AN00055

STARplug efficient low power supply

Rev. 02 — 4 June 2009 **Application note**

Document information

Info	Content
Keywords	TEA152x, STARplug, Portable products, AC/DC conversion, DC/DC conversion, High efficiency, Flyback converter, Standby supply, Low power standby, Cellular phones, GSM chargers
Abstract	This application note describes the application of TEA152x flyback controller as follows: • Provides simple guidelines for creating an efficient AC/DC conversion. • Describes the basic operation of a standard flyback or Buck converter. • Gives a general description of the TEA152x (STARplug) controller. • Gives a step-by-step design procedure for a flyback and Buck converter. • Describes the performance of the small demoboard (5 V/3 W).

founded by Philips

Revision history

Rev	Date	Description
02	20090604	• The format of this data sheet has been redesigned to comply with the new identity guidelines of NXP Semiconductors. • Legal texts have been adapted to the new company name where appropriate.
01	-	First issue

Contact information

For more information, please visit: **http://www.nxp.com**

For sales office addresses, please send an email to: **salesaddresses@nxp.com**

1. Introduction

This document explains the operation and application of the STARplug flyback converter.

This chapter describes the contents of this application note and the purpose of each chapter. Every chapter covers a self contained topic, most of which 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 flyback 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 Section 2 "Flyback and buck topology; theory and operation" the basic operation of a flyback converter is described 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 flyback or Buck converters can be found in electronic reference books.

Section 3 "Functional description" serves as background information about the STARplug features in general.

The actual application design is covered by Section 4 "General step-by-step design procedure", which provides a guide through the design procedure. With this chapter it is easy to achieve a successful flyback or Buck converter design.

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

2. Flyback and buck topology; theory and operation

This section describes the operation of the isolated flyback converter and the non-isolated Buck (down) converter.

2.1 Flyback converter

In many applications isolation from the mains is necessary for safety. The flyback converter does not need an additional inductive element for mains isolation because the inductor itself can be provided with an additional winding for mains isolation. In comparison with the push-pull and the forward converter the flyback converter is a less expensive and a simpler system. It is a single circuit needing only one inductive element.

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

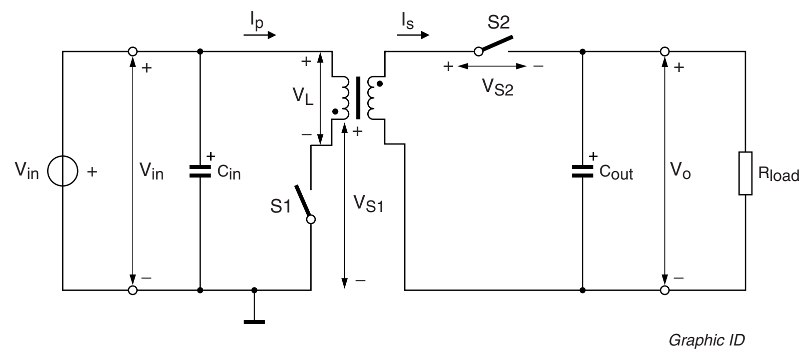


Fig 1. Basic flyback converter

The circuit is defined by the state of the switches. There are four possible modes with the two switches, 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 the discontinuous conduction mode. Mode 4 must be prevented. The configuration of the switches for the four different modes is displayed in Table 1.

Table 1. Mode table

Mode	S1	S2	Duration
1	On	Off	δ_1.T
2	Off	On	δ_2.T
3	Off	Off	δ_3.T
4	On	On	δ_4.T

Figure 2 shows the equivalent circuit diagrams for the three applicable modes. Simplified waveforms for one complete switching cycle are also shown.

Information about the exact operation can be found in electronic reference books.

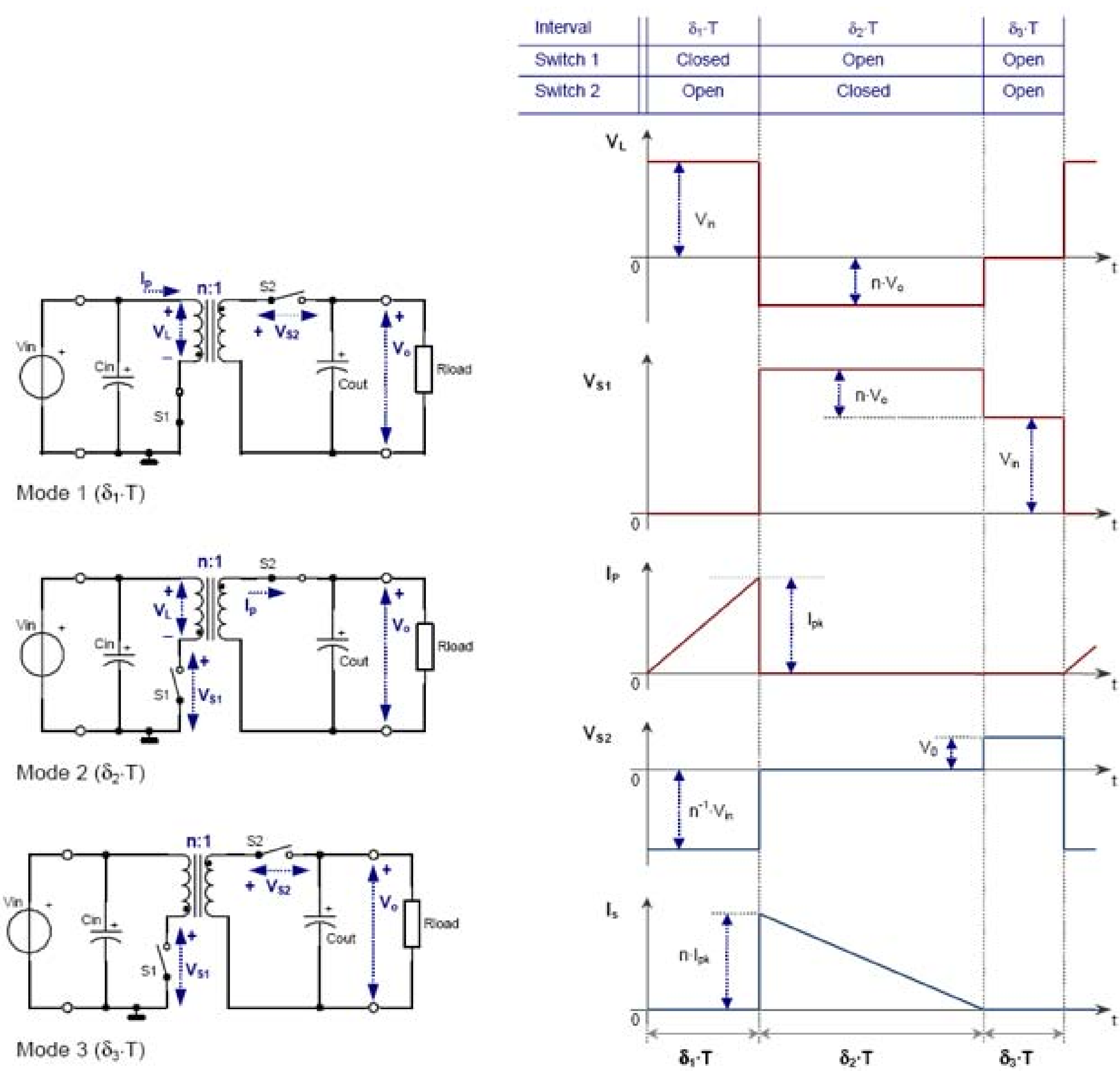


Fig 2. Flyback converter modes of operation

During the time δ_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 the discontinuous conduction mode. The border between the discontinuous conduction mode and the continuous conduction mode is reached when the time δ_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 instead of a transformer with (at least) two windings as used in the flyback converter.

Figure 3 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.

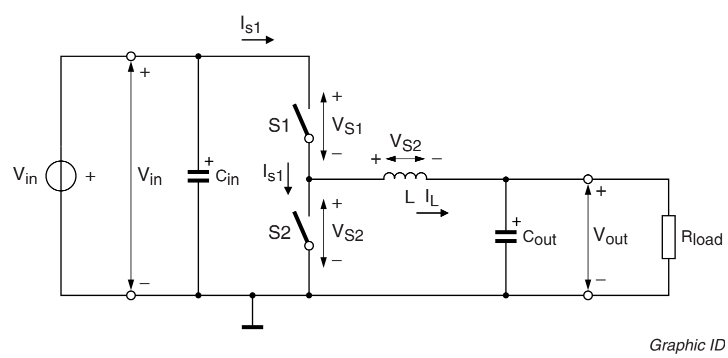


Fig 3. Basic Buck converter

The polarity of relevant voltages and currents is also included in this diagram. For a 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.

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 the discontinuous conduction mode. Mode 4 must be prevented. The state of the switches in the different modes is displayed in Table 2.

Table 2. Table of possible modes

Mode	S1	S2	Duration
1	On	Off	δ_1.T
2	Off	On	δ_2.T
3	Off	Off	δ_3.T
4	On	On	n/a

Operation of the flyback converter is briefly explained below. Figure 4 shows the equivalent circuit diagrams for the three applicable modes. Simplified waveforms for one complete switching cycle are also shown.

Information about the exact operation can readily be found in electronic reference books.

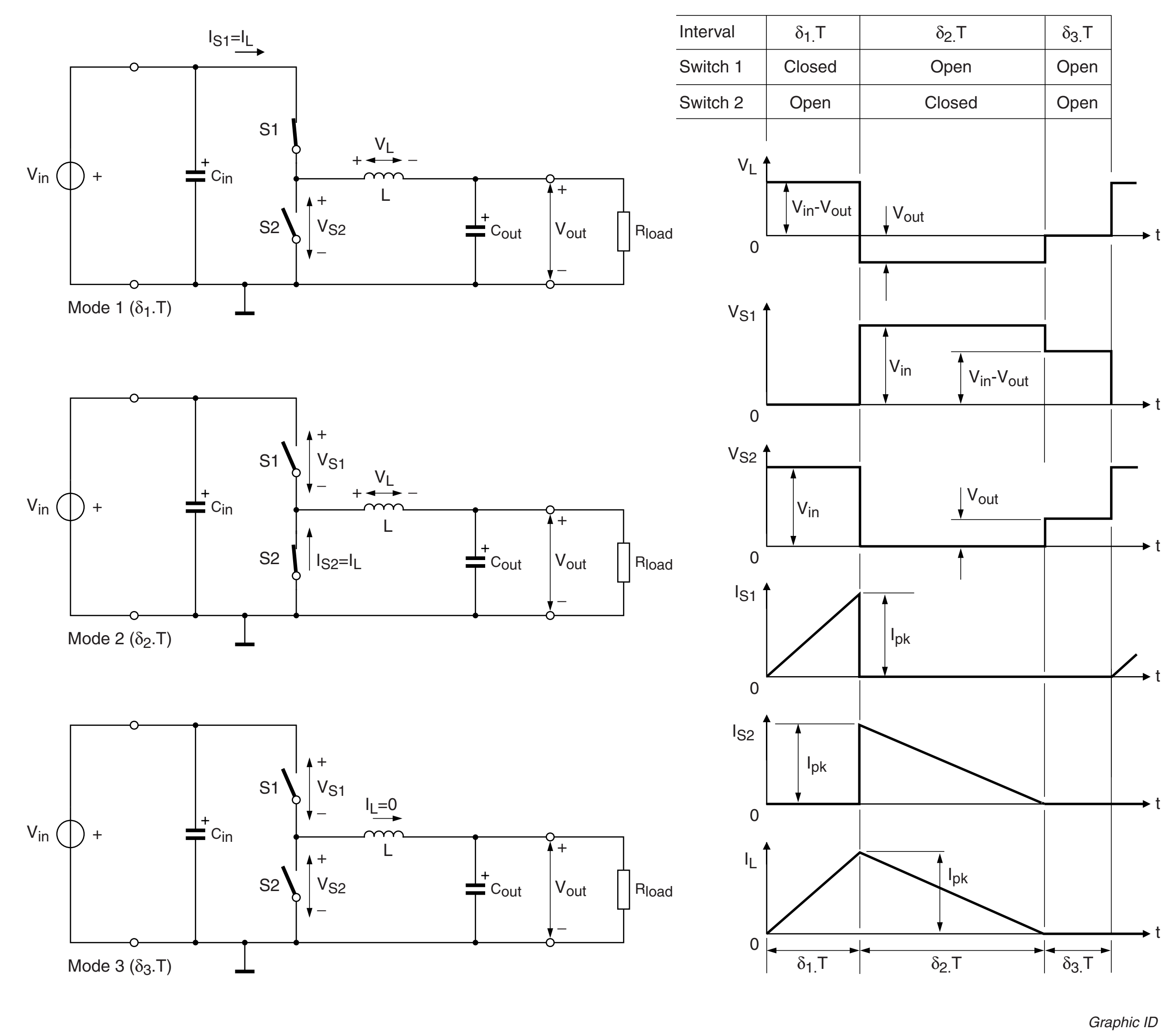


Fig 4. Buck converter modes of operation

During the time δ1.T (mode 1) switch S1 is switched on and an increasing current starts to flow through the inductor towards the output. When switch S1 is switched off, the inductor current flows through 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 the inductor has decreased to zero.

The mode of operating just described is called the discontinuous conduction mode. The border between the discontinuous conduction mode and the continuous conduction mode is reached when the time δ3.T has become zero seconds.

3. Functional description

This chapter serves as background information. It describes the features and control mechanism of the STARplug controller. Most features can be identified in Figure 5.

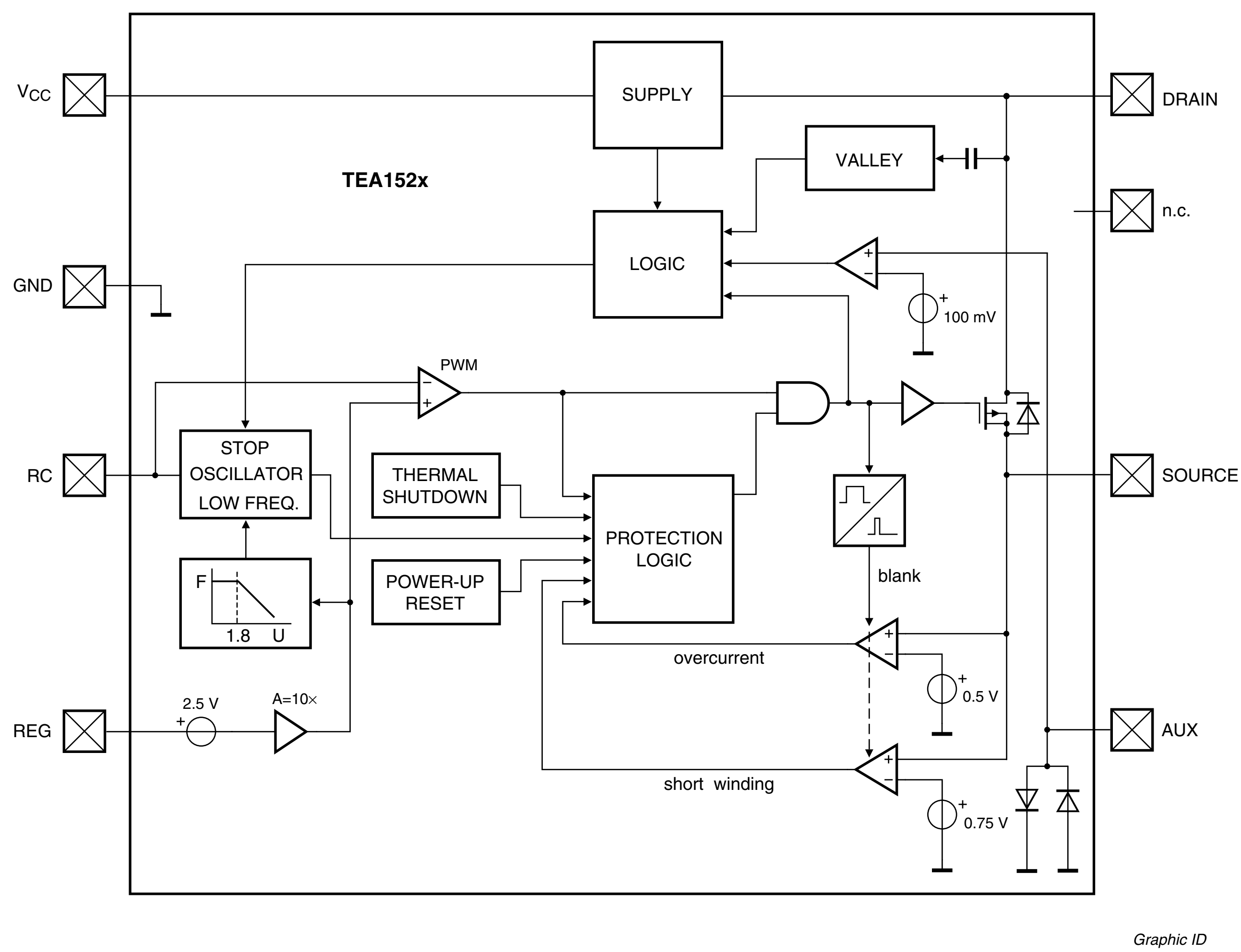


Fig 5. STARplug block diagram

3.1 Start-up and UnderVoltage LockOut (UVLO)

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 V_{CC} pin. The STARplug starts switching as soon as the voltage on the V_{CC} pin passes the $V_{CC\text{-}start}$ level.

The supply drawn from the drain pin of the IC is, for high efficiency operation, stopped and taken over by the auxiliary winding of the transformer as soon as the V_{CC} voltage is high enough.

When the auxiliary supply is not sufficient, the internal high voltage supply will also supply the IC. As soon as the voltage on the V_{CC} 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 onboard power switch. The switch is capable to withstand 650 V 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_{DSon}) of the MOS transistor depends on the type of STARplug that is chosen. See the data sheet for more information.

3.3 Oscillator

A parallel connection of a capacitor and a resistor to the RC pin sets 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 discharged by the resistor to the $V_{RC\text{-}min}$ level. As soon as the $V_{RC\text{-}min}$ level has been reached, the capacitor is charged again. The switching frequency is calculated with Equation 1.

$$\frac{1}{f_{sw}} = t_{charge} + R_{osc} \cdot C_{osc} \cdot 1n\left(\frac{V_{RC-max}}{V_{RC-min}}\right) \quad (1)$$

The frequency is reduced as soon as the switching duty cycle drops below a certain value. The reduction in frequency is accomplished by increasing the charge time of the oscillator.

3.4 Control mechanism

The STARplug uses voltage mode control. The conduction time of the internal MOS transistor, and therefore also the primary peak current, is modulated through the transformer (= converted power). This method of controlling the primary peak current is called Pulse Width Modulation (PWM). The implementation is shown in Figure 6.

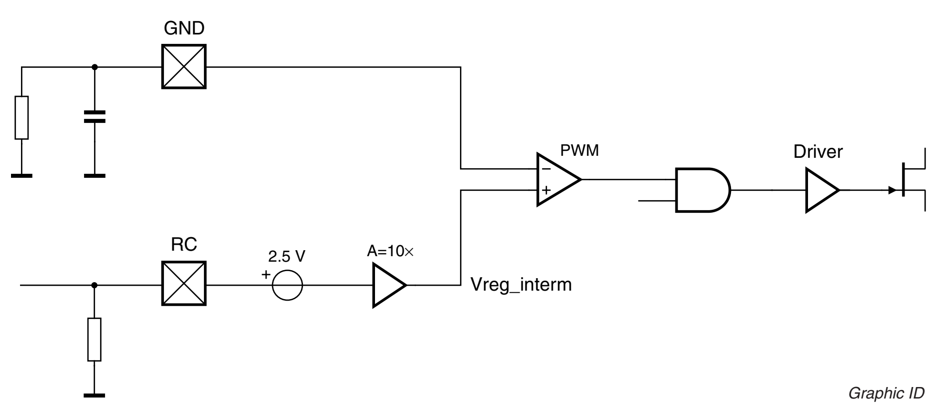


Fig 6. STARplug regulation mechanism

3.4.1 PWM control

The internal regulation voltage (V_{reg_intern}) is equal to the difference between the external regulation voltage and the internal voltage source (2.5 V) multiplied by 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 7 visualizes this mechanism of controlling the conduction time of the MOST.

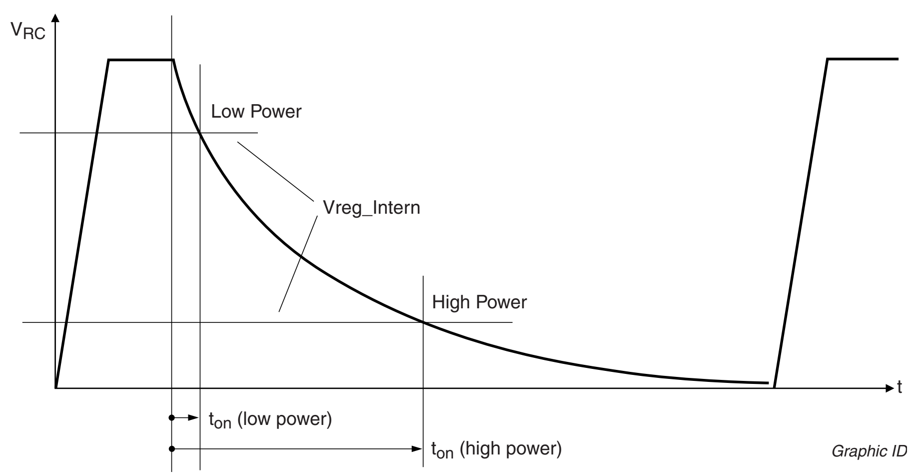


Fig 7. Regulation mechanism

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 140 mV). The maximum conduction time of the power MOS transistor is calculated with Equation 2.

$$t_{on-max} = R_{osc} \cdot C_{osc} \cdot 1n\left(\frac{V_{RC-max}}{V_{RC-min}}\right) \quad (2)$$

3.4.3 Minimum duty cycle

The minimum duty cycle is 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 8, results in a variation of the conduction time of the MOS transistor. 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.

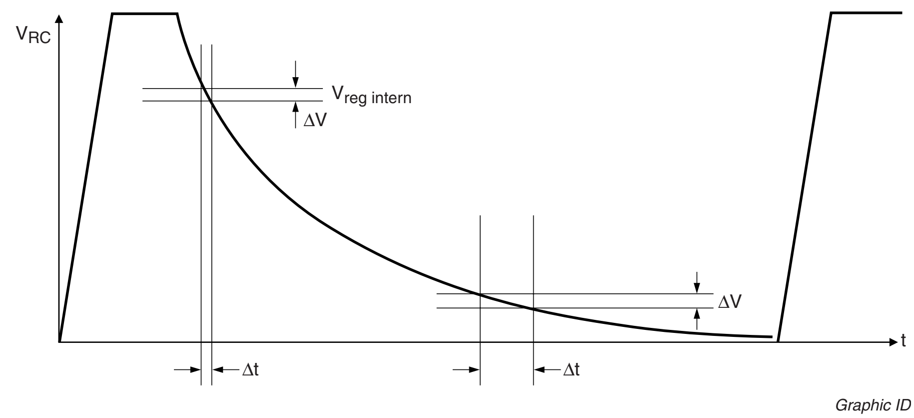


Fig 8. Regulation mechanism

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 ensures stable operation at low duty cycle levels.

3.5 Demagnetization

The STARplug will always operate in discontinuous conduction mode.

The auxiliary winding of the transformer is connected to the AUX pin of the STARplug 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 the AUX pin depends on the auxiliary winding voltage of the transformer.

As long as the secondary 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 100 mV, the oscillator will not start a new primary stroke.

Demagnetization recognition is suppressed during the t_{suppr} time. This time starts when switching off the integrated power MOS transistor. Especially for applications with low output voltages and transformers with a large leakage induction this might be necessary to prevent a false demagnetization detection. t_{suppr} time starts when switching off the power MOS transistor.

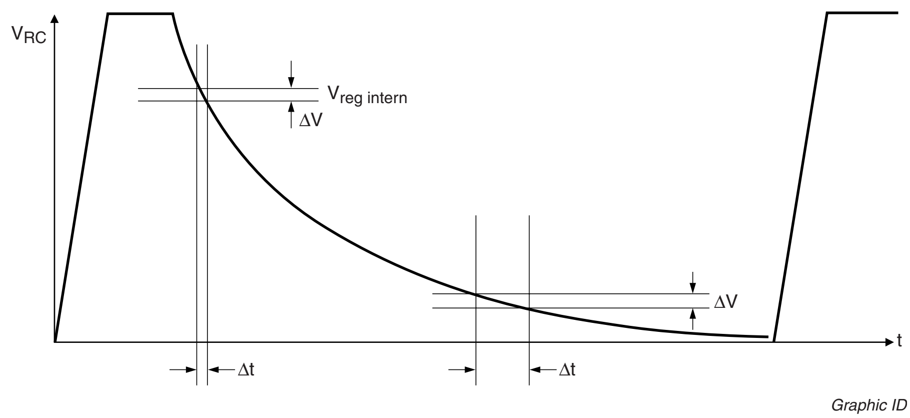
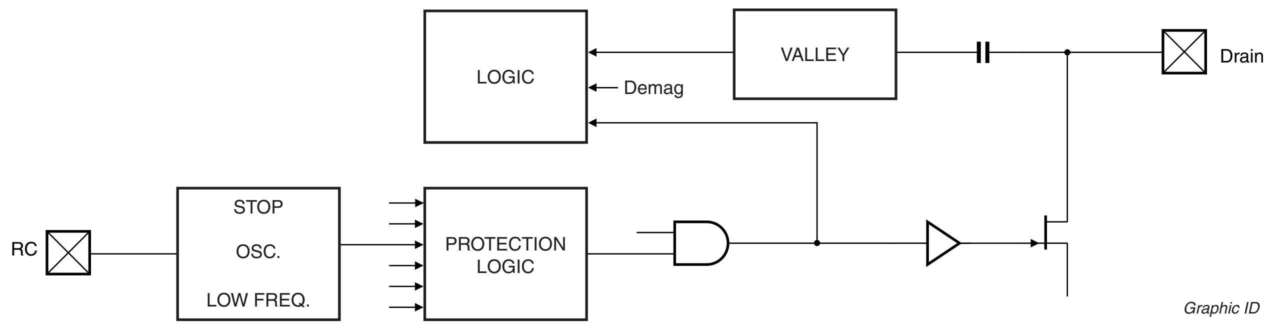


Fig 9. Demagnetization circuit

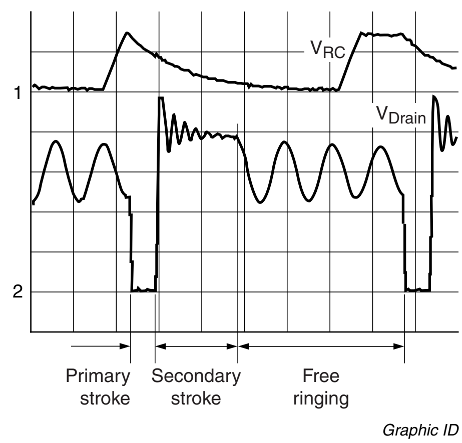
3.6 Valley switching

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

Minimizing the switch-on losses of the power MOS transistor increases the efficiency of the converter. See Figure 10 and Figure 11.



a. Circuit



b. Graph

Fig 10. Valley switch circuit

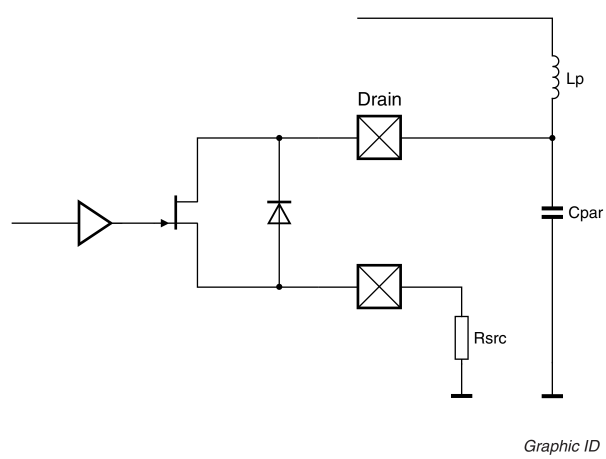


Fig 11. Components at the drain pin

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 Section 3.4.1). Now 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 demagnetization function. Due to the inductance of the primary transformer 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.

As soon as the oscillator is ready ($V_{RC} = V_{RC\text{-}max}$) and the secondary stroke has ended (V_{AUX} < 100 mV), 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).

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

$$P_{switch-on} = \frac{1}{2} \cdot C_{par} \cdot V_{DRAIN}^{2} \cdot f_{Switching} \tag{4}$$

The power MOS transistor can be switched on just before (at low ringing frequencies) or just after (at high ringing frequencies) the actual valley. For a flyback application with a reflected output voltage (nV_{out}) of 80 V, a typical curve is drawn in Figure 12.

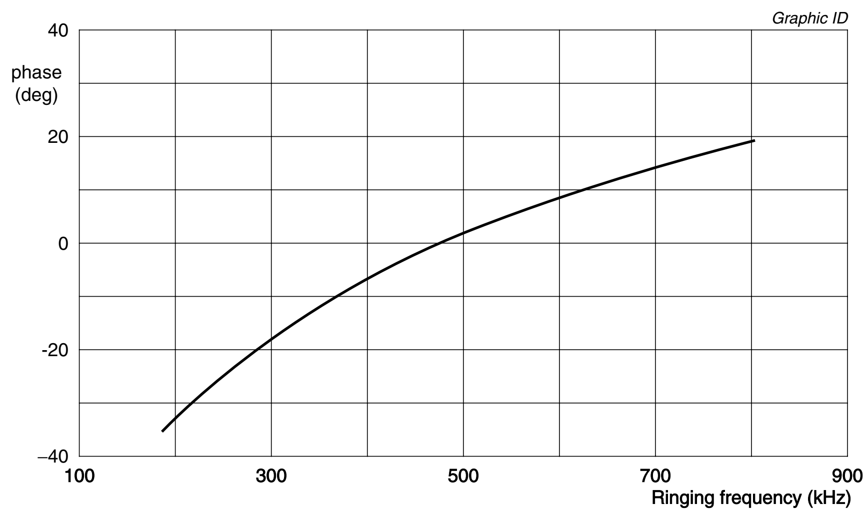


Fig 12. Typical switch-on angle (at nV_{out} = 80 V)

Figure 12 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 the 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 comparators. With these two comparators two types of current protections are implemented in the STARplug. See Section 3.7.1 and Section 3.7.2.

3.7.1 OverCurrent 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 0.5 V). To prevent a false OCP detection at switching on the power MOS transistor, the comparator is disabled during the t_{LEB} time (typical 350 ns).

3.7.2 Short Winding Protection (SWP)

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

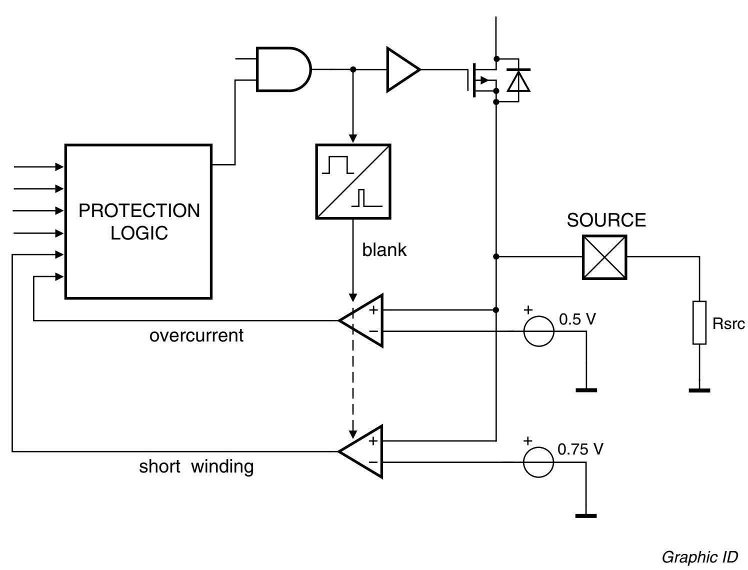


Fig 13. Current protections

3.8 OverTemperature Protection (OTP)

An accurate temperature protection is provided with the STARplug. When the junction temperature exceeds the thermal shut-down 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 flyback or Buck converter with the STARplug.

4.1 Designing the basic STARplug application

Figure 14 shows the most basic application using the STARplug. This application behaves like a primary regulated voltage source.

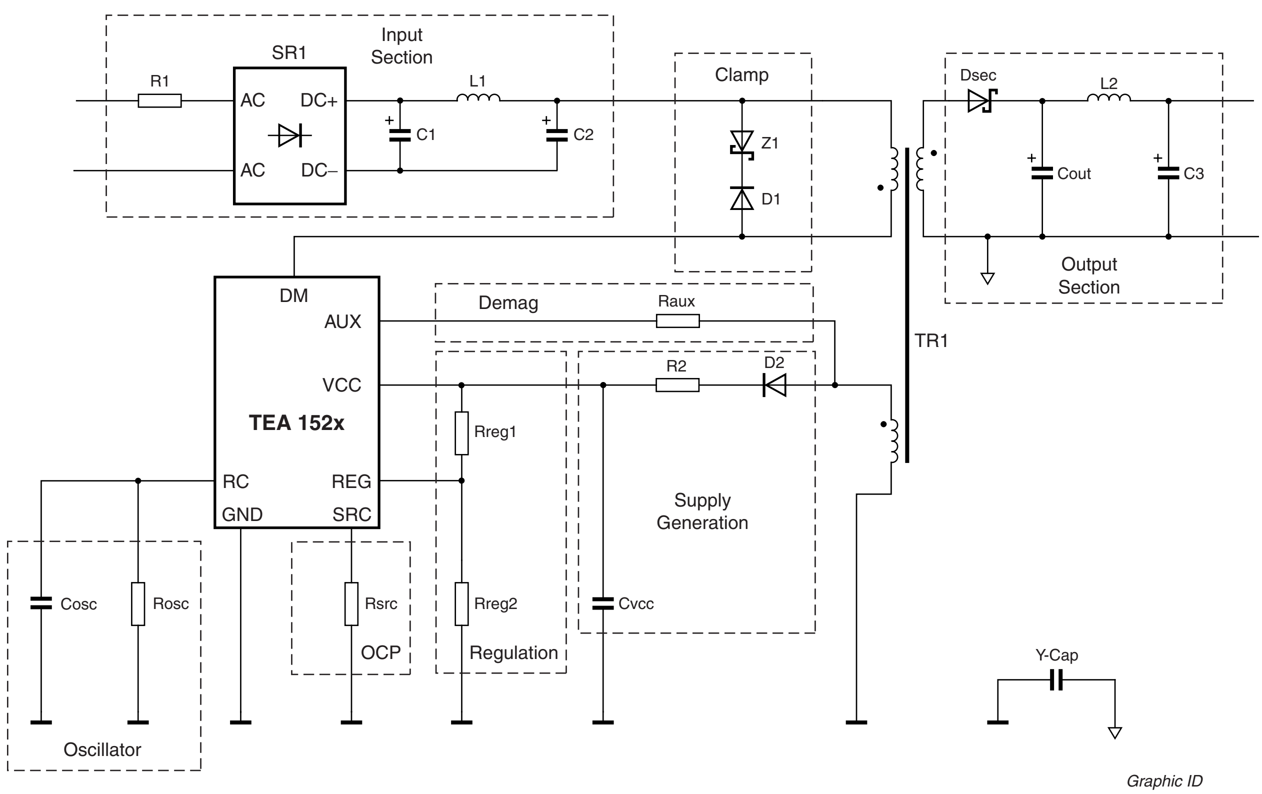


Fig 14. Basic STARplug application

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 and SWP
- Regulation
- 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 voltage overshoot that is too high on the drain pin of the STARplug when the internal power MOS transistor is switched off.

4.1.1 Input section

4.1.1.1 Determine system requirements

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

- Minimum and maximum AC input voltage

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

Table 3. Input voltage ranges

Input voltage range	$V_{AC\text{-}min}$	$V_{AC\text{-}max}$
110 V	80 V (AC)	135 V (AC)
230 V	195 V (AC)	276 V (AC)
Universal mains	80 V (AC)	276 V (AC)

- Frequency of the mains

  The frequency mentioned is the minimum line frequency possible. Tolerances are included.
- Required output power and voltage
- Estimated efficiency

  Efficiency loss due to output diode:

  The voltage drop across the output diode effects the efficiency of the whole converter. An increase in the voltage drop across the output diode results in a decrease of the efficiency of the converter.

  If the output voltage is below about 7 V and high efficiency is required, use a Schottky Barrier diode or a Fast PN diode.

  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 primary winding of the transformer is required 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.

  Efficiency loss due to other components:

  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.

$$P_{loss,\,Dout}\,(\%) = \frac{V_{f,\,Dout}}{V_o} \cdot 100\ \% \qquad (5)$$

PN diode: $V_{f,Dout} = 0.7$ V

Schottky diode: $V_{f,Dout} = 0.5$ V

Table 4. Clamp/snubber efficiency loss

	Power range	Efficiency loss
RC snubber	$P_o < 3$ W	20 %
RCD clamp	Full range	15 %
Zener clamp	Full range	10 %

$$\eta = \frac{100 - P_{loss,\,diode} - P_{loss,\,clamp} - P_{loss,\,additional}}{100} \quad (6)$$

4.1.1.2 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 7. For almost all diode bridge rectifiers, the IFSM parameter is about 20 A.

$$R_{inrush} = \frac{\sqrt{2} \cdot V_{AC,\,max}}{I_{FSM}} \quad (7)$$

4.1.1.3 Calculate the minimum DC voltage

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

- The total buffer capacitance

  Select the C_{buf} multiplier from Table 5 and determine the total input capacitance $C_{buf,tot}$.

Table 5. C_{buf} multipliers

Input voltage range	C_{buf} (μF/W)
110 V	3
230 V	1
Universal mains	3

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

- 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 3 ms.

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

$$V_{DC,\,min} = \sqrt{2 \cdot V_{AC-min}^{\;2} - \frac{2 \cdot P_o \cdot \left(\frac{1}{2 \cdot f_{mains}} - t_c\right)}{\eta \cdot C_{buf,\,tot}}} \quad (9)$$

4.1.1.4 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 an additional voltage increase due to mains transients ($\Delta V_{transient}$).

The first part is easily defined by Equation 10.

$$V_{pk,\,mains} = \sqrt{2} \cdot V_{ac,\,max} \tag{10}$$

The second part is more difficult to determine. See Equation 11.

$$\Delta V_{transient} = V_{tran,\,pk} \cdot \frac{\alpha}{\alpha - \beta} \cdot \left(e^{-\frac{\beta}{\alpha-\beta} \cdot 1n\left(\frac{\alpha}{\beta}\right)} - e^{-\frac{\alpha}{\alpha-\beta} \cdot 1n\left(\frac{\alpha}{\beta}\right)} \right) \tag{11}$$

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

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

The equations for calculating the voltage increase due to a transient are not practical. A more convenient method is applying Figure 15. This figure shows the increase in DC supply voltage as a function of the input filter time constant ($R_{inrush} \times C_{buf,tot}$) for a high energy mains transient (1 kV/50 μs).

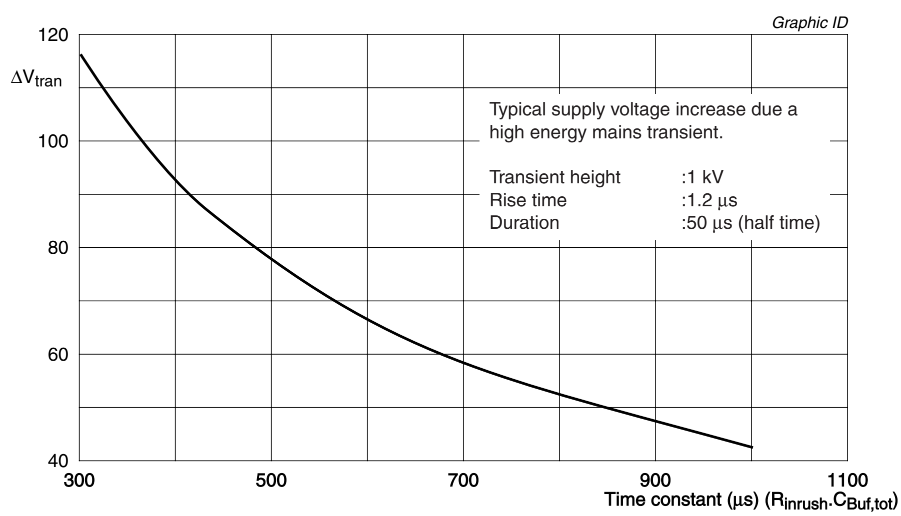


Fig 15. Supply voltage increase due to mains transient

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

$$V_{DC,\,max} = V_{pk,\,mains} + \Delta V_{tran} \tag{12}$$

Check if the maximum DC bus voltage exceeds the 475 V. 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:

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

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 integrated power MOS transistor of the STARplug. Since the power MOS transistor is not avalanche rugged, a small safety margin is added (a V_{margin} of 25 V is sufficient).

$$V_{clamp,max} = BV_{DSS} - V_{DC,max} - V_{margin} \quad (13)$$

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 10 kHz and 200 kHz. Common switching frequencies that are used are 40 kHz to 50 kHz and 100 kHz.

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} = 1 μs).

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

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 220 pF 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 200 kHz and C_{osc} = 10 nF a power 12.5 mW is dissipated in the oscillator).

Example:

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

4.1.4 OCP resistor

The OCP resistor (R_{src}) sets 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.

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

In this equation the new variable nV_{out} represents the reflected output voltage. At this moment, no transformer parameters are available. A suitable value for nV_{out} can be found when the clamp voltage, calculated with Equation 13, is divided by approximately 1.5. In practical situations a nV_{out} of 80 V up to 120 V is often used.

The capacitor C_{par} is represents the parasitic drain capacitance. A typical value for C_{par} is 100 pF.

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

$$R_{src} \leq \frac{V_{src-max}}{I_p} \tag{16}$$

Example:

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

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 air gap in the center leg of an E-core.

4.1.5.1 Calculate the primary inductance

The inductance value (L_p) of the primary winding (N_p) is calculated with Equation 17:

$$L_p = \frac{2 \cdot P_o}{\eta \cdot I_p^{\ 2} \cdot f_{switch}} \tag{17}$$

4.1.5.2 Selecting the core type

If a core fits the application is determined by the maximum stored energy in the transformer together with the required air gap. A core with a large air gap can store more energy in its ferried material than a core with a small air gap. Also the spread on the primary inductance (L_p) of the transformer will be lower for wide air gaps. The disadvantage of a wide air gap 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 air gap for a flyback transformer is about 100 μm up to 300 μm.

With Equation 18 the maximum energy stored in the transformer is calculated:

$$E_{core} = I^2 L = I_p^{\ 2} \cdot L_p \tag{18}$$

Select a suitable core from Table 6. Use Equation 19 as selection criteria:

$$E_{core(100\ \mu m)} \leq E_{core} \leq E_{core(300\ \mu m)} \tag{19}$$

Table 6. Core selection table

Maximum E_{core} (mJ) for		Core type	Effective core area A_e (mm^2)
l_{gap} = 100 μm	l_{gap} = 300 μm		
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 only contains 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 330 mA (Equation 15) and the primary inductance equals 1.5 mH (Equation 17), the maximum stored energy E_{core} equals 0.163 mJ. The following E-cores can be used: E13 and E16 types.

4.1.5.3 Determine the air gap

The length of the required air gap can be calculated with Equation 20:

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

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

Example:

Core type: E13/7/4 (A_e = 12.4 mm^2)

I_p: 330 mA

L_p = 1.5 mH

B_{max} = 275 mT

The air gap length will be 0.1 mm = 100 μm

4.1.5.4 Primary winding count

Determine the number of primary winding with Equation 21:

$$N_p = \frac{B_{max} \cdot l_g}{4 \cdot \pi \cdot I_p} \cdot 10^4 \tag{21}$$

4.1.5.5 Secondary winding count

Apply Equation 22 for the number of secondary windings:

$$N_s = N_p \cdot \frac{V_o + V_{f,Dsec}}{nV_{out}} \tag{22}$$

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

4.1.5.6 Auxiliary winding count

The number of windings for the auxiliary output of the transformer 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 40 V. To prevent the internal high voltage supply from supplying the IC a minimum V_{CC} voltage of 13 V is acceptable. A practical V_{CC} value is 20 V.

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

$$N_a = N_s \cdot \frac{V_{CC} + V_{f,Daux}}{V_o + V_{f,Dsec}} \tag{23}$$

Normally the auxiliary diode is a General Purpose PN-diode. The voltage drop across the PN diode is 0.7 V. 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 the primary and the secondary regulations is possible. In case of the 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 flyback 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 turn ratio N_a/N_s of the transformer. The supply voltage is calculated with Equation 24:

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

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:

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

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 10 kΩ.

4.1.7 Demagnetization

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 5 mA and 10 mA. 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:

$$R_{AUX} \approx 7 \cdot nVout\ (k\Omega) \quad (26)$$

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 1 μF is required (470 nF 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:

$$V_{br,\,Daux} = \frac{N_a}{N_p} \cdot V_{dc,\,max} \quad (27)$$

The transformer parameters N_a and N_p are determined in Section 4.1.4 and the maximum DC voltage in Section 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 100 Ω to 560 Ω.

4.1.9 Output section

4.1.9.1 Output diode

What kind of diode will be used (PN or Schottky) is decided in Section 4.1.1. Equation 28 can be used to determine the minimum breakdown voltage for the diode:

$$I_{\mathrm{pk,Dsec}} = \frac{N_p}{N_a} \cdot I_p \quad (28)$$

$$I_{\mathrm{pk,Dsec}} = \frac{N_p}{N_a} \cdot I_p \qquad \text{See Equation 15 for } I_p \quad (29)$$

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

$$t_{fb} = \frac{N_s \cdot L_p}{N_p \cdot (V_o + V_{\mathrm{f,Dsec}})} \cdot I_{\mathrm{pk,Dsec}} \quad (30)$$

$$I_{\text{avg,Dsec}} = \frac{N_p}{N_a} \cdot I_p \cdot t_{fb} \cdot f_{switch} \quad (31)$$

4.1.9.2 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.

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

4.1.9.3 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.

$$LC = \frac{100}{(\pi \cdot f_{switch})^2} \quad (33)$$

$$L_{filter} = \frac{LC}{C_{filter}} \quad (34)$$

4.1.10 Flyback converter formula overview

4.1.10.1 Select input voltage range

Table 7. Select input voltage range

Input voltage range	$V_{AC\text{-}min}$	$V_{AC\text{-}max}$	C_{buf} (μF/W)	For equations
110 V	80 V (AC)	135 V (AC)	3	(1) = $V_{ac,max}$
230 V	195 V (AC)	276 V (AC)	1	(2) = $V_{ac,min}$
Universal mains	80 V (AC)	276 V (AC)	3	(3) = C_{buf}

4.1.10.2 Mains frequency

Table 8. Mains frequency

Line frequency (f_{line}): … Hz	
Tolerance (tol): … %	
$f_{mains} = \left(1 - \frac{tol}{100}\right) \cdot f_{line}$	(4) = f_{mains}

4.1.10.3 Output

Table 9. 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

4.1.10.4 Estimate efficiency

Table 10. Output diode voltage drop

($V_{f,Dout}$): … V

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

Table 11. Snubber / clamp losses

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

Additional losses are about 5 %.

Table 12. Calculate system efficiency

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

(8) = η

4.1.10.5 Total buffer capacitance

Table 13. Total buffer capacitance

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

(9) = $C_{buf,tot}$

4.1.10.6 Minimum DC supply voltage

Table 14. Minimum DC supply voltage

Set conduction time bridge rectifier:

t_c = 3 ms

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

(10) = $V_{DC,min}$

4.1.10.7 Inrush resistor

Table 15. Inrush resistor

Get the non-repetitive peak forward current rating (I_{FSM}) of the bridge

Rectifier diodes (commonly used 20 A)

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

(11) = R_{inrush}

4.1.10.8 Maximum DC voltage

Table 16. Maximum DC voltage

a) Peak mains voltage

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

b) Transient influence. A typical transient is defined as:

Height: V_{tran} = 1 kV

Half-time: t_{tran} = 50 µs

(12) R_{inrush}

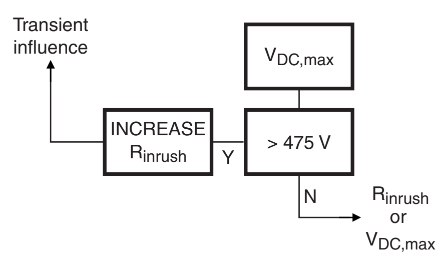
$$\begin{cases} \Delta V_{transient} = V_{tran,\,pk} \cdot \dfrac{\alpha}{\alpha - \beta} \cdot \left(e^{-\frac{\beta}{\alpha-\beta} 1n\left(\frac{\alpha}{\beta}\right)} - e^{-\frac{\alpha}{\alpha-\beta} 1n\left(\frac{\alpha}{\beta}\right)} \right) \\ \alpha = \dfrac{1}{R_{inrush} \cdot C_{buf,\,tot}}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

c) Calculate $V_{DC,\,max}$

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

(13) $V_{DC,max}$

d) Check $V_{DC,max}$



4.1.10.9 Maximum peak clamp voltage

Table 17. Maximum peak clamp voltage

Breakdown voltage (BVDSS) = 650 V

Marginal voltage (V_{margin}) = 25 V

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

(14) $V_{cl,max}$

4.1.10.10 Oscillator

Table 18. 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 220 pF and 1000 pF and calculate the oscillator resistor:

C_{osc}: ... pF

Table 18. Oscillator *…continued*

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

4.1.10.11 Reflected output voltage

Table 19. Reflected output voltage

Typical values for nV_{out}:	
$80\ V \leq nV_{out} \leq 120\ V$	
$nVout \approx \frac{Vclamp}{1.5}$	(18) nV_{out}

4.1.10.12 Primary peak current

Table 20. Primary peak current

C_{par} represents the parasitic capacitor on the drain node (typical value 100 pF)
$I_p = f_{switch}(17) \cdot \left(\frac{2 \cdot P_o(5)}{\eta(8) \cdot f_{switch}(17)} \cdot \left(\frac{1}{V_{DC,\,min}(10)} + \frac{1}{nVout(18)}\right) + \pi \cdot \sqrt{\frac{2 \cdot P_o(5) \cdot C_{par}}{\eta(8) \cdot f_{switch}(17)}}\right)$

4.1.10.13 Source resistor

Table 21. Source resistor

$R_{src} = \frac{0.5}{I_p}$	(19) I_p (20) R_{src}

4.1.10.14 Primary inductance

Table 22. Primary inductance

$L_p = \frac{2 \cdot P_o(5)}{\eta(8) \cdot I_p^{\,2}(19) \cdot f_{switch}(17)}$	(21) L_p

4.1.10.15 Transformer's air gap

Table 23. Transformer's air gap

Effective core area (A_e): … mm^2	
Maximum flux density (B_{max}): … mille-tesla (Typical value for B_{max} = 275 mille-tesla)	
$I_{gap}(mm) = \frac{4 \cdot \pi \cdot L_p(21) \cdot I_p^{\,2}(19) \cdot 10^8}{A_e \cdot B_{max}^{\,2}}$	(22) I_{gap}

4.1.10.16 Primary winding

Table 24. Primary winding

$N_p = \frac{B_{max} \cdot I_{gap}(22)}{4 \cdot \pi \cdot I_p(19)} \cdot 10^4$	(23) N_p

4.1.10.17 Secondary winding

Table 25. Secondary winding

$$N_s = N_p(23) \cdot \frac{V_o(6) + V_{\mathrm{f,\,Dsec}}}{nVout(18)}$$	(24) N_s

4.1.10.18 Auxiliary winding

Table 26. Auxiliary winding

Set V_{CC} to 20 V	
Set $V_{f,Daux}$ to 0.7 V	
$$N_a = N_s(24) \cdot \frac{V_{CC} + V_{f,\,Daux}}{V_o(6) + V_{\mathrm{f,\,Dsec}}}$$	(25) N_a

4.1.10.19 Recalculate supply voltage

Table 27. Recalculate supply voltage

$$V_{CC} = \frac{N_a(25)}{N_s(24)} \cdot (V_o(6) + V_{\mathrm{f,\,Dsec}}) - V_{f,\,Daux}$$	(26) V_{CC}

4.1.10.20 Regulator resistors

Table 28. Regulator resistors

Set R_{reg2} between 1 kΩ and 10 kΩ	
$$R_{reg1} = \left(\frac{V_{CC}(26)}{2.5} - 1\right) \cdot R_{reg2}$$	(27) R_{reg1} (28) R_{reg2}

4.1.10.21 Auxiliary resistor

Table 29. Auxiliary resistor

$$R_{aux}(\mathrm{k\Omega}) \approx 7 \cdot nVout(18)$$	(29) R_{aux}

4.1.10.22 Auxiliary supply

Table 30. Auxiliary supply

Set supply capacitor 470 nF	
$$V_{br,\,Daux} = \frac{N_a(25)}{N_p(23)} \cdot V_{DC,\,max}(13)$$	(30) $V_{br,\ Daux}$

4.1.10.23 Output diode

Table 31. Output diode

Minimum required breakdown voltage:	
$$V_{\mathrm{br,\,Dsec}} = \frac{N_s(24)}{N_p(23)} \cdot V_{DC,\,max}(13)$$	(31) $V_{br,\ Dsec}$

Table 31. Output diode

Minimum required average current:

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

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

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

4.1.10.24 Output capacitor

Table 32. Output capacitor

Select a low ESR capacitor with a high ripple current specification.

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

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

4.1.10.25 Output filter

Table 33. Output filter

Select a filter capacitor and determine the filter inductance

Filter capacitor (A_e): … μF

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

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

(34) C_{filter}

(35) L_{filter}

4.2 Designing the Buck application

Figure 16 shows the application diagram of a Buck converter built up around the STARplug. This circuit is capable of producing a regulated output voltage (13 V to 40 V) directly from the rectified mains voltage. How the different blocks need to be dimensioned is explained below.

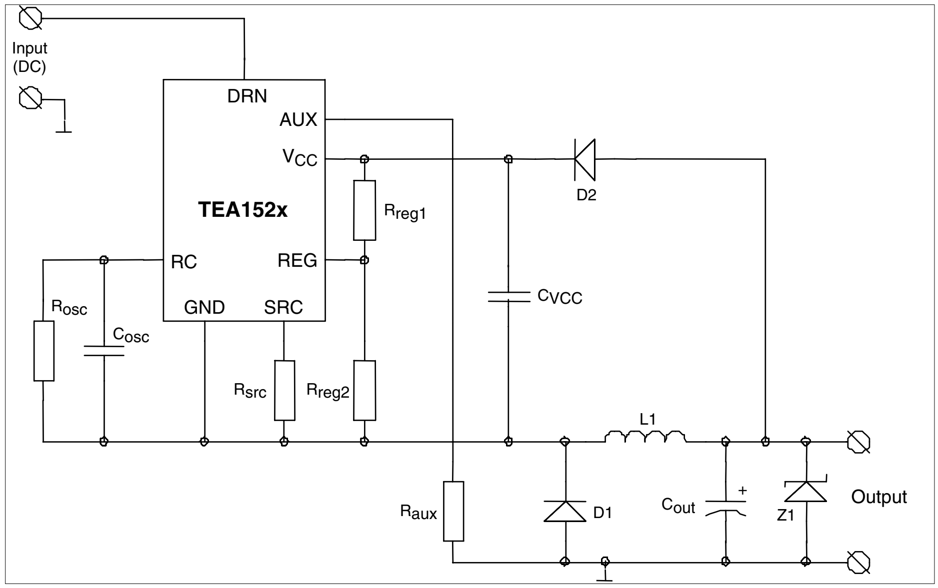


Fig 16. STARplug Buck converter

4.2.1 OverCurrent Protection (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.

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

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

4.2.2 Output section

4.2.2.1 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 ($V_{src-max}$) 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 450 ns.

$$L_{min} = \frac{(V_{DC,\,max} - V_O) \cdot V_o \cdot t_{LEB,\,max}}{2 \cdot P_{o,\,max}} \tag{36}$$

At full output power, the circuit operates on the edge of continuous 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.

$$f_{switch,\,max} \approx \frac{(V_{DC,\,max} - V_o)}{V_{DC,\,max}} \cdot \frac{V_0^{\;2}}{2 \cdot P_o \cdot L_{min}} \tag{37}$$

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 Equation 38.

$$L_{min} \approx \frac{(V_{DC,\,max} - V_o)}{V_{DC,\,max}} \cdot \frac{V_0^{\;2}}{2 \cdot P_o \cdot f_{switch,\,max}} \tag{38}$$

Example:

Buck converter with V_0 = 15 V and P_o = 5 W

Input voltage range: 80 V (DC) to 400 V (DC) and a maximum switching frequency of 50 kHz.

For an accurate OCP on the output, the minimum value for L1 is 270 μH (Equation 36). This value gives a maximum switching of 80 kHz (Equation 37). The inductance value for L1 needs to be increased to 430 μH (Equation 38) in order to achieve a maximum switching frequency of 50 kHz.

4.2.2.2 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.

4.2.2.3 Freewheeling diode

Every time the integrated power MOS transistor of the STARplug 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.

$$I_{D,\,avg} = \frac{2 \cdot P_o^{\;2}}{V_o^{\;3}} \cdot L \cdot f_{switch,\,max} \tag{39}$$

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

4.2.2.4 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 results in a transfer of too much power, which causes an increasing output voltage. The zener diode prevents the reaching unacceptable high voltages of the output.

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 = $R_{osc} \times C_{osc}$).

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

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

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

4.2.4 Demagnetization

Via the demagnetization resistor (R_{aux}) which is connected to the AUX pin of the STARplug, the circuit detects whether the freewheeling diode is still conducting. As long as this diode is conducting, no new switching cycle is started. This limits the maximum output current, in short the circuit condition.

The AUX pin is internally connected to the GND pin of the STARplug via two anti-parallel diodes. Due to these diodes, a current can flow into or out of the IC. The R_{aux} 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 10 mA.

The minimum value for this resistor can be calculated with Equation 42. Equation 41 can be used to calculate the losses in this resistor.

$$R_{aux} = \frac{V_{DC,\,max}}{I_{aux,\,max}} \tag{41}$$

$$P_{loss,\,Raux} = \frac{V_{DC,\,max}^{\;2}}{R_{aux}} \cdot \frac{2 \cdot P_o \cdot L}{V_o \cdot (V_{DC,\,max} - V_o)} \cdot f_{switch,\,max} \tag{42}$$

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

The supply voltage is provided to the REG pin of the STARplug via a resistor divider. 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} – DC = 2.5 V).

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

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

4.2.6 Buck converter formula overview

4.2.6.1 OCP resistor

Table 34. OCP resistor

Get output requirements:	
V_o = ... V	
P_o = ... W	
$I_{pk} = \frac{2 \cdot P_o}{V_o}$	(1) V_o (2) P_o
$R_{src} = \frac{0.5}{I_{pk}}$	(3) I_{pk} (4) R_{src}

4.2.6.2 Minimum inductance

Table 35. Minimum inductance

Get maximum DC voltage:	
$V_{DC,max}$ = ... V	
$t_{LEB,max}$ = 450 ns	
$L = \frac{(V_{DC,max} - V_o(1)) \cdot V_o(1)}{2 \cdot P_o(2)} \cdot t_{LEB,max}$	(5) $V_{DC,max}$ (6) L

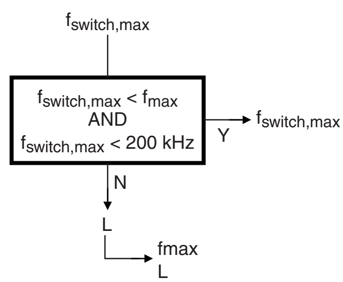
4.2.6.3 Maximum frequency

Table 36. Maximum frequency

Set maximum frequency

f_{max} = ... V

$$f_{switch,\,max} \approx \frac{(V_{DC,\,max}(5) - V_o(1))}{V_{DC,\,max}(5)} \cdot \frac{V_0{}^2(1)}{2 \cdot P_o(2) \cdot L(6)}$$ (7) $f_{switch,max}$



$$L \approx \frac{(V_{DC,\,max}(5) - V_o(1))}{V_{DC,\,max}(5)} \cdot \frac{V_0{}^2(1)}{2 \cdot P_o(2) \cdot f_{max}(8)}$$ (7) f_{max}

(6) L

4.2.6.4 Output capacitor

Table 37. Output capacitor

$$I_{ripple,\,RMS} = \frac{P_o(2)}{V_o(1)}$$ (8) $C_{out,RMS}$

4.2.6.5 Freewheeling diode

Table 38. Freewheeling diode

$$I_{D,\,avg} = \frac{2 \cdot P_o{}^2(2)}{V_o(1)} \cdot L(6) \cdot f_{switch}(7)$$ (9) $I_{D,avg}$

$$V_{br,\,min} = V_{DC,\,max}(5)$$ (10) $V_{br,min}$

4.2.6.6 Oscillator

Table 39. Oscillator

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

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

C_{osc} = ... pF

$$R_{osc} = \frac{RC_{osc}}{C_{osc}}$$ (11) R_{osc}

(12) C_{osc}

4.2.6.7 Demagnetization

Table 40. Demagnetization

Set the auxiliary resistor (R_{aux}) to 220 kΩ (13) R_{aux}

4.2.6.8 Regulation

Table 41. Regulation

Set R_{reg2} between 1 kΩ and 10 kΩ	
$R_{reg1} = \left(\frac{V_o(1)}{2.5} - 1\right) \cdot R_{reg2}$	(14) R_{reg1} (15) R_{reg2}

4.2.6.9 Supply

Table 42. Supply

Set the supply capacitor to 470 nF.	(14) C_{VCC}
The breakdown voltage for the diode is equal to the maximum DC voltage (5)	(15) $V_{br,DVCC}$

5. Demoboard

A small demoboard has been built in order to demonstrate the basic operation of the STARplug controller. The requirements for this application are:

Table 43. Application requirements

Input	Output
• Voltage range: Universal mains (80 V (AC) to 276 V (AC)). • Frequency: 50/60 Hz ± 10 % • Standby power: < 100 mW (full range) • Net transients: High-energy transient (1 kV/50 ms)	• Voltage: 5 V ± 2 % • Current: 600 mA • Power: 3 W

The narrow output voltage tolerance requires a secondary regulated (TL431) system.

Furthermore, the maximum switching frequency of the converter is set to approximately 100 kHz.

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

In Figure 17 the electrical circuit diagram of the STARplug demoboard is shown, a secondary regulated voltage source.

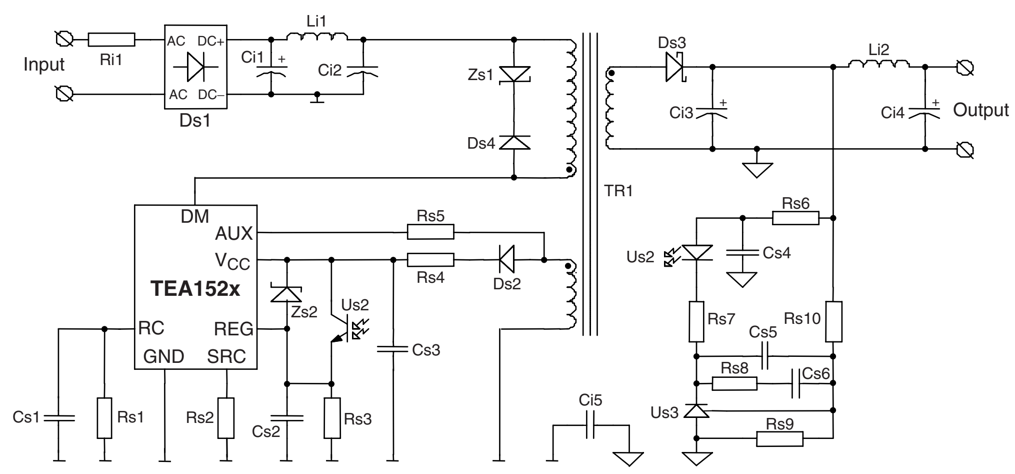


Fig 17. Schematic of STARplug

The mains input is in the upper left corner. The mains output is top right. 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 bottom corner.

An overvoltage protection is built-in by the zener diode Zs2. If the opto coupler fails, the output voltage of the converter increases. This can be seen on the supply voltage of the IC. If the supply voltage is too high (= high output voltage), the zener diode will take over the regulation.

5.1.1 List of used components

Table 44. Odd components

Ref.	Description	Value	Ordering code	Manufacturer	Internet
Ri1	Fusistor	KNP; 1 W; 5 %; 47 Ω	C152M43Y5UQYFSP	TyOhm	www.tyohm.com.tw
Ci1	Elco	6.8 µF; 400 V; 105 °C; BXA	400 BXA 6E8 M 10x16	Rubycon	www.rubycon.co.jp
Ci2	Elco	4,7 µF; 400 V; 105 °C; YXA	400YXA 4E7 M 10x16		
Ci3	Elco	330 µF; 16 V; 20 %; 105 °C; ZA	16 ZA 330 M 10x12.5		
Ci4	Elco	120 µF; 16 V; 20 %; 105 °C; JXA	16 JXA 120 M 6.3x11		
Ci5	Y1-cap	Y1-cap; 2.2 nF; 20 %; 250 V	2251 837 51227	Philips	www.bccomponents.com
Li1	Inductor	SP0508; 1 mH; 10 %; 190 mA	SPT0508A-102KR19	TDK	www.tdk.com
Li2	Inductor	SP0508; 10 µH; 10 %; 1900 mA	SPT0508A-100K1R9		

Table 44. Odd components *…continued*

Ref.	Description	Value	Ordering code	Manufacturer	Internet
Con1	Connector	MTA-100; 3 pins	640454-3	AMP	connect.amp.com
Con2	Connector	MTA-100; 2 pins	640454-2		
Tr1	Transformer	CE133t or CE135t (E13/7/4); L_p = 1.8 mH; N_p = 134; N_s = 8; N_a = 22	Custom made transformer	Philips Ovar (Portugal)	

5.1.2 SMD components

Table 45. SMD components

Ref.	Description	Value	Ordering code	Manufacturer	Internet
Rs1	Resistor	RC11; 7.5 kΩ; 2 %	2322 730 31752	Philips	www.acm.components.philips.com
Rs2	Resistor	RC11; 2.0 Ω; 2 %	2322 730 31208		
Rs3	Resistor	RC11; 5.1 kΩ; 5 %	2322 730 61512		
Rs4	Resistor	RC11; 10 Ω; 5 %	2322 730 61109		
Rs5	Resistor	RC11; 75 kΩ; 5 %	2322 730 61753		
Rs6	Resistor	RC11; 1 kΩ; 5 %	2322 730 61102		
Rs7					
Rs8	Resistor	RC11; 22 kΩ; 5 %	2322 730 61223		
Rs9	Resistor	RC11; 2.4 kΩ; 2 %	2322 730 31242		
Rs10					
Jp1	Jumper	RC01: Jumper 0 Ω	2322 711 91032		
Cs1	Capacitor	NP0; 330 pF; 2 %; 50 V; 0805	2238 861 14331		
Cs2	Capacitor	X7R; 100 nF; 20 %; 16 V; 0805	2222 780 15749		
Cs3	Capacitor	Y5V; 470 nF; 20 %; 50 V; 1206	2238 581 19716		
Cs4	Capacitor	X7R; 47 nF; 20 %; 16 V; 0805	2222 780 15745		
Cs6					
Cs5	Capacitor	X7R; 10 nF; 20 %; 25 V; 0805	2222 910 15736		
Ds1	Diode	Diode bridge 600 V; 1 A	S1ZB60	Shindengen	www.shindengen.co.uk
Ds2	Diode	BAV101; SOD80C	9336 993 40115	NXP	www.nxp.com
Ds3	Diode	STPS340U; 40 V; 3 A; DO-214AA	STPS340U	Stmicroelectronics	us.st.com

Table 45. SMD components *…continued*

Ref.	Description	Value	Ordering code	Manufacturer	Internet
Ds4[1]	Diode	BYD37J; SOD87	9338 123 00115	NXP	www.nxp.com
Zs1[1]	Zener	BZD27-C160; SOD87	9338 677 60115		
Zs2	Zener	Zenerdiode; 22 V; 2 %; 500 mW	9339 317 70115		
Us1	STARplug	TEA152x			
Us2	Opto coupler	SFH6106-2 option 9	SFH6106-2 X009T	Siemens	www.infineon.com
Us3	Reference	Voltage reference TL431/SOD89	TL431CPK	Texas Instruments	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 in Figure 18 and Figure 19.

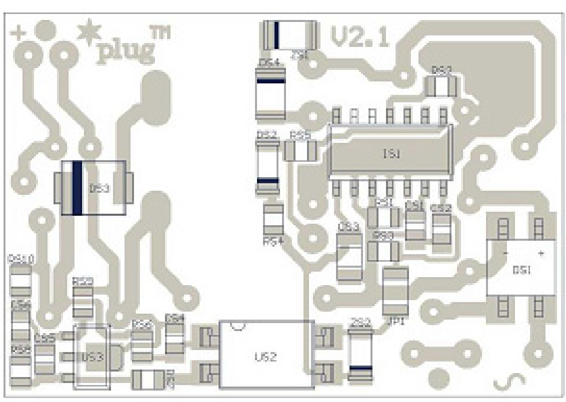


Fig 18. Bottom view

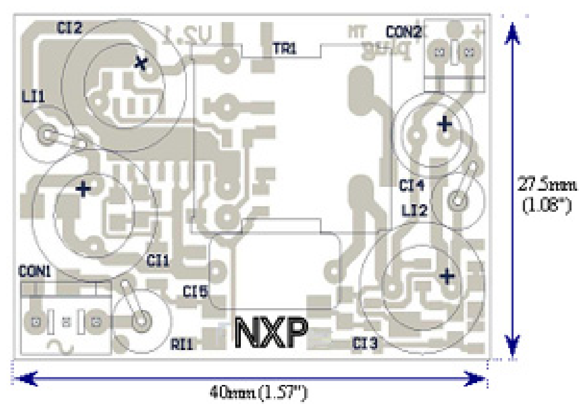


Fig 19. Top view

5.3 Measurements

5.3.1 No load performance

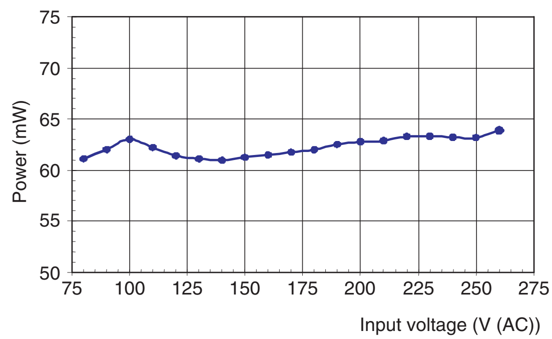


Fig 20. No load input power consumption

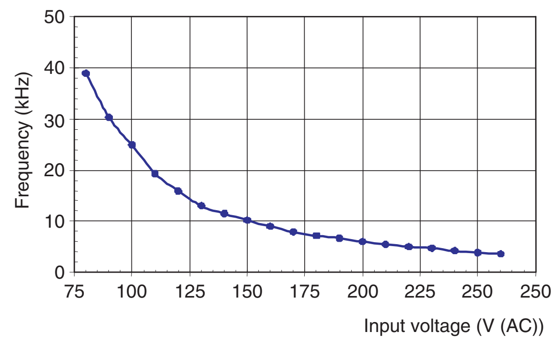


Fig 21. No load switching frequency

5.3.2 Efficiency

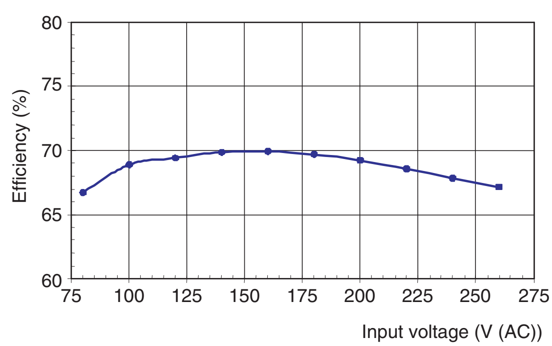


Fig 22. Efficiency versus input voltage (P_o = 3 W)

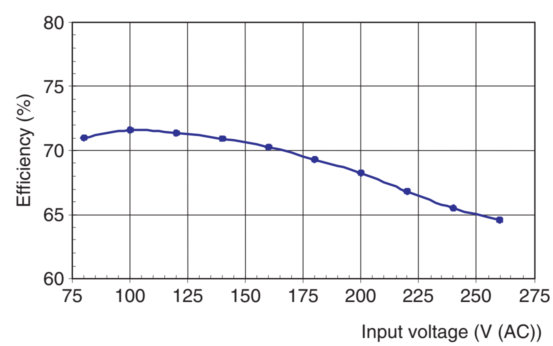


Fig 23. Efficiency versus input voltage (P_o = 1.5 W)

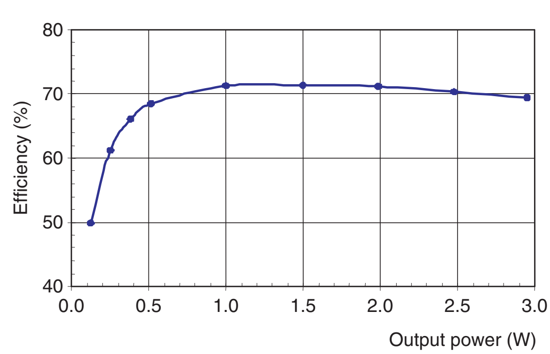


Fig 24. Efficiency versus output power (V_{in} = 120 V (AC))

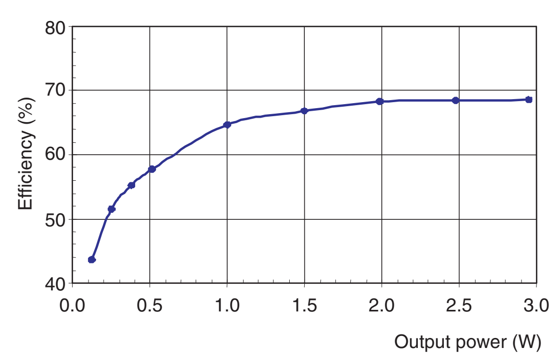


Fig 25. Efficiency versus output power (V_{in} = 220 V (AC))

5.3.3 Regulation

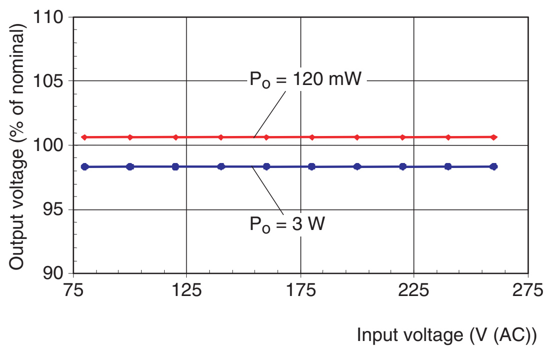


Fig 26. Line regulation

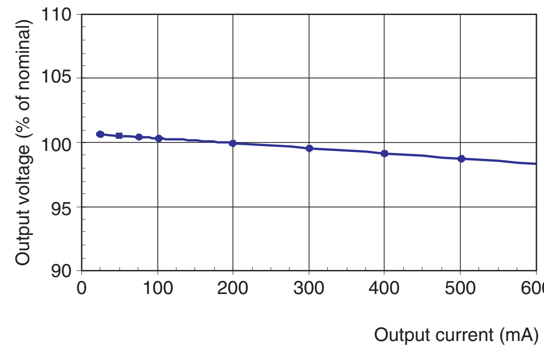


Fig 27. Load regulation (V_{in} = 220 V (AC))

5.3.4 Frequency behavior

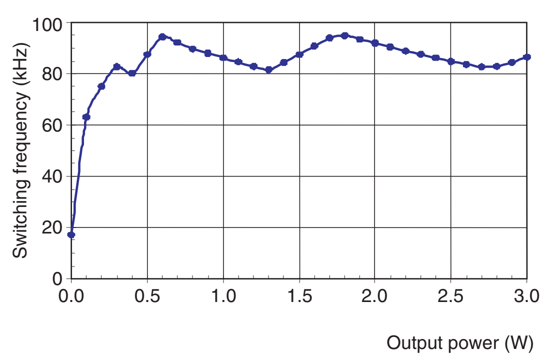


Fig 28. Switching frequency (V_{in} = 115 V (AC))

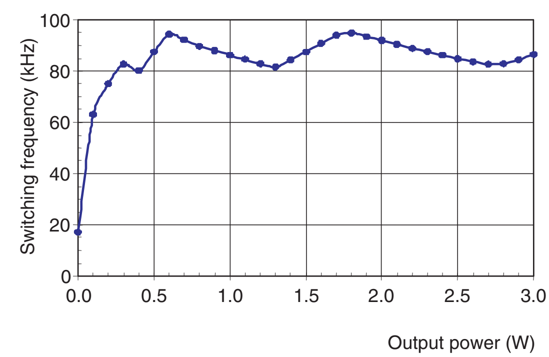


Fig 29. Switching frequency (V_{in} = 235 V (AC))

5.3.5 Turn-on delay

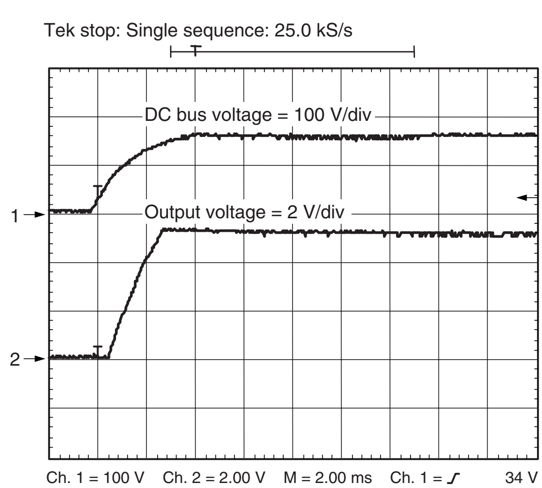


Fig 30. Turn-on delay (R_o = 8 Ω / V_{in} = 115 V (AC))

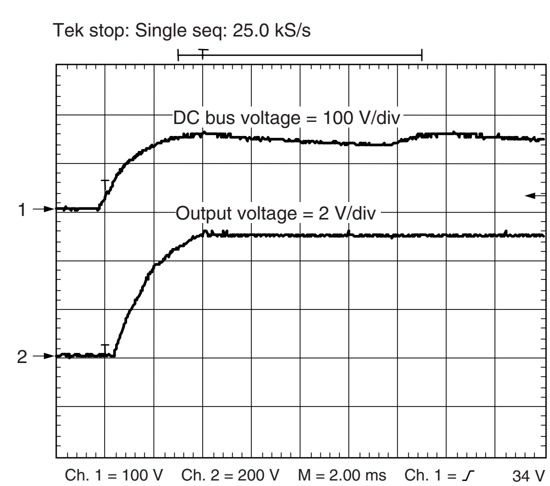


Fig 31. Turn-on delay (R_o = 7.5 Ω / V_{in} = 115 V (AC))

5.3.6 Output voltage ripple

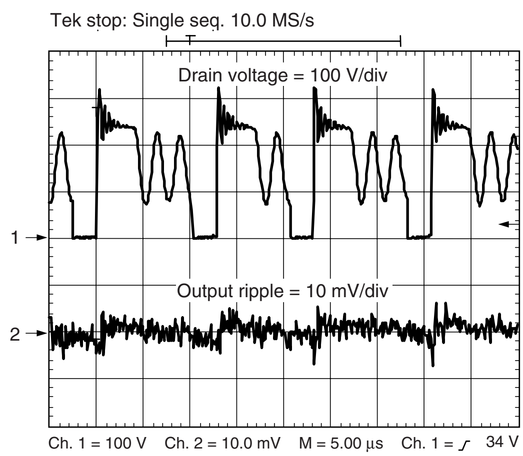


Fig 32. Output switching ripple (P_o = 3 W/V_{in} = 115 V (AC))

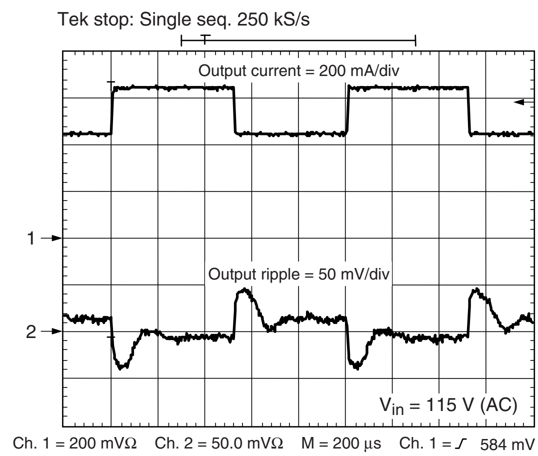


Fig 33. Transient load response (75 % to 100 %)

6. Legal information

6.1 Definitions

Draft — The document is a draft version only. The content is still under internal review and subject to formal approval, which may result in modifications or additions. NXP Semiconductors does not give any representations or warranties as to the accuracy or completeness of information included herein and shall have no liability for the consequences of use of such information.

6.2 Disclaimers

General — Information in this document is believed to be accurate and reliable. However, NXP Semiconductors does not give any representations or warranties, expressed or implied, as to the accuracy or completeness of such information and shall have no liability for the consequences of use of such information.

Right to make changes — NXP Semiconductors reserves the right to make changes to information published in this document, including without limitation specifications and product descriptions, at any time and without notice. This document supersedes and replaces all information supplied prior to the publication hereof.

Suitability for use — NXP Semiconductors products are not designed, authorized or warranted to be suitable for use in medical, military, aircraft, space or life support equipment, nor in applications where failure or malfunction of a NXP Semiconductors product can reasonably be expected to result in personal injury, death or severe property or environmental damage. NXP Semiconductors accepts no liability for inclusion and/or use of NXP Semiconductors products in such equipment or applications and therefore such inclusion and/or use is at the customer's own risk.

Applications — Applications that are described herein for any of these products are for illustrative purposes only. NXP Semiconductors makes no representation or warranty that such applications will be suitable for the specified use without further testing or modification.

Export control — This document as well as the item(s) described herein may be subject to export control regulations. Export might require a prior authorization from national authorities.

6.3 Trademarks

Notice: All referenced brands, product names, service names and trademarks are the property of their respective owners.

STARplug — is a trademark of NXP B.V.

7. Contents

continued >>

Date of release: 4 June 2009
Document identifier: AN00055_1