficiency versus output power ($V_{in}$=220$V_{AC}$)*

## Regulation

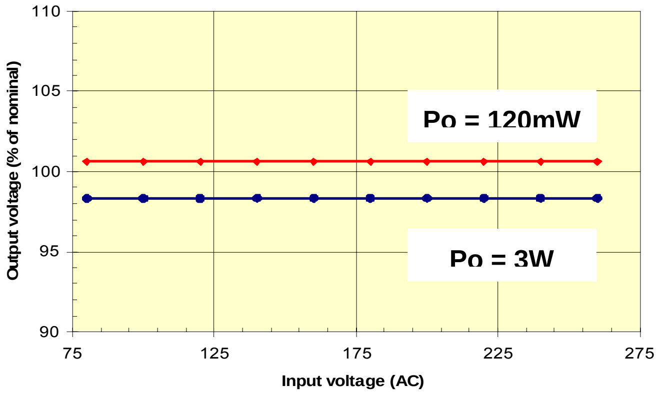


*Figure 21: Line regulation*

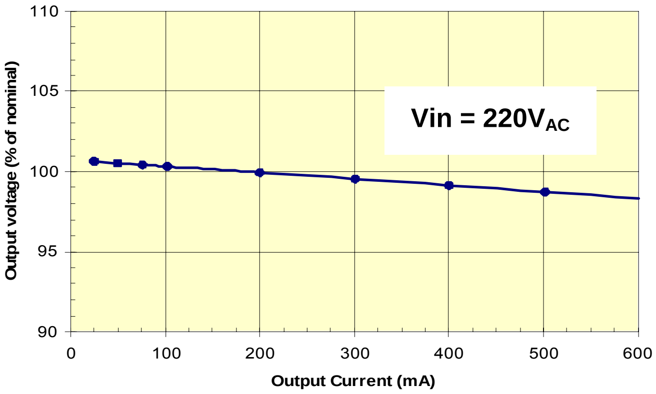


*Figure 22: Load regulation*

## Frequency behavior

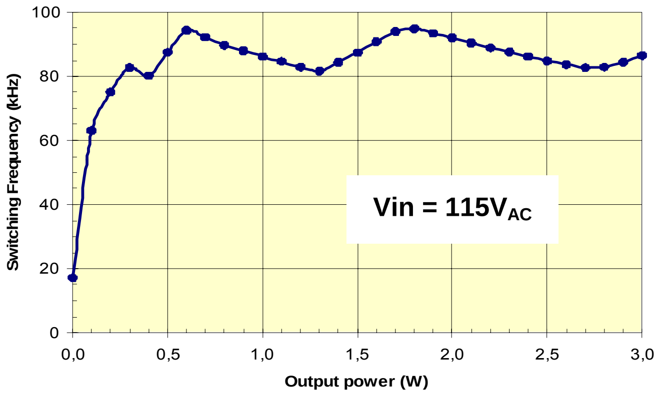


*Figure 23: Switching frequency (Vin=115$V_{AC}$)*

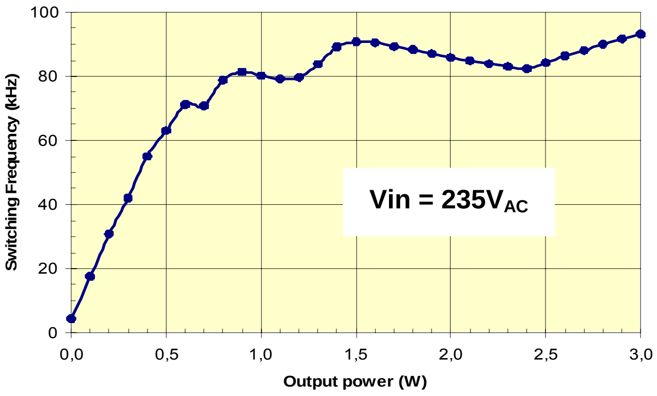


*Figure 24: Switching frequency (Vin=235$V_{AC}$)*

## Turn-on delay

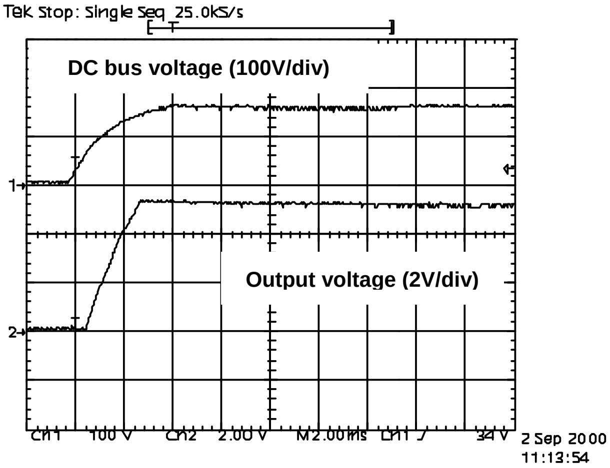


*Figure 25: Turn-on delay ($R_o=\infty\Omega$ / $V_{in}$ = 115$V_{AC}$)*

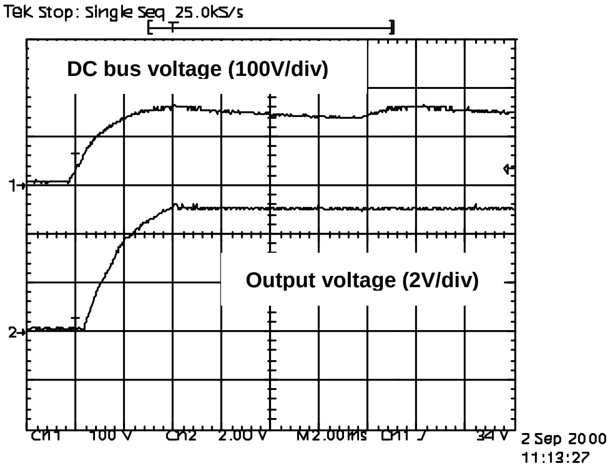


*Figure 26: Turn-on delay ($R_o$=7.5$\Omega$ / $V_{in}$ = 115$V_{AC}$)*

## Output voltage ripple

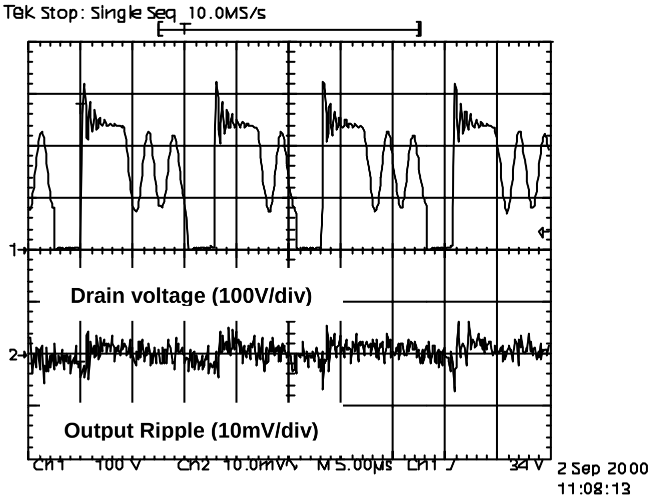


*Figure 27: Output Switching ripple ($P_o$=3W / $V_{in}$ = 115$V_{AC}$)*

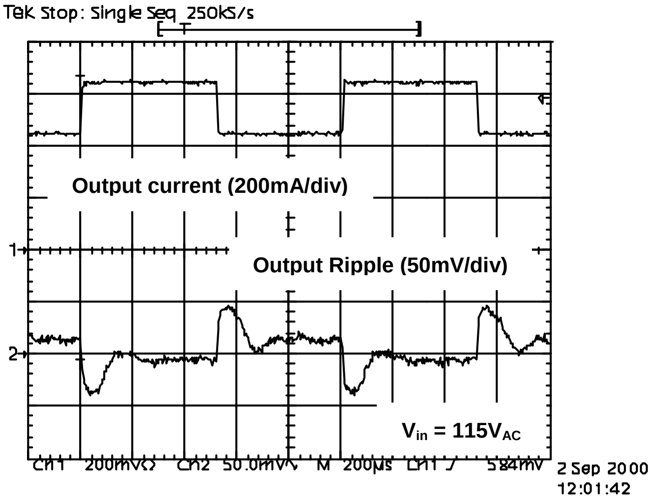


*Figure 28: Transient load response (75% to 100%)*

# *Philips Semiconductors – a worldwide company*

**Argentina:** see South America

**Australia:** 3 Figtree Drive, HOMEBUSH, NSW 2140,
Tel. +61 2 9704 8141, Fax. +61 2 9704 8139

**Austria:** Computerstr. 6, A-1101 WIEN, P.O. Box 213,
Tel. +43 1 60 101 1248, Fax. +43 1 60 101 1210

**Belarus:** Hotel Minsk Business Center, Bld. 3, r. 1211, Volodarski Str. 6,
220050 MINSK, Tel. +375 172 20 0733, Fax. +375 172 20 0773

**Belgium:** see The Netherlands

**Brazil:** see South America

**Bulgaria:** Philips Bulgaria Ltd., Energoproject, 15th floor,
51 James Bourchier Blvd., 1407 SOFIA,
Tel. +359 2 68 9211, Fax. +359 2 68 9102

**Canada:** PHILIPS SEMICONDUCTORS/COMPONENTS,
Tel. +1 800 234 7381, Fax. +1 800 943 0087

**China/Hong Kong:** 501 Hong Kong Industrial Technology Centre,
72 Tat Chee Avenue, Kowloon Tong, HONG KONG,
Tel. +852 2319 7888, Fax. +852 2319 7700

**Colombia:** see South America

**Czech Republic:** see Austria

**Denmark:** Sydhavnsgade 23, 1780 COPENHAGEN V,
Tel. +45 33 29 3333, Fax. +45 33 29 3905

**Finland:** Sinikalliontie 3, FIN-02630 ESPOO,
Tel. +358 9 615 800, Fax. +358 9 6158 0920

**France:** 51 Rue Carnot, BP317, 92156 SURESNES Cedex,
Tel. +33 1 4099 6161, Fax. +33 1 4099 6427

**Germany:** Hammerbrookstraße 69, D-20097 HAMBURG,
Tel. +49 40 2353 60, Fax. +49 40 2353 6300

**Hungary:** see Austria

**India:** Philips INDIA Ltd, Band Box Building, 2nd floor,
254-D, Dr. Annie Besant Road, Worli, MUMBAI 400 025,
Tel. +91 22 493 8541, Fax. +91 22 493 0966

**Indonesia:** PT Philips Development Corporation, Semiconductors Division,
Gedung Philips, Jl. Buncit Raya Kav.99-100, JAKARTA 12510,
Tel. +62 21 794 0040 ext. 2501, Fax. +62 21 794 0080

**Ireland:** Newstead, Clonskeagh, DUBLIN 14,
Tel. +353 1 7640 000, Fax. +353 1 7640 200

**Israel:** RAPAC Electronics, 7 Kehilat Saloniki St, PO Box 18053,
TEL AVIV 61180, Tel. +972 3 645 0444, Fax. +972 3 649 1007

**Italy:** PHILIPS SEMICONDUCTORS, Via Casati, 23 - 20052 MONZA (MI),
Tel. +39 039 203 6838, Fax +39 039 203 6800

**Japan:** Philips Bldg 13-37, Kohnan 2-chome, Minato-ku,
TOKYO 108-8507, Tel. +81 3 3740 5130, Fax. +81 3 3740 5057

**Korea:** Philips House, 260-199 Itaewon-dong, Yongsan-ku, SEOUL,
Tel. +82 2 709 1412, Fax. +82 2 709 1415

**Malaysia:** No. 76 Jalan Universiti, 46200 PETALING JAYA, SELANGOR,
Tel. +60 3 750 5214, Fax. +60 3 757 4880

**Mexico:** 5900 Gateway East, Suite 200, EL PASO, TEXAS 79905,
Tel. +9-5 800 234 7381, Fax +9-5 800 943 0087

**Middle East:** see Italy

**Netherlands:** Postbus 90050, 5600 PB EINDHOVEN, Bldg. VB,
Tel. +31 40 27 82785, Fax. +31 40 27 88399

**New Zealand:** 2 Wagener Place, C.P.O. Box 1041, AUCKLAND,
Tel. +64 9 849 4160, Fax. +64 9 849 7811

**Norway:** Box 1, Manglerud 0612, OSLO,
Tel. +47 22 74 8000, Fax. +47 22 74 8341

**Pakistan:** see Singapore

**Philippines:** Philips Semiconductors Philippines Inc.,
106 Valero St. Salcedo Village, P.O. Box 2108 MCC, MAKATI,
Metro MANILA, Tel. +63 2 816 6380, Fax. +63 2 817 3474

**Poland**: Al.Jerozolimskie 195 B, 02-222 WARSAW,
Tel. +48 22 5710 000, Fax. +48 22 5710 001

**Portugal:** see Spain

**Romania:** see Italy

**Russia:** Philips Russia, Ul. Usatcheva 35A, 119048 MOSCOW,
Tel. +7 095 755 6918, Fax. +7 095 755 6919

**Singapore:** Lorong 1, Toa Payoh, SINGAPORE 319762,
Tel. +65 350 2538, Fax. +65 251 6500

**Slovakia:** see Austria

**Slovenia:** see Italy

**South Africa:** S.A. PHILIPS Pty Ltd., 195-215 Main Road Martindale,
2092 JOHANNESBURG, P.O. Box 58088 Newville 2114,
Tel. +27 11 471 5401, Fax. +27 11 471 5398

**South America:** Al. Vicente Pinzon, 173, 6th floor,
04547-130 SÃO PAULO, SP, Brazil,
Tel. +55 11 821 2333, Fax. +55 11 821 2382

**Spain:** Balmes 22, 08007 BARCELONA,
Tel. +34 93 301 6312, Fax. +34 93 301 4107

**Sweden:** Kottbygatan 7, Akalla, S-16485 STOCKHOLM,
Tel. +46 8 5985 2000, Fax. +46 8 5985 2745

**Switzerland:** Allmendstrasse 140, CH-8027 ZÜRICH,
Tel. +41 1 488 2741 Fax. +41 1 488 3263

**Taiwan:** Philips Semiconductors, 5F, No. 96, Chien Kuo N. Rd., Sec. 1,
TAIPEI, Taiwan Tel. +886 2 2134 2451, Fax. +886 2 2134 2874

**Thailand:** PHILIPS ELECTRONICS (THAILAND) Ltd.,
60/14 MOO 11, Bangna Trad Road KM. 3, Bagna, BANGKOK 10260,
Tel. +66 2 361 7910, Fax. +66 2 398 3447

**Turkey:** Yukari Dudullu, Org. San. Blg., 2.Cad. Nr. 28 81260 Umraniye,
ISTANBUL, Tel. +90 216 522 1500, Fax. +90 216 522 1813

**Ukraine**: PHILIPS UKRAINE, 4 Patrice Lumumba str., Building B, Floor 7,
252042 KIEV, Tel. +380 44 264 2776, Fax. +380 44 268 0461

**United Kingdom:** Philips Semiconductors Ltd., 276 Bath Road, Hayes,
MIDDLESEX UB3 5BX, Tel. +44 208 730 5000, Fax. +44 208 754 8421

**United States:** 811 East Arques Avenue, SUNNYVALE, CA 94088-3409,
Tel. +1 800 234 7381, Fax. +1 800 943 0087

**Uruguay:** see South America

**Vietnam:** see Singapore

**Yugoslavia:** PHILIPS, Trg N. Pasica 5/v, 11000 BEOGRAD,
Tel. +381 11 3341 299, Fax.+381 11 3342 553

**For all other countries apply to:** Philips Semiconductors,
Marketing Communications, Building BE-p, P.O. Box 218, 5600 MD EINDHOVEN,
The Netherlands, Fax. +31 40 27 24825

**Internet:** http://www.semiconductors.philips.com

SCB70

Let's make things better.

**Philips**
**Semiconductors**

PHILIPS