Two Transistor Forward Converter with Loop Compensation using TL431

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Abstract—This paper presents the design of two switch forward converter with a primary clamped diode and loop compensation using optocoupler and TL431. The converter is operating from DC Voltage (18V to 32V) providing regulated output voltage of 54V (2.2A). To realize the converter in a compact size and lower weight high switching frequency is used. MOSFET is switched ON and OFF using a UC28025 with switching frequency of 250 kHz. The converter also incorporates Zero current switching during turn on. The design procedure is presented in detail. For the tight regulation of the output, the compensation network is designed with optocoupler and TL431. Implementation of TL431 in the closed loop regulation is presented in the paper. The paper also presents simulation results using orcad and MATLAB. The ZCS is observed in the simulation result. Regulation is observed by performing closed loop simulation.

Keywords—Two switch forward converter ,TL431 , Type 3 compensator.

I. INTRODUCTION

The conventional two switch forward converter is shown in Fig 1.

Due to its simple operation and high reliability two switch forward converter is used more commonly. The switches used in two switch forward converter operate in hard switching and has high switching loss. During turn on and turn off, resonance occurs because of the reverse recovery parameter of the rectifying diode and the power transformer leakage inductance. Due to resonance, ringing and over shooting is seen. This results in overvoltage across the output freewheeling diode.

By using a RCD snubber on output diode, the over voltage may be limited to a safe level. The RCD snubber used at the diode is simple and less expensive. But due to the presence of high resistor value in the snubber there is high power dissipation at high power levels and hence efficiency is decreased. However, over voltage cannot be reduced completely because of the lead inductance of tracks. The damage due to over voltages may be overcome by using diode of higher voltage rating. However, this results in higher conduction and more recovery time.

In another method to minimize the over voltage and to recycle the energy active switched snubbers were used[1][2]. Active switched snubbers require additional active switches and control circuits for that switch. This will increase the cost and reduce the reliability of the circuit. A non-dissipative LC snubber is used[3]. But problems still existed with the additional components L,C and diode.

Fig2 :Two switch Forward converter with diodes clamped at the primary side of transformer

To overcome the problems mentioned above, a two switch converter topology with two diodes at the primary is proposed as shown in Fig2 [5]. Turn off di/dt of the rectifying diode is limited by adding an inductance in series with the power transformer primary. By introduction of series inductor the turn off di/dt of the rectifying diode is limited but heavy ringing is observed at the junction of Lr and power transformer. The heavy ringing is limited by introducing a clamping diodes namely D3 and D4, on the power transformer primary.

The clamping diodes have smaller rating compared to converter overall rating. By using this method the voltage applied to transformer primary is clamped to input voltage. This results in clamped voltage at the power transformer secondary and also at the rectifying diodes namely D5 and D6. Low leakage inductance of the transformer can avoid overvoltage which is produced when the voltage is applied to rectifying diodes. Because of finite leakage inductance of the...
transformer, a small snubber is introduced across the output diode. The leakage inductance must be kept as low as possible. This technique of having clamping diodes at the transformer primary has one more advantage. Due to the introduced inductor $L_r$ which takes finite time to set up the primary winding current, the switches can be turned-on at zero current switching (ZCS) . This also improves overall efficiency because, the excess energy stored in the inductor ($L_r$) will be supplied back to the source[5].

Power converter is controlled by a compensation network implementing an optocoupler and TL431. TL431 is selected because it lends itself very well into optocoupler control[7].

II. DESIGN FOR THE PROPOSED CONVERTER

Converter specifications:
$V_{in} = 18V$
$V_o = 54V$
Switching frequency = 250KHz
Output ripple, $\Delta V_o = 1\%$ of $V_o=0.54$
Load resistor, $R = 25\Omega$

Output current $I_o = V_o / R = 2.2A$
Therefore, output power $P_o = I_o^2*R=120W$

Determination of output inductor and capacitor values:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formulae</th>
<th>Value obtained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Inductor</td>
<td>$L_o = \frac{(V_o-V_{in})*V_o}{I_{ripple}*V_{in}*F_5}$</td>
<td>0.5mH</td>
</tr>
<tr>
<td>Output Capacitor</td>
<td>$C_o = \frac{L_o + \Delta V_o}{2 * V_o + \Delta V_o}$</td>
<td>470nF</td>
</tr>
</tbody>
</table>

Output capacitor controls the ripples in output voltage as well as settling time. Higher the value of capacitor, lower the value of ripple but higher settling time and vice versa.

DESIGN OF TRANSFORMER FOR THE PROPOSED CONVERTER:

Area Product may be calculated by the equation
$Area\ Product\ Ap = \frac{(V_o*D_{on}*2*I_{min})}{(F*\Delta B_m*J*kw)}$

Based on the Area product the core selected is PC 36/22
Number of primary turns $N_1 = \frac{V_{cmax}+D_{min}}{A_c+E_{m}+E} = 1$
Number of secondary turns $N_2 = \frac{N_1*V_{out}}{Def*V_{in}} = 9$

III. TL431 IN SWITCHING POWER SUPPLIES

A. TL431

The TL431 is the popular choice in recent days design. Figure 3 shows the internal circuitry of a TL431. The device is shown with three terminals namely cathode k, anode A and a reference. A TL431 configured with a reference point, cathode k and grounded anode behaves as an active 2.5V zener diode.

In a configuration such as classical loop-control, TL431 sees a fraction of the output voltage at its ref pin and converts the observed fraction of output voltage into an output current which is sunk between the cathode and the anode. As such, TL431 can be considered as a trans-conductance amplifier[7]

To understand its operation, let us assume that negligible base current flows through all the transistors which implies transistors with a high current gain in the circuit. The secret of operating the device lies in the equilibrium imposed by transistors $Q_9$ and $Q_1$. when output voltage reaches its targeted value that is when conditions are properly met, the voltage at the reference pin $V_{ref}$ will be equal to 2.5 V, and same current will be shared by transistors $Q_9$ and $Q_1$. $V_{ka}$ remains constant. Any changes in this condition due to change in output power demand on the regulated converter changes the currents flowing through $Q_9$ or $Q_1$ thereby changing the bias of the output darlington configuration made around transistors $Q_{10}$ and $Q_{11}$. Because of this action the voltage across anode and cathode $V_{ka}$ goes down or up respectively and results in current variation in the LED diode which is attached to the cathode of TL431 in a power supply loop application.
B. Implementing Type 3 Compensator with TL431

A type 3 compensator circuit using TL431 and optocoupler is as shown in fig 4. To create a fixed dc level a zener diode is used. The transfer function of the circuit presented in fig 4, provided R3<<R1 obeys the following equation [7]:

\[ \frac{V_{FB}(s)}{V_{OUT}(s)} = \frac{CTR \cdot (sR2C1 + 1)(sR3C3 + 1)}{R3 \cdot sR1C1 \cdot (1 + \frac{R3}{sR1C2})(sR3C3 + 1)} \]

![Figure 4: Type 3 compensator with TL431](image)

C. Design of Type 3 Compensator with TL341

Calculation steps:

- \( \text{ESR}(C_o) = 8 \text{m}Ω \)
- \( F_s = 250 \text{kHz} \)
- \( I_{bias} = 1 \text{k}Ω \) connected in parallel with LED (usually for a 1-mA bias)
- \( V_{TL431,\text{min}} \) is equal to 2.5v and represents the minimum voltage attainable by TL431.
- \( V_f \) is the forward drop across optocoupler LED (=1V)
- \( CTR_{\text{min}} \) is the minimum current transfer ratio of selected optocoupler (30%)
- \( V_{CE,sat} \) is the saturation voltage of optocoupler (=300mV at a 1-mA collector current)
- \( V_{d\text{d}} \) is the internal bias of the pull-up resistor

Assume \( R_{\text{pullup}} = 20 \text{k}Ω \)

\( R_{LED,\text{max}} = 1.5 \text{k}Ω \)

Allowing 50% margin \( R_{LED,\text{max}} = 750 \text{Ω} \)

2) Considering \( I_{bias} = 250 \mu\text{A} \) current through divider bridge which is a good trade-off between noise immunity and standby power performance[7] and Calculating the upper and lower resistors:

\( R_{\text{Upper}} = \frac{2.5}{250 \mu} = 10 \text{k}Ω \)

Considering 12v input to compensator through voltage divider from the converter output we have,

\( R_1 = \frac{12 - 2.5}{250 \mu} \)

The compensator component values are calculated as given in the table 3.

<table>
<thead>
<tr>
<th>Table 3: Values of compensator component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>( C_3 )</td>
</tr>
<tr>
<td>( R_3 )</td>
</tr>
<tr>
<td>( R_2 )</td>
</tr>
<tr>
<td>( C_1 )</td>
</tr>
<tr>
<td>( C_2 )</td>
</tr>
</tbody>
</table>

After the calculation of all the components, a zener bias resistor \( R_z \) can be chosen. The total current flowing through \( R_z \) is made up of current flowing through 1kΩ bias resistor plus LED current which depends on CTR of optocoupler plus the current flowing through the zener diode which also depends on CTR.

\( R_z < \frac{V_{OUT} - V_z}{1kΩ} \)

To improve the ac rejection of \( V_{OUT} \) a capacitor of value 0.1µF has been added across the diode [7].
IV. SIMULATION RESULTS

A. Open Loop Simulation

Soft switched two switch forward converter is verified using the software ORCAD and MATLAB. This gives the expected waveforms when simulation is done with the following specifications:

Specifications:
Input voltage = 18V
Output voltage = 54V
Output current = 2.2A
Output power = 120W
Switching frequency = 250kHz
Designed values of the components are: \( L_r = 0.2u, L_o = 0.5m, C_o = 470n \)

The open loop and closed loop response of the converter for duty cycle \( D=0.5 \) is presented.

The obtained waveforms from the simulation of open loop converter shown in Fig 7 and Fig 8 reveals that ZCS has been achieved during turn on.

B. Closed Loop Simulation in MATLAB

The output voltage is found to be 54 volts with very low ripple as indicated by the waveform shown in Fig 8.
The output voltage is also obtained from simulation of closed loop converter circuit using MATLAB software and is shown in fig 10. The result obtained shows the regulation using the designed compensator network for the input voltage of 18v.

The full load output current as obtained by closed loop simulation in MATLAB is shown in fig 11 and is found to be 2.2amps tallying with the theoretical value.

The waveform shown in Fig 12 & Fig 13 are the current through the switch for the input voltage equal to 18v and 23 volts respectively. They reveal that the pulse width is varying to provide regulation of output voltage. The on period varied from 2µs to 1.5 µs for a change of input voltage from 18v to 23v.

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REFERENCES


