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DEVELOPMENT OF AC REACTORS BY USING METAL POWDER MATERIALS

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***Abstract* – In this paper, AC reactors for PWM converters using the metal powder are introduced. Metal powder AC reactors were developed to substitute conventional iron core typed AC reactors in PWM converter applications. The characteristics of the metal powder AC reactors are analyzed and tested. A new reactor has reduced switching noise and loss.**

Introduction

Recently, the trend of applying metal powder to the electrical machines arises in industrial fields due to its low loss, small size capabilities, and superior characteristics, compared with the conventional lamination sheets [1-2]. In addition, eliminating the lamination and its related process could reduce the manufacturing cost, so that it is expected that its application area is expanded in the electric machines.

The AC reactor, which is commonly used to eliminate current ripples in the PWM converter, generates noises, serious heat due to switching current ripples, and iron and copper losses. These noises become serious according to subtle application areas, such as home appliance. Even though increasing inductance value can mitigate this noise problem, it can cause total volume and voltage drop to be increased.

In this paper, a metal powder reactor, which is designed to reduce the noise and heat in conventional AC reactor in the PWM converter, is introduced and compared with the general iron-core type reactor. In order to verify the validity of the proposed reactor, an experiment has set based on 3kW rated PWM converter and the performance of the metal powder has been analyzed with the informative experimental results.

Application for Metal Powder AC Reactor

Metal Powder Core

Generally, laminated silicon steel sheets are used to reduce the iron loss of the energy conversion machines, however, there are many studies to apply the metal powder to the electrical machines. The metal powder is manufactured by pressing the mixture of insulation coated metal scales, epoxy, and blending liquid. The thin insulation layers between scales are still preserved even after high-pressure treatment, and this insulation layer reduces the loss due to eddy current remarkably [1]. Moreover, making a core to be divided and have various shapes can increase the lamination ratio, and the copper loss can be reduced. Therefore, the compaction, lightweight, and easy assembling are possible.

In the electrical machines, lamination is used to reduce the eddy current loss, but it causes excessive manufacturing cost and limits the degree of design freedom seriously. Moreover, its manufacturing is hard and expensive. In addition, the scratch, which can affect the characteristics of the electrical machines, can be made during manufacturing process, while the metal powder enables easy shaping, which is hard or even impossible to be performed through lamination, and ensures robust characteristics of material with little eddy current loss at the frequency of commercial supply voltage [1]. In addition, in the aspect of noise and vibration, the metal powder has great value, since the core, which is made of the metal powder, has no vibration and erosion. However, the metal powder has 500 of less maximum relative permeability than the laminated silicon steel sheets.

AC Reactor Apply to PWM Converter

Recently, as the necessity of energy savings and regulations of harmonic components in the power supply arises, the diode rectification is rapidly being replaced by the PWM control in converter, which converts AC supply to DC. With the PWM converter, it is possible low THD of current as well as regenerative operation with superior controllability of power factor. As shown in Fig. 1, to control the current, which flows from input source to DC link, in converter, an AC reactor must be combined with the semi conductor device in serial.

When designing PWM converter, the size of AC reactor is determined by DC link voltage, input voltage, input frequency, and rated power. In the aspect of current control of converter, higher DC link voltage is better, however the margin of over-voltage fault should be considered, and the current increases as the DC link voltage becomes high. When the input frequency goes high, the voltage drop in the reactor at the same rated current increases. Therefore, it becomes difficult to control the converter current. Meanwhile, low input voltage results in the more fundamental current to supply rated output power. Therefore, the upper limit of the inductance of AC reactor is determined by the difficulty of current control and the lower limit is determined by the fact that the ratio of the ripple current over fundamental current is getting small, as the value of reactor inductance is high. According to the voltage equation (1) and equation (2), high inductance of AC reactor needs high output voltage of PWM converter to control the current and the power factor. Equation (1) and (2) are voltage equations of the PWM converter in the synchronously rotating frame.

$$E_{de} = 0 = V_{de} + Ri_{de} - \omega_e L i_{qe} \tag{1}$$

$$E_{qe} = E_s = V_{qe} + Ri_{qe} + \omega_e L i_{de} \tag{2}$$

where E_{qe}, E_{de}, E_s are source voltage vector, V_{qe}, V_{de} are converter out put voltage vector, I_{qe}, I_{de} are current vector and L, R are phase inductance and resistance of AC reactor.

Generally, the value of the reactor inductance of PWM converter is designed to have the voltage drop of 10% of input voltage at the rated current of PWM. With this estimation, the inductance of the AC reactor for 3kW power is designed to be about 7mH with the 3-phase 380V input. However, in reality, serious switching noises occur in AC reactor. Increasing the switching frequency can solve that problem but it increases the switching loss in the semiconductor, which has great influence in system design and are the troublesome.

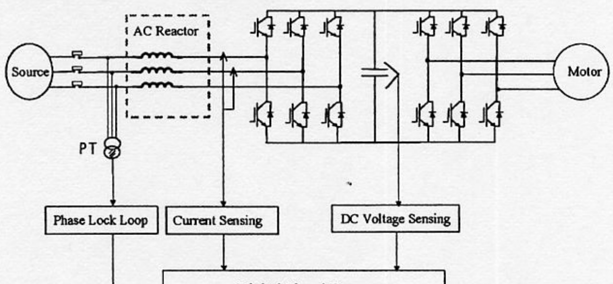


Fig. 1 Diagram of PWM converter with AC Reactor

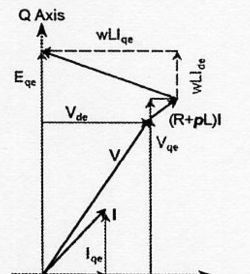


Fig. 2 Space Phase Diagram

Design of the AC Reactor

In Fig. 3, the inductance characteristics of 3 reactors according to the current and the frequency are shown. In this figure, Type A reactor shows the characteristic to minimize the allowable error at overload and rated power, Type B does the general characteristic of Iron-cored reactor, and Type C does the Swing type, which is economic type. Type A is used in the case that it is impossible to allow the inductance tolerance at rated and over load, and B Grade Core is applied to this type and air-gap positioning and partition should be cautiously considered.

Type A increases the manufacturing cost and this is unfavorable in cost and dimension. Therefore, it is recommended to design the reactor due to have low inductance as Air-Cored type. The Type A reactor assumed to have the general characteristics of Iron-Cored type reactor with various allowable errors, which are generally ±10% at rated, ±20~30% at over load, and more economical than Type B but caution is required in the cases of over load, short-circuit, and considering harmonics. The characteristic of Type C is very economical as a swing type. That is, it has increased inductance at rated or light load and decreased inductance at over load. Lightweight and low cost of Type C reactor can be accomplished by circuit and system analysis technology.

It can be said that Type A is the most appropriate reactor for PWM converter among 3 reactors, especially, in a system where there are frequent repetitive accelerations and decelerations which current flows 1.5~3 times of rated current. Therefore, for facile control and less switching current ripples, less variation of inductance per current variation is required. In addition, the reactor, which is used in PWM inverter, must have fine frequency characteristics. Since there are current ripples due to switching frequency, increased inductance can reduce harmonic current ripple. Therefore, it has advantages in the aspect of noises and iron loss. A reactor having general iron core has remarkably reduced inductance at switching frequency band, while air-cored type shows good characteristics at high frequency, but the volume and cost of air-cored type are increased to have the same value of low frequency inductance because of the increased turn number.

Metal powder has very low relative permeability comparing with laminated silicon steel sheets, but in the application of AC reactor, that is not a drawback, because general 3-phase reactors have air-gaps and consist of laminated iron sheets to reduce eddy current loss. The air gap is introduced to prevent saturation in iron core, however metal powder core does not require air gap because of the air gap in each particle. Air gap between particles varies with the pressure of the press machine, and the pressure of the press machine can vary relative permeability. Fig. 4 shows the structure of both Iron-cored type reactor and metal powder type one. Since magnetic air gap varies with the pressure exerted to the metal powder, it can be assumed that there is no air gap, and relative permeability can be considered by iron and coating material property. However, it is hard to estimate the relative permeability in the reactor. Therefore, the relative permeability is estimated by experimental measurement from a sample, and then applied to the reactor. The relative permeability from the experiment is 32. In this paper, the metal powder core has diameter of 66mm and height of 39mm. Fig. 5 shows the variation of the inductance according the relative permeability and the magnetic flux density distribution when rated current flows in the designed reactor with FEM (Finite Element Method). The Flux density level is 0.8T at the rated current by FEM simulation.

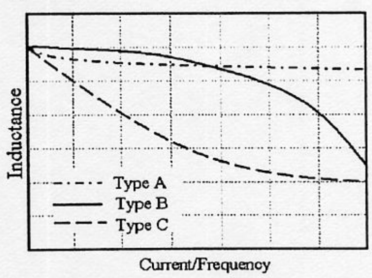
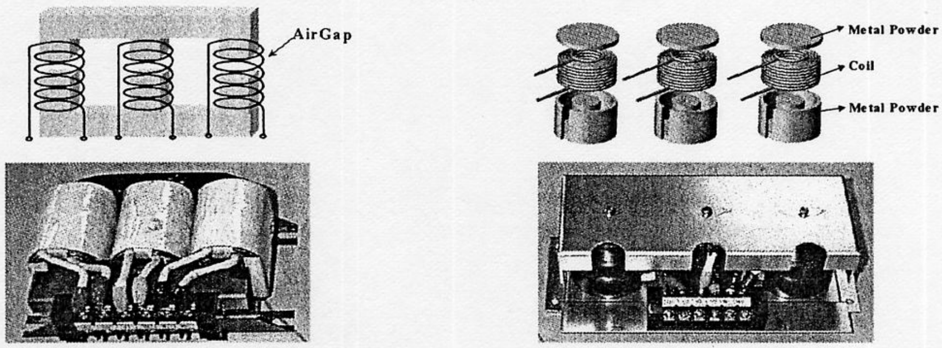
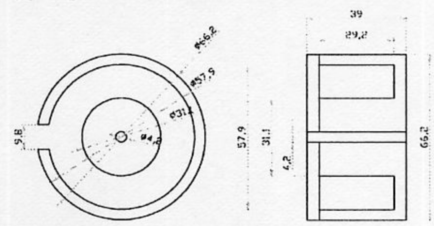


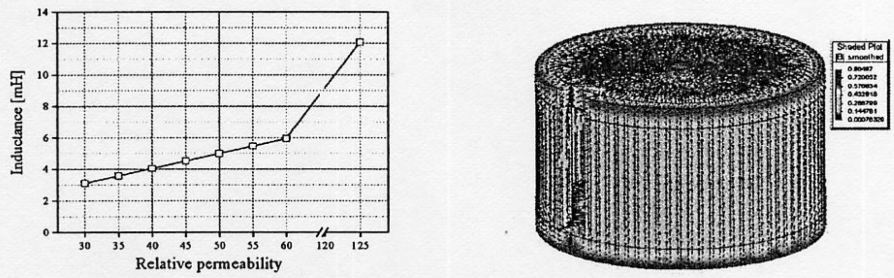
Fig. 3 Inductance characteristics according to the current and the frequency



(a) Iron-core Type Reactor (b) metal powder Reactor

Fig. 4 Comparison of Two type 3 phase AC reactor





(a) Inductance of relative permeability (b) Flux Distribution

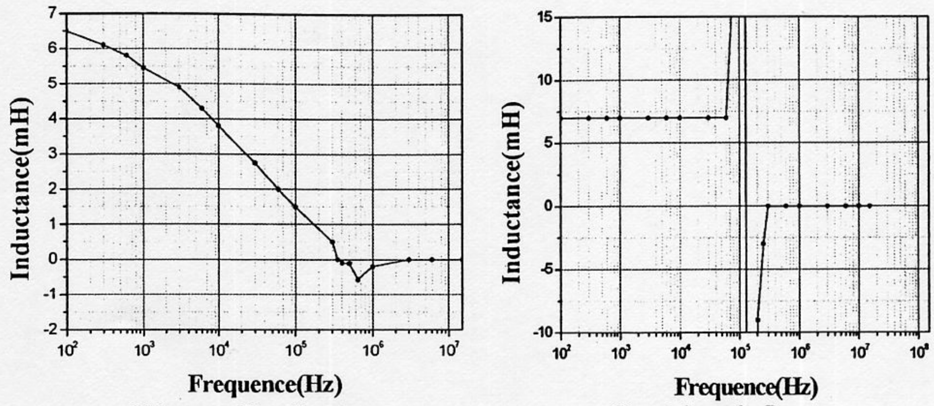
Fig. 5 Flux Distribution and Inductance of relative permeability in metal powder AC Reactor

Experimental Results

Frequency Characteristics of Metal Powder AC Reactor

Fig. 6 shows the frequency characteristics of the AC reactor made of metal powder. The characteristic is analyzed by HP4194 impedance analyzer. Form the result it is shown that the Metal powder core has better frequency characteristics than lamination core. For the general reactors, as the frequency increases, its inductance decreases remarkably, while the metal powder reactor maintains its inductance according to the frequency variation. Therefore, this impedance characteristic reduces the switching current ripple, and induces to reduce switching loss and noises.

The inductance of lamination core designed to have 7mH of rated inductance maintains its value at low frequency, but at the switching frequency that is 10kHz, its inductance is 3.9mH. However, for the metal powder reactor, it maintains approximately 7mH at switching frequency. This shows well the superiority of the metal powder. In addition, it is expected that high inductance value at high frequency can reduce EMI at low frequency band.



(a) Iron-core Type Reactor (b) metal powder Reactor

Fig. 6 Comparison with frequency characteristic (by using HP 4194)

Noise Characteristics of Metal Powder AC Reactor

Table I shows test conditions to compare with Iron-cored type and Metal powder type. Experiment is performed with the input of 300V, 60Hz of 3-phase to control 700V DC with rated 6Arms. For this test, 1200V, 30A IGBT is used. Fig. 7 shows the noise according to current. In the figure, the curve represents the total noise of Iron-Core type, B curve represents the noise of switching frequency (8kHz), C curve represents the total noise of metal powder reactor, and D represents the switching noise under same conditions. The noise of the metal powder reactor at the switching frequency band (8kHz) is less about 9dBA than Iron-Core reactor at rated current. The variation of magnetic flux density in lamination core induces attraction and repulsion forces between cores. Therefore, the noise of the lamination is increased in the lamination core rather than the metal powder of one body. When the current in the AC reactor, which connected to the PWM converter, is controlled, the current in the reactor is shown in Fig. 8. It is shown that the switching current ripple is reduced in this figure. Moreover, temperature increase is lessened due to the reduced the harmonic components of switching frequency of 8kHz.

Fig.9 is the picture of infrared camera to measure temperature rising of the AC reactor at the rated current. Surface temperature of metal power type reactor is lower than iron-core type by 36 degree. It means lower loss of core. Table❐ shows the summary of AC reactor Test. Metal powder AC reactor has better performances considering switching noises, which is reduced to 10dBA, and thermal characteristics than general laminated silicon steel sheets

Table I Test Condition of AC Reactor

Line Voltage	380Vac, 60Hz
DC Bus Voltage	700V
Iductance	7mH @ 6Arms
PWM	S-PWM

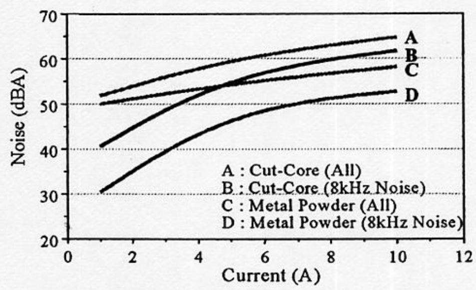
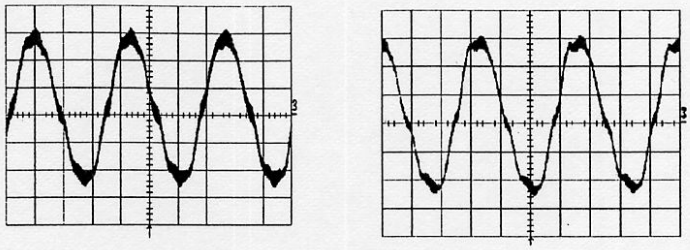
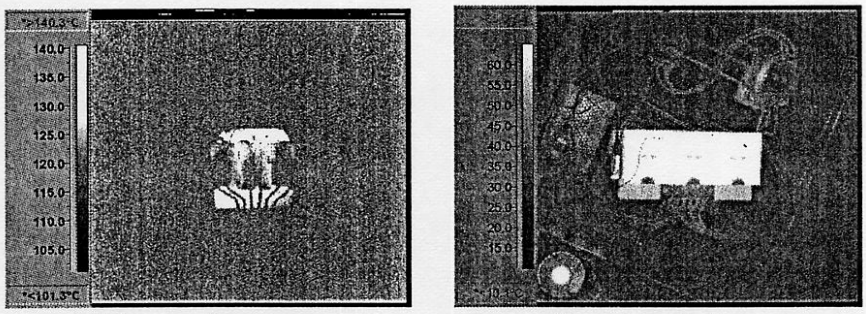


Fig. 7 Test Result of Noise (Audible Weighting)



(a) Iron-core Type Reactor (b) metal powder Reactor

Fig. 8 Phase current of AC Reactor at the PWM Converter



(a) Iron-core Type Reactor (b) metal powder Reactor

Fig. 9 Temperature Rising Test

Table I. Comparisons of Iron-core Reactor with metal powder Reactor

Item	Iron-core Reactor	metal powder Reactor
Current ripple @ 8kHz	Large	Small
Noise	Large (64.5 dBA)	Small (58.2 dBA)
Variation of Temperture	High (113 °C)	Low (77 °C)
Size	Same	

Conclusion

In this paper, the metal powder AC reactor of rated 6Arms, which is designed to reduce noises and heat, is designed and tested. This reactor converts the 3-phase AC power to DC power. And its performance is proved through experimental results.

From the results, it is shown that the metal powder AC reactor has better performances considering switching noises, which is reduced to 10dBA, and thermal characteristics than general laminated silicon steel sheets. In the future, it is expected that the metal powder be applied to the large electrical machines.

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