Study and Design Aspects of Inductors for DC-DC Converter

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Abstract— DC-DC converters are electronic devices used to change DC electrical power efficiently from one voltage level to another. The choice of inductor plays an important role in the design of DC-DC converter as there is a diverse range of power converter requirements supplying a wide range of power levels at a multiplicity of voltages and currents. This paper focuses on the design, selection and the choice of materials for inductors in order to obtain the required inductance, avoid saturation, and acceptable low dc winding resistance and copper loss. A hardware model of the inductor using ferrite core has been developed to validate the theoretical results

Index Terms— Coercivity, Ferrite core, Inductor, Magnetic flux density, Parasitic elements, Remanence, Winding constant,

I. INTRODUCTION

DC-DC converters used in the electronic switch mode convert one DC voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors). This conversion method is more power efficient (often 75% to 98%) than linear voltage regulation (which dissipates unwanted power as heat) [1-5]. The amount of power transferred can be controlled by adjusting the duty cycle of the charging voltage (ratio of on/off time). Usually, this is applied to control the output voltage, though it could also be applied to control the input current, the output current, or maintain a constant power.

In these DC-to-DC converters, energy is periodically stored into and released from a magnetic field in an inductor or a transformer, typically in the range from 300 k Hz to 10 M Hz. Although the transformers can isolate the input from the output, they result in transformer losses (hysteresis and eddy current losses) and add to the increase in size. This is where the role of an inductor comes in. Inductor is an efficient device that can eliminate these problems. It uses the fly-back mode where the energy goes from the input and gets stored in the inductor. It is then released from the inductor to the load[5-6] .This paper focuses on the design, selection and the choice of materials for inductors in order to obtain the required inductance, avoid saturation, and acceptable low dc winding resistance and copper loss. The paper primarily features the design of the hardware of the ferrite core inductor as well as its modeling. The paper concludes with the hardware design results for the ferrite core inductor.

II. MATERIALS FOR THE DESIGN OF INDUCTOR

Inductor (also a coil or reactor), is a passive two-terminal electrical component which resists changes in electric current passing through it and stores energy in its coil. Inductor Design consists of electric and magnetic circuit. Design includes the size of the wire to be used for the electric circuit to carry the rated current safely and the size and shape of the magnetic core. It is designed to carry the peak flux without any saturation in the magnetic core and also to accommodate the required size of the conductors safely in the core. Inductor design also depends on the number of turns of the electric circuit to obtain the desired inductance. This paper primarily focuses on the design relationships and the step by step design procedure for a ferrite core inductor, meeting the specified requirements. Design challenges and material constraints during the design procedure included aspects like the limitations of the given wire (conducting material) that could carry only certain maximum current per cross-sectional area of the wire. This limit when exceeded resulted in the wire getting over heated from the heat generated from (i^2R) losses. The maximum current limit that the wire could carry depended on the value J A/m^2.Added to this the magnetic core could carry a fixed maximum flux density without saturation in the magnetic core. When this limit exceeded, the material saturation and the permeability dropped substantially. The limit depended on the maximum flux density of the core B m T [7].

Hard and Soft magnetic materials are two types of materials used in making the magnetic core of an inductor. Having no magnetic core (an air core) provides very low inductance in most of the situations, a wide range of high permeability materials are used to concentrate the field. Soft magnetic materials are easy to magnetize and demagnetize. They have low hysteresis loss due to small hysteresis area. Susceptibility and permeability are high. Since they have low retentivity and coercivity, they are not used for making permanent magnets. Magnetic energy stored is less. The eddy current loss is less because of high resistivity. B sat (Saturation flux density) is around 1-2 T generally.2.6 T for soft iron materials. Soft iron and carbonyl iron are some examples.

1. Hard Magnetic materials

Materials which retain their magnetism and are difficult to demagnetize are called hard magnetic materials. These materials retain their magnetism even after the removal of the applied magnetic field. Hence these materials are used for making permanent magnets. They have large hysteresis loss due to large hysteresis loop area. Susceptibility and permeability are low. Coercivity and retentivity values are large. Magnetic energy stored is high. They possess high value of BH product. The eddy current loss is high. B sat is higher than soft magnetic materials. Laminated silicon steel and ferrites are some examples. This paper presents an inductor made of ferrite core. Ferrites can be hard or soft.

2 .Soft Ferrites

They have a low coercivity and are called soft ferrites. The low coercivity means the material's magnetization can easily reverse direction without dissipating much energy (hysteresis losses), whereas the material's high resistivity prevents eddy currents in the core, another source of energy loss. Because of their comparatively low losses at high frequencies, they are extensively used in the cores of RF transformers and inductors in applications such as switched-mode power supplies. The most common soft ferrites are Manganese and zinc.

3. Hard Ferrites

In contrast, hard ferrites have a high coercivity and high remanence after magnetization. They also conduct magnetic flux well and have a high magnetic permeability. This enables these so-called ceramic magnets to store strong magnetic fields. The high coercivity means the materials are very resistant to becoming demagnetized, an essential characteristic for a permanent magnet. The most common hard ferrites are Strontium ferrite.

III. DESIGN PROCEDURE FOR INDUCTOR

Electromagnetic circuit elements consist of an electric circuit and a magnetic circuit coupled to each other. The electric current in the electric circuit sets up the magnetic field in the magnetic circuit with resultant magnetic flux [7-9]. Seen as an electrical circuit element, the electromagnetic element possesses the property of energy storage without dissipation. Ampere’s law and Faradays law relate the electric and magnetic circuits of the electromagnetic element. Ampere’s law states that the magneto motive force in a magnetic circuit is equal to the electric current enclosed by the magnetic circuit [7-9]. With further assumption that the magnetic material is isotropic and homogenous and that the magnetic flux -distribution is uniform, we may relate the magnetic flux in the magnetic circuit as

$$\Phi = \Sigma I / R \qquad (1)$$

$$\Phi = N \square I / R \qquad (2)$$

Faraday’s law relates the voltage induced in an electric circuit that is coupled to a magnetic circuit as.

$$v = N d\Phi / dt \qquad (3)$$

$$v = N \square N / R (di/dt) \qquad (4)$$

The quantity N^2/R is defined as the inductance of the electric circuit. Thus an electromagnetic circuit provides us an electric circuit element (inductor).The voltage across an inductor is directly proportional to the rate of rise of current through it. The energy stored in the magnetic circuit is

$$E = 1/2 \mathrm{L} \square I \square I \qquad (5)$$

$$E = 1/2 (F \square F / R) \qquad (6)$$

$$E = 1/2 (\Phi \square \Phi) R \qquad (7)$$

$$E = 1/2 \Phi \square F \qquad (8)$$

The equivalent circuit of an inductor showing both its electric and magnetic parts may be conveniently represented. However in practice, the inductor will have certain parasitic resistance (of the wire in the electric circuit) and magnetic leakage (in the magnetic circuit). These non-idealities may conveniently be incorporated in the equivalent circuit. The design of an inductor involves the design of the electrical (Number of turns and wire size) and the magnetic (geometry of the magnetic core and its required magnetic property) circuit [9].

Inductor consists of electric and magnetic circuit. The design includes the following:

- Size of the wire to be used for the electric circuit, to carry the rated current safely.
- Size and shape of the magnetic core
- To carry the peak flux without any saturation in the magnetic core
- The required size of the conductors are accommodated safely in the core
- Number of turns of the electric circuit to obtain the desired inductance [9].

IV. DESIGN RELATIONSHIPS

In order to design an inductor of inductance of ‘L’ henry carrying an r m s current and peak current, let the wire size be given by [9]

$$a_w = I_{rms} / J \quad (9)$$

Peak flux density B m for core area Ac corresponding to peak current is given as [2]

$$LI_p = N\Phi_p = NB_m A_c \quad (10)$$

Winding of the inductor is accommodated in the window area which is given by

$$K_w A_w = Na_w = N(I_{rms}/J) \quad (11)$$

Cross-multiplying

$$LI_p N(I_{rms}/J) = K_w A_w (NB_m A_c) \quad (12)$$

$$LI_p I_{rms} = K_w A_w B_m JA_c \quad (12)$$

This equation gives the relationship between the inductor stored energy

$$0.5Li^2$$

and size of the core. K_w depends on how well the windings can be accommodated. It ranges from 0.3 to 0.5[9].B m is the maximum unsaturated flux density which is 1 T for iron and 0.2 T for ferrites. J is the maximum allowable current density of the conductor [9]. Copper conductors have current density ranging from

$$20 \times 10^6 A m^2 - 50 \times 10^6 A m^2$$

V. STEP BY STEP DESIGN PROCEDURE

- Compute the area product [9]

$$A_c A_w = (LI_p I_{rms}) / K_w JB_m \quad (12)$$

- Choose the core whose area product is slightly higher than the one that is found in step 1
- Choose the core area and window area from the core table for the selected core
- Compute the number of turns

$$N = LI_p / B_m A_c \quad (10)$$

Choose the nearest whole number for the number of turns N

- Compute the area of cross-section

$$a_{w1} = I_{rms} / J \quad (9)$$

Choose the nearest whole number for wire gauge and aw1 from the wire tables

- Compute the air gap length

$$l_g = \mu N I_p / B_m \quad (13)$$

- Check for the assumptions

∗ Core reluctance<<air-gap reluctance

$$L/\mu_r \ll l_g \quad (14)$$

$$R_c \ll R_g \quad (15)$$

∗ No fringing

$$L_g \ll A_c \quad (16)$$

- Recalculate the new J1

$$(J_1) = I_{rms} / a_{w1} \qquad (9)$$

- Recalculate

$$(K_{w1}) = N a_{w1} / A_w \qquad (11)$$

Compute from the geometry of the core the mean length per turn and the length of the winding. From the wire tables, resistance of the winding is also computed [9].

Inference:

Inductor design procedure is carried out in step-wise manner and the desired inductor is designed according to the design specifications. Generally, an air gap is used to prevent the saturation of the core by the peak inductor current. The losses are kept as minimal as possible and the geometry of the inductor core is computed [9].

VI. HARDWARE DESIGN & RESULTS

A hardware model of the inductor using ferrite core has been developed to validate the theoretical results. The design challenges and material constraints include aspects like the limitations in the wire carrying current. The wire (or the conducting material) could carry only certain maximum current per cross-sectional area of the wire. On exceeding this limit, excessive heating of the wire occurs. This happens due to the i^2R losses [9]. Therefore, the maximum current limit that the wire could carry depended on the value J A/m^2. In addition to this, the magnetic core could only carry a fixed maximum flux density without saturation in the magnetic core. When this limit is exceeded, the material saturation and the permeability are dropped substantially [9]. The limit depended on the maximum flux density of the core B_m T. The specifications for the inductor design is shown in table I

Table I: Design specifications for the Inductor

S no	Parameters(with the related formulas)	Parameter Values
1.	L (Inductance)	224.5µH
2.	Δi% (Ripple Current percentage)	10%
3.	I_{avg} (Average current)	2.623A
4.	Frequency	100KHz
5.	J (Current Density)	$4A/mm^2$
6.	K_w (Winding Constant)	0.6
7.	B_m (Maximum Flux Density)	0.2 T
8.	I_{rms} (RMS current) $I_{rms} = I_{avg}\sqrt{1 + 1/3(\Delta i / I_{avg})^2}$	2.628A(On substitution)
9.	I_p (Peak Current) $I_p = I_{avg} + \Delta i/2$	2.754A(Nearly 3A) (On substitution)

VII. PROCEDURE FOR HARDWARE DESIGN

The step-wise procedure for inductor design is discussed as follows:

$$A_c A_w = L I_p I_{rms} / K_w J B_m \qquad (1)$$

$$A_c A_w = 224.5 \square 10^{-6} \square 2.754 \square 2.628 / (0.6 \square 4 \square 0.2 \square 10^{-6}) = 3385.4mm^4 \qquad (1)$$

- Choosing the core with slightly higher product area ($4567.5mm^4$) than step one from the core tables. Type No= E 25/13/7

- Choose Ac and A w values from the core tables

$$Ac = 52.5mm^2 \; Aw = 87mm^2$$

- Compute the number of turns

$$N = L I_p / B_m A_c = (224.5 \square 10^{-6} \square 2.754)/(0.2 \square 10^{-6} \square 52.5) = 58.8 \qquad (10)$$

Choose the nearest whole number N=59 turns

- Area of cross-section of the wire

$$a_{w1} = I_{rms} / J = 2.628/4 = 0.6567mm^2 \qquad (9)$$

- Choose the wire with area obtained in step 4 from the wire tables.

- Air gap length

$$l_g = \mu N I_p / B_m \qquad (13)$$

$$lg = 4 \square 3.14 \square 10^{-7} \square 59 \square 2.754 / (0.2) = 1.020mm \qquad (13)$$

- Assumptions are checked

∗ Core reluctance<<Air gap reluctance

$$L/\mu_r \square\; l_g \qquad (14)$$

$$R_c \square\; R_g \qquad (15)$$

∗ No fringing

L_g □ A_c (16)

- Recalculate

$$(J_1) = I_{rms}/(a_{w1}) = 2.628/0.6567 = 4.0018A/mm^2 \quad (9)$$

- Recalculate

$$(K_{w1}) = Na_{w1}/A_w = 59 \square 0.6567/87 = 0.445 \quad (11)$$

- Practical value of the inductor

$$L = 214\mu H$$

Therefore, the inductor is designed with the required specifications.

VIII. MODELING OF INDUCTOR

Fig.1 shows the various parasitic elements of a coil. In this figure, ESR represents equivalent series resistance and C represents the winding capacitance of the coil L. Fig. 2 shows the estimated frequency response of the coil. In the lower frequency region f1, the impedance is purely resistive (ESR), middle frequency f m, the impedance is purely inductive (L) and high frequency region f h, the impedance is capacitive impedance© [10].

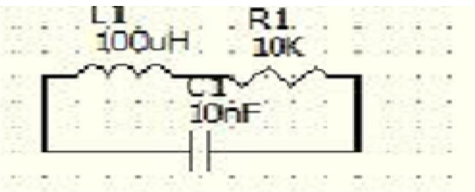

Fig.1 Parasitic elements of the Coil

The frequency at which coil and the capacitance winding resonates is called resonating frequency f r [10].

So, from Fig.2, it is easy to find L, ESR and C of any coil.

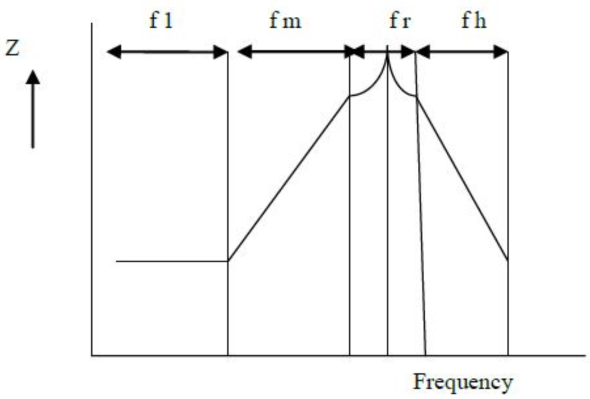

Fig. 2 Frequency response curve of the inductor

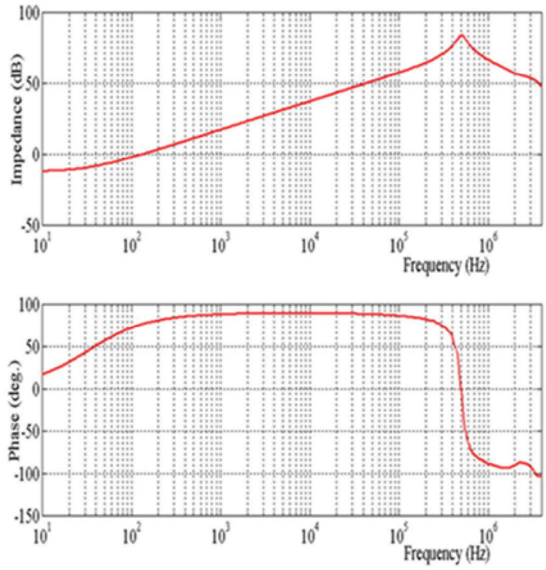

Fig.3 Impedance and phase plot of Inductor

Fig.3 shows the impedance and phase plot of the inductor of value 1mH for different frequencies. From the response, it is observed that for frequencies less than 100Hz, the impedance is resistive (ESR), frequencies 100Hz to 200 kHz, the impedance is inductive. The resonance occurs at 500 kHz which is du

e to winding capacitance and inductance. Above 600 kHz, the impedance is capacitive (winding capacitance) [10-11]. Therefore, proper modeling and design of inductor is mandatory in the prototype development of power electronic converter for any application.

IX. CONCLUSION

This paper introduced the design aspects of inductor for DC-DC converter. It mainly focused on the design, selection and the choice of materials for inductors in order to obtain the required inductance, avoid saturation, fringing and acceptable low dc winding resistance and copper loss. A .detailed design procedure is illustrated for the inductor using ferrite core. A hardware model of the inductor using ferrite core has been developed to validate the theoretical results.

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