EVTeC 2023
6th International Electric Vehicle Technology Conference 2023

20231028

A Model-Based Study on a DCDC converter Reactor Miniaturization using a Variable Bias Magnet suitable for Vehicle Drive Applications

Shunya Sakamoto [1)] Kensuke Sasaki [1)]

1) EV system Laboratory, Nissan Motor Co., Ltd, Atsugi, Kanagawa, Japan

E-mail: shunya-sakamoto@mail.nissan.co.jp

ABSTRACT: In this paper, a magnetic circuit, which has an opportunity to realize volume reduction of a reactor used in a DCDC converter for vehicle drive applications is proposed. The magnetic circuit is based on a magnetic bias reactor and variable magnets are applied to manipulate its magnetization direction by the external magnetic field induced by the reactor winding. For vehicle drive applications, DCDC converters are demanded to supply wide-output-power-range operations. The proposed reactor changes the magnetization direction of the bias magnets based on operating conditions such as power or regeneration to widen the operable range of reactor cores and realize the downsizing of reactors. In this paper, the design principle of the reactor is discussed, and its effectiveness is evaluated by simulation.

KEY WORDS: electric vehicle, magnetic bias reactor, power electronics, powertrain

1. INTRODUCTION

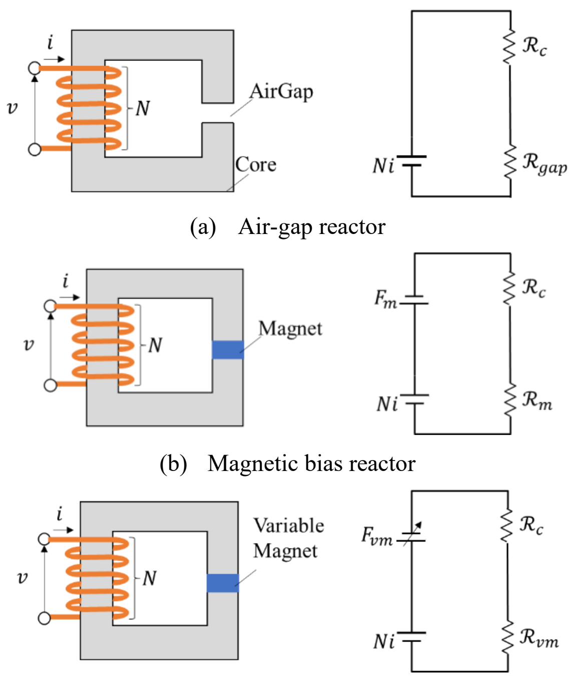
Diversification of electric vehicles induces the demand for downsizing electrified powertrain(e-PT) components including inverters and DCDC converters. To maximize e-PT performance, DC bus voltage needs to be set at optimum values for each segment of cars and DCDC converters are one of the solutions. So, smaller DCDC converters provide further opportunities to improve e-PT performance while saving its volume.

A Method to reduce the size of the reactor would contribute to the DCDC miniaturization. Magnetic bias reactors, which contain magnets inserted in the air gap portion, are proposed as a method to reduce the size of the reactor for DCDC converters. [1]-[7]. Magnets are inserted to bias in the opposite direction of the magnetic flux induced by the current, and the magnetic field margin to core saturation can be improved. Therefore, the magnetic bias reactors can be one of the solutions to downsize the reactor. However, the preferred magnetization direction of the magnets is different between power and regeneration. So, the miniaturization effect is not expected when this method is applied to vehicle drive applications that repeat power and regeneration cycles.

In this paper, we propose variable magnetic bias reactors, which are expected to have a downsizing effect even for vehicle drive applications. By using variable magnets, the magnetized direction can be changed depending on the external magnetic field in the air gap section for both power and regeneration. This enables a wider operating range of the reactor core and expects to lead to a downsizing effect in automotive applications as well. This paper shows the design principle of the reactors, and its effectiveness are verified by simulation results.

2. Variable magnetic bias reactor

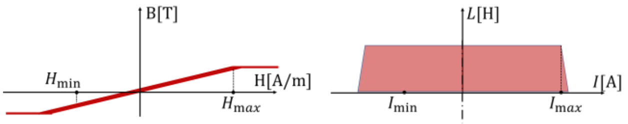
2.1. Principle of variable magnetic bias

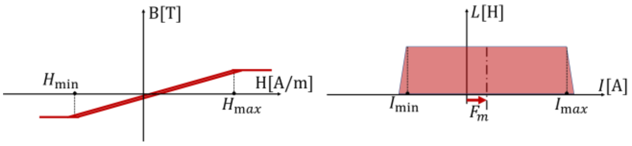


(c) Proposed variable magnetic bias reactor

Fig. 1 Magnetic circuit of each reactor types

Fig.1 shows the magnetic circuit of the air-gap reactor, magnetic bias reactor, and proposed variable magnetic bias reactor. In Fig.1 (c), variable magnetomotive force sources are added because of the variable magnet. Fig.2 shows Typical B-H curves and L-I


(a) Air-gap reactor


(b) Magnetic bias reactor

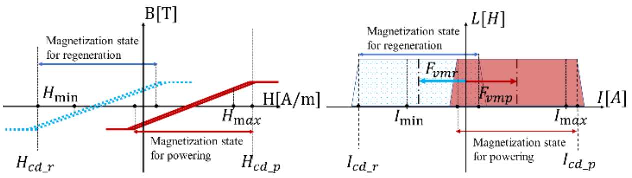

(c) Variable magnetic bias reactor

Fig. 2 Typical B-H curves and L-I profiles of cores for each reactor types

profiles of the reactor core for each reactor type. Where, F_m, F_{vmp}, F_{vmr} is magnetomotive force of magnet, H_{cd_p}, H_{cd_r} is magnetic field to change magnetizing direction and I_{cd_p}, I_{cd_r} is current to change magnetizing direction. From Fig.2, magnets change the operation range of the reactor core without saturation. L-I profiles in Fig. 2 also imply the approximate size of each reactor. The energy handling capability of a reactor can be calculated as LI^2 and is proportional to the size of the reactor therefore the area enclosed by L-I profiles can provide an intuitive estimation of the required reactor size [7]. By using a variable magnetic bias reactor, size reduction is expected because the operating area of the core can be limited while changing the magnetization direction. LI product for magnet reactors is as following equation.

$$LI = L\left(I_{max} - \frac{F}{N}\right) = B_{max}NS_{core} \cdots (1)$$

where, L is inductance, I_{max} is maximum current, F is magnetomotive force of the magnet, B_{max} is maximum flux density of the core and S_{core} is the cross-sectional area of the core. Conventional magnetic bias reactors can decrease effective LI product by magnetomotive force of magnet. However, in case of I_{max} is negative, direction of magnetomotive force of magnet and coil are aligned in same direction thus magnetic saturation occurs. Therefore, in applications which require bidirectional DCDC converter, variable magnetic bias reactors are desirable.

2.2. Design method of variable magnetic bias reactor

Four main parameters need to be considered when designing a variable magnetic bias reactor. One is inductance L, which

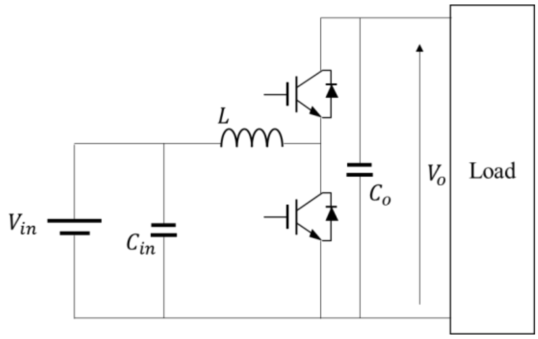


Fig. 3 Bidirectional DCDC converter

determines circuit performance such as current ripple as same as the conventional reactor. The others are the coercive force of the magnet H_{cj}, the thickness of the magnet l_{mag}, and the number of turns N, which determines the strength of the external magnetic field to change the magnetized direction. These three parameters need to be designed with the correct values in order for the magnitude of the external magnetic field to set a given value. In this section, the possible values of these parameters are illustrated on the graph and determine approximate values first. In addition, the relation between each circuit constant and design variables will be shown to clarify the design method of the variable magnetic bias reactor.

First, the required inductance to operate at a desired current ripple ratio r at a certain operating point will be determined. The assumed circuit is a bidirectional DCDC converter in this study as shown in Fig. 3. The relationship between the voltage applied to the winding of the reactor V_L, the inductance L, and the winding current di_L is expressed as

$$V_L = L\frac{di_L}{dt} \cdots (2)$$

$$\eta = \frac{V_o I_o}{V_{in} I_{in}} \cdots (3)$$

$$I_{in} = \frac{V_o I_o}{V_{in}\eta} \cdots (4)$$

$$di_L = rI_{in} = r\frac{V_o I_o}{V_{in}\eta} \cdots (5)$$

$$dt = T_{ON} = \frac{D}{f_{sw}} = \frac{1}{f_{sw}}\frac{V_o - V_{in}}{V_o} \cdots (6)$$

where, V_L is applied voltage to the winding of the reactor, L is the inductance, di_L is the winding current, η is efficiency of DCDC converter at the certain operating point, V_{in}, V_o is input and output voltage of DCDC converter respectively, I_{in}, I_o is output current of DCDC converter respectively, r is current ripple ratio, T_{ON} is on time of power semiconductor, D is the duty, f_{sw} is switching frequency. From Eq. (2) to Eq. (6), the required inductance L_{req} at the assumed operating point is expressed as following equation.

$$L_{req} = \frac{V_{in}^2(V_o - V_{in})\eta}{V_o^2 I_o r f_{sw}} \cdots (7)$$

As shown in Fig. 1 (c), the magnet is inserted in the gap section in close contact with the core. The inductance value L_d, which is derived from the magnetic circuit perspective is as following equation.

$$L_d = \frac{N^2\mu_0 S_{core}}{l_{mag}} \cdots (8)$$

where, N is the number of turns, μ_0 is a permeability in vacuum, S_{core} is the cross-sectional area of the core, l_{mag} is the thickness of the magnet. It is assumed that the magnetic resistance of the core is neglected in this study thus inductance can be derived to be determined only by the magnetic resistance of the magnet or air gap. The cross-sectional area of the core and the magnet are the same. To change the direction of magnetization during driving, it is necessary to apply an external magnetic field that exceeds the Knick point. Based on this, the direction or amount of bias flux by the magnet can be varied by determining the number of turns, magnet thickness, and coercive force to satisfy the following equation.

$$\frac{l_{mag}H_{cj}}{i_{cd}} \leq N \cdots (9)$$

where, i_{cd} is desired current value to change magnetizing direction. Variable magnetic bias reactor with the desired electromagnetic characteristics can be designed by selecting a combination of the number of turns N, magnet thickness l_{mag}, and coercive force of the magnet H_{cj} that satisfies Eq. (7) and Eq. (8) as well as Eq. (9). Fig. 4 shows a designable space that satisfies Eq. (7) to Eq. (9). Where, the required inductance L_{req} is set to desired constant value and thickness of magnet l_{mag} is set to satisfy Eq. (8) and Eq. (9) and cross-sectional area of core S_{core} is set to appropriate constant value. From Fig. 4, the sensitivity of the inductance L_d is linear to the number of turns N. This implies that one design degree of freedom is used since Eq.(9) must be satisfied when designing a variable magnetic bias reactor. In this calculation, the magnet thickness l_{mag} increases in proportion to the square of the number of turns N. Since the magnetic resistance moves in the direction of increase, the sensitivity of the inductance L to the number of turns N is not a square but a proportional relationship. This Figure also expresses that increasing the coercive force H_{cj} can reduce the number of turns N. Assuming constant inductance values, the sensitivity of the number of turns N and coercive force of the variable magnet H_{cj} is shown in Fig. 5. Fig. 5 shows that the range of the number of turns N, which can be designed, determined when material properties are considered. Since the upper limit of the coercivity of a typical neodymium magnet is about 2000 kA/m,

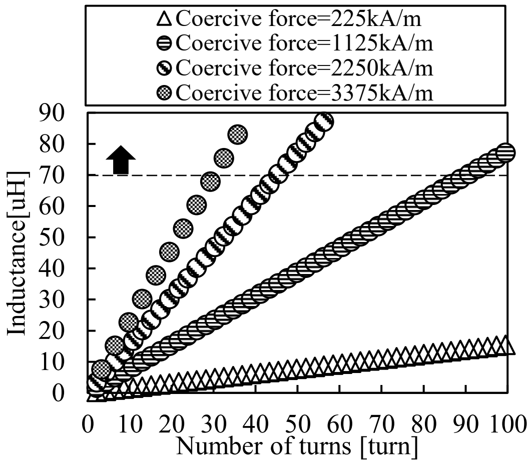


Fig. 4 Designable space of L versus N satisfy Eq. (7) to Eq. (9)

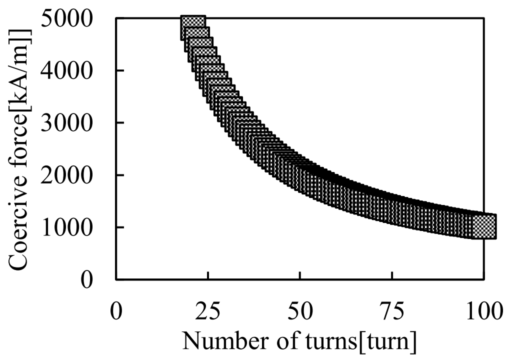


Fig. 5 Sensitivity versus N and Hcj

the 2250 kA/m coercive force value of the variable magnet is selected for this study.

2.3. Simulation and discussion

In order to demonstrate the miniaturization effect of variable magnet bias reactors, the parameter study for the cross-sectional area of the core S_{core}, which had been assumed to be an appropriate constant value in the previous sections was also conducted. The sensitivity of the cross-sectional area of core S_{core} versus the volume of variable magnetic bias reactor V_{vm} will be shown in this section. In this parameter study, the 2250 kA/m coercive force magnets are used, and the inductance value is set to a constant value as the previous section. To calculate the volume, the window area of the reactor S_{win} is determined according to the following equation, and the current density D_c and coil space factor k_{sf} are kept constant value.

$$S_{win} = \frac{N i_{max}}{D_c k_{sf}} \ldots (10)$$

It is assumed that the window of reactor and cross-section of the core are square. The volume of the core V_{core} can be calculated as

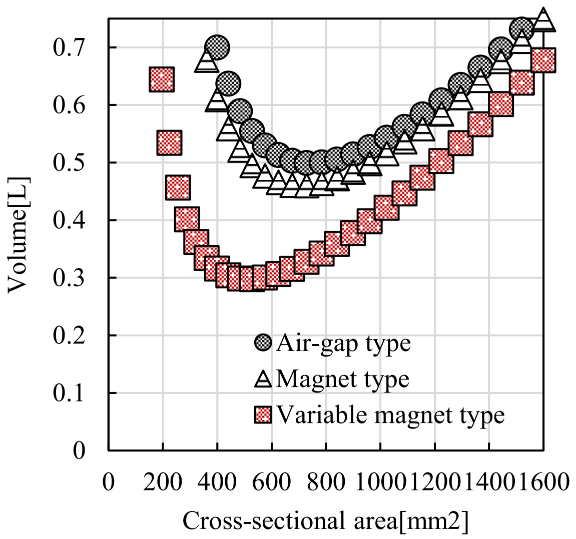


Fig. 6 Volume versus Cross-sectional area of core for each type of reactor

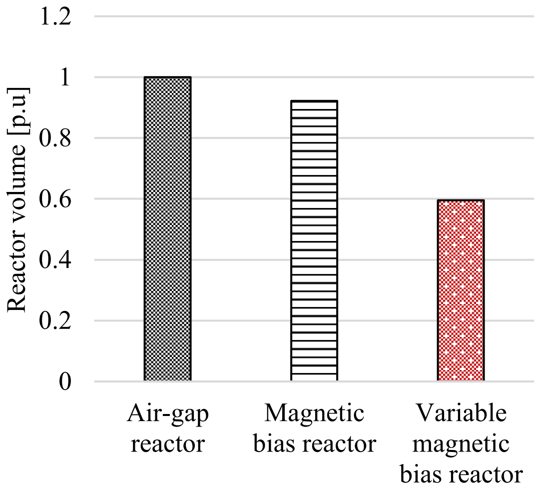


Fig.7 Reactor volume comparison for each type

Table 1 Design parameter

	Variable	Unit	Value
Coercive force of magnet	Hcj	kA/m	2250
Maximum magnetic flux density of core	B_sat	T	1.20
Switching frequency	fsw	kHz	20.0
Ratio between magnetization current and maximum current	kmag	-	1.30
Ratio between regeneration and powering	kpr	-	0.80
Ripple current ratio	r	-	0.10
Efficiency of DCDC converter	η	-	0.95
Voltage min	Vin	V	250
Output voltage	Vo	V	400
Maximum power under powering	Pmaxp	kW	100
Maximum power under regeneration	Pmaxr	kW	-80
Maximum dc current under powering	Idcmax	A	400
Maximum dc current under regeneration	Idcmin	A	-320
Peak current under powering	Ipeak+	A	440
Peak current under regeneration	Ipeak-	A	-352
Current to change magnetizing direction under powering	Icd_p	A	520
Current to change magnetizing direction under regeneration	Icd_r	A	-520

Table 2 The typical parameters of designed reactors

	Variable	Unit	Value
Number of turns(Air-gap type)	Ng	turns	56
Number of turns(Magnet bias type)	Nm	turns	55
Number of turns(Variable magnet bias type)	Nvm	turns	39
Inductance(Air-gap type)	Lg	uH	111
Inductance(Magnet bias type)	Lmag	uH	111
Inductance(Variable magnet bias type)	Lvm	uH	111
Air gap length(Air-gap type)	lg	mm	25.8
Magnet thickness of magnet (Magnet bias type)	lm	mm	23.0
Magnet thickness of magnet (Variable magnet bias type)	lvm	mm	8.9
Cross-sectional area of core(Air-gap type)	Scg	mm2	729
Cross-sectional area of core(Magnet bias type)	Scm	mm2	676
Cross-sectional area of core(Variable magnet bias type)	Scvm	mm2	529
Length of core per side(Air-gap type)	lcg	mm	95.4
Length of core per side(Magnet bias type)	lcm	mm	93.0
Length of core per side(Variable magnet bias type)	lcvm	mm	83.4
Volume(Air-gap type)	Vair	L	0.50
Volume(Magnet bias type)	Vmb	L	0.46
Volume(Variable magnet bias type)	Vvmb	L	0.30

$$V_{core} = 4 l_{core} S_{core} \ldots (11)$$

where, l_{core} is the length of one side of the outline of the core and calculated as following equation.

$$l_{core} = 2\sqrt{S_{core}} + \sqrt{S_{win}} \cdots (12)$$

The volume of the winding V_{coil} can be calculated as following equation.

$$V_{coil} = N(S_{win} + 2\sqrt{S_{win}}\sqrt{S_{core}}) \ldots (13)$$

The volume of the reactor V is calculated as following equation so that this volume includes only volume of the core and winding, not including other components such as a cooling case in this study.

$$V = V_{core} + V_{coil} \ldots (14)$$

Table 1 shows the assumed design parameters where,

$$k_{mag} = \frac{I_{dc\_max}}{I_{cd\_p}} \ldots (15)$$

$$k_{pr} = \left|\frac{P_{max_r}}{P_{max_p}}\right| \ldots (16)$$

Fig. 6 shows the sensitivity of volume versus cross-sectional area of the core for each type of reactor. From Fig. 6, in case of designing reactors with the same output power and inductance value, the proposed variable magnetic bias reactor can be the most effective to reduce the size. Table 2 shows the typical parameters of designed reactors. Fig.7 shows the reactor volume comparison. From Fig.7, 8% of the size was reduced by the magnetic bias reactor and 40% of the size was reduced by the variable magnetic bias reactor compare with the conventional air gap reactor respectively.

3. CONCLUSION

Variable magnetic bias reactors are proposed as a method to reduce the size of bidirectional DCDC converters for vehicle applications. By using this magnetic circuit, it is feasible to reduce 40% of the reactors size. As a future work, magnetize and de-magnetize control method is considered. Additionally, detail magnet material design and thermal design, which are strongly correlated with reactor size.

REFERENCES

(1) J. T. Ludwig, “Inductors biased with permanent magnets: Part I—Theory and analysis,” Trans. Amer. Inst. Elect. Eng. I, Column. Electron., vol. 79, no. 3, pp. 273–278, Jul. 1960.

(2) Kou Baoquan, Song Liwei, Zhang Qianfan and Cheng Chukang, "The principle and design of the permanent magnet bias DC reactor," ICEMS'2001. Proceedings of the Fifth International Conference on Electrical Machines and Systems (IEEE Cat. No.01EX501), 2001, pp. 230-232 vol.1, doi: 10.1109/ICEMS.2001.970653.

(3) G. M. Shane and S. D. Sudhoff, "Permanent magnet inductor design," 2011 IEEE Electric Ship Technologies Symposium, 2011, pp. 330-333, doi: 10.1109/ESTS.2011.5770892.

(4) A. R. Aguilar and S. Munk-Nielsen, "Method for introducing bias magnetization in ungaped cores: “The Saturation-Gap”," 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, 2014, pp. 721-725, doi: 10.1109/APEC.2014.6803387.

(5) T. Fujiwara and H. Matsumoto, "A new downsized large current choke coil with magnet bias method," The 25th International Telecommunications Energy Conference, 2003. INTELEC '03., 2003, pp. 416-420.

(6) A. Revilla Aguilar, S. Munk-Nielsen, M. Zuccherato and -. Thougaard, "Size Reduction of a DC link Choke Using Saturation-gap and Biasing with Permanent Magnets," PCIM Europe 2014; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2014, pp. 1-8.

(7) A. Revilla Aguilar and S. Munk-Nielsen, "Half Size Reduction of DC Output Filter Inductors with the Saturation-Gap Magnetic Bias Topology," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 2, pp. 382-392, June 2016.