April 3, 2001

FAIRCHILD SEMICONDUCTOR™

# AN4100

## FPS Designer Software Revision 1.0.0 User Guide.



### 1. General Description

FPS Designer software is a software package that is designed to simplify the process of designing off-line switched mode power supplies using the Fairchild Semiconductor range of Fairchild Power Switch devices. FPS Designer is supplied free of charge on the basis that it will be used to help design applications of the above devices.

Certain design approximations have been made in the software. It is designed to provide an initial design ready for optimisation. FPS designer does not calculate every factor involved and therefore results are to be used as a starting point for further practical optimisation.

FPS Designer will compare calculated parameters against a database of FPS devices and offers a choice of devices that will suit the application.



Note that Fairchild is always updating its range of parts. A current database of parts can be downloaded from our web site.

### 1.1. Installation

FPS Designer is currently compatible with Windows98 and Windows95. A Windows NT version will be released at a later date.

To work correctly, FPS Designer requires that DCOM98 be installed. This is part of Windows98 and can be downloaded from:

http://www.microsoft.com/com/tech/dcom.asp

If the user is running Windows 98 then it is not required.

To install FPS Designer, simply run the "setup.exe" program in the supplied installation package. Follow the prompts.

FPS Designer may try to update some Windows files on your machine. If this is not done, installation will not be completed.

FPS Designer will install Microsoft Data Access 2.1 on your machine. If this is not already installed it will be necessary to re-boot your machine before FPS Designer will run correctly.

### 1.2. Removal

FPS Designer can be removed via the "Add/Remove Programs" icon in the Control Panel.

## 1.3. Starting and Using FPS Designer

Once installed, from the “Start” button select Programs>FPS Designer>FPS Designer.

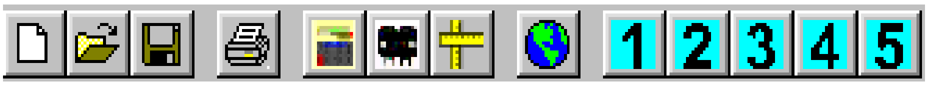
FPS Designer screen is split into two sections: upper and lower. Each section consists of tabbed pages, which can be selected individually. The top section is used for user input and the bottom section is used for FPS Designer outputs. The user cannot enter any data in the lower section. FPS Designer will access a database and suggest which FPS devices are applicable to the design.

Each time a change is made to a parameter, it is necessary to re-calculate the design. This process is automatic. Pressing the Calculate button or selecting Calculate from the menu will trigger calculation manually.

## 1.4. Parameter Settings.

FPS Designer will start up and initialise itself with a sample design as shown in Appendix A. This is for a typical 19 Watt example. This design could typically be used in a set-top box and is also shown in Fairchild applications note, AN-4106, Switched Mode Power Supply for a Set-top Box. The transformer core used is a TDK PC40EI28-Z

## 1.5. Tool-Bar Buttons




In sequence, the buttons are:

| | |
|---|---|
| New: | Causes FPS Designer to initialise all parameters to the default values. |
| Open: | Opens an existing design. |
| Save: | Saves current design. |
| Print: | Prints the current window. |
| Calculate: | Causes FPS Designer to calculate the current design. |
| Core Loss Calculator: | Opens the Core Loss Calculator. |
| Schematic: | Shows the schematic window. |
| Web: | If a link to the internet is available this will start up Internet Explorer and navigate to the Fairchild web site at www.fairchildsemi.com. |
| Steps 1-5: | These buttons select design steps 1 to 5. |

## 2. Simplified Design Process

To calculate a new design, follow the steps described below. Although FPS Designer calculates the complete design each time a parameter is changed, not all calculations are valid until the procedure is complete.

Components calculated or used in calculations are shown in red on the schematic output that can be obtained by clicking the schematic button on the toolbar.

## 2.1. Step 1 - Initial Calculations

Select step 1 from the toolbar or select the step 1 tabs.

Set the values appropriately in the upper input panel. It is recommended that a large value of Cin be set to start with. This prevents errors in the calculations. FPS Designer will suggest a value for the input capacitance in the lower panel. A real practical value close to the ideal should be set in the upper panel. The lower panel will then show the resulting ripple together with other useful values.

### 2.2. Step 2 – Transformer Design

Select step 2 from the toolbar or select the step 2 tabs.

Set the values appropriately in the upper input panel. It may be necessary to experiment with Ae and Bmax to get acceptable results shown in the lower panel.

FPS Designer will then calculate values for the required turns and core gap.

### 2.3. Step 3 – FPS Selection

Select step 3 from the toolbar or select the step 3 tabs.

Select an appropriate device from the list shown in the lower panel. Clicking on the "Use selected FPS Device" button will automatically transfer the appropriate values into the boxes in the upper panel. Alternatively user defined values may be entered if appropriate. Selecting "Show All" in the FPS Options box will show a full list of available devices.

Note that the "Max Switch Current" section puts a high limit on the devices selected. It plays no part in calculations and simple a filter. This avoids selecting 15A devices for a 1A application for instance.

### 2.4. Step 4 – Efficiency

Select step 4 from the toolbar or select the step 4 tabs.

Set the values appropriately in the upper input panel.

FPS Designer will then calculate the efficiency of the design. The power losses in various sections are broken down in the lower panel. It may be necessary to iterate through the previous sections to improve efficiency where required.

If the calculated efficiency differs greatly from the target, the value of calculated efficiency in the lower panel should be entered back in the upper panel, iterating until the two numbers converge.

### 2.5. Step 5 – Additional Calculations

Select step 5 from the toolbar or select the step 5 tabs.

This section contains several additional calculations for convenience.

## 3. Detailed Design Process

This section describes the parameters that are set each stage of the design process and the outputs available from FPS Designer. It also describes any design compromises that may be made.

### 3.1. Step 1 - Initial Calculations

The following parameters should be set.

#### 3.1.1. AC Input Voltage.

This defines the maximum and minimum line input voltages. The maximum should be greater or equal to minimum. Line input frequency is also set here. If the input is DC then set the frequency to 0. To avoid calculation errors it is best to set the frequency first.

#### 3.1.2. Input Capacitor.

This is the value of the input filter capacitor. It is ignored if the input is DC. The ripple voltage is the target ripple across the capacitor. It is recommended that initially, a large value be used for the smoothing capacitor since too small a value may cause calculation errors. This is due to total discharge resulting in zero minimum input voltage. FPS Designer will suggest a value for the input smoothing capacitor in the lower panel. The closest real value should be entered in the upper panel and FPS Designer will re-calculate the design showing the maximum and minimum voltages at the primary in the lower panel.

#### 3.1.3. Output Parameters.

Set output voltage, current and FPS Vcc voltage as required.

### 3.1.4. Rectifier Voltage Drops.

This is the forward voltage drop across the main secondary rectifier diode and the Vcc rectifier diode.

### 3.1.5. Target Efficiency.

This should be less than 100%.

## 3.2. Step 2 - Transformer Design

The following parameters should be set. The transformer data is available in the lower panel.

### 3.2.1. Switching Frequency and DC.

Switching frequency for the FPS device is set here. Note that the maximum duty cycle is not actually be the maximum duty cycle for the part but the maximum duty cycle that we want to work with. Maximum duty cycle should be limited to 0.5. If larger values are required, slope compensation can be implemented with FPS but this requires extra external components. It is recommended to set this to around 0.45

### 3.2.2. Discontinuous Conduction Mode.

FPS Designer starts by assuming that continuous conduction mode will be implemented. If this is so then a value of primary inductance can be chosen to give an acceptable primary current. If discontinuous conduction mode is checked, FPS Designer calculates the value of primary inductance since it is fixed by design. Selecting DCM shows the minimum value for primary inductance. A smaller inductance cannot be used since it cannot store enough energy each cycle.

### 3.2.3. Primary Inductance in CCM.

If DCM is not selected, a value of primary inductance should be entered here. The minimum value can be seen in the lower panel by selecting DCM. The primary inductance should always be equal to or above this.

### 3.2.4. Peak Flux Density.

This should be set according to the selected core material data. Practical limits are around 300mT. The value set is a maximum working value. Higher values will result in greater core loss.

### 3.2.5. Ae.

This should be set according to the selected transformer.

### 3.2.6. Leakage Inductance.

This value must reflect what is practical. A value between 2% and 5% is normally achievable. Larger values will result in greater snubber loss.

### 3.2.7. Current carrying capacity.

A value of 5A / mm$^2$ is recommended here. It is used to calculate wire diameters.

### 3.2.8. Average Length per Turn.

This is set from transformer bobbin data.

### 3.2.9. Practical Note on Wire Selection.

FPS Designer will calculate the cross sectional area for the primary and secondary windings. This is based on the specified current carrying capacity. See below for additional comments that relate to efficiency. FPS Designer does not cater for multi-stranded windings. These can result is lower copper loss and should be considered where currents are high.

### 3.2.10. Multiple output supplies.

If the power supply being designed has multiple outputs, then the required turns for each output can be calculated simply: switch back to Step 1, input panel. Type in the required voltage in the Vcc box. FPS Designer will then calculate the required number of turns, which will be displayed in the “Real Bias Winding Turns” box on the Step 2 output panel.

### 3.3. Step 3 – FPS Device Selection.

Once the design has reached this stage, FPS Designer will offer several devices in the lower panel. Devices offered are based on the following points. It is possible to use parameters that do not correspond to a specific FPS device by writing the parameters into the appropriate boxes.

#### 3.3.1. FPS Options.

Auto restart and external frequency synchronisation can be specified here.

#### 3.3.2. Filter.

Max Switch Current is used simply to limit the number of devices offered. Without this parameter, FPS Designer would offer high power devices for low power designs. It is not used in calculations but simple to filter out higher current devices.

The filter function can be switched off by selecting “Show All Devices”.

Currently FPS Designer does not follow a design process that is applicable to quasi-resonant topologies. Therefore, FPS devices such as the KA5Qxxxx series are not suggested. They are shown when the complete list of devices is shown.

A device can be selected by clicking on any of the parameters associated with that device. Clicking on the “Use Selected FPS Device” button will cause the relevant parameters to be transferred to the upper panel. Alternatively, the user may enter other parameters.

The devices offered will be ordered by voltage rating, and Rdson.

#### 3.3.3. Vdsmax.

This is the avalanche breakdown voltage of the device. It is used when calculating the snubber values. In the lower panel the Vds voltage is shown during flyback. This does not include any voltage spike generated by the leakage inductance.

#### 3.3.4. Vds overhead.

This is used in calculating the snubber components. This can be set to 0V in which case the drain voltage is allowed to go to the Vdsmax value specified in the upper panel. Setting a value of 100V would allow the spike to go to within 100V of Vdsmax. This parameter is not specified in the database since it can be set to various values.

#### 3.3.5. Possible Stop Here

It is perfectly possible to stop here since the critical parameters have been calculated. If this is chosen then the next step is BUILD IT. The designer can however go further And examine efficiency and start to optimise the design.

### 3.4. Step 4 – Efficiency Analysis.

FPS Designer allows the following parameters to be added that will be considered in the final estimate of efficiency. They are not essential but if not specified will result in an artificially low estimate of efficiency. They should all be set to 0 if not used.

The following parameters are specified:

#### 3.4.1. Line Filter.

This defines the resistance of the line filter. Typical values should be no more than 1 or 2 ohms although low power applications can have higher values.

#### 3.4.2. NTC Resistor.

This defines the NTC Resistor value once at operational temperature. The resistor will be a high value at switch on and will limit inrush currents associated with charging the input smoothing capacitor. Once up to operating temperature it should have a small resistance.

**3.4.3. Bridge Diode Drop**.
This defines the voltage drop of the diodes in the bridge rectifier. This is typically set to 0.7V.

**3.4.4. Core Volume.**
This is set from core data.

**3.4.5. Core Loss Coeff a, x.**
These parameters are used to calculate core loss. Calculation of core loss is a complex problem. The core loss coefficients a and x referred to above allow FPS Designer to estimate the core loss versus peak flux density. Core loss is related to peak flux density as below:

$$P = a \cdot B^x$$

If we have two pairs of values for P and B we can calculate values for a and x and use them to calculate P versus B. FPS Designer will calculate the values for a and x by using the Core Loss Calculator feature. Two pairs of values of *P* and *B* should be obtained from core data and used to calculate *a* and *x*. The values of B should be either side of the calculated peak flux density. FPS Designer can then calculate loss against peak flux density. The calculation is not exact but provides a good estimate provided the peak flux density is in the range of the values used to calculate *a* and *x*. i.e. if flux densities in the range of 200mT are used then values of B should be 50mT and 300mT perhaps. There are two extra fields in the core loss calculator. They relate to switching and measurement frequency. If data is not available for the specified switching frequency then the closest data should be entered. FPS Designer then scales the core loss accordingly since for small changes in frequency, the core loss is linear with frequency. If you are operating at 66kHz then values for 50kHz will be sufficient provided they are scaled accordingly. Clicking the calculate button on the core loss calculator will calculate the values for a and x. Clicking the Exit button will insert these values into the design. Cancel will return without changing the design.

**3.4.6. Measurement Frequency.**
This is the frequency at which core loss coefficients are measured. It should be as close to the switching frequency as possible. If it is not the same, the core losses are extrapolated linearly from the measurement frequency to the switching frequency.

**3.4.7. Target Efficiency.**
This is the same as was defined in Step 1. However to avoid changing panels during optimisation, it is repeated here.

**3.4.8. Practical Note on transformer wire selection.**
FPS Designer calculates wire losses based on the ideal cross sectional area calculated above. It does not include calculations for multi-stranded windings. Using multiple strands for the high current windings can reduce wire losses. Due to skin effect, only the surface of the wire carries the current. This skin layer reduces with increased frequency. Hence multiple small diameter wires will exhibit less resistance than a single conductor of equal cross sectional area.

**3.4.9. Practical Note on Efficiency Optimisation.**
It can be seen from the lower panel where the losses arise. Input side losses from the bridge can only be reduced by changing the bridge diode drop. Similarly the line filter and NTC resistor losses can only be reduced by changing the resistance of the two components.

Transformer losses are split into 2 sections: core and wire. The core material, peak flux density and core volume set core loss. Winding resistance sets wire loss. Transformer loss may be optimised in various ways but clearly the higher the flux density, the higher the loss. Also for a given core, a lower flux density will result in more turns and hence a higher wire loss. Therefore the flux density may be optimised to give a good balance between core and wire loss. Practically however decreasing the flux density will increase the gap. Larger gaps also result in increased leakage inductance. This results in increased system loss.

Picking a higher power part may reduce FPS Power losses since higher power parts will have a lower Rdson and therefore show lower conduction losses. Be careful however that switching losses do not become dominant since some higher power parts also have larger switching times.

Reducing leakage inductance reduces snubber losses. Generally a smaller inductance will also have a smaller leakage. However smaller inductance also leads to higher currents. In some cases switching from CCM to DCM may not increase efficiency significantly. However power loss will become more balance between the FPS device and the snubber making thermal management easier.

Temperature will also change efficiency. FPS Designer uses one set of numbers to calculate losses. Core losses will decrease with temperature. This effect can be quite significant. FPS Device losses may increase with temperature although not by the same degree as core losses.

The major point on efficiency optimisation is understanding where the losses occur. Once a system is designed it should be built and optimised practically. Don't sped too much time on the theory.

FPS Designer also calculated efficiency at only one temperature. Lower losses are generally obtained at higher temperatures.

### 3.5. Step 5 – Additional Calculations.

The following parameters should be set.

#### 3.5.1. Reference Feedback.

Set the reference voltage here. This is typically 2.5V since an LM431 shunt reference is normally used. Also set the current through the resistive divider that measures the output voltage. This is normally set at around 1mA. FPS Designer will then calculate the value for the feedback resistors.

#### 3.5.2. Start-up Network.

Set the startup voltage value for the selected FPS Device. This is normally 15V. Also set the FPS current before start-up. For a KA5xxxxx device this would be 170uA max. It may be higher for KA1xxxxx devices. The value of Vcc capacitor is not used in calculations but will appear on the schematic output. FPS Designer will then calculate a **maximum** value for the start-up resistor. Provided it is set less than this the device will start. Low values will lead to decreased start-up time but higher power dissipation in the start-up resistor. Setting a value above the maximum calculated will result in unreliable start up if at all.

#### 3.5.3. Rectifier Diode.

Also shown in the lower panel is the reverse voltage that the main power rectifier diode has to withstand. This helps in diode selection.

## 4. Worked Example

The following example is based on the 45W specification below:

| | |
|---|---|
| Input Voltage: | 85 – 265VAC, 60Hz |
| Output Voltage: | 12V |
| Output Current: | 3.75A |
| Target Efficiency: | 80% |

### 4.1. Step 1 - Initial Calculations

Select step 1 from the toolbar or select the step 1 top and bottom tabs.

- Set the input capacitor to 1000uF to avoid errors while setting up.
- Set the input voltages as above.
- Set a voltage ripple of 30V.
- Set the output conditions as above including Vcc = 18V.
- Set the target efficiency to 80%.
- Set the rectifier drops to: Main = 0.7V, Vcc = 0.7V

Note that the suggested input smoothing capacitor is 114uF. Set 100uF in the top panel. Note the minimum input voltage is 85.0V which gives a ripple of 35.2V Close enough! We can now proceed to step 2.

### 4.2. Step 2 – Transformer Design

Select step 2 from the toolbar or select the step 2 top and bottom tabs.
Although the transformer core is selected from the TDK EI data book, other manufactures cores are just as valid a choice.

- Chose a switching frequency of 100kHz and set this.
- Set a max duty cycle of 0.45.
- Click on the DCM box to select discontinuous conduction mode.

We see that the minimum primary inductance that we can use is 130uH. This would give a maximum primary current of around 2.94A. This rather large for good efficiency so we choose CCM.

- Deselect DCM
- Set the value of primary inductance to 1000uH.
- Set a value for leakage inductance of 1%. This will require care but can be achieved.

Note that the peak primary current has now dropped to 1.66A. This will help transformer and FPS power dissipation. As inductance increases, leakage inductance may also increase. Since energy lost in the leakage inductance is normally dissipated in the snubber, this would lead to higher snubber dissipation. Therefore increasing inductance to change to CCM may not necessarily increase overall efficiency. We'll come to that later. It will certainly reduce FPS device dissipation and help EMI.

We now have to select the transformer core. The TDK data book shows that the PC40EI30-Z core has an Ae value of 111mm$^2$. We pick a maximum flux density of 130mT as a starting point. We may change these values later during efficiency optimisation. In practice it will normally be the case that Ae is actually less than quoted. From experience, set Ae to 80mm$^2$.

If it was required to use a pre-gapped core, Bmax could be varied to achieve the required gap.

- Set the average length per turn from transformer bobbin data at 6cm.

FPS Designer has now calculated an ideal number of turns for the primary. From this it has calculated an ideal number of turns for the primary. However since this will hardly ever be a n integer number, FPS Designer will round this to the nearest integer number. From this it then works backwards to get a real number for the primary and bias windings.

The transformer windings have now been calculated at:

| | |
|---|---|
| Primary | 38 turns |
| Secondary | 7 turns |
| Bias | 10 turns |

The gap is calculated at 0.145mm.

Wire diameters are calculated at:

| | |
|---|---|
| Primary | 0.5mm |
| Secondary | 1.2mm |

### 4.3. Step 3 – FPS Selection

Select step 3 from the toolbar or select the step 3 top and bottom tabs.

Make sure the following are set:

- Restart Required
- Sync Not Required
- Max Switch Current 5A
- Show Suggested Devices Selected

We see that FPS Designer is offering a choice of devices. We also see that the maximum Vds will be 444V. Note this does not include the spike generated by the leakage inductance at switch off.

- Click on one of the parameters for the KA1H0565R.
- Click on the Use Selected Device button.

FPS Designer will now have updated the top panel with the appropriate values for the selected device. The following values should have been selected:

- FPS Number KA1H0565R
- Vdsmax 650V
- FPS Rdson 2.2ohm
- FPS Swicth time 60nS
- Coss 130pF

### 4.4. Step 4 – Efficiency

Select step 4 from the toolbar or select the step 4 top and bottom tabs.

- Set the line filter, bridge diode drop and NTC resistor value appropriately: 0.5, 0.7, 0.5.
- From core data, set the core volume to 6.44cm$^3$.

Also from core data we should set the core loss coefficients. However they are not directly accessible so we have to calculate them.

- Click on the Core Loss Calculator.
- Since core loss data is available for the PC40 material at 100kHz, change the measurement frequency to 100kHz.
- To calculate for worst case, take the values for low temperatures at 100kHz: at B=50mT, P = 22mW, at B=300mT, P = 1500mW. These are available in the core material data for most core materials.
- Set these values in the calculator.
- Click on Exit. The values in the core parameters will be updated.
- Alternatively, if you have the values for a and x you can enter them directly.

We can now see where the power losses are. At this stage we're doing fairly well since the efficiency is 81.6%. This is close to target and so there is no need to iterate. However as an example, if we now put 81.6% back into the target efficiency box we see that FPS Designer re-calculates the design and comes up with an answer closer to the target. Actually this design converges close to 82%.

### 4.5. Step 5 – Additional Calculations

Select step 5 from the toolbar or select the step 5 top and bottom tabs.

Our design is almost complete. At this stage FPS Designer does some additional calculations that are useful. FPS Designer calculates the maximum value for the start-up resistor and the voltage feedback resistors.

- Set Vref to 2.49V - reference voltage.
- Set Iref to 1mA - current through feedback resistors.

FPS Designer then calculates the feedback resistors at 9.51kohm and 2.49kohm. Clearly these are ideal values.

- Set Vstart to 15V - the high side under-voltage threshold for the FPS device.
- Set Istart to 170uA – the FPS start up current.

FPS Designer then calculates a maximum vale for the start-up resistor. Note that if this value is actually fitted the device will not start reliably. Set a real value smaller than this.

FPS Designer calculates Rstart at 619kohm maximum.

At this stage we should set a value for the Vds overhead. Note that since FPS devices are avalanche rated, we can allow the snubber spike to exceed the Vdsmax value provided that the device does not suffer too great a thermal penalty.

- Set Vds overhead to 0V.

FPS Designer now calculates the snubber components: Rc = 30.6kohm, Cc = 6.5nF. It also calculates the maximum reverse voltage over the snubber diode at 443V.

### 4.6. Step- 6 Build it

Once a theoretical design is complete the next step is built it and optimise practically. Many of the calculations performed by FPS Designer are worst case.

## 5. Detailed Calculation Descriptions.

Below follows detailed descriptions of the calculations performed by FPS Designer.

### 5.1. Initial Calculations

FPS Designer first calculates the input power based on the output power required and the target efficiency:

$$Pin = \frac{Pout}{\eta t}$$

If the input frequency is 0, FPS Designer treats the input as DC otherwise it is AC. FPS Designer then calculates the minimum and maximum input voltages after rectification and smoothing.

If the input is AC:

First calculate the capacitor discharge time:

$$Td = \frac{1}{4 \cdot Fline} \cdot \left[ 1 + \frac{\arcsin\left( \frac{Vac\min \cdot \sqrt{2} - Vr}{Vac\min \cdot \sqrt{2}} \right)}{\frac{\pi}{2}} \right]$$

Now calculate the energy discharged per cycle:

$$Win = Pin \cdot Td$$

From this we can calculate the required value for the input smoothing capacitor:

$$Cinc = \frac{2 \cdot Win}{\left(Vac\min \cdot \sqrt{2}\right)^2 - \left(Vac\min \cdot \sqrt{2} - Vr\right)^2}$$

The user can then pick the closest real value for input smoothing capacitance. FPS Designer then uses this to calculate a more realistic value for the minimum dc input voltage and ripple.

### 5.2. Transformer Calculations

We can now calculate the transformer parameters. Start with the primary. We have to decide on the operating mode. If this is discontinuous conduction mode (DCM), FPS Designer will calculate the primary inductance. If it is continuous conduction mode (CCM), the user can specify the inductance. It must be greater that the DCM value.

Calculate the on time of the switch:

$$Ton = \frac{DC\max}{Fsw}$$

For DCM calculate the peak primary current. Using this, calculate the primary inductance:

$$Ippk = \frac{2 \cdot Pin}{Vdc\min \cdot D\max} \qquad Lp = \frac{Vdc\min \cdot D\max}{Ippk \cdot Fsw}$$

For CCM set a value of primary inductance greater than the DCM value. This has the advantage of reducing the primary and secondary currents. Using the user set value for Lp in CCM or the value above in DCM, we can calculate the primary maximum and minimum currents:

$$Ippk = \frac{Vdc\min^2 \cdot Ton^2 \cdot Fsw + 2 \cdot Lp \cdot Pin}{2 \cdot Lp \cdot Vdc\min \cdot Ton \cdot Fsw}$$

$$Ip\min = \frac{\dfrac{2 \cdot Pin}{Vindc\min \cdot Ton \cdot Fsw} - \sqrt{\left(\dfrac{2 \cdot Pin}{Vindc\min \cdot Ton \cdot Fsw}\right)^2 - 4 \cdot \left(\dfrac{2 \cdot Pin \cdot Ippk}{Vindc\min \cdot Ton \cdot Fsw} - Ippk^2\right)}}{2}$$

If the system is operating in DCM the value for Ippk will agree with the first value calculated and Ipmin will be zero. The core can now be selected from manufacturer's data. Using Ae from the core data and Bmax, the maximum flux density, we can calculate the primary turns and the core gap. Bmax should be set by the user at an appropriate level to avoid large core losses although a small gap is also preferred to avoid large leakage inductances. Note that the formula below calculates the gap in cm units.

$$Np = \frac{Vindc\min \cdot Ton}{B\max \cdot Ae} \qquad \lg = \frac{Np^2 \cdot \mu_0 Ae}{Lp \cdot 1000}$$

Now we can calculate the secondary turns. This calculation gives the exact number for the secondary. Since we can only have an integer number, we then correct the primary based on the real secondary as below:

$$n = \frac{Vdc\min \cdot D\max}{(1 - D\max) \cdot (Vout + Vd)} \qquad Ns = \frac{Np}{n} \qquad Nsreal = round(Ns) \quad Npreal = Nsreal \cdot n$$

This is another reason why once wound, the core gap should be adjusted to give the correct inductance.

Now we can calculate the cross sectional area required for the primary and secondary wire. This is based on a value of current carrying capacity that can be assigned by the user. This is set at 5A/mm$^2$ by default. Start by calculating the rms currents for the primary and the secondary. We are half way there for the primary.

$$Iprms = \sqrt{\left(Ippk^2 + Ippk \cdot Ip\min + Ip\min^2\right) \cdot \frac{D\max}{3}}$$

For the secondary, we first calculate the maximum and minimum currents:

$$Ispk = Ippk \cdot \frac{Np}{Ns} \qquad Is\min = \frac{Ispk \cdot Ip\min}{Ippk}$$

Similarly we can calculate the rms secondary current:

$$Isrms = \sqrt{\left(Ispk^2 + Ispk \cdot Is\min + Is\min^2\right) \cdot \frac{1 - D\max}{3}}$$

We can now calculate the wire cross sectional area using the current capacity per mm$^2$, Ipmm.

$$Dpri = 2 \cdot \sqrt{\frac{\frac{Iprms}{Ipmm \cdot 100}}{\pi}} \qquad D\sec = 2 \cdot \sqrt{\frac{\frac{Isrms}{Ipmm \cdot 100}}{\pi}}$$

### 5.3. Snubber Network Design

The purpose of the snubber network is to clamp the voltage spike on the primary that occurs due to the leakage inductance in the transformer. If these spikes are not clamped, the power switch in the FPS device can be damaged or destroyed or excessive EMI noise can be created on the mains input. The circuit consists of a resistor Rc, a capacitor, Cc and a diode.

Leakage inductance should be specified to FPS Designer. As a rule of thumb it can be estimated at around 1-2% for a gapped core but as low as 1% for a toroid. This should be specified to FPS Designer. First we should calculate the power loss due to the leakage inductance.

$$Psn = \frac{1}{2} \cdot Ll \cdot Ippk^2 \cdot F_{SW}$$

We now calculate flyback voltage and the allowable voltage spike across the snubber.

$$Vfl = (Vout + Vd) \cdot \frac{Np}{Ns} \qquad Vsn = Vds\max - Vdsoh - Vfl - Vdc\max$$

We can now calculate the snubber resistor value and then use that to calculate the capacitor value.

$$Rc = \frac{Vsn^2}{Psn} \qquad Cc = \frac{20}{Fsw \cdot Rc}$$

We should now calculate the maximum inverse voltage stress on the snubber diode as below.

$$Vdinv = (Vout + Vd)\frac{Np}{Ns} + Vdc\max$$

### 5.4. Power Rectifier Diode Stress

The reverse voltage stress on the secondary diode can be calculated as below:

$$Vdr = Vout + Vdc\max \cdot \frac{Nsreal}{Npreal}$$

## 6. Design Evaluation

This is primarily an efficiency calculation. It involves calculating the losses attributed to the transformer core and the windings, losses in the primary clamp (leakage inductance loss), losses in the FPS switch, losses in the rectifier diode and some additional significant losses.

### 6.1. Snubber network Losses

This has been calculated above as part of the snubber network design.

### 6.2. Transformer Core Losses

This is not a simple calculation and is often inaccurate. However, provided we have the correct core parameters we can make a good estimate. Core loss is specified in terms of power loss per unit core volume at a specific flux density and switching frequency. It is sometimes specified at the correct flux density of switching frequency but sometimes not. A practical note is that the core loss per $cm^3$ follows the formula below.

$$P = a \cdot B^x$$

Where P is the power loss, B is the flux density, a and x are constants. Taking two points for P and B from the core data enables easy calculation of a and x. If these are not available for the switching frequency used, then use the closest data. FPS Designer adjusts linearly. The core loss at 125kHz would be 1.25 times the loss at 100kHz for instance.

Using a pair of values for P and B, FPS Designer calculates the core loss coefficients a and x as below:

$$x = \frac{\log(P2) - \log(P1)}{\log(B2) - \log(B1)} \qquad a = \frac{P1}{B1^x}$$

Note that some core manufacturers specify core loss curves in terms of Bmax/2 for unipolar excitation. Either way the user has to enter a value for the core loss per unit volume. Once we have *a* and *x* we can calculate a value for the core loss per unit volume at the appropriate frequency and flux density.

Once the value for core power loss per unit volume is entered, FPS Designer will then calculate a value for core loss based on this and the core volume as below:

$$Pc = CL \cdot Ve$$

### 6.3. Transformer Copper Losses

We already have a value for the primary and secondary wire cross sectional area. However, we cannot simply use these areas to calculate the resistance of the wire. This is because of skin effect. The current actually travels along a surface layer of a conductor. The skin depth depends on the frequency. This can be estimated in cm units from the formula below:

$$\delta = \frac{6.61}{\sqrt{Fsw}}$$

Using this we can estimate the effective cross sectional area. FPS Designer uses the whole are if the skin depth is greater than the radius of the wire. We can the move on to estimating the wire resistance.

$$Ae = A - \pi \cdot (r - \delta)^2 \qquad Rx = Alpt \cdot Nxreal \cdot \rho$$

We can then calculate the winding losses as below:

$$Pp = Iprms^2 \cdot Rp \qquad Ps = Isrms^2 \cdot Rs$$

### 6.4. Losses in the Rectifier Diode

This can be estimated by using Ohm's law and using the average secondary current and the voltage drop. FPS Designer requires the diode voltage drop to be specified.

$$Pd = Isout \cdot Vd$$

### 6.5. Static and Switching Losses in the FPS Device.

Static losses can be calculated from the rms switch current and the Rdson value for the FPS device chosen as below:

$$Pswr = Iprms^2 \cdot Rdson$$

Switching losses are approximated since an exact calculation is complex:

$$Psws = \frac{Coss \cdot Vsw\max^2 \cdot Fsw}{2}$$

The fast switching of the FPS devices minimises switching losses and because of gate to gate driver matching, the risk of EMI is also minimised. The power loss in the FPS device is therefore the sum of the above losses.

$$Psw = Pswr + Psws$$

### 6.6. Other Losses.

We can also estimate other losses in the system. These arise from the input line filter, the bridge rectifier and the NTC resistor if fitted.

$$Plf = Iprms^2 \cdot Rlf \qquad Pb = Ipavg \cdot Vb \cdot 2 \qquad Pntc = Iprms^2 \cdot Rntc$$

### 6.7. Total Power Loss calculation

This is calculated by adding together the power losses from:

i. Primary snubber network.
ii. Transformer core.
iii. Transformer windings.
iv. Rectifier diode.
v. FPS switching loss.
vi. Other losses

We can now get an estimated efficiency for our design. The total power loss is:

$$Ptot = Psn + Pt + Pd + Psw + Plf + Pb + Pntc$$

and therefore the calculated efficiency is:

$$\eta = \frac{Pout}{Pout + Ptot}$$

If the calculated efficiency varies greatly from the target, then parameters should be adjusted accordingly to make them match. If this is not possible, the calculated efficiency should then by inserted as the target efficiency and the design re-calculated. Not that a new value for core loss will be required since the flux density will increase.

Note that there are additional losses not considered here. Once the initial design is complete the best way forward is BUILD IT.

**Appendix A. Default Start-up conditions.**

Step 1 – Initial Calculations

| | |
|---|---|
| AC Input Voltage – universal input | |
| Max: | 265VAC |
| Min | 85VAC |
| Line Frequency | 60Hz |
| Input Capacitor | |
| Ripple | 30V |
| Value | 47uF |
| Output Parameters | |
| Output Voltage: | 5V |
| Output Current: | 3.8A |
| Vcc Voltage | 18V |
| Rectifier Voltage Drops | |
| Main | 0.5V |
| Vcc | 0.7V |
| Target Efficiency | 75% |

Step 2 – Transformer Design

| | |
|---|---|
| Switching Frequency | 50kHz |
| Maximum Duty Cycle | 0.45 |
| Transformer Parameters | |
| Discontinuous Conduction Mode | False |
| Primary Inductance in CCM | 1000uH |
| Peak Flux Density | 250mT |
| Core Ae | $70mm^2$ |
| Leakage Inductance | 1% |
| Wire Parameters | |
| Current Carrying Capacity | $5A/mm^2$ |
| Average Length per Turn | 6cm |

Step 3 – FPS Device Selection

| | |
|---|---|
| FPS Options | |
| Restart | True |
| Sync | False |
| Filter | |
| Max Switch Current | 5A |
| Show Suggested Devices | True |
| Show All Devices | False |
| FPS Parameters | |
| FPS Number | KA5L0380R |
| Vdsmax | 800V |
| FPS Rdson | 5ohm |
| FPS Switch Time | 40nS |
| Coss | 76pF |

Step 4 – Efficiency

| | |
|---|---|
| Input Side Parameters | |
| Line Filer | 0.5ohm |
| Bridge Diode Drop | 0.7V |
| NTC Resistor | 0.5ohm |

| | |
|---|---|
| Core Parameters | |
| Core Volume | $4.58cm^3$ |
| Core Loss Coeff a | 12.1594 |
| Core Loss Coeff x | 2.3711 |
| Measurement Frequency | 50kHz |

Step 5 – Additional Calculations

| | |
|---|---|
| Reference Feedback | |
| Vref | 2.49V |
| Iref | 1mA |

| | |
|---|---|
| Startup Network | |
| Vstart | 15V |
| Istart | 170uA |
| Cvcc | 10uF |

| | |
|---|---|
| Vds Overhead | 0V |

**Appendix B. Mathematical symbols used in the calculations.**

Symbols marked with a * are user defined and FPS Designer requires these to be input. Those not marked with * are calculated by FPS Designer.

Step 1 - Initial Calculations

| | | |
|---|---|---|
| Vacmax | * | Maximum input voltage |
| Vacmin | * | Minimum input voltage |
| Vr | * | Maximum allowable ripple on input smoothing capacitor |
| Fline | * | Line input frequency (mains) |
| Vout | * | Output voltage required |
| Iout | * | Rated output current |
| Vcc | * | Fairchild Power Switch Vcc voltage |
| Vd | * | Secondary Rectifier diode voltage drop |
| Vdcc | * | Vcc rectifier diode voltage drop |
| ηt | * | Target Efficiency |
| Cin | * | User Specified Input smoothing capacitor value |
| | | |
| Pout | | Output power |
| Pin | | Input power |
| Vdcmax | | Maximum input voltage after rectification and smoothing. |
| Vdcmin | | Minimum input voltage after rectification and smoothing and including smoothing filter droop. |
| Td | | Smoothing capacitor discharge time |
| Win | | Smoothing capacitor energy per cycle |
| Cinc | | Calculated ideal smoothing capacitor value |

Step 2 – Transformer Design

| | | |
|---|---|---|
| $\mu_0$ | | Permeability of free space. A constant within FPS Designer |
| Fsw | * | FPS device switching frequency |
| Dmax | * | Maximum duty cycle of the FPS device |
| DCM | * | Set to TRUE if design is discontinuous conduction mode (DCM) |
| Bmax | * | Maximum flux density allowed |
| Ae | * | Transformer core Ae value. |
| Ll | * | Leakage Inductance as a percentage of primary inductance. This is not actually used here but it is the logical place to specify it. |
| | | |
| Ton | | On time for the switch. |
| Ippk | | Maximum primary current. |
| Ipmin | | Minimum primary current. |
| Lp | | Transformer primary inductance |
| Np | | Primary turns. |
| lg | | Transformer gap width. |
| | | |
| N | | Transformer turns ratio |
| Ns | | Secondary turns |
| Nsreal | | Real integer number of secondary turns. |
| Npreal | | Real integer number of primary turns. |
| Dpri | | Primary wire diameter. |
| Dsec | | Secondary wire diameter. |

Step 3 – FPS Device Selection

There are no calculations in this section.

Step 4 – Efficiency

| | | |
|---|---|---|
| Iprms | | Transformer primary rms current |
| Ispk | | Transformer secondary peak current |
| Ismin | | Transformer primary minimum current |
| Isrms | | Transformer secondary rms current |
| | | |
| Ve | * | Effective core volume |
| PV1, PV2 | * | Pair of transformer core material power losses corresponding to the B1, B2 values below. |
| B1, B2 | * | As above |
| Rntc | * | NTC resistor resistance |
| Vb | * | Bridge rectifier voltage drop |
| Rdson | * | Fairchild Power Switch Rdson value |
| Coss | * | Power Switch FET output capacitance |
| | | |
| X, A | | Steinmetz equation parameters for core loss. |
| Pc | | Core loss |
| Pt | | Transformer loss. |
| Pntc | | NTC resistor power loss |
| Pb | | Bridge rectifier power loss |
| Pswr | | Fairchild Power Switch Loss - Rdson |
| Psws | | Fairchild Power Switch Loss – switching |
| Pswt | | Fairchild Power Switch Loss – total |
| Pd | | Secondary side rectifier power loss |
| Ptot | | Total Power Loss |
| Ec | | Calculated Efficiency |

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