Design of a 1.5 kW Full Bridge DC-DC Converter

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***Abstract*-This paper presents soft switching PWM DC-DC converters using power MOSFETs. The attention is focused mainly on the full-bridge converters suitable for high-power applications. The properties of the PWM converters are described in comparison to other categories of soft switching converters. An overview of the switching techniques using in the DC-DC converters is included. Considerations are also given to the control methods.**

***Index terms* : Constant frequency, coupled inductor, full bridge, phase shift, zero voltage switching.**

I. INTRODUCTION

The switching mode power supply (SMPS) operating at a high frequency can provide small size and weight, as the filtering inductance and capacitance are reduced and power density is increased. However, a high switching frequency results in high switching losses which reduce the efficiency of the converter. In this paper, different topologies and different controlling methods are discussed. There are several types of isolated dc-dc converter; they are buck converter, boost converter ,forward converter, flyback converter, push-pull converter, half-bridge converter and full bridge converter. Dc-dc converters used in SMPS can be of isolated or non-isolated. In an isolated dc-dc converter the input and output are separated mechanically by means of a transformer. Whereas, a non-isolated dc-dc converter, does not have transformer to isolate the input and the output circuits. Isolated dc-dc converter is mainly for safety consideration and to reject common mode voltage**.** The (zero voltage switching) full-bridge phase-shifted converters are suitable for high power applications. The complexity of the full-bridge is almost highest among the conventional topologies due to its large switch count and complicated control and driving. There are two feedback control methods that are widely used in SMPS; one is the voltage mode control (VMC) that senses only the output voltage, V_{out} and another is current mode control (CMC) that senses both the V_{out} and the filter inductor current as the feedback signals. In order to achieve better performance the converter design must incorporate the circuit parasitic elements, such as stray capacitance and stray inductance of the magnetic and semiconductor devices. Moreover, it is necessary that the command and control circuitry be as simple as possible.

II. INTRODUCTION TO DIFFERENT TOPOLOGIES

A . Buck Converter

In a buck converter (Fig.1), a switch (Q_1) is placed in series with the input voltage source V_{IN}. The input source V_{IN} feeds the output through the switch and a low-pass filter, implemented with an inductor and a capacitor. In a steady state of operation, when the switch is ON for a period of T_{ON}, the input provides energy to the output as well as to the inductor (L). During the T_{ON} period, the inductor current flows through the switch and the difference of voltages between V_{IN} and V_{OUT} is applied to the inductor in the forward direction, During the T_{OFF} period, when the switch is OFF, the inductor current continues to flow in the same direction, as the stored energy within the inductor continues to supply the load current. The diode D1 completes the inductor current path during the Q_1 OFF period (T_{OFF}); thus, it is called a freewheeling diode. During this T_{OFF} period, the output voltage V_{OUT} is applied across the inductor in the reverse direction[1]..

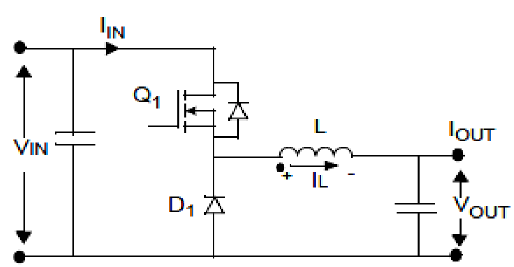

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Figure 1 . Buck Converter

B. Boost Converter

In a boost converter (Fig.2), an inductor (L) is placed in series with the input voltage source V_{IN}. The input source feeds the output through the inductor and the diode D_1. In the steady state of operation, when the switch Q_1 is ON for a period of T_{ON}, the input provides energy to the inductor. During the T_{ON} period, inductor current (I_L) flows through the switch and the input voltage V_{IN} is applied to the inductor in the forward direction, Therefore, the inductor current rises linearly from its present value I_{L1} to I_{L2}. During this T_{ON} period, the output load current I_{OUT} is supplied from the output capacitor C_O. The output capacitor value should be large enough to supply the load current for the time period T_{ON} with the minimum specified drop in the output voltage. During the T_{OFF} period when the switch is OFF, the inductor current continues to flow in the same direction as the stored energy with the inductor, and the input source V_{IN} supplies energy to the load. The diode D_1 completes the inductor current path through the output capacitor during the Q_1 OFF period (T_{OFF}). During this T_{OFF} period, the inductor current flows through the diode and the difference of voltages between V_{IN} and V_{OUT} is applied to the inductor in the reverse direction, Therefore, the inductor current decreases from the present value I_{L2} to I_{L1}.

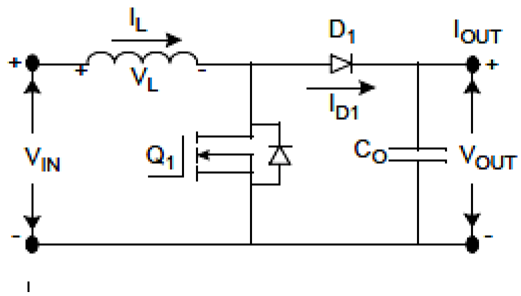

Figure 2 . Boost Converter

C. Flyback Converter

In a flyback converter (Fig.3), a switch (Q_1) is connected in series with the transformer primary. The transformer is used to store the energy during the ON period of the switch, and provides isolation between the input voltage source V_{IN} and the output voltage V_{OUT}. In a steady state of operation, when the switch is ON for a period of T_{ON}, the dot end of the winding becomes positive with respect to the non-dot end. During the T_{ON} period, the diode D_1 becomes reverse-biased and the transformer behaves as an inductor. The value of this inductor is equal to the transformer primary magnetizing inductance and the stored magnetizing energy from the input voltage source V_{IN}. Therefore, the current in the primary transformer rises linearly from its initial value to peak current. As the diode D_1 becomes reverse-biased, the load current (I_{OUT}) is supplied from the output capacitor . The output capacitor value should be large enough to supply the load current for the time period T_{ON}, with the maximum specified drop in the output voltage[1].

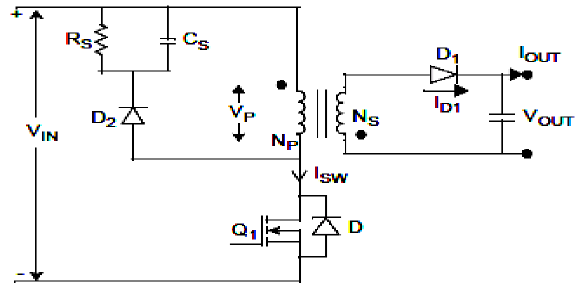

Figure.3 Flyback Converter

D. Push-pull Converter

The high-voltage DC is switched through the center-tapped primary of the transformer by two switches (Fig. 4), Q_1 and Q_2, during alternate half cycles. These switches create pulsating voltage at the transformer primary winding. The transformer is used to step down the primary voltage and to provide isolation between the input voltage source V_{IN} and the output voltage V_{OUT}. The transformer used in a push-pull converter consists of a center-tapped primary and a center-tapped secondary. The switches Q_1 and Q_2 are driven by the control circuit, such that both switches should create equal and opposite flux in the transformer core. In the steady state of operation, when Q_1 is ON for the period of T_{ON}, the dot end of the windings become positive with respect to the non-dot end. The diode D_5 becomes reverse-biased and the diode D_6 becomes forward-biased. Thus, the diode D_6 provides the path to the output inductor current I_L through the transformer secondary. As the input voltage V_{IN} is applied to the transformer primary winding N_{P1}, a reflected primary voltage appears in the transformer secondary. The difference of voltages between the transformer secondary and output voltage V_{OUT} is applied to the inductor L in the forward direction. Therefore, the inductor current I_L rises linearly from its initial value of I_{L1} to I_{L2}, During this T_{ON} period while the input voltage is applied across the transformer primary N_{P1}, the value of the magnetic flux density in the core is changed from its initial value of B_1 to B_2 . The switch Q_2 will be turned ON after half of the switching period . Thus, during the T_{OFF} period, both of the switches (Q_1 and Q_2) are OFF. When switch Q_1 is turned OFF, the body diode of the switch provides the path for the leakage energy stored in the transformer primary, and the output rectifier diode D_5 becomes forward-biased. As the diode D_5 becomes forward-biased, it carries half of the inductor current through the transformer secondary N_{S1}, and half of the inductor current is carried by the diode D6 through the transformer secondary N_{S2}. This results in equal and opposite voltages applied to the transformer secondary, assuming both secondary windings N_{S1} and N_{S2} have an equal number of turns. Therefore, the net voltage applied across the secondary during the T_{OFF} period is zero, which keeps the flux density in the transformer core constant to its final value B_2. The output voltage V_{OUT} is applied to the inductor L in the reverse direction when both switches are OFF[1].

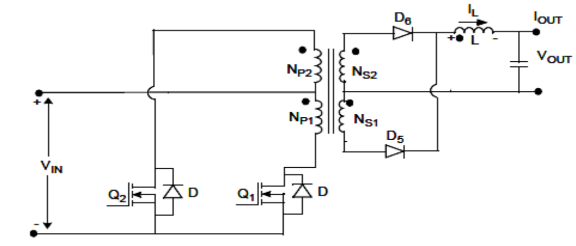

Figure 4. Push pull converter

E. Half –bridge converter

The switches Q_1 and Q_2 form one leg of the bridge (Fig.5), with the remaining half being formed by the capacitors C_3nand C_4. Therefore, it is called a half-bridge converter. The switches Q_1 and Q_2 create pulsating AC voltage at the transformer primary. The transformer is used to step down the pulsating primary voltage, and to provide isolation between the input voltage source V_{IN} and the output voltage. In the steady state of operation, capacitors C_3 and C_4 are charged to equal voltage, which results in the junction of C_3 and C_4 being charged to half the potential of the input voltage. When the switch Q_1 is ON for the period of T_{ON}, the dot end of the primary connects to positive V_{IN}, and the voltage across the capacitor C4 (V_{C4}) is applied to the transformer primary. This condition results in half of the input voltage being V_{IN}, which is applied to the primary when the switch Q_1 is ON, The diode D_4 becomes reverse-biased, and the diode D_3 becomes forward-biased, which carry the full inductor current through the secondary winding N_{S1}. The difference of the primary voltage reflected on the secondary N_{S1} and output voltage V_{OUT} is applied to the output inductor L in the forward direction. During T_{ON} period, the reflected secondary current, plus the primary magnetizing current flows through the switch Q_1. As the voltage is applied to the primary in the forward direction during this T_{ON} period, and when the switch Q_1 is ON, the flux density in the core changes from its initial value of B1 to B2. At the end of the T_{ON} period, the switch Q_1 turns OFF, and remains off for the rest of the switching period TS. The switch Q2 will be turned ON after half of the switching period $T_{S/2}$, therefore, during the T_{OFF} period, both switches are off. When switch Q_1 is turned off, the body diode of the switch Q_2 provides the path for the leakage energy stored in the transformer primary, and the output rectifier diode D_4 becomes forward-biased. As the diode D_4 becomes forward-biased, it carries half of the inductor current through the transformer secondary N_{S2} and half of the inductor current is carried by the diode D_3 through the transformer secondary N_{S1},Therefore, the equal and opposite voltage is applied at the transformer secondary, assuming both secondary windings N_{S1} and N_{S2} have an equal number of turns. As a result, the net voltage applied across the secondary during the T_{OFF} period is zero, which keeps the flux density in the transformer core constant to its value of B_2. The output voltage V_{OUT} is applied to the inductor L in the reverse direction when both switches are OFF. The body diodes of switches Q1 and Q2 provide the path for the transformer leakage energy.

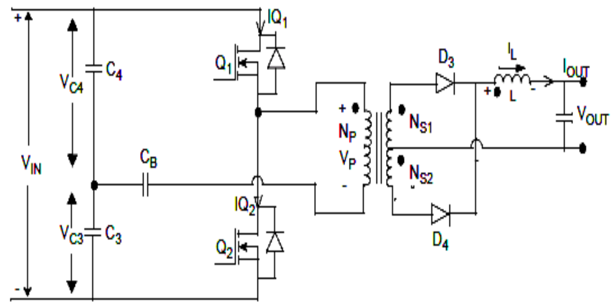

Figure 5. Half bridge converter

F. Full bridge converter

The transformer primary is connected between the two legs formed by the switches Q_1 - Q_4 and Q_3 - Q_2 (Fig.6). The switches Q_1 - Q_2 and Q_3 - Q_4 create a pulsating voltage at the transformer primary. The transformer is used to step down the pulsating primary voltage, as well as to provide isolation between the input voltage source and the output voltage V_{OUT}. A full-bridge converter configuration retains the voltage properties of the half-bridge topology, and the current properties of push-pull topology. The diagonal switch pairs, Q_1 - Q_2 and Q_3 - Q_4, are switched alternately at the selected switching period. In the steady state of operation when the diagonal switches pair, Q_1 -Q_2, is ON for a period of T_{ON}, the dot end of the winding becomes positive with respect to the non-dot end. The diode D_4 becomes reverse-biased and diode D_3 becomes forward-biased. The diode D_3 carries the full load current through the secondary winding N_{S1}. As the input voltage is applied across the transformer primary, the switch carries the reflected load current, plus the transformer primary magnetizing current. The flux density in the core changes from its initial value of B_1 to B_2. The difference of the primary reflected voltage to the secondary and the output voltage is applied across the inductor L in the forward direction. At the end of the ON period, when the switch pair Q_1 - Q_2 is turned OFF, and when it remains OFF for the rest of the switching period TS, the switch pair Q_3 - Q_4 will be turned ON after half of the switching period $T_{S/2}$, . Therefore, during the T_{OFF} period, all four switches are OFF. When the switch pair Q_1 - Q_2 are turned OFF, the body diode of the switch pair Q_3 - Q_4 provides the path for the leakage energy stored in the transformer primary. The output rectifier diode D_4 becomes forward-biased, and it carries half of the inductor current through the transformer secondary N_{S2}. Half of the inductor current is carried by the diode D_3 through the transformer secondary N_{S1}, Therefore, the net voltage applied across the secondary during T_{OFF} period is zero as previously discussed in half-bridge topology operation. This keeps the flux density in the transformer core constant to its final value of B_2. The output voltage V_{OUT} is applied to the inductor L in the reverse direction when both switches are OFF. After the time period $T_{S/2}$, when the diagonal switches Q_3, Q_4 are turned ON for a period of T_{ON}, the dot end of the winding becomes negative with respect to the non-dot end. The diode D_3 becomes reverse-biased and the diode D_4 becomes forward-biased. The diode D_4 carries the full load current through the secondary winding. As the input voltage is applied across the transformer primary, the switch carries the reflected load current plus the transformer primary magnetizing current. As the input, voltage is applied to the transformer in the reverse direction, the flux density in the core changes from its initial value of B_2 to B_1. The difference of the primary reflected voltage to the secondary and the output voltage is applied across the inductor L in forward direction.

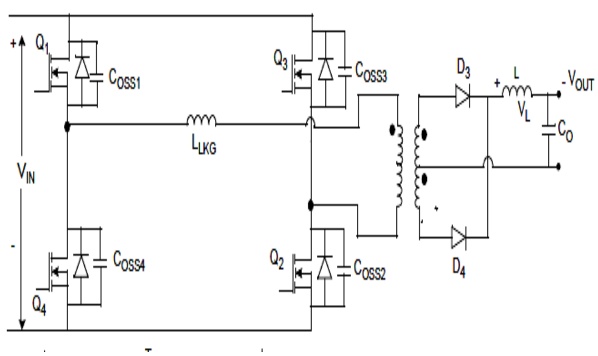

Figure 6. Full bridge converter

Topology/ Parameter	Buck	Boost	Inverting	Flyback	Push-Pull	Half Bridge	Full Bridge
V_{out}/V_{in} (CCM)	D	$\frac{1}{1-D}$	$-\left(\frac{D}{1-D}\right)$	$D\cdot\sqrt{\frac{T\cdot V_{out}}{2I_{out}L_{pri}}}$	$2\frac{N_2}{N_1}D$	$\frac{N_2}{N_1}D$	$2\frac{N_2}{N_1}D$
I_d MOSFET	$1.5I_{out}$	$\frac{5.5P_{out}}{V_{in}}$	$\frac{5.5P_{out}}{V_{in}}$	$\frac{5.5P_{out}}{V_{in}}$	$\frac{1.4P_{out}}{V_{in}}$	$\frac{5.5P_{out}}{V_{in}}$	$\frac{1.4P_{out}}{V_{in}}$
$V_{ds(max)}$ MOSFET	V_{in}	V_{out}	$-(V_{in}-V_{out})$	$V_{in}+V_{out}\frac{N_1}{N_2}$	$2\cdot V_{in}$	V_{in}	V_{in}
Useful power	<1KW	<150W	<150W	<150W	>150W	250W-1KW	>1KW
Approx. cost (relative to Buck)	1	1	1	1.2	2	2	3

Table-I Comparison Between Different Topology Parameter

III. Controlling Methods

The structure and complexity of the converter control depends on specific application requirements. A cascaded loop control structure with an inner current loop and a superimposed voltage loop is used as a standard control in DC-DC converters to provide high performance, wide bandwidth output voltage regulation [2]

1. Current Control Method:

The current mode control technique (Fig.7)requires two feedback loop. In this mode, two parameters are measured for control purposes. The output voltage is measured at the output capacitor or at the load end (known as remote sensing). The output inductor/primary switch current is also measured. In current mode control, the output voltage is first compared with the reference voltage (desired output voltage). This error is then processed by the compensation block to generate the reference signal for the current loop. This current reference is compared to the measured current. Any error generated by the comparison of the reference generated by the voltage compensation block and the actual current drawn from the input is processed by the current compensation block. This generates the required duty cycle to maintain the output voltage within the specified limit. As current mode control senses the circuit current, any change in output load current or the input voltage can be corrected before it affects the output voltage. Sensing the input current, which depends on input voltage, provides the inherent feed-forward feature. Current mode control provides inherent input current symmetry for the push-pull and bridge converters, inherent current limiting features and load sharing features for multiple converters connected in parallel. It also improves step load response and transient response because of the inner current loop.

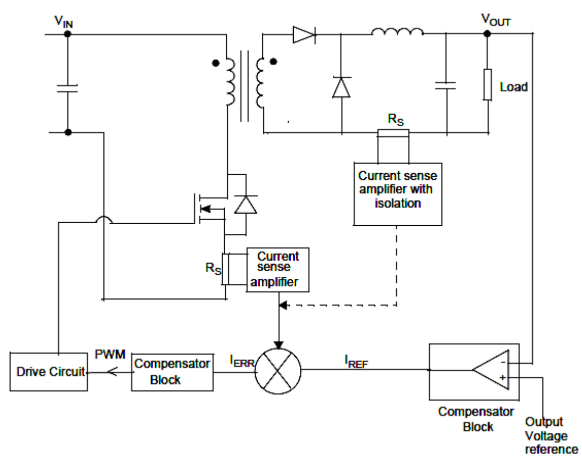

Figure 7. Current Control Method

2 . Voltage Mode Control:

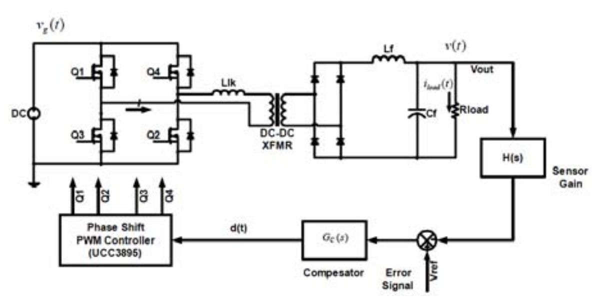

Figure 8 :Voltage Mode Control by UCC3895

A feedback loop can be constructed for regulation of the output voltage. The output voltage v(t) is compared to a reference voltage Vref, to generate an error signal [3]-[4] .This error signal is applied to the input of a compensation network, and the output of the compensator drives the control signal d(t) as shown in Fig. 8. In case of a full bridge converter, the control signal d(t) is given to a full bridge controller IC which in this case is implemented by the Texas Instruments UCC3895. This control IC generates the appropriate turn on signals for all four switches in the full bridge pattern. The output voltage waveforms are shown below (fig.8a):

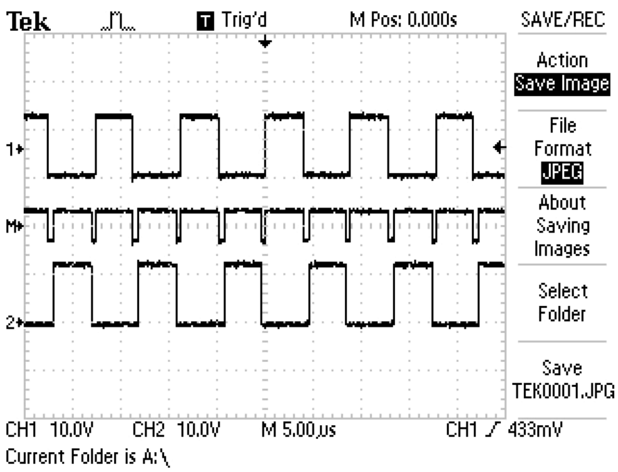

Figure 8(a) : Waveform for Gate Pulse

IV. CONTROLLING BY IC UCC3895

Features:

- Programmable Output Turn-on Delay
- Adaptive Delay Set
- Bidirectional Oscillator Synchronization
- Voltage-Mode , Peak Current-Mode, or Average Current-Mode Control
- Programmable Soft start / Soft stop and Chip Disable via a Single Pin
- 0% to 100% Duty-Cycle Control
- 7-MHz Error Amplifier
- Operation to 1 MHz
- Typical 5mA Operating Current at 500 kHz
- Very Low 150µA Current During UVLO

Applications:

- Phase-Shifted Full-Bridge Converters
- Off-Line, Telecom, Datacom and Servers
- Distributed Power Architecture
- High-Density Power Modules

Additional features;

- Includes an adaptive delay set feature, greatly reduced supply-current demand, and an internal-discharge transistor on the RAMP pin.
- Internal logic of the IC is redesigned to allow complete shutdown of the power stage using a comparator to detect the error-amplifier output going below 0.5 V.
- The IC pinout is improved to provide the maximum separation possible between the control and driver outputs

- The ability to program the delay between switch commands in the A–B leg is independent of the delay between switch commands in the C–D leg.

Feature	UC3875/6/7/8	UC3879	UCC3895	Units
UVLO start threshold	10.75 or 15.25	10.75 or 15.25	11	V
UVLO hysteresis	1.25 or 6.0	1.75 or 6.0	2	V
Supply current start	150	150	150	µA
Supply current run	30	23	5	mA
Error amplifier slew rate	11	11	2.2	V/µsec
Error amplifier unity gain	11	10	6.5	MHz
Ramp to OUT delay	65	115	70	ns
Oscillator line/load variation	20	20	2.5	%
Ramp valley	0	0.2	0.2	V
Ramp peak	3.8	2.9	2.35	V
Current limit level pulse-by-pulse	no	2	2	V
Current fault sense level	2.5	2.5	2.5	V
Current sense delay to output	85	160	75	ns
OUT drive current	200	100	100	mA
Delay time variation	150–400	300–600	450–600	ns
No load on/off comparator	no	no	yes	

Table - II Comparison Between Part Family:

Transformer Design:

The following procedure is followed to design the transformer [5] for 1.5kVA full bridge converter based on IC UCC3895.

1. Output power $Po = (Vo+Vrl+Vd)*Io$

$$= (110+11+1.5)*15$$

$$= 1858 \text{Watt}$$

Where, Vo = Output voltage
Vrl = 10 % of the Vo
Vd = 1.5v for worst

2. The area product for this converter configuration is given by

$$Ap = \frac{(\bullet 2+1/n)*Po}{(4*kw*Bm*fs*J)}$$

$$= \frac{(\bullet 2+1/0.95)*1838}{4*0.40*0.3*0.18*5}$$

$$= 104.95 \text{ mm}^4$$

Where, Kw = winding factor = 0.4,

J = current density
Bm = flux density =0.18 tesla
Fs = switching frequency
Ap = area product
Ac = cross section area

By using the table[5], the values are taken as under:

$$Ac = 645mm^2$$

$$Aw = 2914mm^2$$

$$Ap = 1879500mm^2$$

3. Number of primary turns:

$$N1 = \frac{Vssmax}{(4*Ac*Bm*fs)}$$

$$= \frac{230}{4*645*0.18*5}$$

$$= 99 \text{ turns}$$

4. Turns ratio can be calculated by:

$$n = \frac{Vo'}{(2*Dmax*Vmin)}$$

$$= \frac{122.5}{(2*0.48*160)}$$

$$= 0.85$$

Where , Dmax=0.48

5. Number of secondary:

$$N2 = nN1$$

$$= 0.85*99$$

$$= 84 \text{ turns}$$

6. Wire Guage selection:

$$I2 = Io•Dmax$$

$$= 15*•0.48$$

$$= 10.06 \text{ amp}$$

$$I1 = n\,Io$$

$$= 0.85*15$$

$$= 12.75 \text{ amp}$$

7. The wire area can be calculated by:

$$A1 = \frac{I_1}{J}$$

$$= 4.2$$

$$A2 = \frac{I_2}{J}$$

$$= 3.35mm^2$$

From the wire table the wire guage can be selected

13 SWG.

V. CONCLUSION

Different controller strategies were explored, including voltage and current mode based controls. The adaptive controller that was developed here makes use of a model of the system to be controlled, which is used in place of the system itself in order to provide estimates of the control state values. Since the input current in the dc-dc converter was relatively large, the converter's operation in the continuous conduction mode was verified for loads up to 1.8kW.

VI. REFERENCES

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