

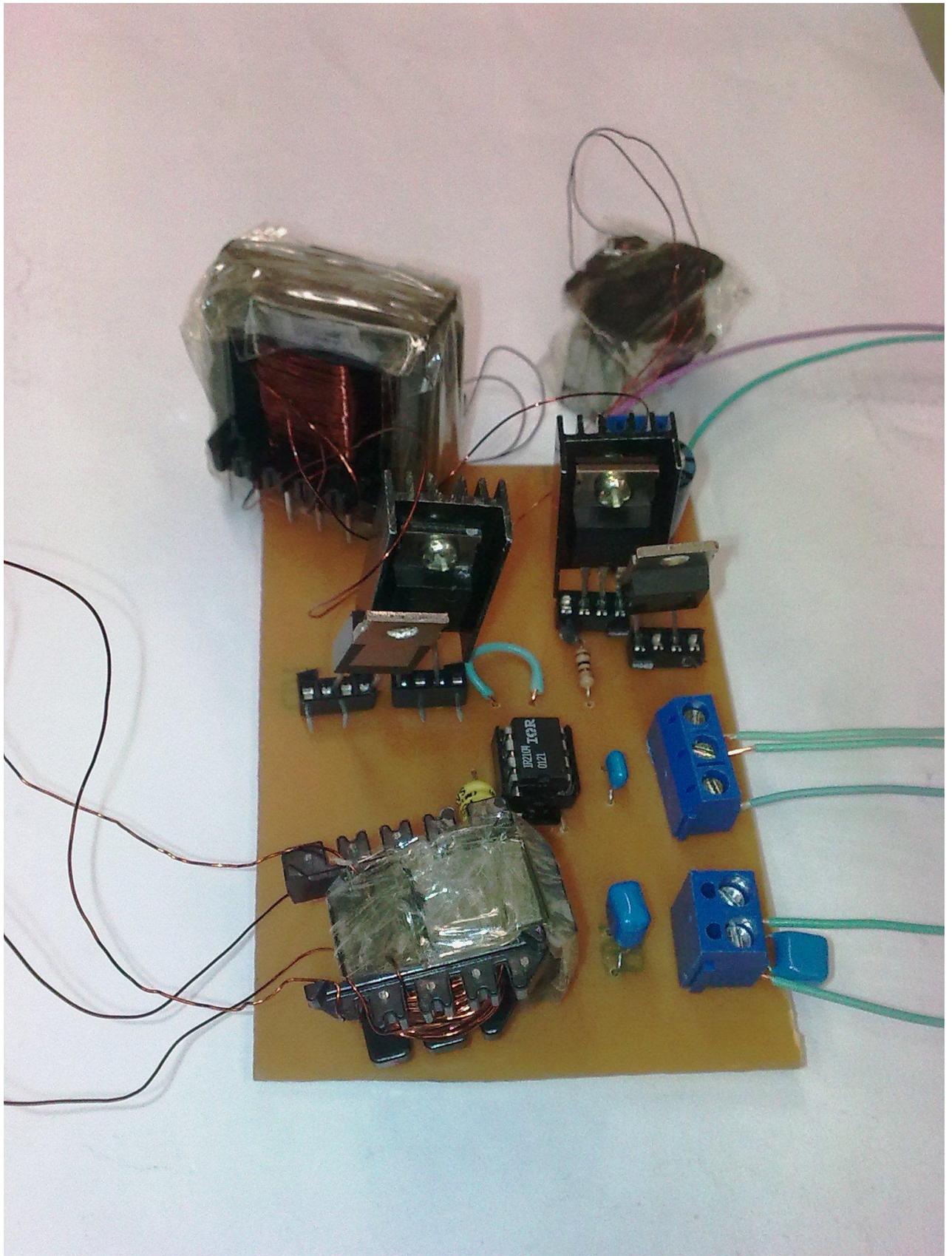
Project Report

EE452: Power Electronics

Forward Converter

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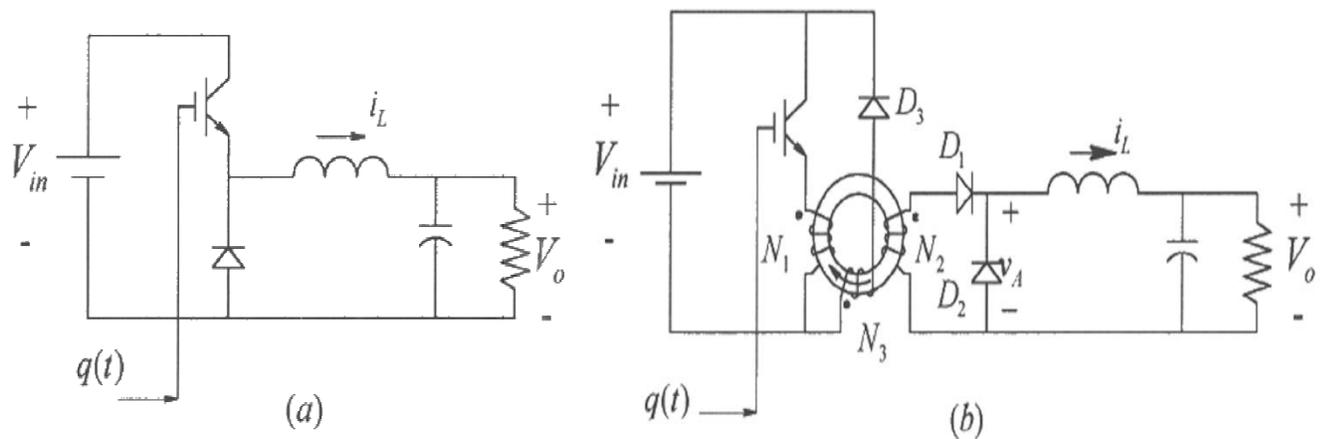


Introduction

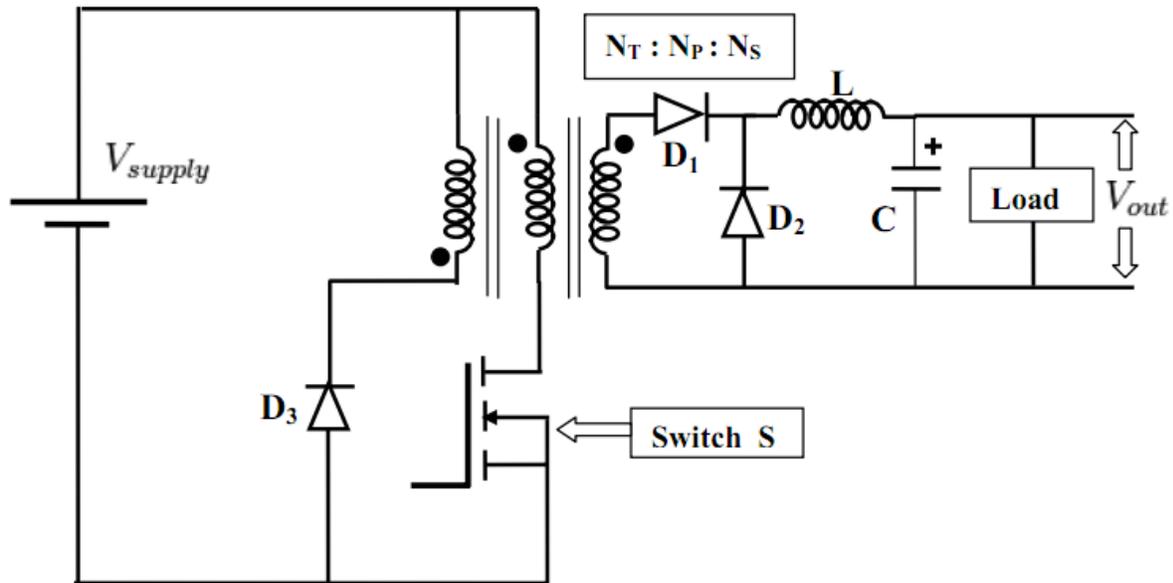
A forward converter is a power electronics circuit which is used to step up or step down DC voltage at the output by controlling the duty cycle of semiconductor switches. Switches are realized using a transistor and a diode, and given proper control circuitry is applied at the gate of the transistor, any voltage can be obtained at the output (ideally). A forward converter also provides the advantage of ground isolation, which means that input and output are electrically isolated, and energy is transferred using the magnetic field of the transformer coils. We intend to implement a forward converter and also devise a suitable control circuit for controlling the switching action of the transistor.

Converter Derivation and Switch Realization

Forward converter and its variations derived from a Buck converter are commonly used in applications at low power levels up to a kW. A Buck converter is shown in Fig. (a). In this circuit, a three-winding transformer is added as shown in Fig. (b) to realize a Forward converter. The third winding in series with a diode D3, and the diode D1 are needed to demagnetize the core every switching cycle. The winding orientations in Fig. 8-4b are such that the current into the dot of any of the windings will produce core flux in the same direction.



Converter Analysis



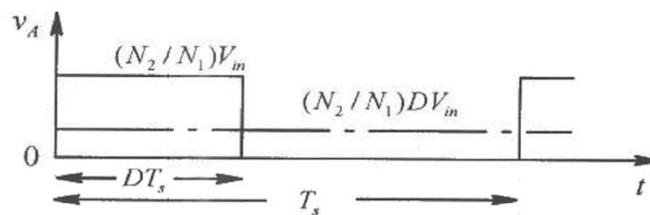
We will consider steady state converter operation in the continuous conduction mode where the output inductor current i_L flows continuously. In the following analysis, we will assume ideal semiconductor devices, $v_o(t) = V_o$, and the leakage inductances to be zero.

Initially, assuming an ideal transformer in the Forward converter of Fig. (b), the third winding and the diode D3 can be removed and D1 can be replaced by a short circuit. In such an ideal case, the Forward converter operation is identical to that of the Buck converter, as shown by the waveform in Fig below, except for the presence of the transformer turns-ratio

$$n = \frac{N_2}{N_1}$$

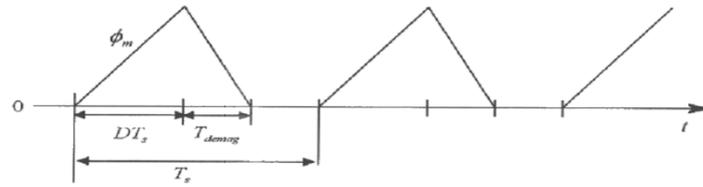
Therefore, in the continuous conduction mode,

$$V_o = \left(\frac{N_2}{N_1}\right) DV_{IN} = nDV_{in}$$



Forward converter operation

In the case with a real transformer, the core must be completely demagnetized during the off-interval of the transistor, and hence the need for the third winding and the diodes D1 and D3 as shown in Fig. Turning on the transistor causes the magnetizing flux in the core to build up as shown in Fig below. During this on-interval DT_s , D3 gets reverse biased, thus preventing the current from flowing through the tertiary winding. The diode D2 also gets reversed biased and the output inductor current flows through D1.



Forward converter core flux.

When the transistor is turned off, the magnetic energy stored in the transformer core forces a current to flow into the dotted terminal of the tertiary winding, since the current into the dotted terminal of the secondary winding cannot flow due to D1, which results in V_{IN} to be applied negatively across the tertiary winding, and the core flux to decline, as shown in Fig below. (The output inductor current freewheels through D2). After an interval T_{demag} the core flux comes to zero and stays zero during the remaining interval, until the next cycle begins.

To avoid the core from saturating T_{demag} must be less than the off-interval $(1 - D)T_s$, of the transistor. Typically, windings 1 and 3 are wound bifilar to provide a very tight mutual coupling between the two, and hence $N_3 = N_1$. Therefore, to the core is applied an equal magnitude but opposite polarity per-tum voltage during DT_s , and T_{demag} , respectively. At the upper limit, T_{demag} equals $(1 - D)T_s$ and equating it to the on-interval DT_s , of the transistor yields the upper limit on the duty-ratio, D_{max} to be 0.5, with $N_3 = N_1$).

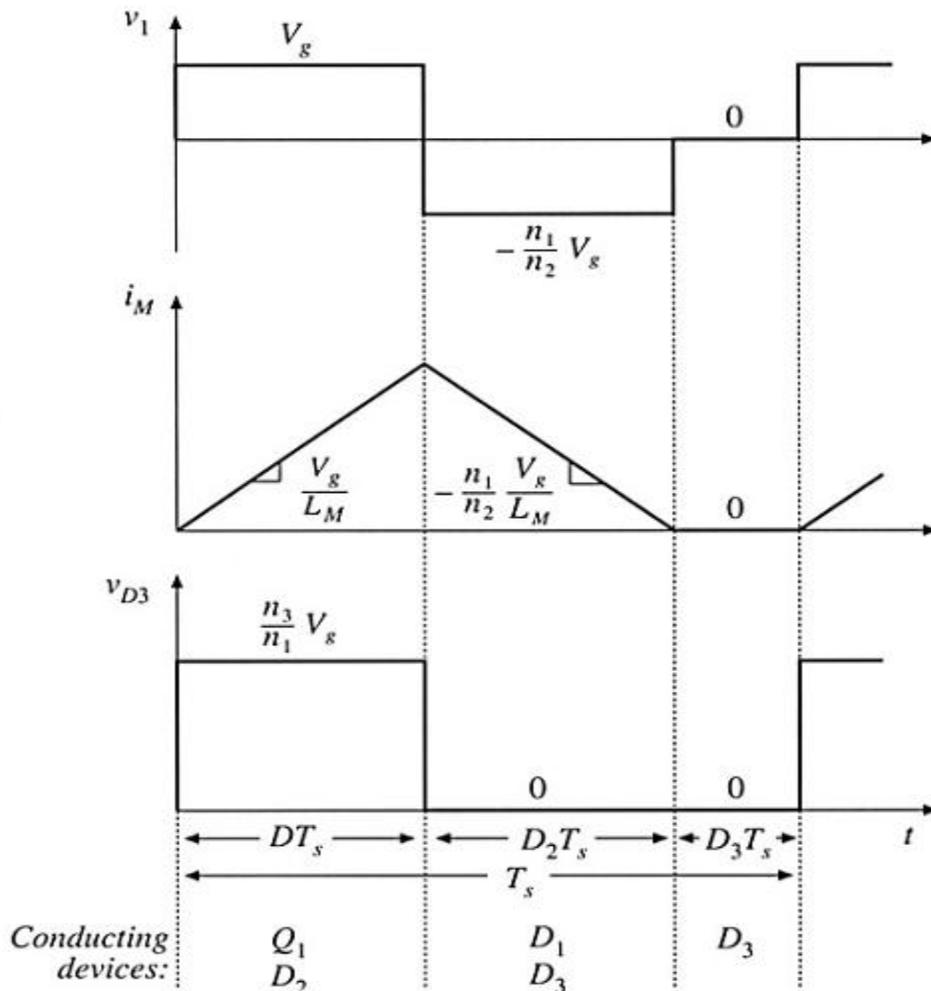
The utilization factor of the converter is

$$U = 0.5\sqrt{D} \text{ when } n_1 = n_2$$

The utilization factor is maximum at $D=0.5$ and $U_{max}=0.353$. The utilization of the transformer of the forward converter is quite good. Since the transformer magnetizing current cannot be negative, only half of the core B-H loop can be used. The utilization of the transformer core of

the forward converter can be as good as in the full- or half-bridge configurations. Utilization of the primary and secondary windings of the transformer is better than in the full-bridge, half bridge, or push-pull configurations, since the forward converter requires no center-tapped windings. During subinterval 1, all of the available winding copper is used to transmit power to the load. Essentially no unnecessary current flows during subintervals 2 and 3. Typically, the magnetizing current is small compared to the reflected load current, and has negligible effect on the transformer utilization. So the transformer core and windings are effectively utilized in modern forward converters.

The forward converter requires a single transistor, and hence finds application at power levels lower than those commonly encountered in the full-bridge and half-bridge configurations. Its non pulsating output current, shared with other buck-derived converters, makes the forward converter well suited for applications involving high output currents.



Converter Analysis

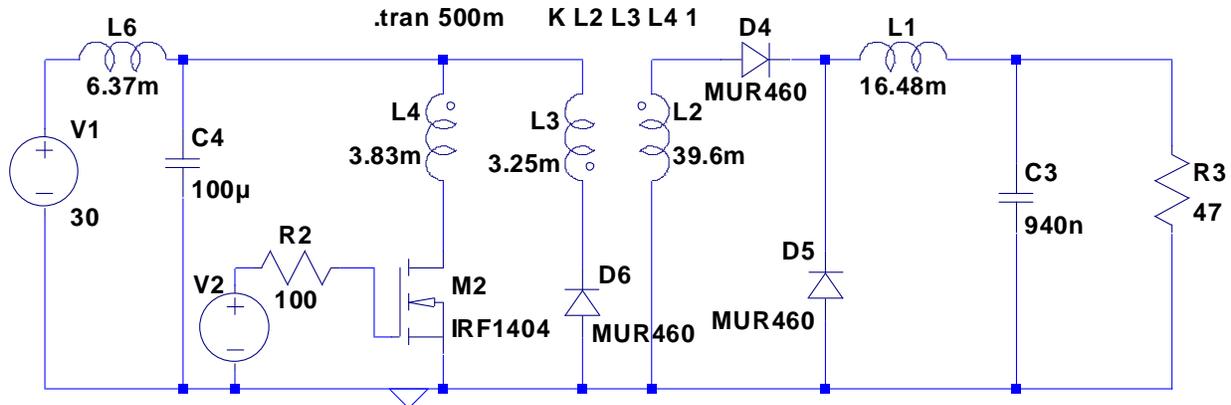
Design Specifications:

Following are our design specifications

- 1) Output voltage (V_{out}) = 10 to 35 Volts (range can be varied depending on input voltage)
- 2) Input Voltage (V_{in}) = 20 to 30 Volts
- 3) Max Output Power = 25 Watts
- 4) Output Voltage ripple ($\Delta V_{out}/V_{out}$) = 5%
- 5) Switching frequency (f_s) = 25 KHz

Design:

The circuit diagram is as follows:



The values are designed as follows.

The circuit is designed for power rating of 25W to 26W at maximum output voltage of 35V. The value of resistance at full load comes out to be

$$R = \frac{V^2}{P} = \frac{35^2}{26} = 47\Omega.$$

The LC filter used at the gate is used as an EMI filter for the voltage supply. It takes in a dc voltage and gives a dc voltage but ac current. Effectively the LC circuit reduces the current

ripple of the supply. The value of L determines the ripple of the current while the value of C determines the voltage ripple. The value of resonance frequency of the LC filter should be much lower than the switching frequency of the MOSFET to make the LC filter act as a low pass filter. So the value of L and C are chosen so that its frequency is 200 times lower than the switching frequency of 25 KHz. It is preferable for us to have a larger value of capacitor to lower the voltage ripple for this filter however due to the voltage restrictions on the higher value capacitors we are forced to use the capacitor of maximum value 100u. So the value of inductor used for central frequency of 200 Hz is from calculations.

$$L = \frac{1}{4\pi^2 f^2 C} = 6.33mH$$

For the LC filter at the output we know that the input output relationship is of

$$V_{out} = D \cdot \frac{N_s}{N_p} \cdot V_{supply}$$

And the current ripple of inductor and voltage ripple of capacitor is given by

$$\begin{aligned} \Delta i_l &= \frac{V(1-D)T_s}{2L} & \frac{\Delta i_l}{i_l} &= \frac{R(1-D)T_s}{2L} \\ \Delta V_c &= \frac{\Delta i_l T_s}{8C} & \frac{\Delta V_c}{V_c} &= \left(\frac{\Delta i_l}{i_l} \right) \frac{T_s}{8RC} \end{aligned}$$

For a 10% ripple for inductor current at load of 47Ω at switching frequency of 25 kHz the value of capacitor comes and 5% for output voltage the value of L and C should be 2mH and 62.5nF. So we have used value of inductor as 2mH and capacitor 100nF.

The inductors should be designed as follows.

$$K_g \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u} 10^8 \quad (\text{cm}^5)$$

So using $\rho=1.724\mu\Omega/\text{cm}$, $L=6\text{mH}$, $B_{max}=0.2$, $R=0.2\Omega$ and $K_u=0.5$. The value of I_{max} is calculated as follows at V_{in} of 20 V if the circuit is operated at full load of 25W then the value of I_{max} from the inductor would be $P_{max}/V_{in}=1.25\text{A}$. Allowing for some power loss due to losses the $I_{max}=1.5\text{A}$. The value of K_g is calculated to be 21.8.

$$\ell_g = \frac{\mu_0 L I_{max}^2}{B_{max}^2 A_c} 10^4 \quad (\text{m})$$

The value of air gap is calculated as follows $\mu_0=4\pi \times 10^{-7}$, $L=6\text{mH}$, $I_{\text{max}}=1.5$, $B_{\text{max}}=0.2$
 $A_c=0.98 \times 1.29=1.264$. So value of air gap is 3.355mm.

$$n = \frac{LI_{\text{max}}}{B_{\text{max}}A_c} \times 10^4$$

The number of turns is calculated to be 296.7=297 turns.

$$A_w \leq \frac{K_u W_A}{n} \quad (\text{cm}^2)$$

The value of $K_u=0.5$, $W_a=0.98 \times 1.35=1.323$ and $n=297$. The value of A_w is calculated to be equal to 2.23×10^{-3} which means we have to use wire of $A_w < 2.23 \times 10^{-3}$ or $\text{AWG} > 23$. When we made the inductor its value was 6.37mH.

Similarly for other inductor of value 16mH the values calculated using above procedure are. $K_g > 3379$, $n=528$ and $A_w < 1.25 \times 10^{-3}$ meaning $\text{AWG} > 26$. The inductor we made had a value of 16.48mH.

Transformer waveforms are illustrated in Fig. 15.6. The applied primary volt-seconds are

The required transformer turn ratio is 1:3:1. The $V_{\text{in}}=30\text{V}$ and $I_{\text{in}}=1\text{A}$ at full load the $V_{\text{out}}=45\text{V}$ and $I_{\text{out}}=0.667\text{A}$. Switching frequency is 25 kHz. Ferrite E core is used for making transformer with $K_{fe}=0.05$ and $\beta=2.6$.

The primary rms current is calculated to be $I_1 = \sqrt{D \cdot I/n} = 0.408\text{A}$

It is assumed that the rms magnetizing current is much smaller than the rms winding currents. For calculation we take I_m be 10% of load current. Since the transformer contains three windings, the secondary rms current is equal to $I_2 = n \cdot I_1 = 1.224\text{A}$. then tertiary winding rms current is $I_3 = 0.1 \cdot 0.408 = 0.0408$.

so $I_{\text{tot}} = I_1 + I_2 + I_3 = 0.857\text{A}$

$\lambda_1 = D \cdot T_s \cdot V = 600\mu$

The core size is evaluated using

$$K_{kfe} \geq \frac{\rho \lambda_1^2 I_{\text{tot}}^2 K_{fe}^{(2/\beta)}}{4 K_u (P_{\text{tot}})^{((\beta+2)/\beta)}} \times 10^8$$

The required size comes to be 5.54×10^{-6} .

$$\Delta B = \left[10^8 \frac{\rho \lambda_1^2 I_{int}^2}{2K_u} \frac{(MLT)}{W_A A_c^3 \ell_m} \frac{1}{\beta K_{fc}} \right]^{\left(\frac{1}{\beta+2}\right)}$$

The calculated flux change is 0.152T. This flux density is considerably less than the saturation flux density of approximately 0.2 Tesla.

The primary turns are determined by

$$n_1 = \frac{\lambda_1}{2\Delta B A_c} 10^4$$

The primary turns are 15.5. The secondary turns are found to be 3 times n1 so equal to 46.5. It is desired that the transformer have a 3:1:1 so tertiary turns are equal to n1=15.5.

The fraction of the window area allocated to windings 1 and 2 are determined to be for primary=0.476 for secondary=0.476 and tertiary=0.048.

We can now evaluate the primary and secondary wire areas

$$A_{w1} \leq \frac{\alpha_1 K_u W_A}{n_1}$$

$$A_{w2} \leq \frac{\alpha_2 K_u W_A}{n_2}$$

The wire area is calculated to be for primary 0.0168, secondary 0.00563 and tertiary 0.0017 the wire gauge can be appropriately chosen using the wire table of Appendix D.

The transformer we designed has rating as follows.

Winding	Inductance	Winding resistance (Ω)	No of turns	Turn ratio
Primary	3.83m	0.427	24	1
Secondary	39.6u	1.144	77	3.215
Tertiary	3.25m	0.385	22	0.921

Results:-

The results of our project are as follows.

V_{in} (V)	I_{in} (A)	P_{in} (W)	D	V_{out} (V)	ΔV (V)	Load (Ω)	P_{out} (W)	η
20	0.0889	1.778	0.20	11.2	0.3	100	1.254	70.5%
20	0.1355	2.71	0.25	14.3	0.4	100	2.045	75.5%
20	0.1876	3.752	0.30	16.9	0.4	100	2.856	76.1%
20	0.253	5.06	0.35	20.1	0.5	100	4.04	79.8%
20	0.324	6.48	0.40	22.8	0.6	100	5.198	80.2%
20	0.403	8.06	0.45	25.3	0.6	100	6.401	79.4%
20	0.433	8.66	0.47	26.1	0.6	100	6.812	78.6%

At low output power

V_{in} (V)	I_{in} (A)	P_{in} (W)	D	V_{out} (V)	ΔV (V)	Load (Ω)	P_{out} (W)	η
20	0.174	3.48	0.20	10.6	0.5	47	2.391	68.7%
20	0.254	5.08	0.25	13.3	0.6	47	3.764	74.1%
20	0.347	6.94	0.30	15.5	0.7	47	5.112	73.7%
20	0.460	9.2	0.35	17.7	0.6	47	6.666	72.5%
20	0.580	11.6	0.40	19.8	0.7	47	8.341	71.9%
20	0.704	14.08	0.45	21.8	0.8	47	10.111	71.8%
20	0.785	15.7	0.48	22.9	0.8	47	11.158	71.1%

At medium output power

V_{in} (V)	I_{in} (A)	P_{in} (W)	D	V_{out} (V)	ΔV (V)	Load (Ω)	P_{out} (W)	η
30	0.260	7.8	0.20	16.4	0.6	47	5.72	73.3%
30	0.394	11.82	0.25	20.2	0.7	47	8.68	73.4%
30	0.532	15.96	0.30	23.5	0.7	47	11.75	73.6%
30	0.710	21.3	0.35	27.2	0.9	47	15.74	73.9%
30	0.879	26.37	0.40	30.1	1.0	47	19.28	73.1%
30	1.096	32.88	0.45	32.8	1.2	47	22.89	69.6%
30	1.217	36.51	0.47	34.1	1.4	47	24.74	67.8%

At high output power