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Design and Modeling of a Miniature DC–DC Converter

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Abstract: The power module for miniature Inertial Navigation System demanded reduction in volume and footprint and it had to be housed inside the miniature INS package. Three such power modules are required for powering the three electrical chains of miniature INS. Also as demanded by the improved sensor electronics, the peak output power was increased from 57 W to 65 W. The reduction in volume and increase in power demanded power density enhancement of around three times from the existing system. The objective of the paper is to design a dc - dc converter satisfying the required specifications for an input voltage range of 22-36 V and providing multiple outputs +5V, +/-15 V, +/-30V and + 28Vwith a targeted efficiency of >80%. Also grouping the outputs to sets into HMCs was also attempted. The paper discusses various steps right from the topology selection to the design of the components. Design validation using SABER software is also done.

Keywords: Miniaturization, power density improvement, magnetic, Hybrid Micro Circuit (HMC), Low Drop out Regulator (LDO)

I. INTRODUCTION

Navigation System provides velocity, position and attitude information. Inertial Navigation System (INS) consists of a set of inertial sensors (Gyroscopes and Accelerometers) and its associated Electronics. Typically INS is realized as three packages- Sensor Electronics module, Power module and Data acquisition module. In order to reduce footprint and mass, a single package miniature INS is realized which combines functions of all the three modules. Miniaturization [1] of electronic systems presents challenges for thermal management and EMI compliance. The power module for miniature INS demanded reduction in volume and footprint and it had to be housed inside the miniature INS package. Three power modules are required for powering the three electrical chains of miniature INS. As demanded by the improved sensor electronics, the peak output power of each module was increased from 57 W to 65 W. The reduction in volume and increase in power demanded power density enhancement of around three times from the existing system. Following measures are taken in Power module Design and Packaging to achieve the objectives:

1. Power dissipated in module is reduced by improving the DC-DC Converter efficiency.
2. Heat dissipating components are mounted on module chassis and major dissipating devices are mounted on bottom wall of module.
3. Conductive path provided for each power module to package base wall.
4. Electrical and Mechanical interfaces provided as required by the package requirement.

The existing converter provides 7 outputs, 57 W output power and a switching frequency of 200 KHz and the power density was found to be 0.3 W/inch^3.
With the ultimate aim of improving power density, miniaturization of the converter is done as power density is given by power per unit volume. The new miniature power module has to provide an output power of 65 W and the module dimensions have to be decreased and hence the volume and the power density has to be improved by about 3 times from the existing converter. Minimizing the volume involve minimization of mainly the magnetics[5] i.e. transformers and inductors which is mainly dependent on frequency. But at the same time losses increase with frequency. So a compromise has to be made between size and efficiency. Similarly careful selection in each step of the design is required. The paper discusses various steps [6] in the design and also SABER simulations are carried out to validate the design.

II. MODULE DESCRIPTION

The various stages in the development of the converter are discussed below:

A. *Selection Phase*

The first and most important step in a converter design is the topology selection [4]. Due to the ease of miniaturization, forward converter topology is selected. The requirement specifications are:

1. Input voltage
   a. Nominal : 28V
   b. Range : 22-36V
   c. No. Of outputs : 9
   d. Peak Output power : 65W
   e. Targeted efficiency : >80%

The specifications for the design were:

TABLE I: SPECIFICATION TABLE

Voltage	Current	
	Nominal	Max
+5V	150	200
+5V	150	200
+15V	100	250
-15V	100	250
+15V	100	250
-15V	100	250
+30V	100	1250
-30V	100	1250
+28V	150	250

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TABLE II. TABLE SHOWING RIPPLE LIMITS

Voltage	Ripple(mV_{pp})	Ripple with 50% safety factor
+5V	50	25
±15V	50	25
±30V	50	25
+28V	50	25

Regarding the transformer core material [3] and shape, due to increased flux density and operation at high frequencies, ferrite R material is chosen and due to height considerations, torroid core shape is chosen. The core loss for various types of cores is given.

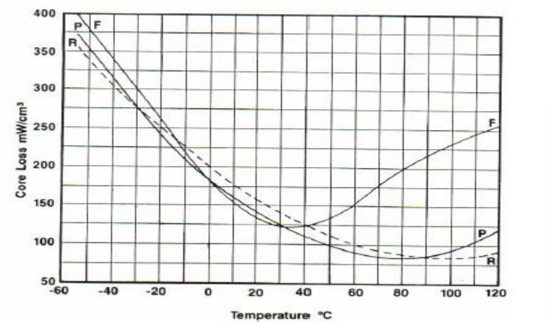

Fig.1 Loss Curves for the Different Core Materials

TABLE III: TABLE SHOWING FLUX DENSITIES OF DIFFERENT MATERIALS

Material Code	Flux Density	Initial Perm	Application	Curie Temp. °C
R	5,000	2,300	Transformers Inductors	> 230
K	4,600	1,500	"	> 230
P	5,000	2,500	"	> 230
F	4,900	3,000	"	> 250
J	4,300	5,000	EMI Filters Broadband xfmrs.	> 140
W	4,300	10,000	"	> 125
H	4,200	15,000	"	> 120

Increased switching frequency [8] reduces the size of transformers, capacitors and inductors but at the cost of increased core losses, switching losses and reduced efficiency. Also skin effect and proximity effect increases with frequency. Hysteresis losses are proportional to frequency and eddy current losses to frequency squared. So at higher frequencies eddy current losses dominate hysteresis losses. Also switching losses increase with switching frequency. So selection of switching frequency is a compromise made between size and efficiency. It can be seen that Bxf product [9] and hence flux density is high for R material at about 400 KHz. So switching frequency is chosen around 400 KHz.

Due to lower on state resistance, MIL-grade IRFM3415 is chosen for primary side MOSFET and UC1525B [10] is selected as the controller. The controller has two outputs, they are OR ed to obtain the signal for switch. Schottky diodes are preferred for the rectifier side diodes due to lower voltage drop.

B. Design Phase

The proposed converter block diagram is shown below:

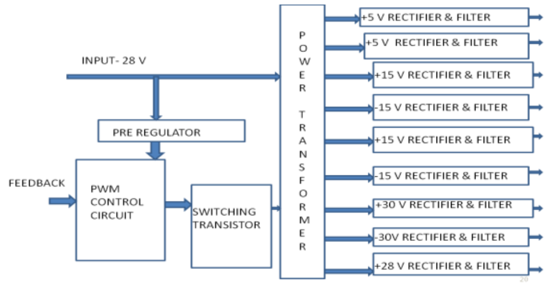

Fig.2 Proposed Converter Block Diagram

Proposal for various converter configurations like:

a. Discrete
b. HMCs(Hybrid Micro Circuits)
c. HMC + Discrete

In discrete configuration all the components are kept as discrete. This leads to difficulty in miniaturisation whereas in HMC configuration the components are grouped into HMCs. But it leads to difficulty in packaging as packages which can withstand such high power are not available. Hence the configuration of HMC + discrete wherein the outputs are grouped into two sets of HMCs with the heat dissipating components mounted on the chassis is adopted. The HMCs are:

a. $_{28}$HMC 1:+5V and ±15V
b. HMC 2 : ±30V and +28V

Design of magnetics consists of:

a. Design of power transformer
b. Design of output filter

1) Transformer Design:

Transformer area product

$$A_p = \frac{\sqrt{D_{max}} \times P_{out} \times (1+1/n)}{K_w \times J \times 10^{-6} \times B_m \times F_{sw}} \quad (1)$$

Number of turns in primary

$$Np = \frac{V_{in} \times D_{max}}{B_m \times A_c \times 10^{-6} \times F_{sw}} \quad (2)$$

Turns ratio

$$T_{ratio} = \frac{V_o + V_d \times D_{max},}{V_{in} \times D_{max}} \quad (3)$$

$$\text{Where } D_{min} = \frac{V_{in\,min} \times D_{max}}{V_{in\,max}} \quad (4)$$

Converter is designed for a maximum of 62% duty cycle and peak output power .Considered efficiency is 80% and B_m: 0.12 T, J=3A/mm^2, Winding factor K_w=0.3. Selected core should have area product greater than the calculated value.

2) Output Filter:

$$L = \frac{V_{out}(1-D_{min})}{2xK \times I_{out} \times F_{sw}} \quad (5)$$

Number of Turns

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$$N_{ind\,out} = \frac{L \times I_{out}(1+K/2)}{B_m \times A_c \times 10^{-6}} \quad (6)$$

$$C = \frac{K \times I_{out}}{8 \times F_{sw} \times V_{ripple}} \quad (7)$$

$$\text{Where } K = \frac{I_{ripple}}{I_{out}}$$

Transformer core with area product greater than calculated and lower core height is selected from the available core datasheet.

For **HMC 1**: P_{out} = 8.865W , Selected Transformer core:41407 TC, N_p= 29Turns, N_{5V} =10 Turns,N_{15V}= 27 Turns and N_{reset} = 18 Turns. For 5V output , L =80.80 uF, C= 625 nF and selected inductor core: C055291 A2. For 15 V output, L= 194.3 uH, C=781.25 nF and selected core: C055050 A2.

For **HMC 2**: P_{out} = 86.315W. Transformer core: Selected core: 42206 TC, Np=15 Turns, N_{30V}= 27 Turns, N_{28V}= 26 Turns, N_{reset} = 9 Turns. For 30V output, L = 39.3 uH, C = 3.9 uF and Selected inductor core: C055206A2. For 28V output, L = 227.13 uF, C = 625 nF and Selected core: C055280 A2.

As the power handled by the second HMC is very high, the ±30V and +28V HMC can be made into two independent HMCs. Thus 3 type HMCs can be realised.

- HMC 1 :+5V/0.2A and ±15V/0.25A
- HMC 2 :+30V /1.25A
- HMC3 : +28V/0.25A

For **HMC 2**: P_{out} = 37.5W, Transformer core: Selected core: 42106 TC, Np=15 Turns, N_{30V}= 27 Turns and N_{reset} = 9 Turns.

For **HMC 3**: P_{out} = 7W, Transformer core: Selected core: 41407 TC, Np=15 Turns, N_{28V}= 50 Turns, N_{reset} = 18 Turns.

So total number of outputs will consist of 2 sets of HMC1 and HMC2 and one set HMC.

3) Regulator Section:

To achieve tighter load regulation and control, post regulators are used to regulate all raw outputs to attain required specification outputs. Without the regulators output inductor would become bulky. Low drop out voltage regulator [2] operates with small input output differential voltage and hence they are chosen for this converter.

A low drop out regulator consists of a voltage reference, an error amplifier, a feedback voltage divider and a series pass element. The output voltage is divided through a voltage divider and compared with a reference to adjust the input to the series pass element. This provides a regulated output.

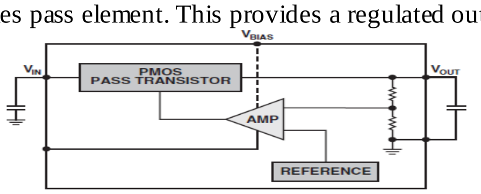

Fig.3 Basic LDO Regulator

III. SIMULATION RESULTS

Simulations for the HMC configuration design were carried out and validated using SABER software. The output voltages before and after regulators are plotted verifying the design.

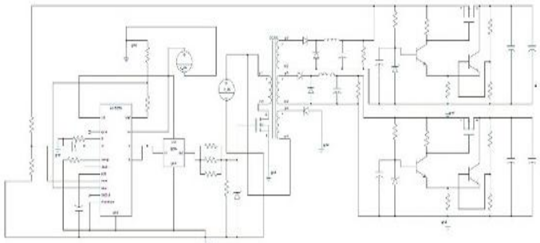

Fig.4 Simulation Diagram for the HMC 1

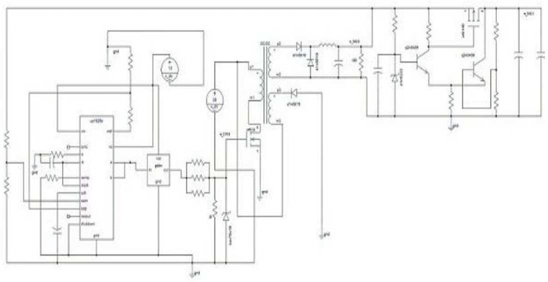

Fig.5 Simulation Diagram for HMC 2 and HMC 3

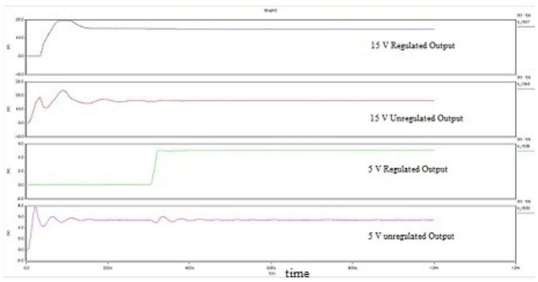

Fig.5 Simulation Results for HMC 1

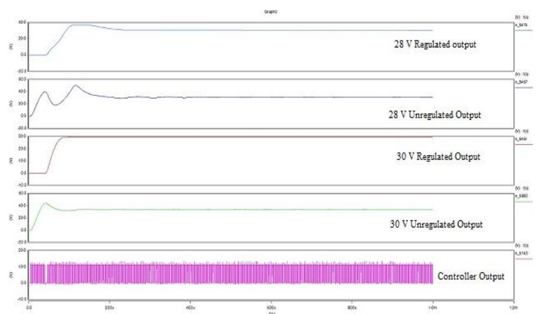

Fig 6 Simulation Results for HMC 2 and HMC 3

IV. RESULTS AND DISCUSSION

The converter was designed for a nominal input voltage of 28V and as the ultimate aim is to miniaturize the converter compared to existing converter, selection and design was done accordingly. The topology and various component selections were done and design for the required specifications were performed. Also a new configuration in which grouping the given sets of outputs to sets of HMCs was attempted. Design for the HMCs was validated through SABER software and results verified.

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V. CONCLUSION

A power module was realized for miniature Inertial Navigation System giving multiple outputs and a new configuration was found out in which outputs are grouped into sets of HMCs. But packaging of the HMCs has to be taken care of and suitable thermal management solutions have to be found out for effective dissipation.

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