Transformer Designer for Isolated High-Voltage Power Design

Create a complete isolated high-voltage power design including the design of a transformer

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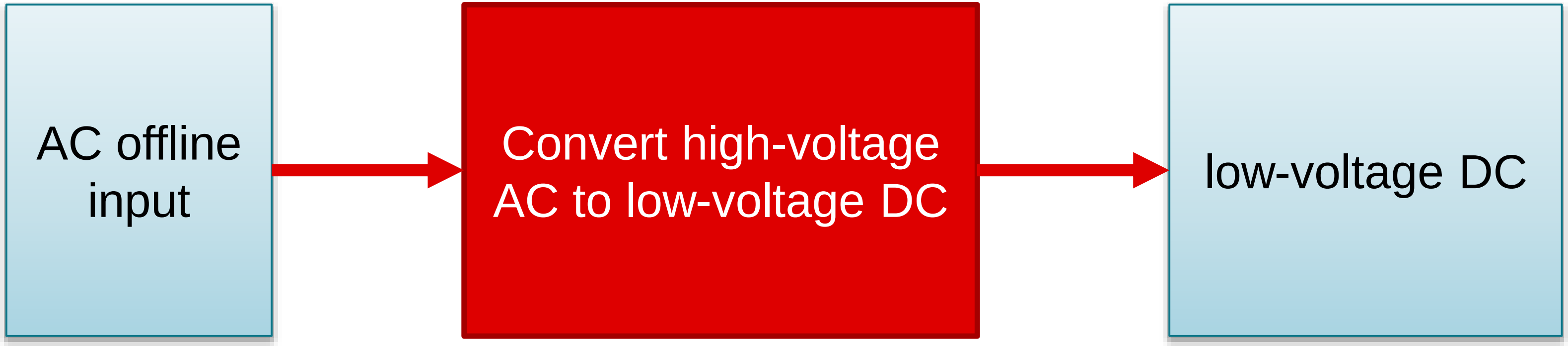
TEXAS INSTRUMENTS

Convert from what we have to what we want

Convert high-voltage AC to low-voltage DC

Convert from what we have to what we want—from high-voltage AC generate low-voltage DC



Key Requirements:

- Provide electrical **isolation**
- Regulate to desired DC level
- Balance efficiency, footprint and cost

Isolation

- **What is it?**
  - No direct conduction path between input and output (galvanic or electrical isolation)
  - Dangerous electrical shorts cannot pass through to either side in the event of component failure or fault
- **Why it is needed?**
  - Protect the primary side from faults and components failures on the secondary side
  - Protect the secondary side from line-level events, e.g. surges, lightening strikes, noise
  - Protect the human operator and the equipment
  - Secondary ground can be configured either positive or negative for negative outputs
  - Regulatory standards require isolation
- **How is it implemented?**
  - Power transferred through a transformer.
  - Secondary-to-primary signal sensing through an opto-coupler & independent grounds

Flyback topology

Flyback is the most popular topology for low-power (~75 W) AC/DC conversion applications:

- A Flyback transformer combines the actions of an isolating transformer and an output inductor into a single element [1] hence, no separate inductor is needed.
- A Flyback transformer provides galvanic (electrical) isolation up to ~5 kV DC, reduces noise [2], and can provide multiple and/or negative outputs.
- Simple design requires just one semiconductor switch (MOSFET) and one freewheeling diode.

- Reference:

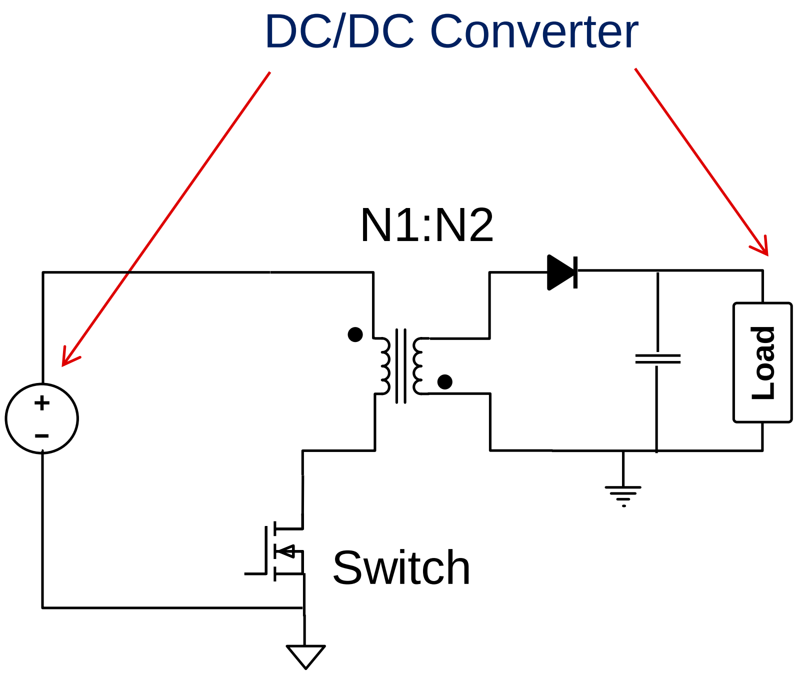
  - [1] J, Picard, Under the hood of Flyback SMPS design. https://www.ti.com/seclit/ml/slup261/slup261.pdf
  - [2] G. Jones, Miniature solutions for voltage isolation. www.ti.com/lit/an/slyt211/slyt211.pdf

Flyback Converter Operation

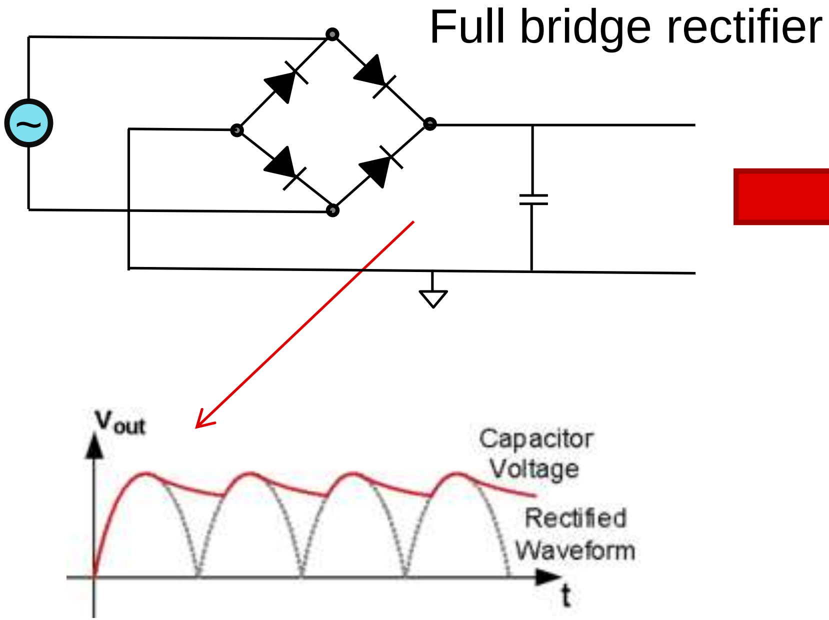
→

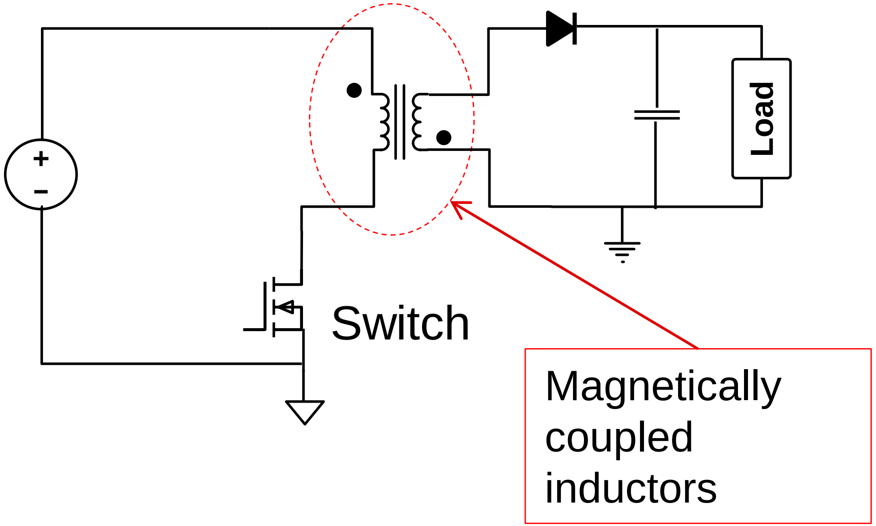
Flyback Topology

- Basic circuit:
  - Primary winding and switch
  - Secondary winding and rectifier
  - Bias winding and rectifier
  - Control circuit
- Note the transformer polarity
- Primary and secondary windings conduct alternately
- Primary winding stores energy in air-gap
- Secondary winding transfers air-gap energy to the output



AC/DC Flyback: Operation





Convert AC voltage to DC using a full-bridge diode rectifier

Flyback operation: Stage 1

- The MOSFET switch is on → transformer primary winding gets connected to the DC source (V_s) → linear increase of current in primary
- The magnetic flux in the transformer windings and core is entirely due to the primary winding current
- Diode is in reverse biased mode due to the induced voltage in the secondary
- Output load receives power from the output capacitor due to the previously stored charge

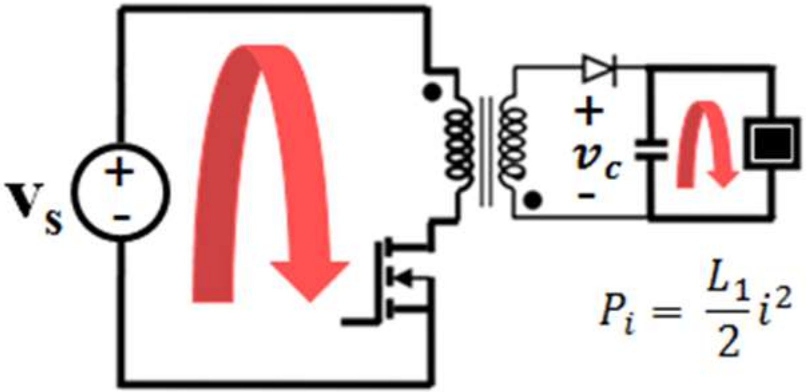


Fig. 2 (a):Current flow during Stage 1

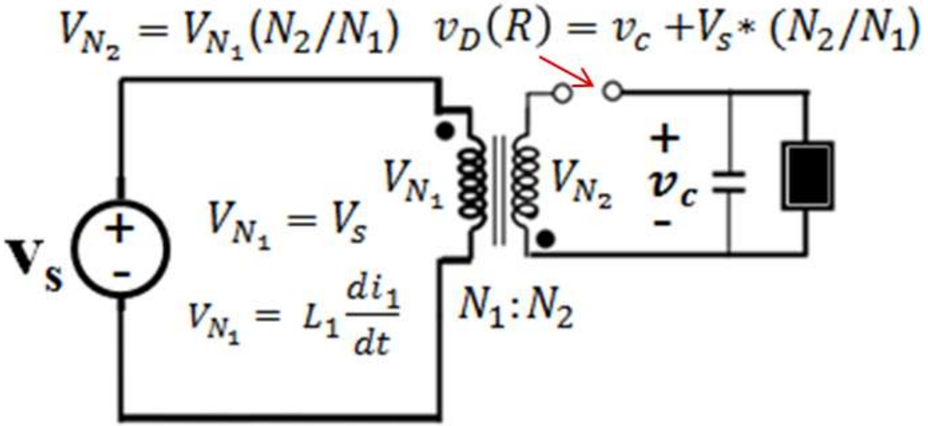


Fig. 2 (b): Equivalent circuit schematic in Stage 1

Flyback operation: Stage 2

- MOSFET switch turned off → the primary winding path is disconnected → the voltage polarities across the windings reverses
- Primary winding current is interrupted → secondary winding immediately begins to conduct→ the magneto motive force (MMF) produced by the windings do not change suddenly → this will ensure no interruption in the magnetic field energy ($E = B^2/2\mu$)
- Diode in the secondary circuit becomes forward biased due to this polarity reversal
- **Capacitor voltage magnitude will stabilize if during each switching cycle, the energy output by the secondary winding equals the energy delivered to the load.**

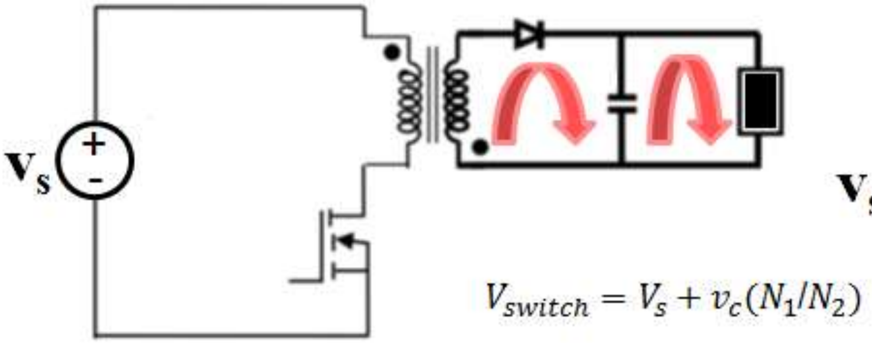


Fig. 3 (a):Current flow during Stage 2

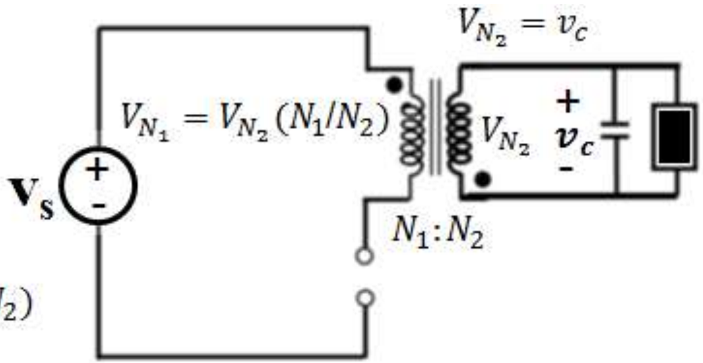


Fig. 3 (b): Equivalent circuit schematic in Stage 2

Flyback operation: Stage 3

- Considering a lengthy period for the off time → the secondary current decay to zero and magnetic field energy is completely discharged → output capacitor continues providing power to the load (discontinuous mode) → complete transfer of the magnetic field energy to the output → the secondary winding EMF as well as current decay to zero → the rectifying diode in secondary winding stops conducting
- Uninterrupted supply voltage to the load if output capacitor is large enough…
- End of Stage 3 → circuit resumes operation from Stage 1

$$EMF = 0 \;\&\; E = \frac{B^2}{2\mu} = 0$$

$$V_{N_1} = V_{N_2} = 0$$

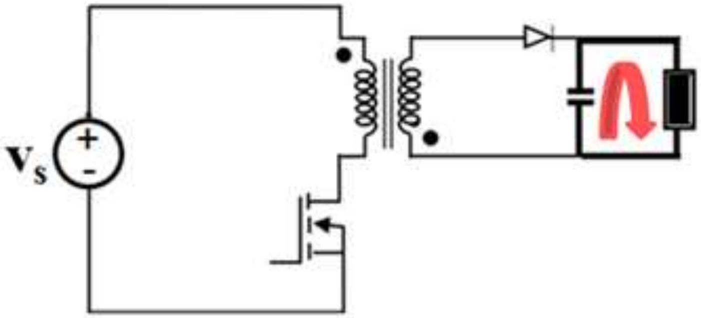


Fig. 4 (a):Current flow during Stage 3

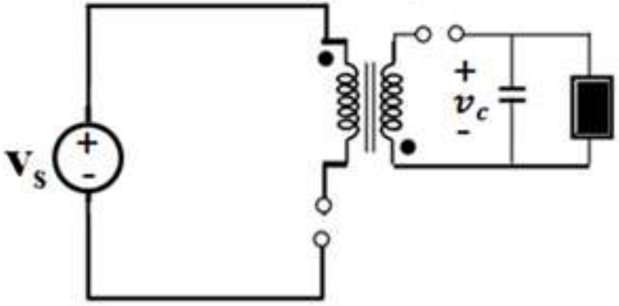
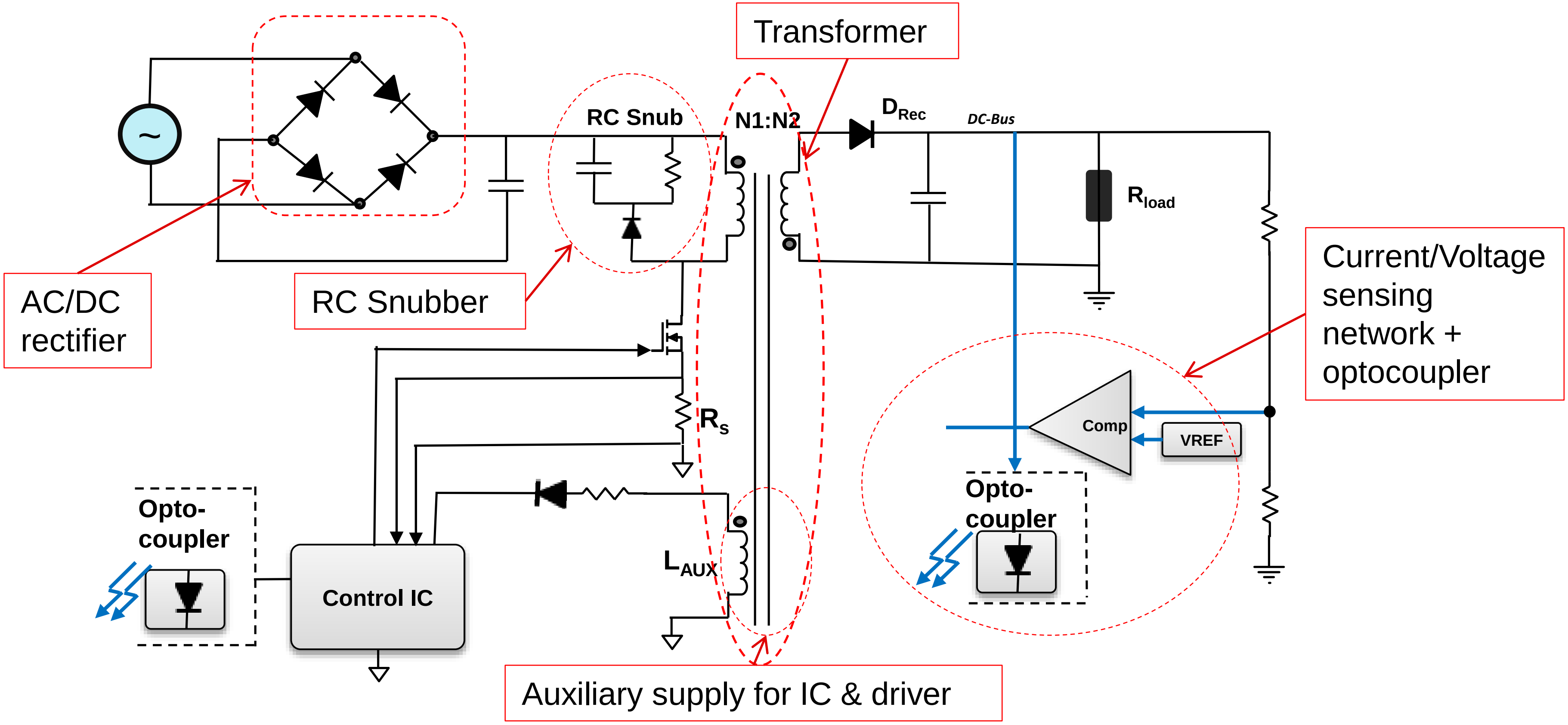


Fig. 4 (b): Equivalent circuit schematic in Stage 3

Typical AC/DC Flyback converter schematic



Flyback Transformers

- **Conventional transformers store minimal energy**
  – E.g. Forward converter, Push-Pull converter etc.
  – Primary and secondary currents flow simultaneously.
  – Energy is transferred by the simultaneous flow of current.
- **Flyback "transformers" are really coupled-inductors**
  – Primary and secondary windings do not conduct simultaneously → they can be seen as two magnetically coupled inductors → often called inductor-transformer
  – Current flows in primary while secondary diode is reverse-biased
  – Primary current stores energy in air-gap
  – When primary current stops, secondary winding reverses polarity → forward-biases output diode → secondary current flows
  – Air-gap energy is transferred to the secondary load:
    - **DCM** => all stored energy is delivered to the load, followed by an interval of zero current flow in both windings
    - **CCM** => only some of the stored energy is delivered to the load, primary current starts before secondary current has decayed to zero

Challenges of Flyback design

Overall Design	Transformer Design
• Balance cost, footprint and performance • Design decisions on modes of operation (CCM, DCM, CRM/TM) • Effective component selection – MOSFET, diodes should withstand the stress • Design RC or RCD snubber to suppress ringing • More complex design process compared to non-isolated topologies	• Customize for the specific power design specifications • Optimize selection of transformer based on efficiency, cost, footprint • Select appropriate core, considering loss and magnetic saturation • Select bobbin based on physical fit • Select wires gauge based on skin effect & current carrying capability • Design the winding strategy

Core and bobbin selection

- **Core**
  - Huge variety of standard cores of different shapes, sizes and material
  - Shapes
    - E-core, Pot core, RM core, PQ core
  - Material
    - 3F3/N87, 3C90/N87, 3C95/N95/PC95, 3C96/N97/PC44
  - Different sizes and combinations of Ae, Aw, Ve and le
- **Bobbin**
  - Vertical or horizontal
  - Lateral or low profile

Transformer design process constraints

- **Electrical Targets / Constraints**
  - Electrically required turns ratio for functionality
  - Primary inductance for target ripple current
  - Wire size designed for skin depth and current capacity
- **Power dissipation**
  - Minimize power losses
  - Balance transformer size with power dissipation
- **Magnetic Constraints**
  - Operating magnetic flux density does not go into saturation region
- **Physical Constrains**
  - Winding physically fits in the core and bobbin window
  - Core geometry factor (K_g) greater than what is required by the design

Constraint 1: Electrical

L_{prim} = Primary inductance, based on ripple
A_c = Core cross−section area
n = Number of turns
μ_0 = Permeability of free space
l_g = Air gap length

$$L_{prim} = \frac{n^2 A_C \mu_0}{l_g} = \frac{n A_C B_{max}}{I_{max}}$$

Constraint 2: Magnetic saturation

B_{max} = Maximum magnetic flux density
= $0.25\text{–}0.3\ \mathrm{T}$ for typical soft ferrite core

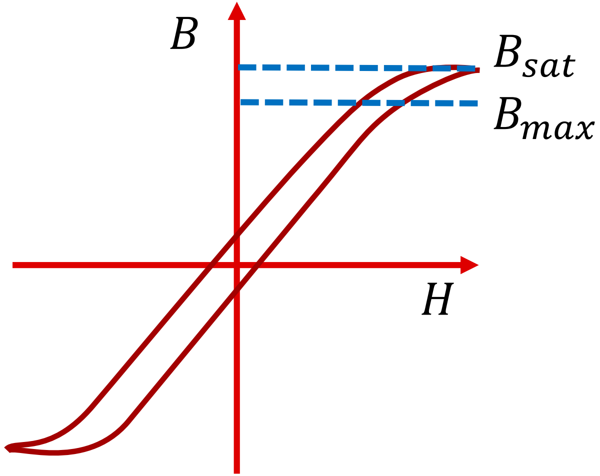
I_{max} = Maximum current

n = Number of turns

μ_0 = Permeability of free space

l_g = Air gap length

$$nI_{max} = B_{max}\frac{l_g}{\mu_0}$$



Constraint 3: Copper loss

Copper Wire DC resistance:

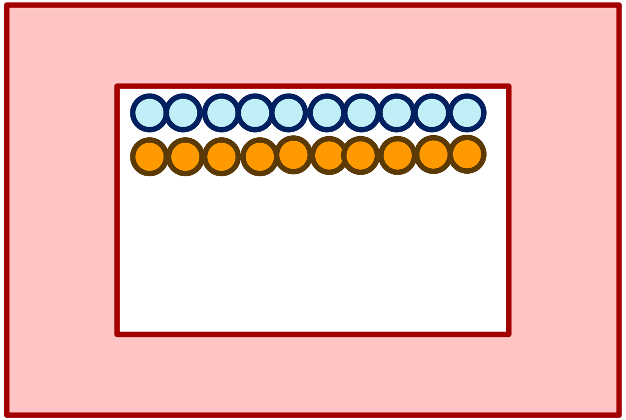
$$R_w = \rho \cdot \frac{n(MLT)}{A_w}$$

Where $MLT =$ mean length of wire per turn

Copper loss based on DC resistance is targeted to be < 1-2 % of P_{out} sets the target R_w

Constraint 4: Physical

A_w = wire cross−section area
W_A = Core window area
n = Number of turns
K_u = Fill factor, typically ~0.5−0.9



$$K_u W_A \geq n A_w$$

Aim is to utilize the core window fully, but space lost due to wire shape and insulation

Combining the constraints

Eliminating the unknowns n, l_g, A_w expresses the requirements of core in terms of the core geometrical constant, K_g

$$K_g = \frac{A_C{}^2 . W_A}{(MLT)} \geq \rho \cdot \frac{L_{prim}^2 . I_{max}{}^2}{R_w K_u B_{max}{}^2}$$

Property of the core only

Property of the design

Select cores whose geometric constant is higher than that required by the design

Now design the rest of the transformer

- Determine the number of turns in the primary

$$n = \frac{L_{prim} I_{max}}{A_C B_{max}}$$

- Based on turns ratio, set number of turns in secondary and auxiliary
- Specify the inductance factor

$$A_L = \frac{L_{prim}}{n^2} = \frac{A_C \mu_0}{l_g}$$

WEBENCH® design examples

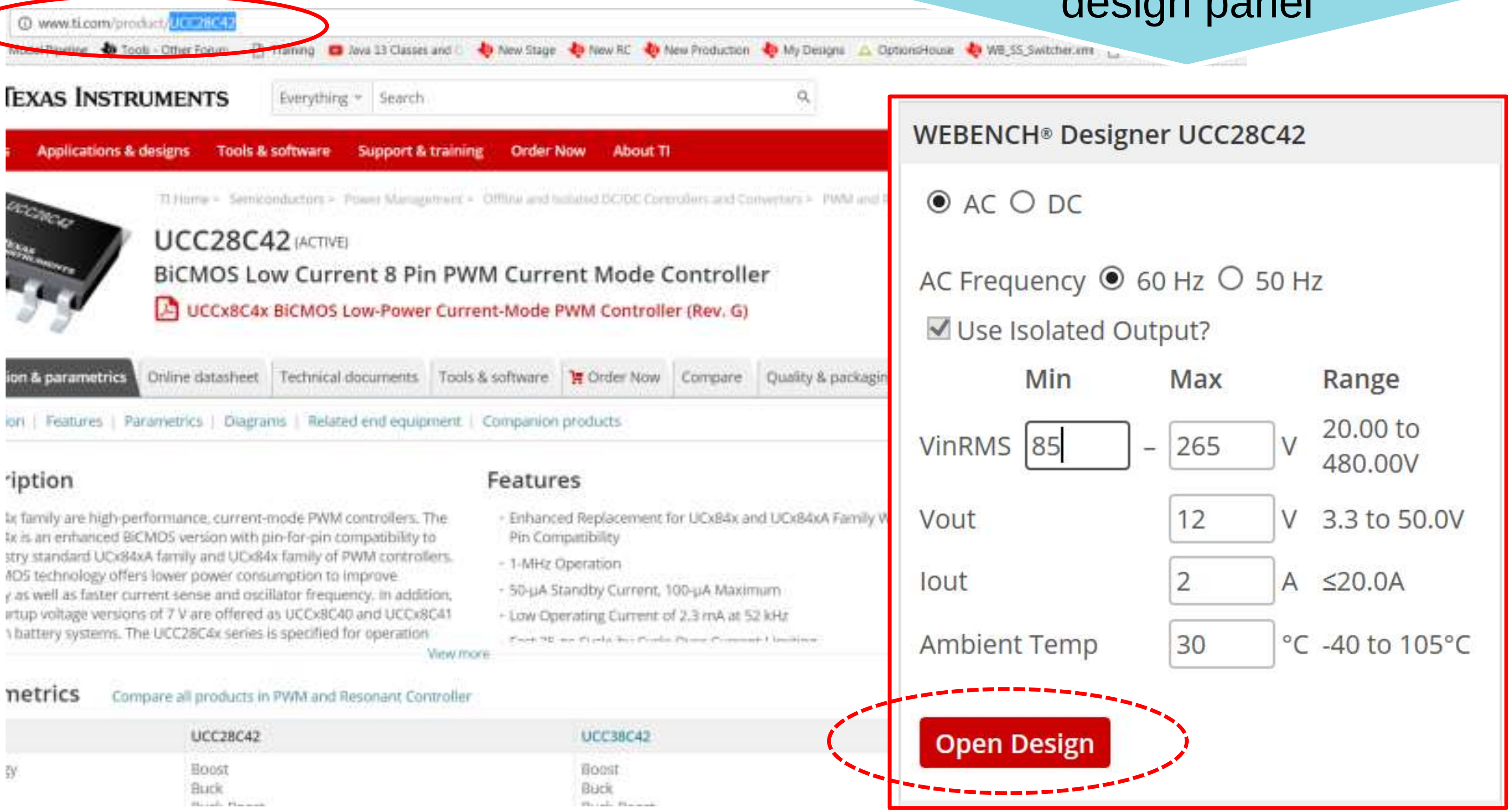
→

90+ High Voltage Products (> 70V) in WEBENCH® Tools

GPN	Comments
UCC28C40/1/2/3/4/5/UCC28C41-Q1 UCC38C40/1/2/3/4/5	Secondary Side Regulated Flyback using Optocoupler Feedback
UC1842/3/4/5 UC2842/3/4/5/UC2843A-Q1 UC1842A/3A/4A/5A UC2842A/3A/4A/5A UC3842/3/4/5 UC3842A/3A/4A/5A	Secondary Side Regulated Flyback using Optocoupler Feedback
UCC28910/1	Primary Side Regulated (PSR) Flyback
TL2842/3/4/5/42B/43B/44B/45B/43B-Q1 TL3842/3/4/5/42B/43B/44B/45B	Secondary Side Regulated Flyback using Optocoupler Feedback
UCC28704	PSR CV/CC Flyback controller
UCC28700/701/2/3/710/711/720/722	PSR CV/CC Flyback controller
UCC28740	CV/CC Flyback using Optocoupler Feedback
UCC28880/1	Non-isolated HV AC/DC HS Buck
LM5023	Quasi-Resonant Mode PWM
UCC28740 + UCC24636	Synchronous Rectifier Controller for USB Type C PD Applications
UCC2800/1800/3800/2800-Q1/UCC2813-0/3813-0 UCC2801/1801/3801/2801-Q1/UCC2813-1/3813-1 UCC2802/1802/3802/2802-Q1/UCC2813-2/3813-2 UCC2803/1803/3803/2803-Q1/UCC2813-3/3813-3 UCC2804/1804/3804/2804-Q1/UCC2813-4/3813-4 UCC2805/1805/3805/2805-Q1/UCC2813-5/3813-5	Low Power Current Mode PWM
UCC28880/1	Flyback Topology

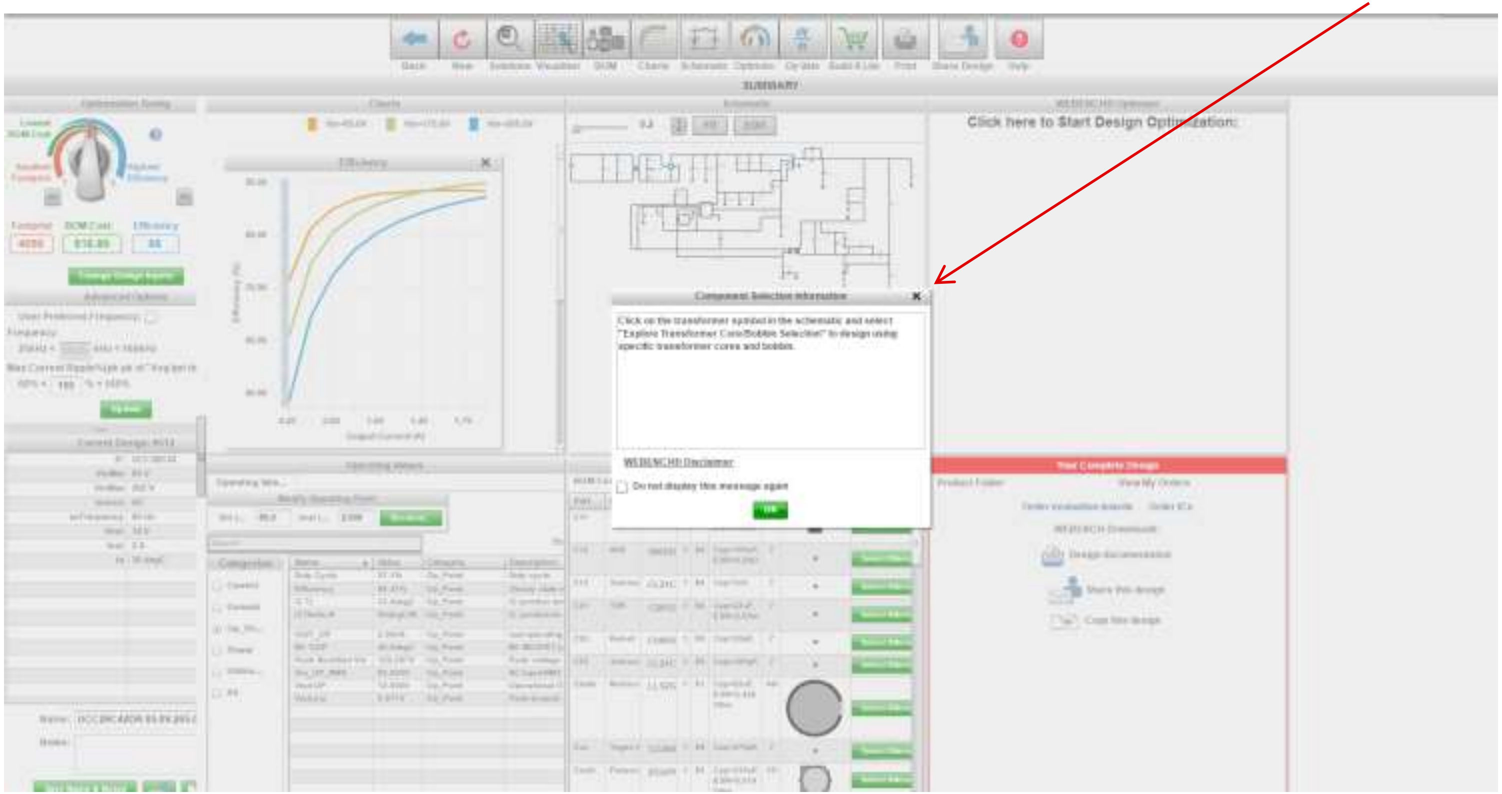
Design example (UCC28C42):

WEBENCH®
design panel

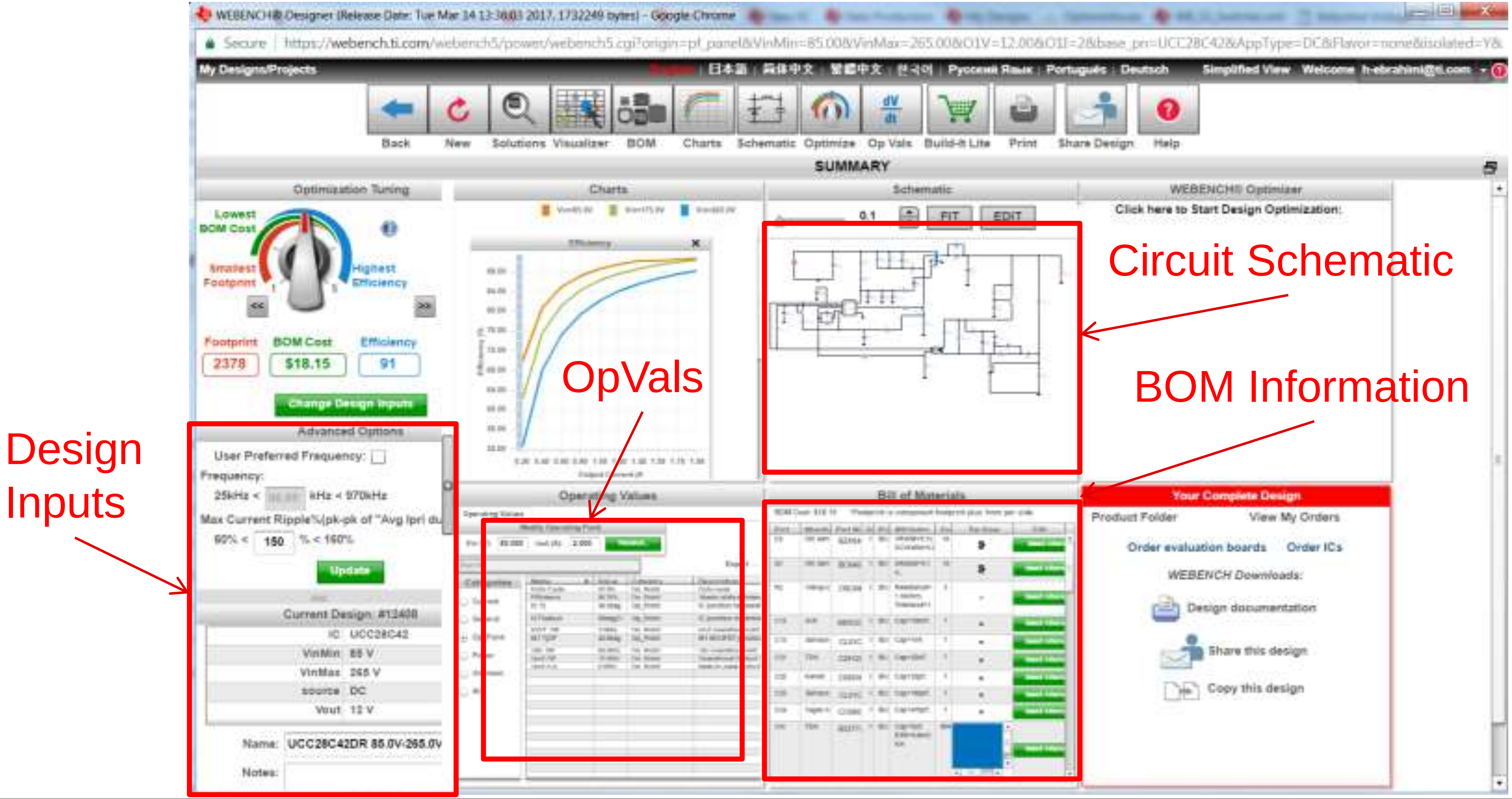


WEBENCH® Design

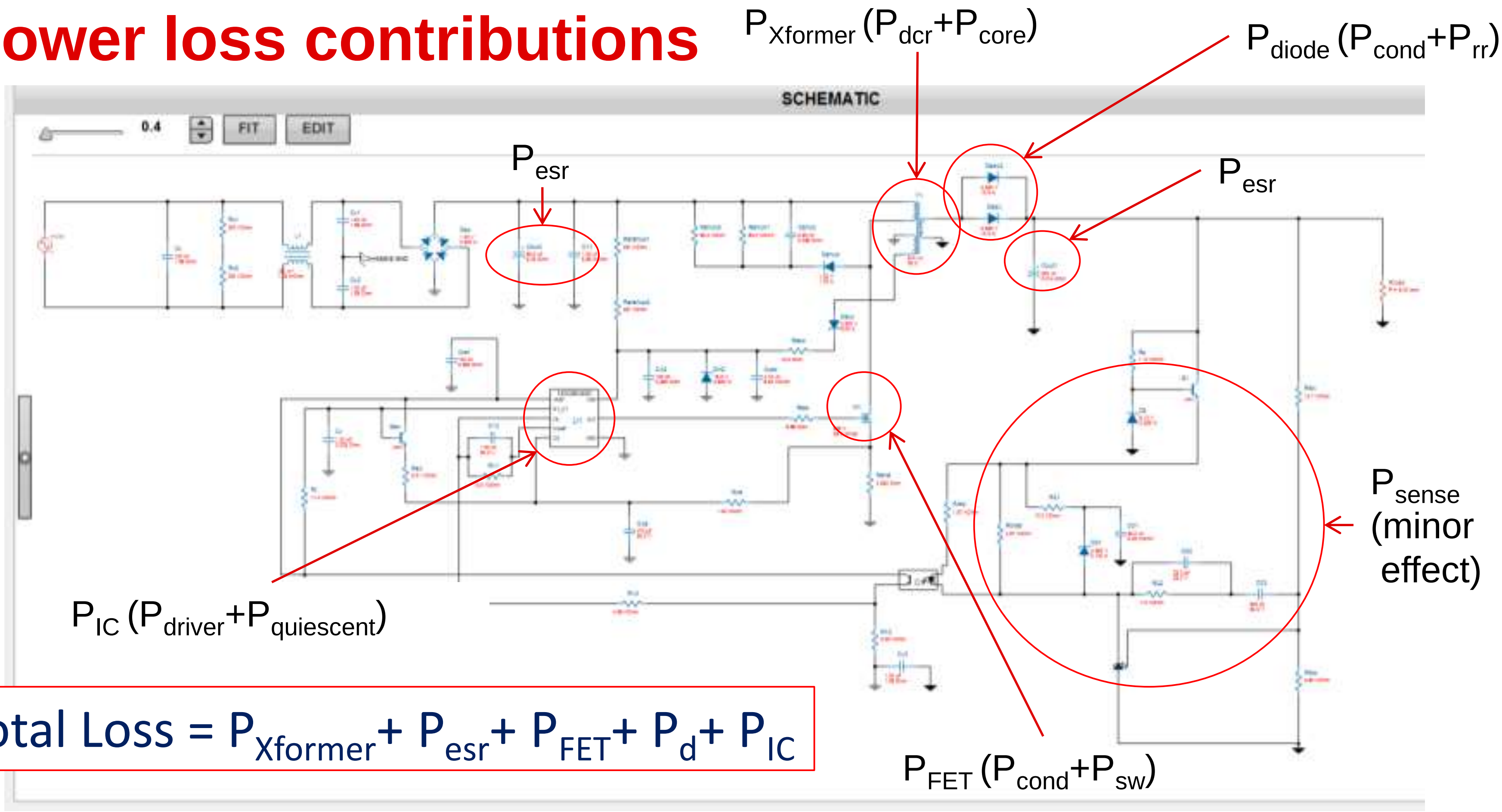
Pop up alerts user of core/bobbin selection for the design



WEBENCH® design summary

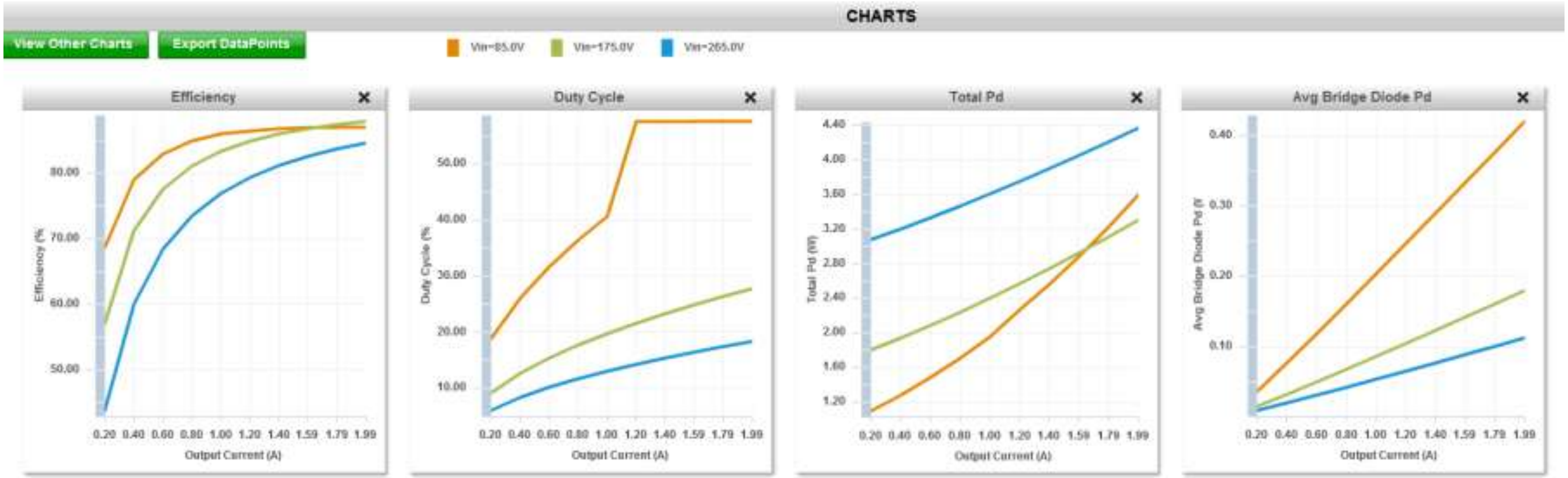


Power loss contributions



Total Loss = $P_{Xformer}$ + P_{esr} + P_{FET} + P_{d} + P_{IC}

Operating charts



Operating values

Operating Values

Modify Operating Point

Vin (V): 85.0 Iout (A): 2.000 Recalculate

Search

Categories

- Current
- General
- Op_Point
- Power
- Unknown
- All

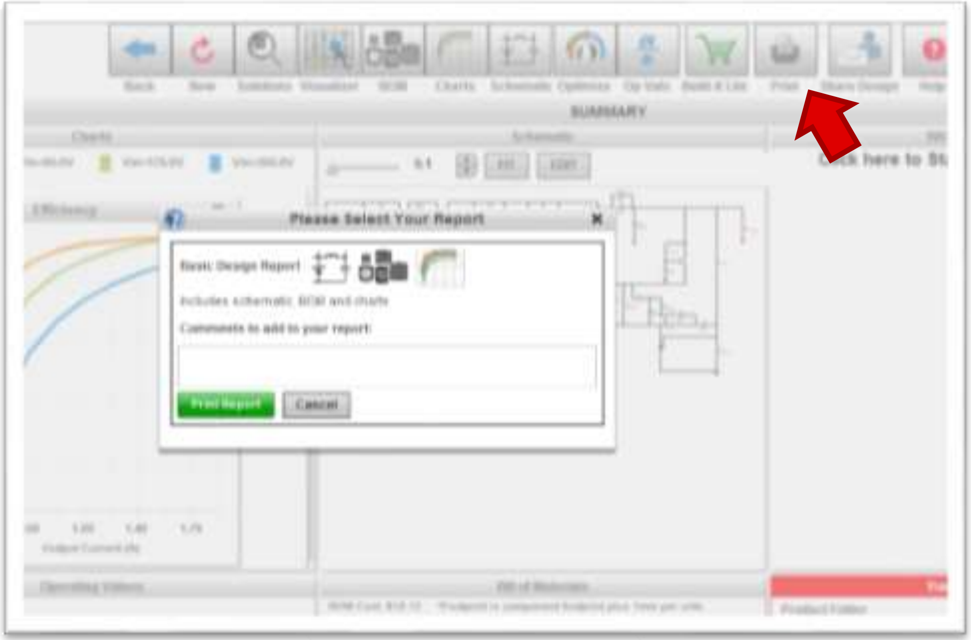
Name ▲	Value	Cat
Duty Cycle	57.6%	Op_
Efficiency	86.97%	Op_
IC Tj	35.8degC	Op_
ICThetaJA	50degC/W	Op_
IOUT_OP	2.000A	Op_
M1 TjOP	44.4degC	Op_
Peak Rectified Vin	120.207V	Op_
Vin_OP_RMS	85.000V	Op_
Vout OP	12.000V	Op_
Vout p-p	0.080V	Op_

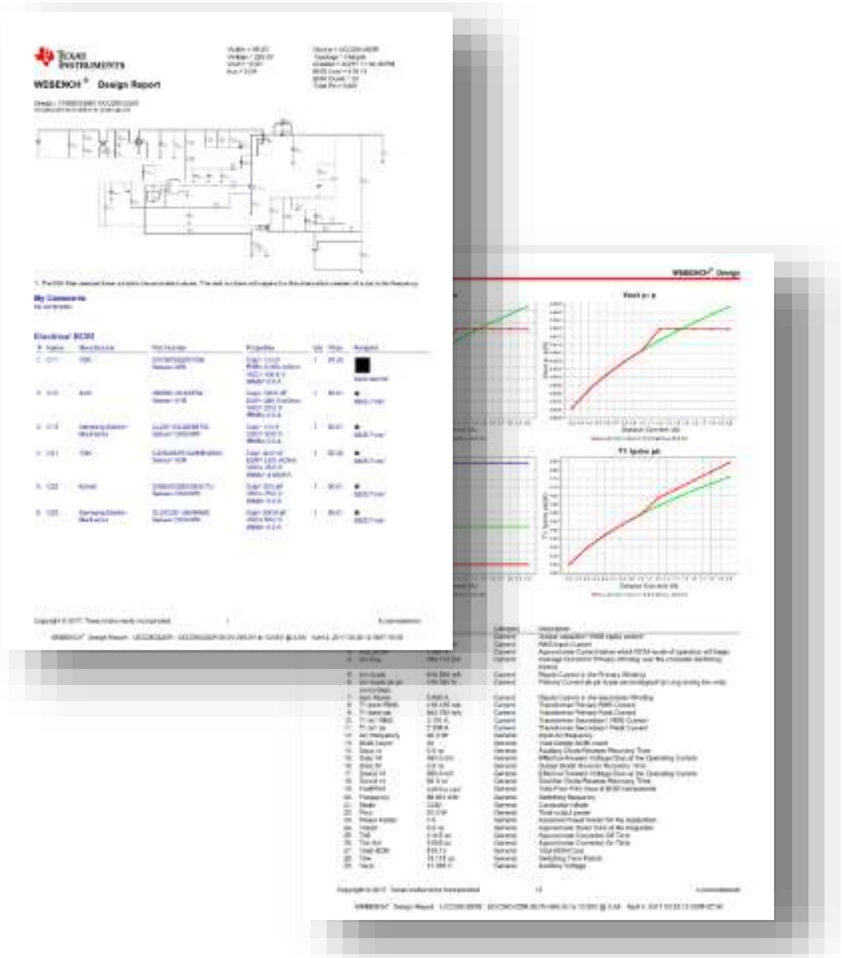
BOM

Export to: Excel   BOM Cost: $18.13   *Footprint is component footprint plus 1mm per side.

Part	Manufacturer	Part Number	Quantity	Price	Attributes	Footprint	Top View	Edit
C11	TDK	C5750X6S2W105K	1	$1.25	Cap=1uF, ESR=6.263mOhm	54		Select Alternate Part
C12	AVX	08053C104KAT2A	1	$0.01	Cap=100nF, ESR=0.28Ohm	7		Select Alternate Part
C13	Samsung Electro-Mechanics	CL21C102JBCNNNC	1	$0.01	Cap=1nF, ESR=0Ohm	7		Select Alternate Part
C21	TDK	C2012X5R1V226M125AC	1	$0.32	Cap=22uF, ESR=2.05mOhm	7		Select Alternate Part
C22	Kemet	C0805C220K3GACTU	1	$0.01	Cap=22pF, ESR=0Ohm	7		Select Alternate Part
C23	Samsung Electro-Mechanics	CL21C201JBANNNC	1	$0.01	Cap=200pF, ESR=0Ohm	7		Select Alternate Part
Cbulk	Nichicon	LLS2G820MELY	1	$1.43	Cap=82uF, ESR=2.426Ohm	484		Select Alternate Part
Css	Yageo America	CC0805KRX7R8BB471	1	$0.01	Cap=470pF, ESR=0Ohm	7		Select Alternate Part
Cout	Panasonic	25SVPF330M	1	$0.70	Cap=330uF, ESR=0.014Ohm	151		Select Alternate Part
Cref	AVX	08053C104KAT2A	1	$0.01	Cap=100nF, ESR=0.28Ohm	7		Select Alternate Part
Csnub	TDK	C3216CH2E392J	1	$0.08	Cap=3.9nF, ESR=0.029Ohm	11		Select Alternate Part
Ct	Kemet	C0805C102J5GACTU	1	$0.02	Cap=1nF, ESR=0.025Ohm	7		Select Alternate Part
Cvdd	MuRata	GRM319R61E475KA12D	1	$0.10	Cap=4.7uF, ESR=4.682mOhm	11		Select Alternate Part
Cx	Kemet	PME844RD6100MR30L2	1	$0.30	Cap=100nF, ESR=1.08Ohm	288		Select Alternate Part
Cy1	TDK	B81123C1102M	1	$0.22	Cap=1nF, ESR=1.59Ohm	140		Select Alternate Part
Cy2	TDK	B81123C1102M	1	$0.22	Cap=1nF, ESR=1.59Ohm	140		Select Alternate Part
Cy3	TDK	B81123C1102M	1	$0.22	Cap=1nF, ESR=1.59Ohm	140		Select Alternate Part
D12	Diodes Inc.	MMSZ5248B-7-F	1	$0.04	VRWM=18V, DCWatts=0.5W, VRSM=0V	13		Select Alternate Part
D21	Panasonic	DB2S31600L	1	$0.04	VFatIo=0.55V, Io=0.1A, VRRM=30V	6		Select Alternate Part
Dac	Diodes Inc.	HD06-T	1	$0.13	VFatIo=1V, Io=0.8A, VRRM=600V	62		Select Alternate Part
Daux	SMC Diode Solutions	SK220ATR	1	$0.05	VFatIo=0.9V, Io=2A, VRRM=200V	37		Select Alternate Part
Drec	SMC Diode Solutions	SBRD10200TR	1	$0.12	VFatIo=0.88V, Io=10A, VRRM=200V	102		Select Alternate Part
Drec2	SMC Diode Solutions	SBRD10200TR	1	$0.12	VFatIo=0.88V, Io=10A, VRRM=200V	102		Select Alternate Part
Dsnub	Microsemi	UFS180JE3/TR13	1	$0.71	VFatIo=1.2V, Io=1A, VRRM=600V	42		Select Alternate Part

Print


SUMMARY
Please Select Your Report
Basic Design Report
Includes schematic, BOM and charts
Comments to add to your report:
Print Report
Cancel


Design Report

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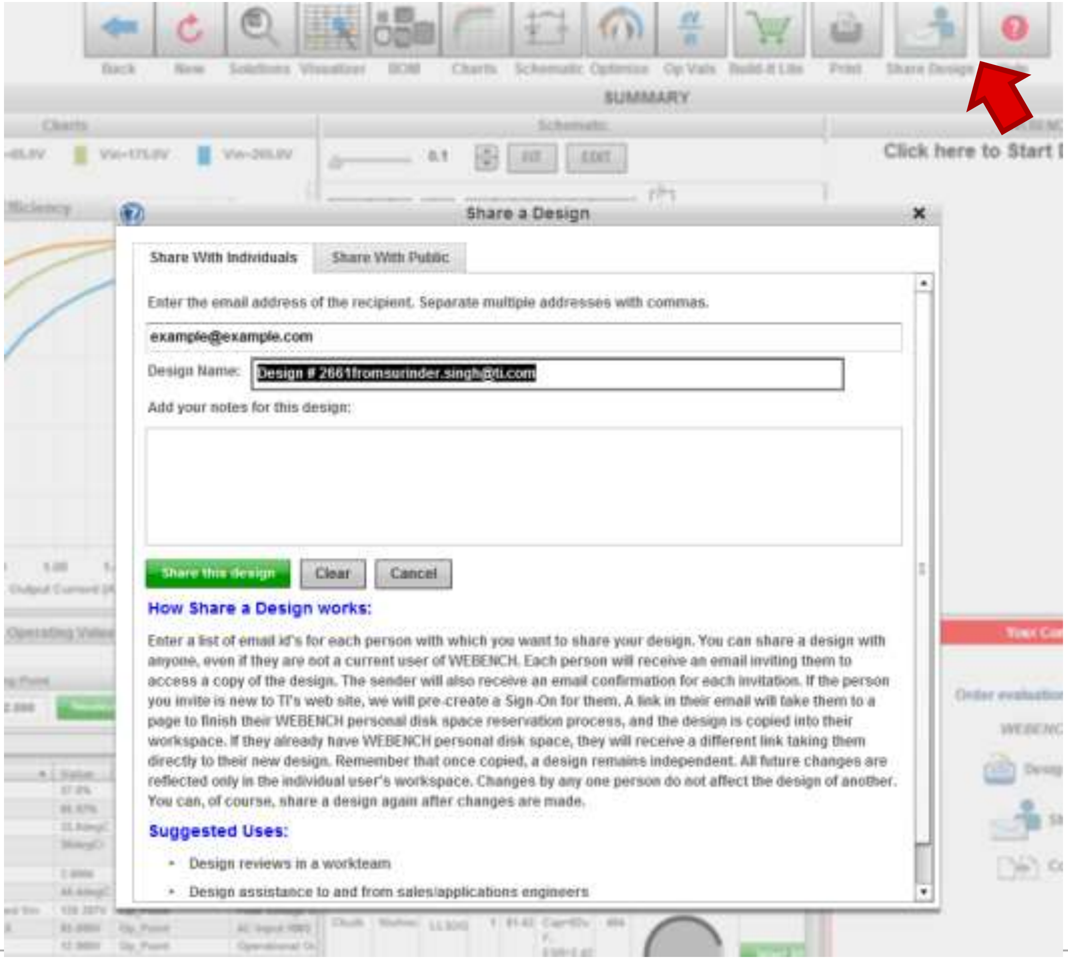
SUMMARY
Click here to Start
Share a Design
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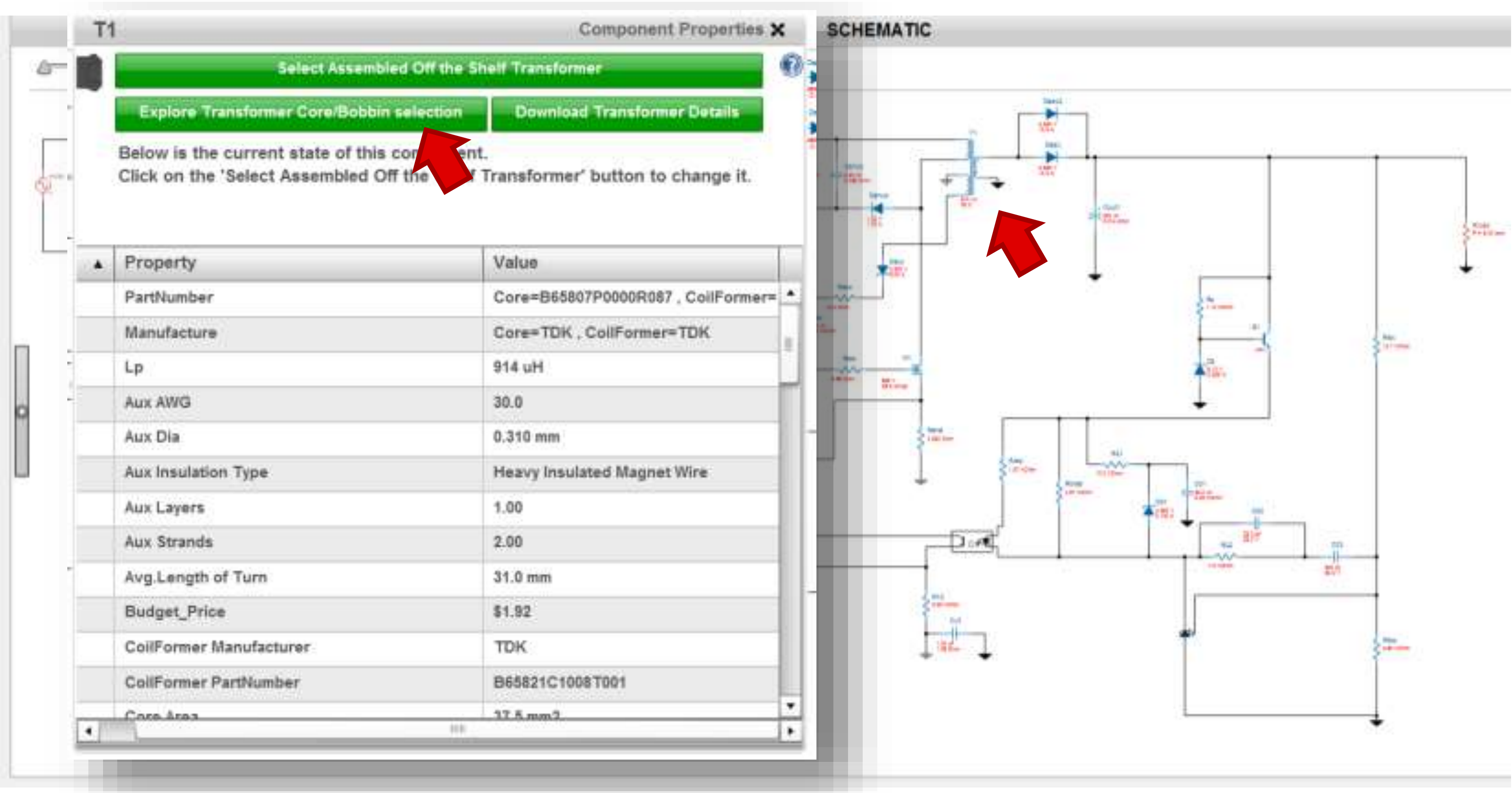
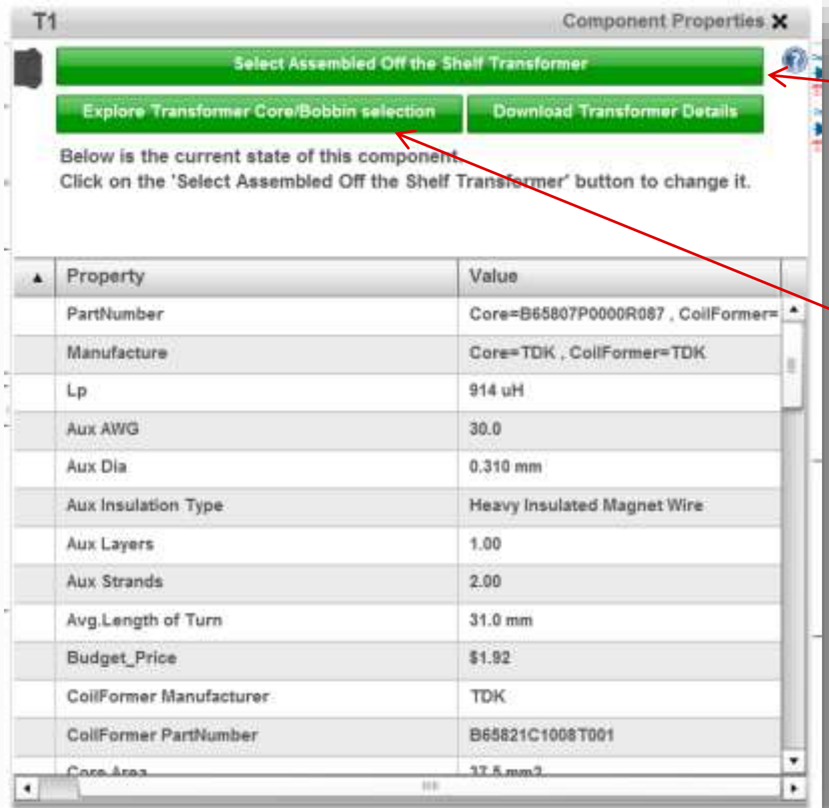
Share With Public
Enter the email address of the recipient. Separate multiple addresses with commas.
example@example.com
Design Name:
Design # 2661fromsurinder.singh@ti.com
Add your notes for this design:
Share this design
Clear
Cancel
How Share a Design works:
Enter a list of email id's for each person with which you want to share your design. You can share a design with anyone, even if they are not a current user of WEBENCH. Each person will receive an email inviting them to access a copy of the design. The sender will also receive an email confirmation for each invitation. If the person you invite is new to TI's web site, we will pre-create a Sign-On for them. A link in their email will take them to a page to finish their WEBENCH personal disk space reservation process, and the design is copied into their workspace. If they already have WEBENCH personal disk space, they will receive a different link taking them directly to their new design. Remember that once copied, a design remains independent. All future changes are reflected only in the individual user's workspace. Changes by any one person do not affect the design of another. You can, of course, share a design again after changes are made.
Suggested Uses:
Design reviews in a workteam
Design assistance to and from sales/applications engineers

Schematic


T1
Component Properties
SCHEMATIC
Select Assembled Off the Shelf Transformer
Explore Transformer Core/Bobbin selection
Download Transformer Details
Below is the current state of this component.
Click on the 'Select Assembled Off the Shelf Transformer' button to change it.
Property
Value
PartNumber
Core=B65807P0000R087 , CoilFormer=
Manufacture
Core=TDK , CoilFormer=TDK
Lp
914 uH
Aux AWG
30.0
Aux Dia
0.310 mm
Aux Insulation Type
Heavy Insulated Magnet Wire
Aux Layers
1.00
Aux Strands
2.00
Avg.Length of Turn
31.0 mm
Budget_Price
$1.92
CoilFormer Manufacturer
TDK
CoilFormer PartNumber
B65821C1008T001

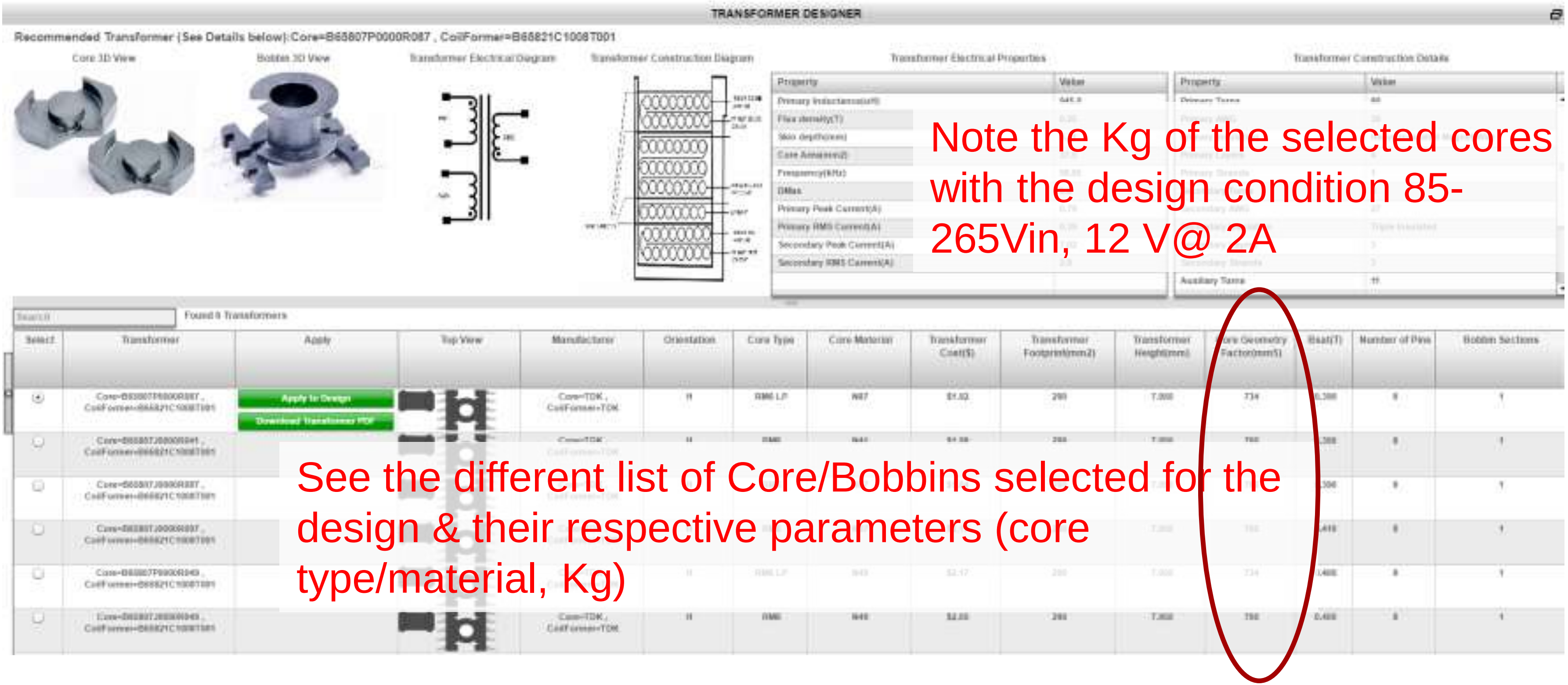
View or change Flyback transformer



Selecting this will give the user any available off-the-shelf transformers

Selecting this will give the user all selected core/bobbins for the current design

Flyback transformer designer



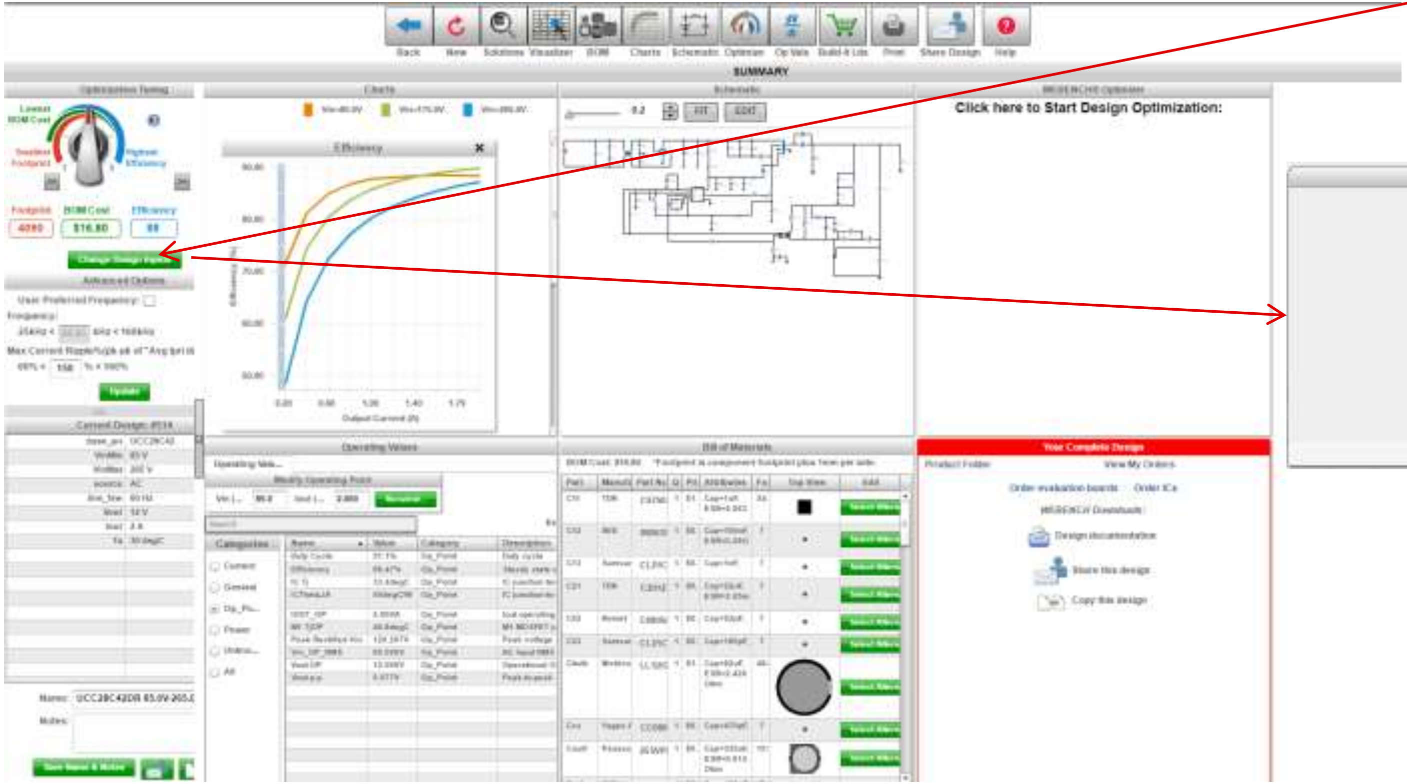
Note the Kg of the selected cores with the design condition 85-265Vin, 12 V@ 2A

See the different list of Core/Bobbins selected for the design & their respective parameters (core type/material, Kg)

Let us change the design condition now…

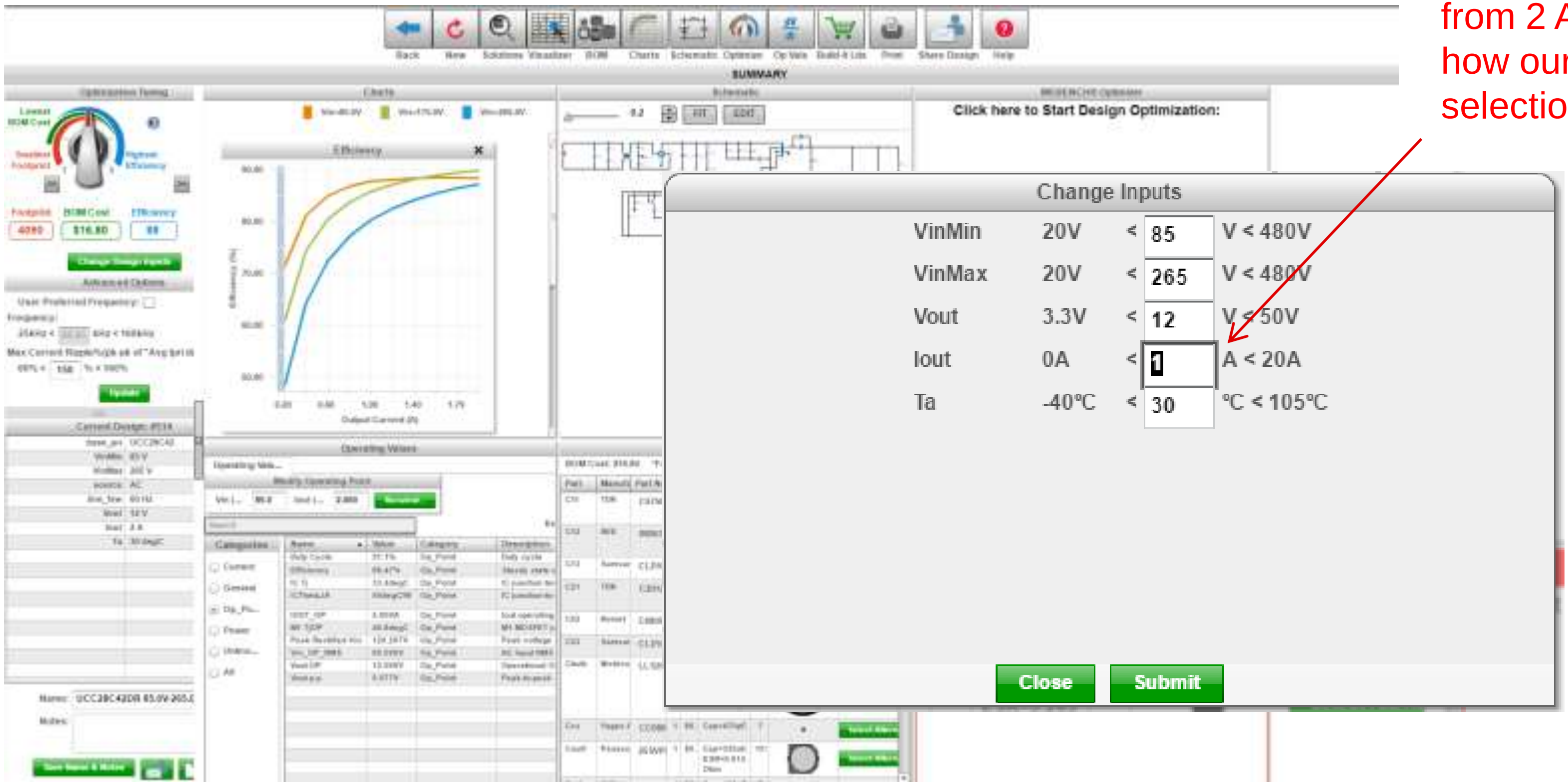
Change the inputs to the design

Click on “Change Design Inputs” button to see this window on the right

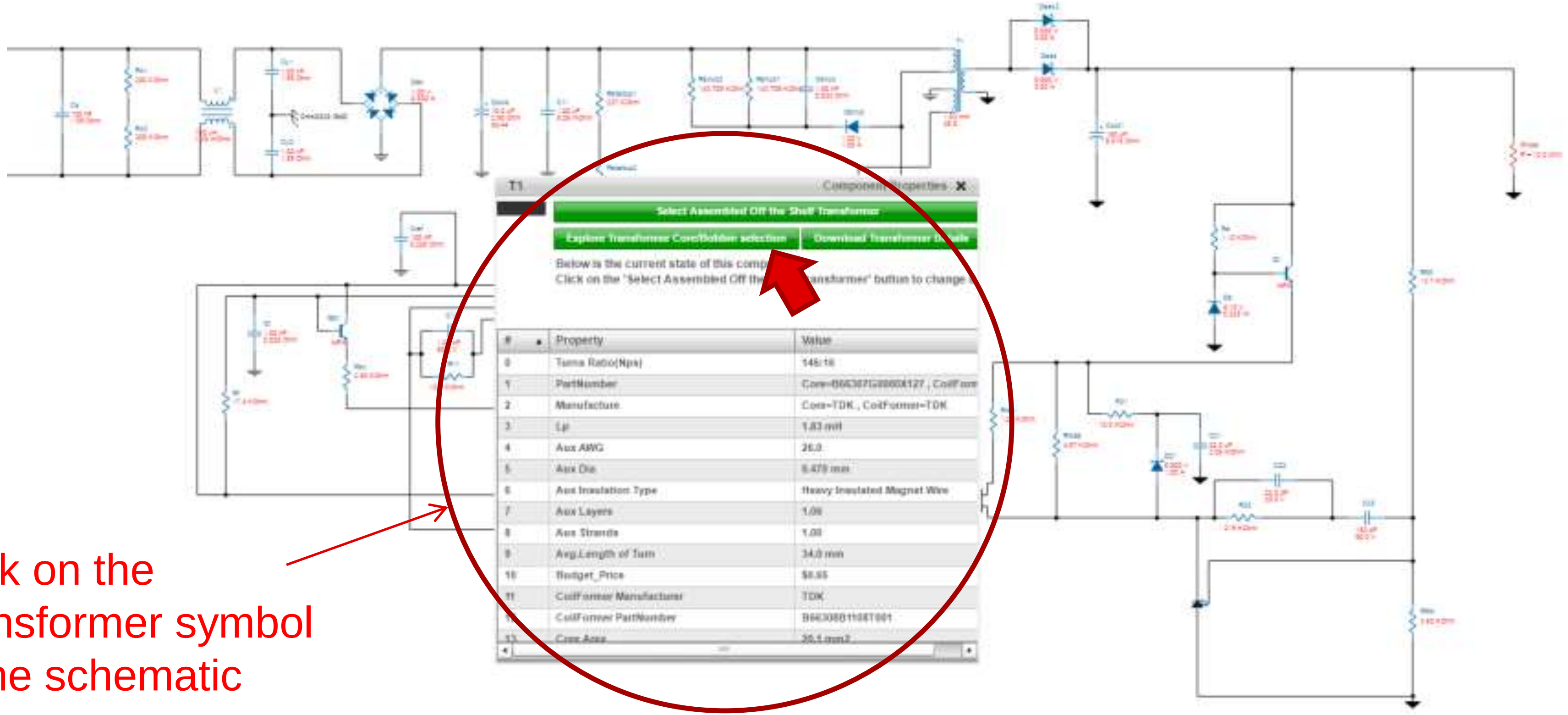


Enter new output current

Lets decrease the output current to 1 A from 2 A and see how our core selection changes

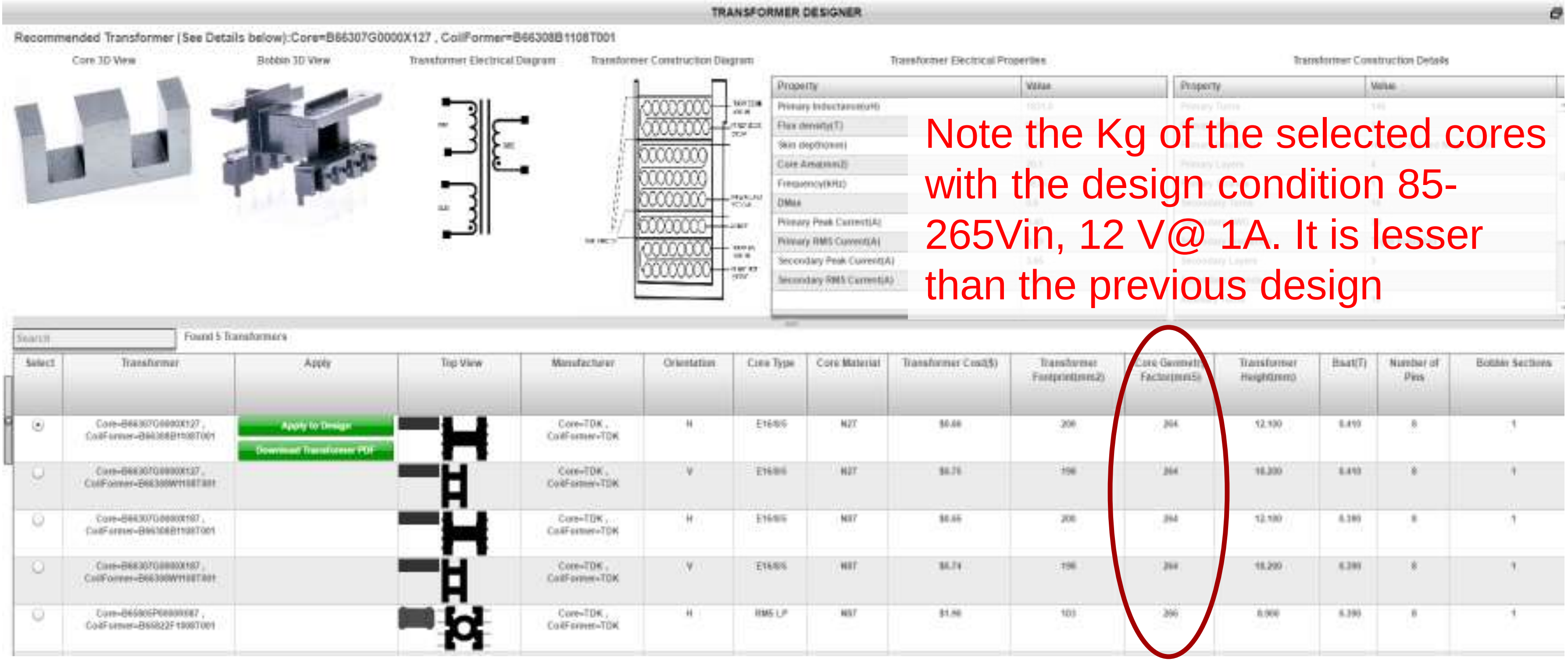


View the Flyback transformer in the schematic



Click on the Transformer symbol in the schematic

Flyback transformer design



Note the Kg of the selected cores with the design condition 85-265Vin, 12 V@ 1A. It is lesser than the previous design

Differences in electrical specs

2-A design

Property	Value
Primary Inductance(uH)	914.0
Flux density(T)	0.25
Skin depth(mm)	0.21
Core Area(mm2)	37.5
Frequency(kHz)	98.85
DMax	0.6

Property	Value
Primary Turns	79
Primary AWG	30
Primary Insulation	Heavy Insulated Magnet Wir
Primary Layers	4
Primary Strands	1
Secondary Turns	9

1-A design

Property	Value
Primary Inductance(uH)	1831.0
Flux density(T)	0.25
Skin depth(mm)	0.21
Core Area(mm2)	20.1
Frequency(kHz)	98.85
DMax	0.6
Primary Peak Current(A)	0.40
Primary RMS Current(A)	0.19

Property	Value
Primary Turns	146
Primary AWG	32
Primary Insulation	Heavy Insulated Magnet W
Primary Layers	4
Primary Strands	1
Secondary Turns	16
Secondary AWG	30
Secondary Insulation	Triple Insulated

1-A design results in larger primary inductance than the 2-A design due to lower ripple current

Lower current design reduces cost, footprint, Kg

2-A design

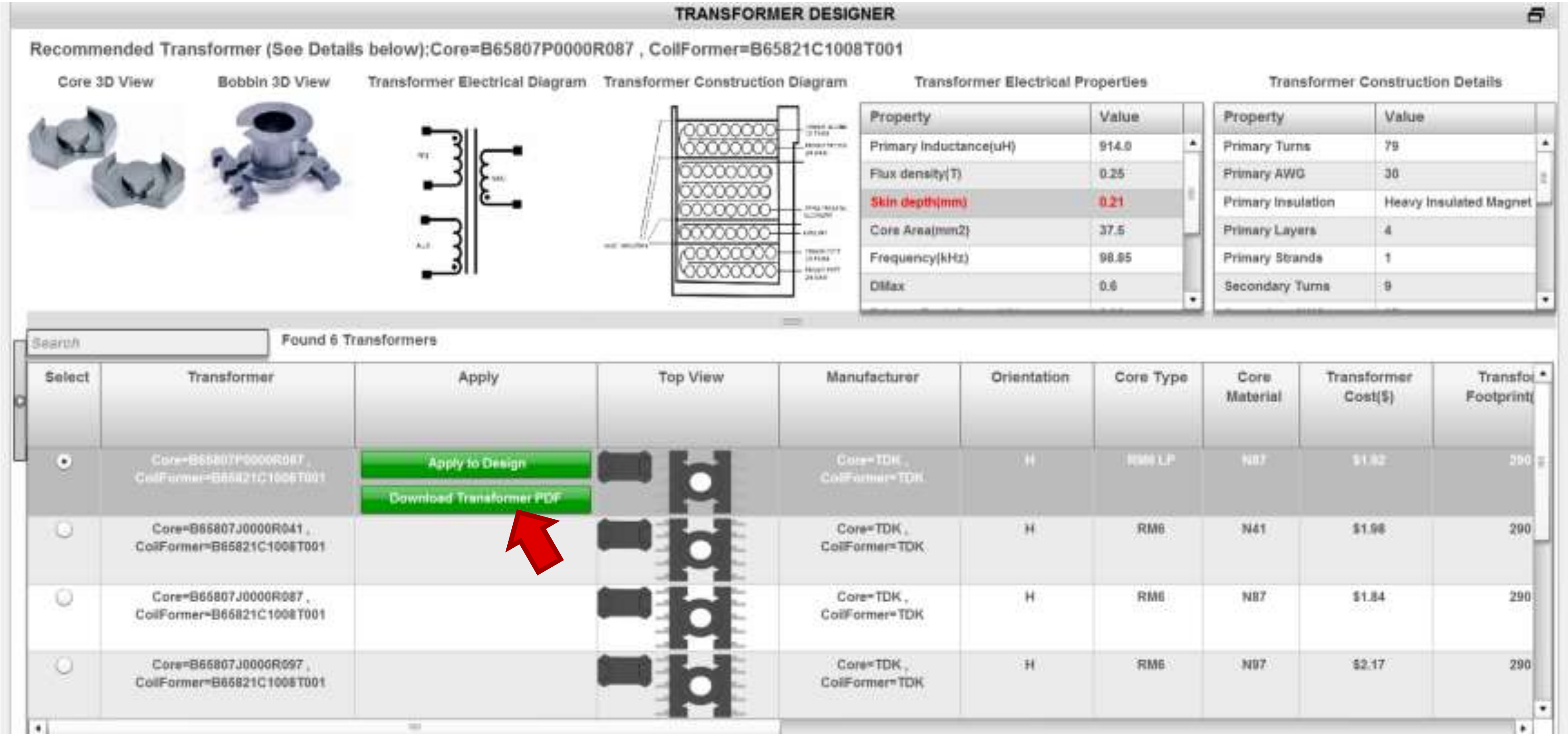
Transformer Cost($)	Transformer Footprint(mm2)	Core Geometry Factor(mm5)
$1.92	290	734
$1.98	290	700
$1.84	290	700
$2.17	290	700
$2.17	290	734
$2.05	290	700

1-A design

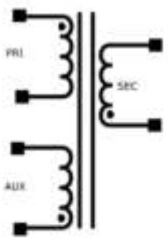
Transformer Cost($)	Transformer Footprint(mm2)	Core Geometry Factor(mm5)
$0.66	200	264
$0.75	198	264
$0.65	200	264
$0.74	198	264
$1.90	103	266

TEXAS INSTRUMENTS

Download the transformer design report

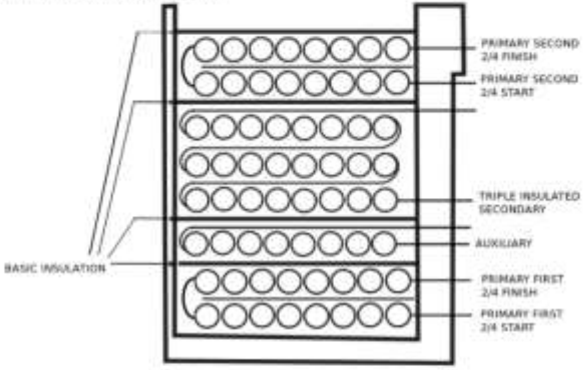


Send the transformer report for fabrication



#	Name	Value
1.	Core Part Number	B65807P0000R087
2.	Core Manufacturer	TDK
3.	Coil Former Part Number	B65821C1008T001
4.	Coil Former Manufacturer	TDK

Transformer Electrical Diagram



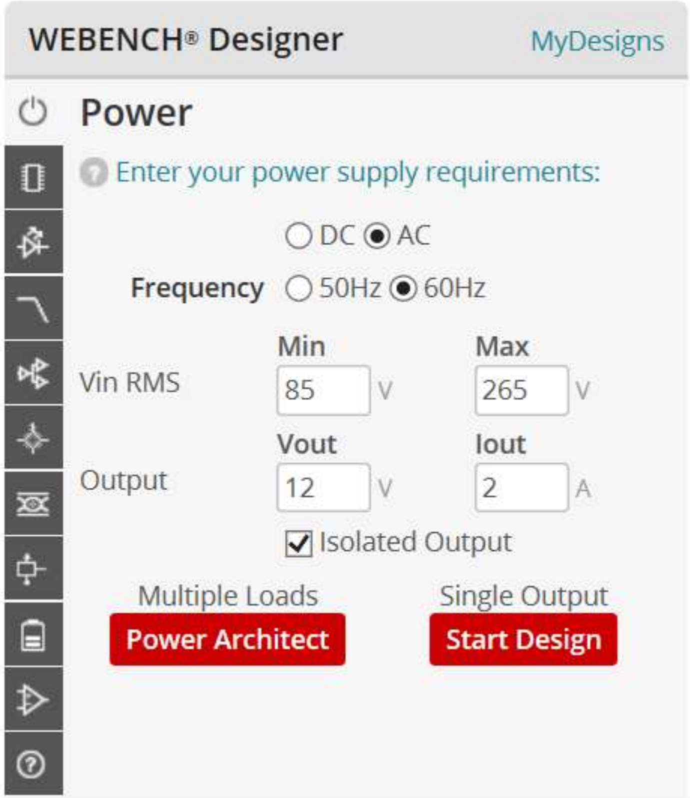
Winding Instruction

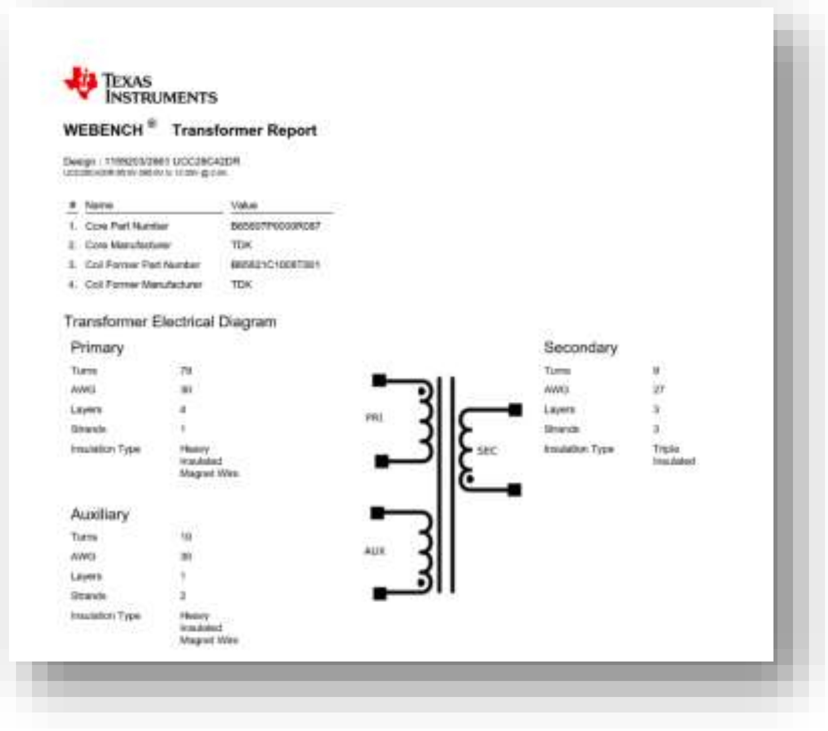
Winding	AWG	Turns	Winding Orientation
Primary First 2/4	30	40	Clockwise
Auxiliary	30	10	Counter Clockwise
Triple Insulated Secondary	27	9	Counter Clockwise
Primary Second 2/4	30	39	Clockwise

Transformer Parameters

#	Name	Value
1.	Lpri	9.14E-4H
2.	Inductance Factor(Al)	147nH
3.	Npri	79
4.	Nsec	9
5.	Naux	10
6.	Core Type	RM8 LP
7.	Core Material	N87
8.	Bmax	0.25T
9.	Switching Frequency	90.05kHz
10.	DMax	0.6
11.	Ipk(Primary)	0.8A
12.	Irms(Primary)	0.39A
13.	Ipk(Secondary)	7.33A
14.	Irms(Secondary)	2.79A

Explore WEBENCH transformer designer for your next isolated high-voltage design





Conclusion – high-voltage and transformer design

- Transformer design is critical for Flyback isolated designs
- WEBENCH tools can help you design your customized transformer
- Using the tool you can prototype and manufacture your transformer rapidly