DC Superposition Characteristic Measurement of Reactors and Comparison with the measured values

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Abstract :
Among the parameters of Reactors, as to the inductance characteristics, stable Inductance over wide range of DC superposed current range. In oder to achieve this, the design of gap at the core is a very important factor to prevent core saturation.
In the initial stage of conventional design routine, the gap length or locations have been determined by the repetitive prototyping of the reactors and this method was obvisouly time consuming and very costly approach for agile engineering.
In order to reduce the prototyping and improve the accuracy of design, we at Tabuchi, have been using CAE software such as JMAG and we succeeded in the reduction of prototype numbers by the engineering simulation for optimum gap length and locations.
This time, the comparison of CAE result and actual measured results on DC superimposition of reactors has been done. It has been found that simulation did not not reflect the measured value at the early stage of project. The deviation was found due to the minor hysteresis loop on major hysteresis curve. Therefore, actual differential permeability and incremental permeability have been measured and the result was modeled to JMAG modules to get the close simulation result on JMAG analysis.

田淵電機株式会社
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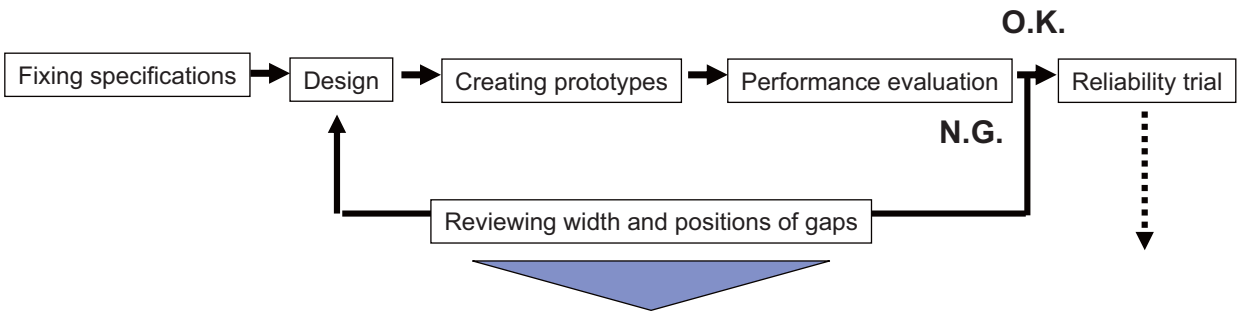
1. Preface Company Introduction

Trade Name	TABUCHI ELECTRIC Co., Ltd.
Head Quarter Location	532-0003 Miyahara 4-2-21, Yodogawa-ku, Osaka, Japan
Establishment	May, 1925
Incorporated	Dec, 1939
Business Domain	Transformers, Power Supplies for Electronic Equipment and Various Electrical Equipment
Capital	3,611,810,000yen (paid-in capital 40,502,000stocks)
Sales	Consolidated 32,900,000,000yen (Mar 2011)
Office	Osaka HQR, Tokyo Branch Office
Subsidiaries	Tabuchi Electronics Industrial Co., Ltd, Thai Tabuchi Electric Co., Ltd, Shanghai Transformer Co., Ltd, Tabuchi Electric Hong Kong Ltd. Vietnam Tabuchi Electric Co., Ltd.

In recent power electronics equipments, stable inductance characteristics at wide range of superimposed direct current region are required for reactors. For that reason, gap In the core that suppresses magnetic saturation is one of the significant factors in the reactor design.

Process flow of reactor development

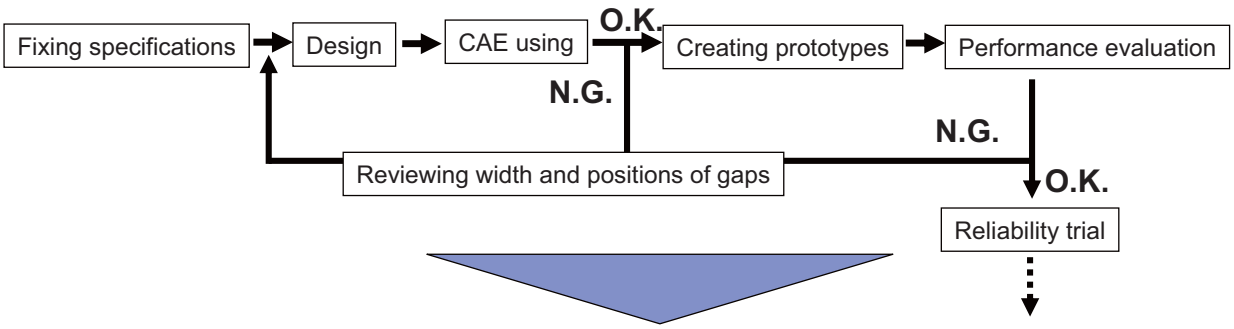


Repeating these steps result in increasing of time and costs.

Method to reduce the number of prototypes and optimization settings

Hanging on the magnetic field CAE

Front-loaded reactor development process

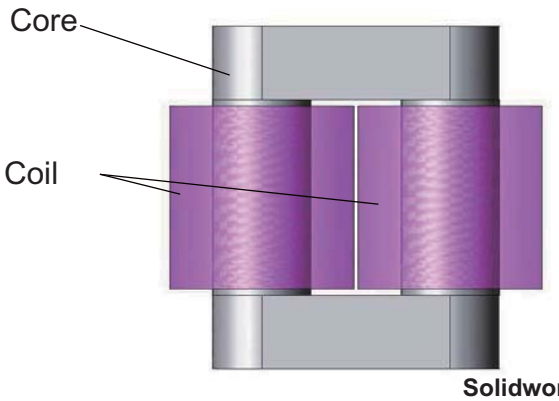


Hopefully introducing CAE will **decline in cost and reduce in working hours.**

Running the analysis of direct current characteristic that is one of the significant factor of reactors and carrying out a comparative review against actual measurements.

2. Verification model

Reactors for inverters (20 kHz high-frequency component superposition)



Solidworks

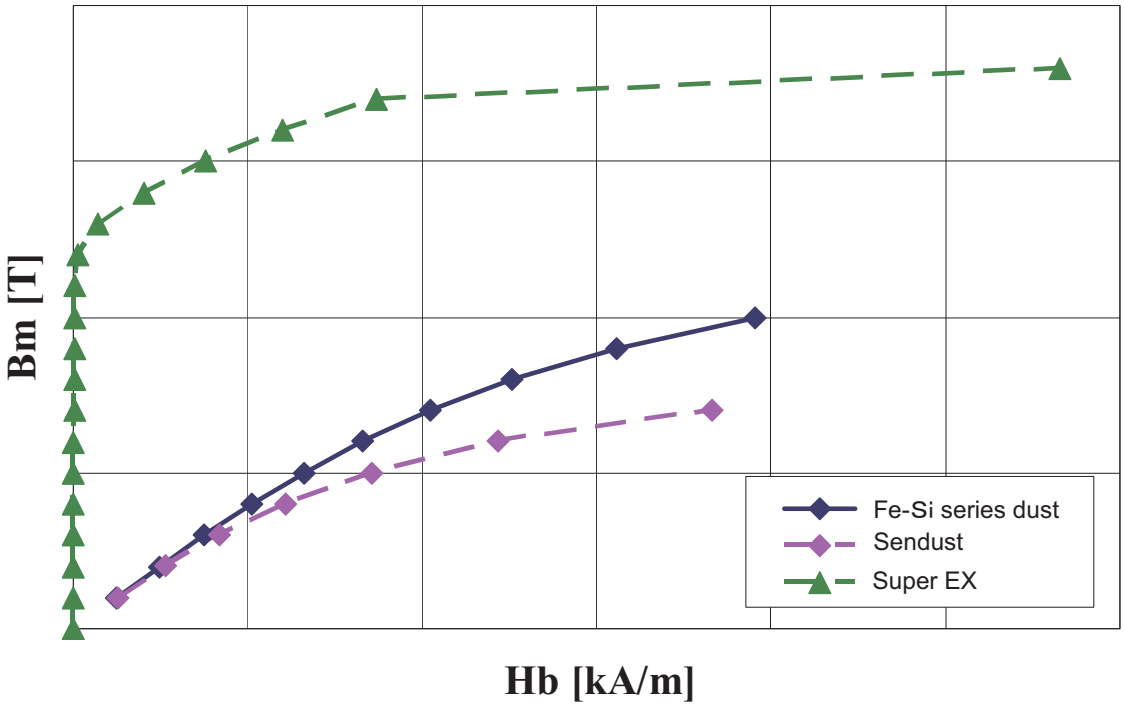
Measurement condition of superimposed direct current characteristic

Frequency	20[kHz]
AC	10[mA]
DC	0 to 30[A]

Core materials

Dust core	Fe-Si series dust
	Sendust
Magnetic steel sheet	Super EX

BH curves of each core material

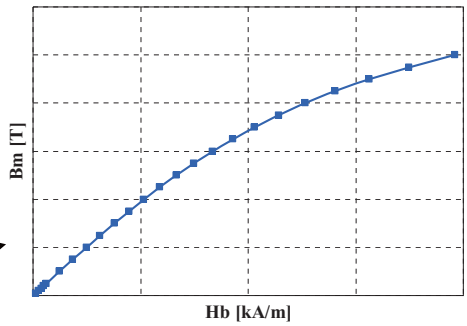


3. Analysis of the Superimposed Direct Current

Analysis process

Creating an analysis model — Solidworks

Core material, Input from BH curves — Measured by Doshisha University



Ex.:Fe-Si series dust

Sample geometry
Dust core : Ring
Magnetic steel sheet : Strip shaped

Magnetic field analysis (Transient Analysis) — JMAG-Designer 10.5

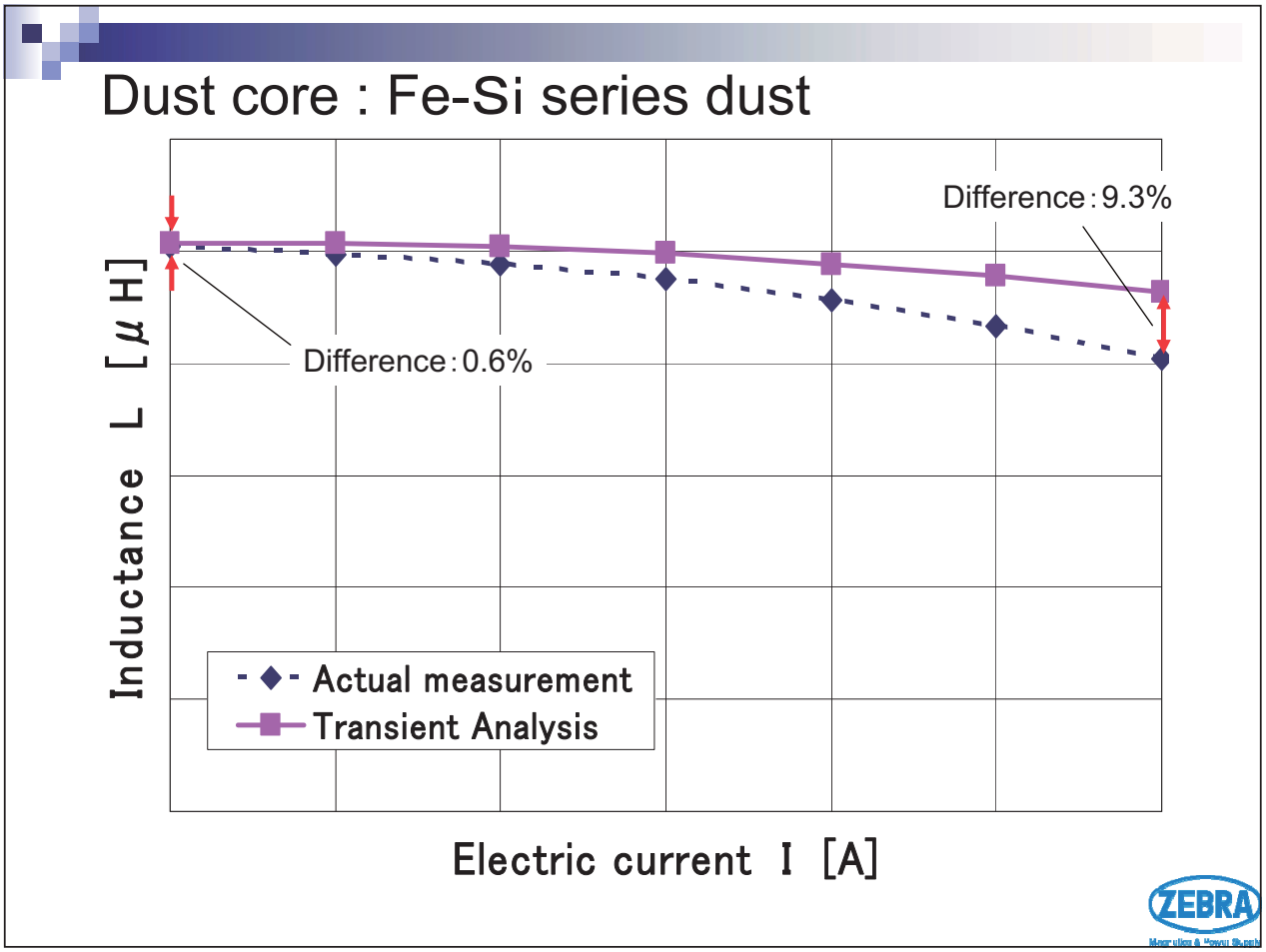
Inductance calculation — Microsoft Excel

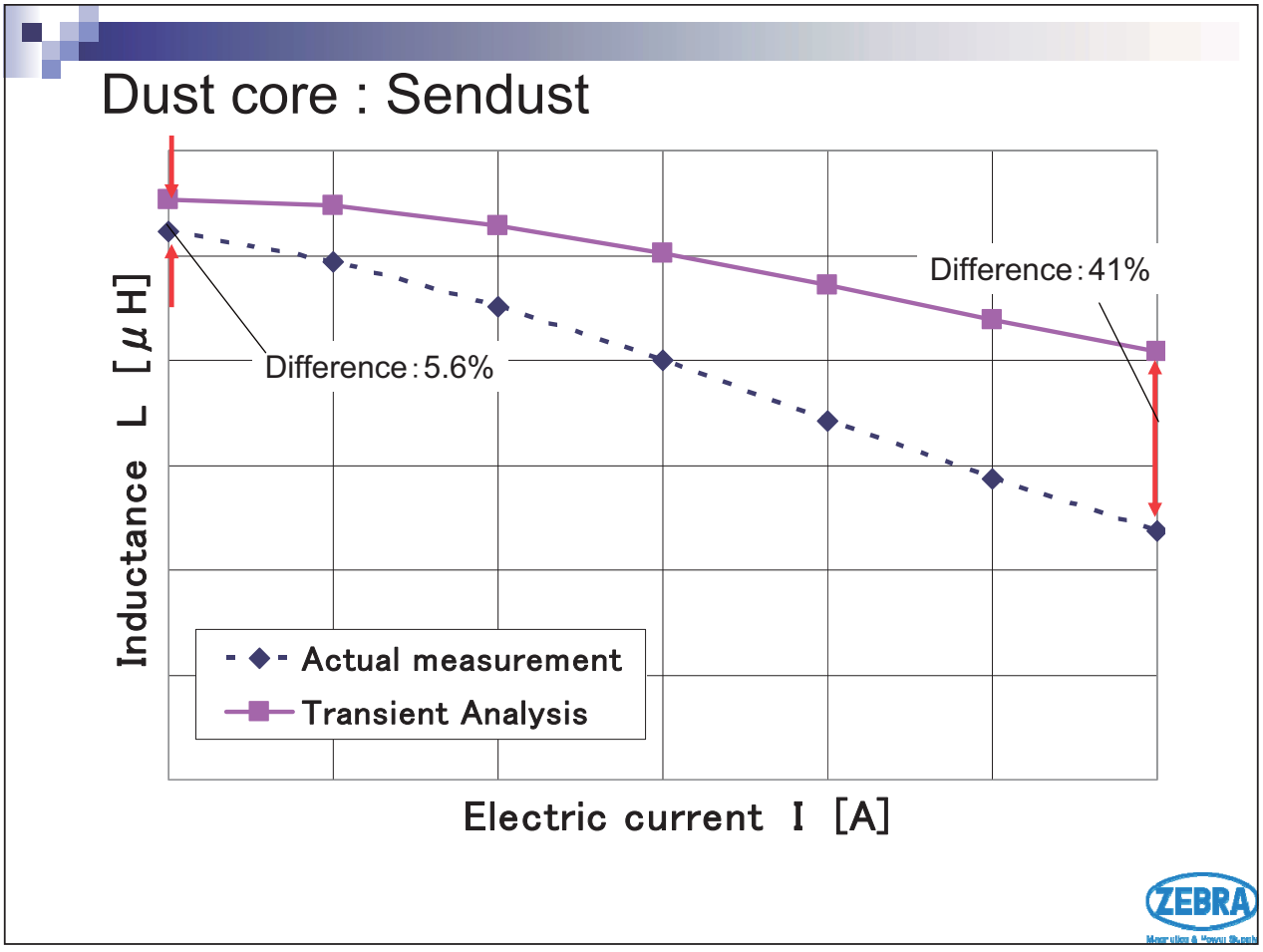
$$L = \frac{\phi}{\mathrm{I}}[H]$$

L: Inductance [H]

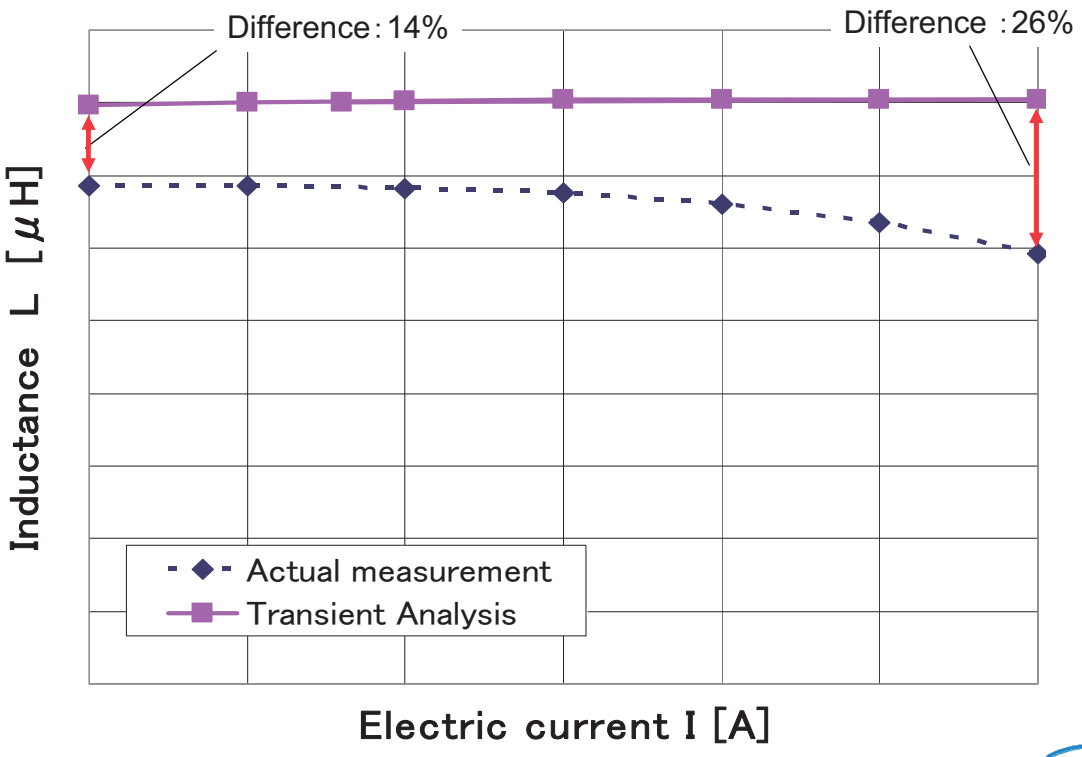
ϕ : Magnetic flux [Wb]

I : Electric current [A]


Dust core : Fe-Si series dust
Difference : 9.3%
Difference : 0.6%
Inductance L [μH]
Actual measurement
Transient Analysis
Electric current I [A]
ZEBRA

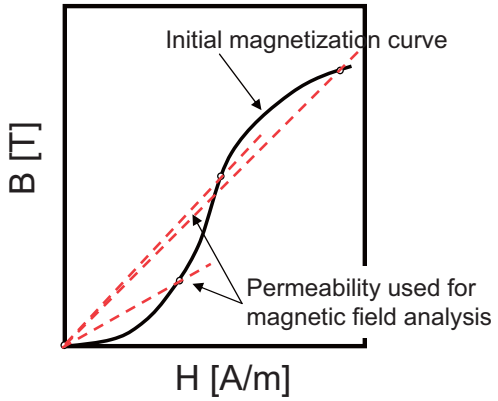

Dust core : Sendust
Difference : 41%
Difference : 5.6%
Inductance L [μH]
Actual measurement
Transient Analysis
Electric current I [A]
ZEBRA

Magnetic steel sheet: Super EX



Deviation was observed between the magnetic simulation and the measured value and this becomes larger with the higher current region. The same tendency was observed on different core material cases.

It is assumed that one reason of this differences is the permeability used for magnetic field analysis.



$$\mu_s = \frac{1}{\mu_0}\frac{B}{H}$$

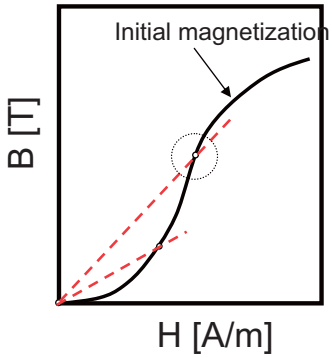
- Calculating with larger permeability μs than the actual value.
- Especially affected in the saturation region.

The analysis using the standard permeability from HB curves tends to have larger value than the measured value.

Requested JMAG-Designer Version Up to JSOL.

Introduced analysis with the permeability distribution from JMAG-Designer Ver.10.4 (December, 2010)

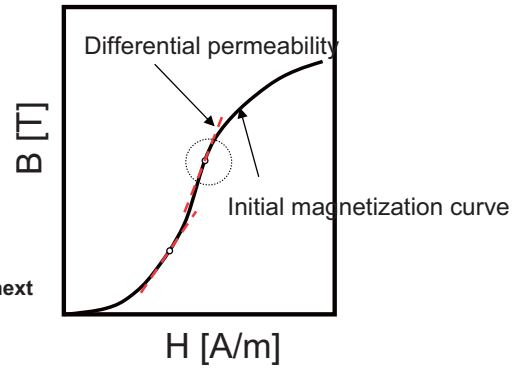
1st analysis



Analysis of Operating Point by DC Component

The result reflection for next

2nd analysis



Recalculation with the gradient at the recorded operating point

Carried Out Sequential Analysis

4. Analysis using differential permeability

Analysis process

Creating an analysis model — Solidworks

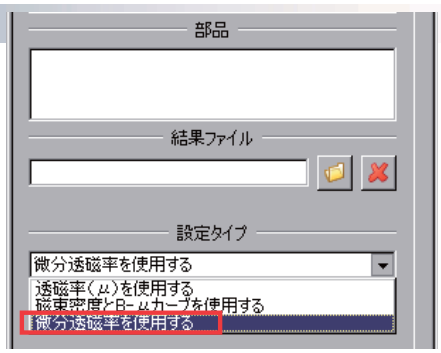
Core material, Input from BH curves — Measured by Doshisha University

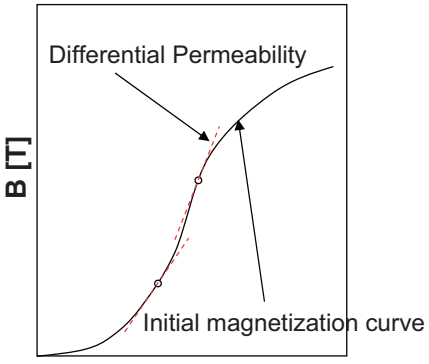
Magnetic field analysis (Static analysis) — JMAG-Designer 10.5

Magnetic field analysis (Frequency response analysis) — JMAG-Designer 10.5

Condition: Adding permeability distribution
Setting type：Use the differential permeability

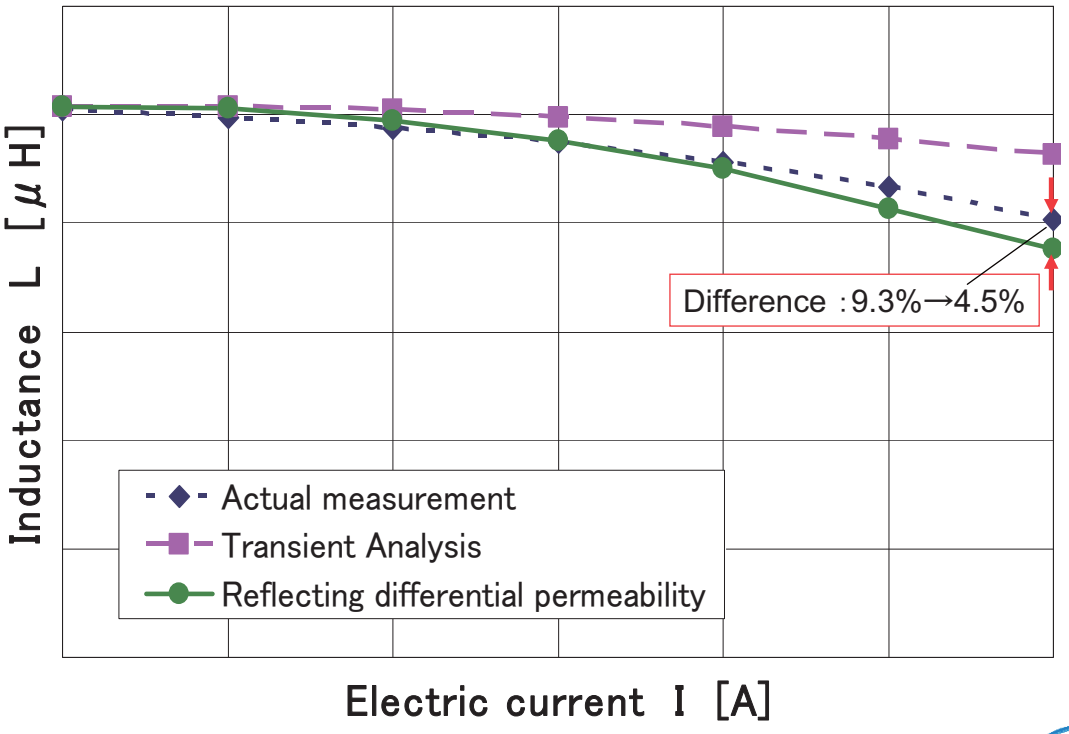
Inductance calculation — Microsoft Excel



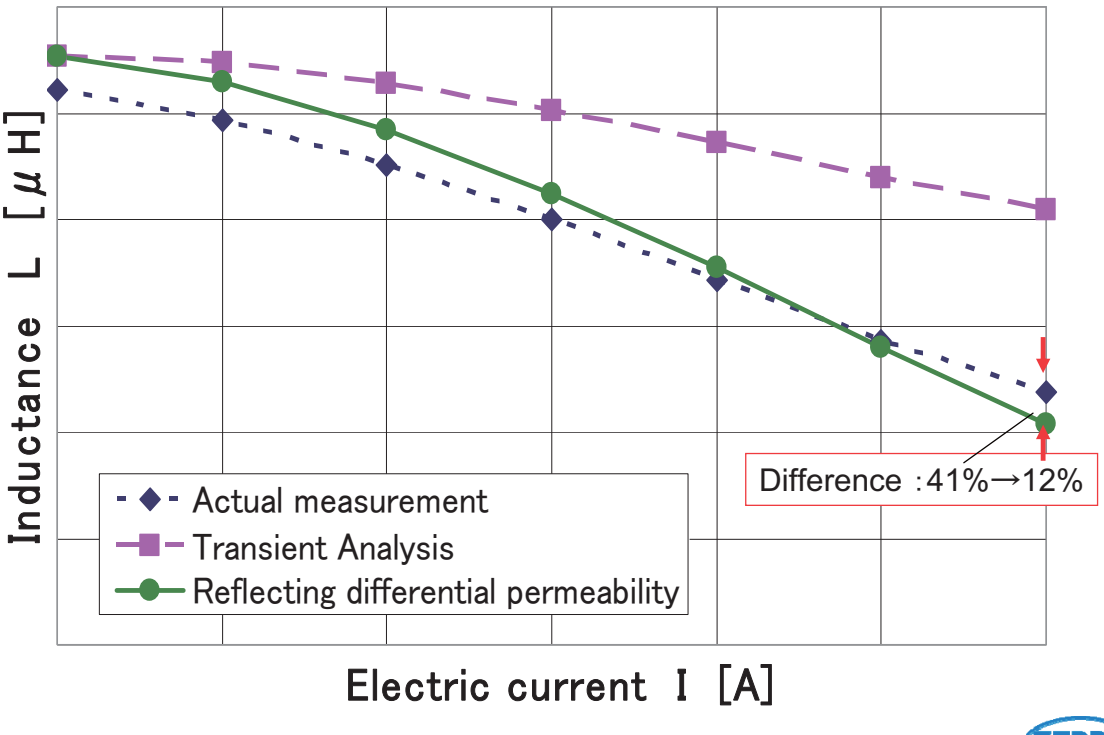


$$\mu_s = \frac{1}{\mu_0}\frac{\Delta B}{\Delta H}$$

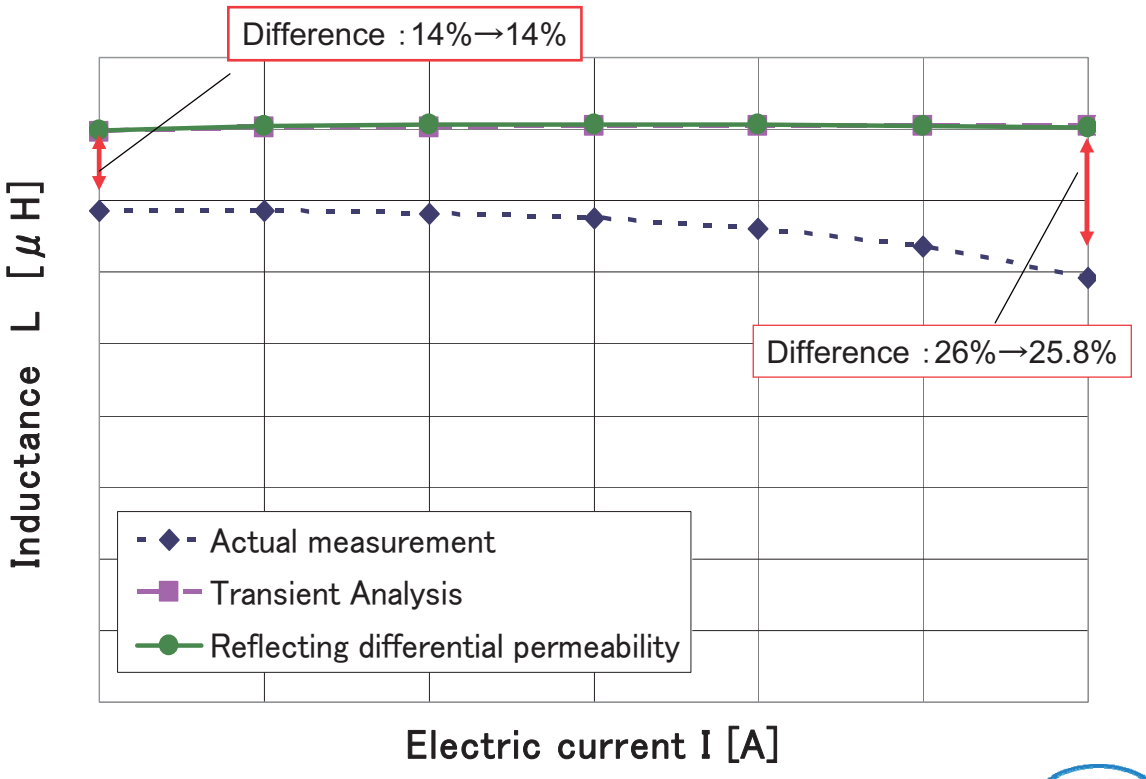
Dust core: Fe-Si series dust



Dust core : Sendust



Magnetic steel sheet: Super EX



•Fe-Si series dust and sendust

By Using the differential permeability of magnetization curves, simulation result is made significantly closer to the measured result.

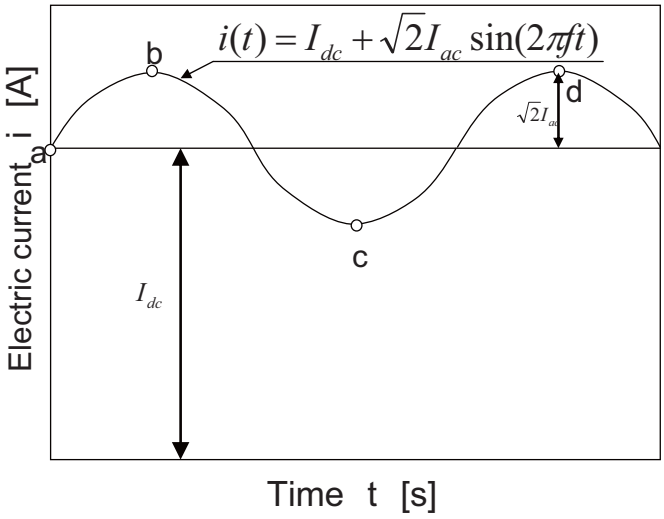
•Super EX

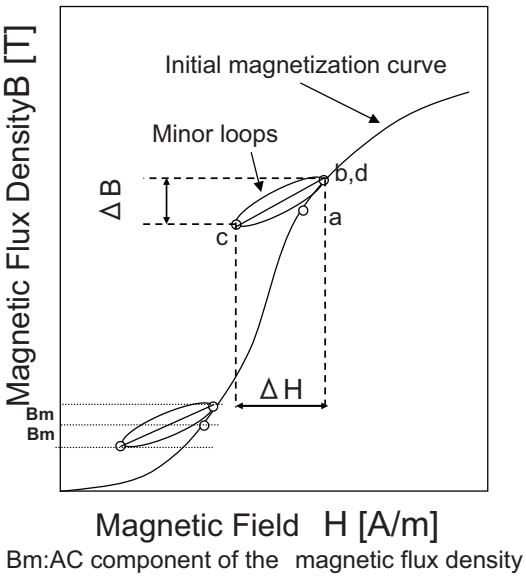
Simulation result remained unchanged in cases of the analysis with differential permeability and the analysis without differential permeability.

In case of superimposed direct current, DC and AC magnetic fields coexist Inside the core, so significant minor loops exist on the BH curves.
It is considered that minor loop influence is much stronger in case of Super EX core

Investigate the analysis with the minor loop consideration.

Concerning the minor loops

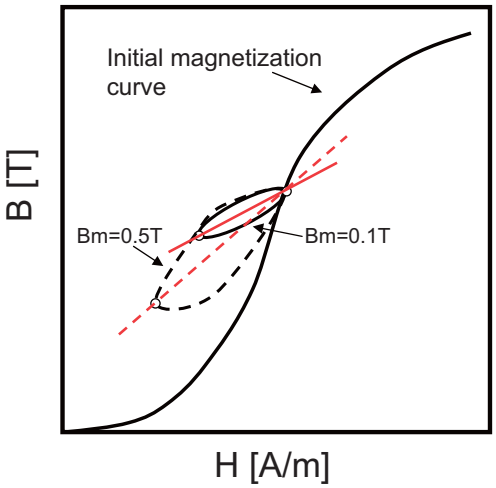


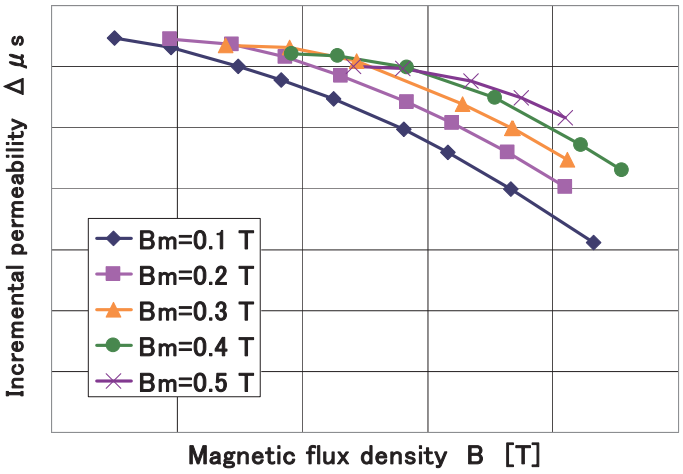


Bm:AC component of the magnetic flux density

Minor loop is defined by the following equation as $\Delta \mu_s$ is incremental permeability.

$$\Delta \mu_s = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H}$$





Bm:AC component of the magnetic flux density

Shape of the incremental permeability varies depending on the value of AC components.

In case of superimposed direct current, its AC components are insignificant, so we used the data at Bm=0.1T for our analysis.

5. Analysis with incremental permeability

Analysis process

Creating an analysis model — Solidworks

↓

Core material Input from BH curves — Measured by Doshisha University

↓

Magnetic field analysis (Static analysis) — JMAG-Designer 10.5

↓

Core material input from B-Δμ curves — Measured by Doshisha University

↓

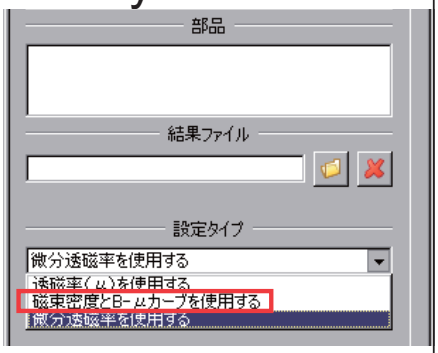
Magnetic field analysis (Frequency response analysis) — JMAG-Designer 10.5

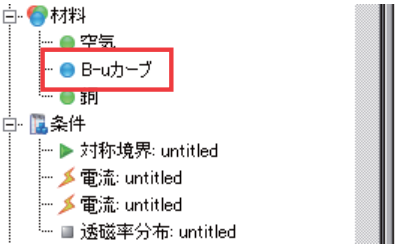
↓

Condition: Adding the distributed permeability
Setting type : Use the magnetic flux density and B-μ curves

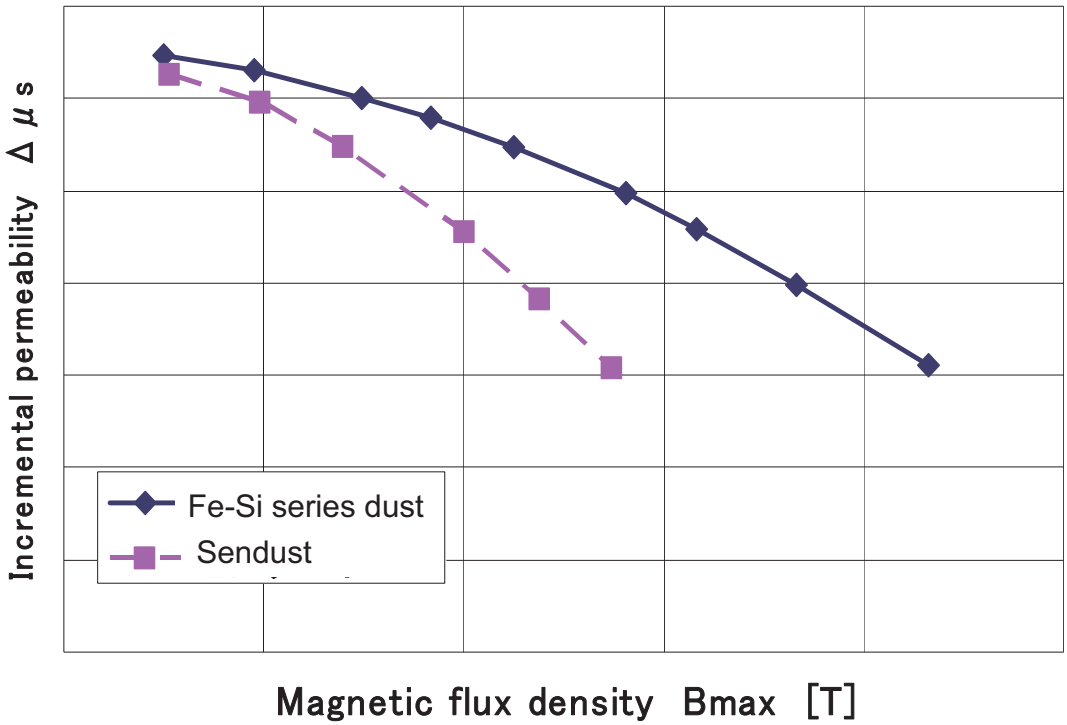
↓

Inductance calculation — Microsoft Excel

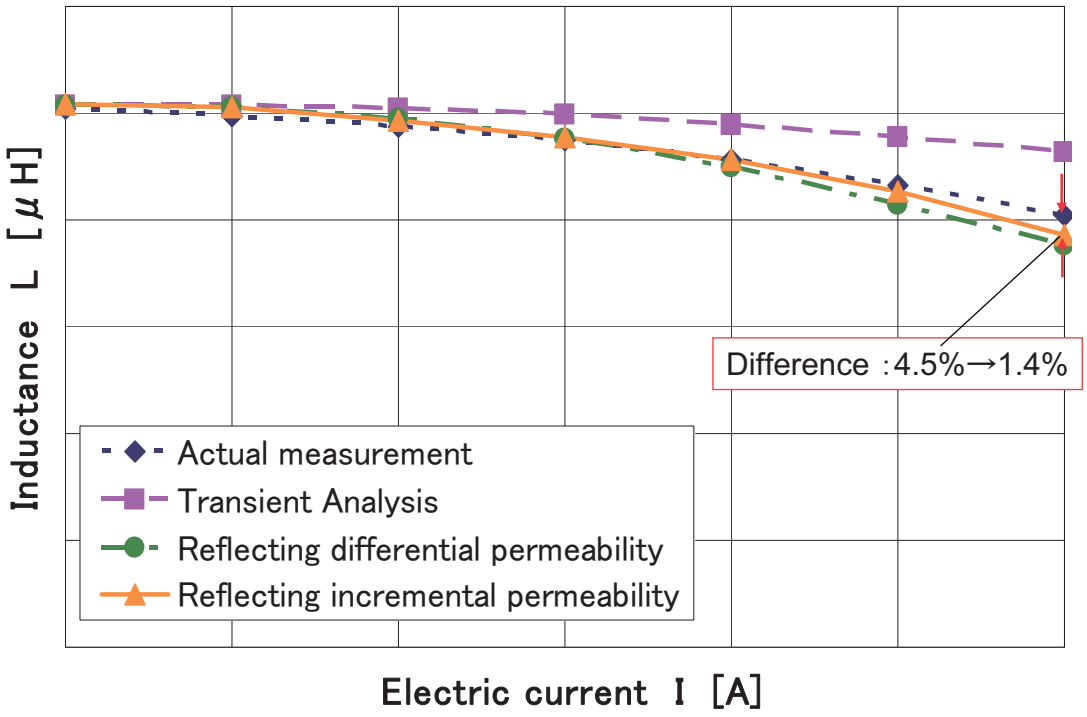




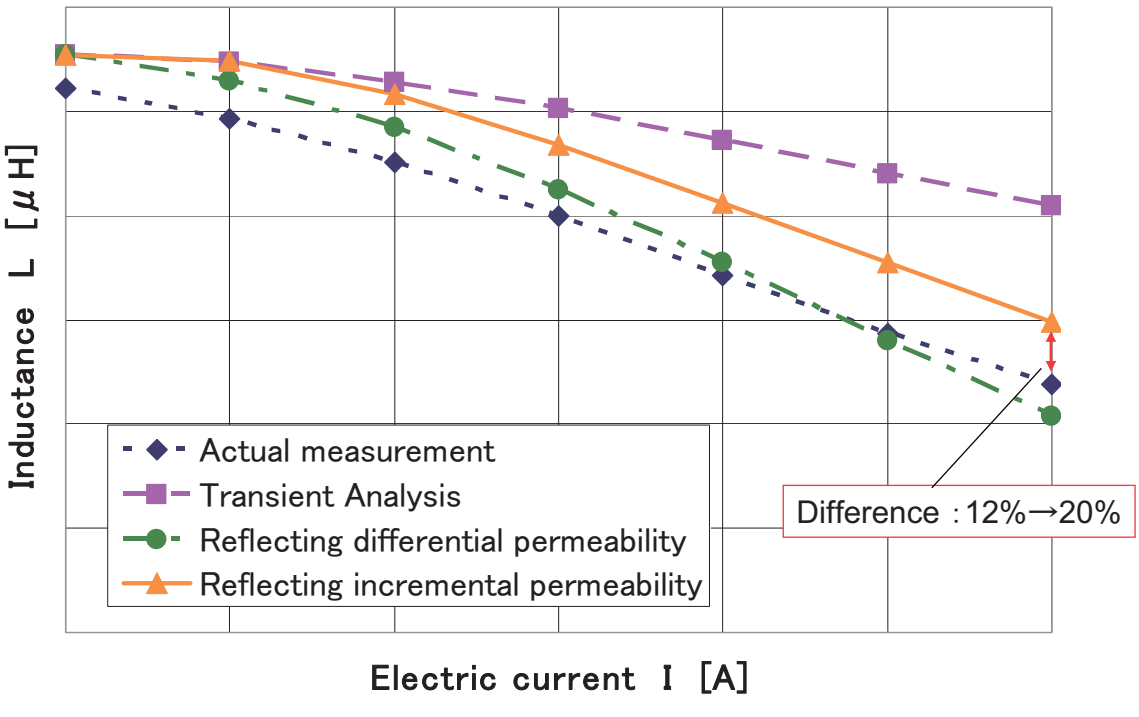
Dust core: B-Δμ curves



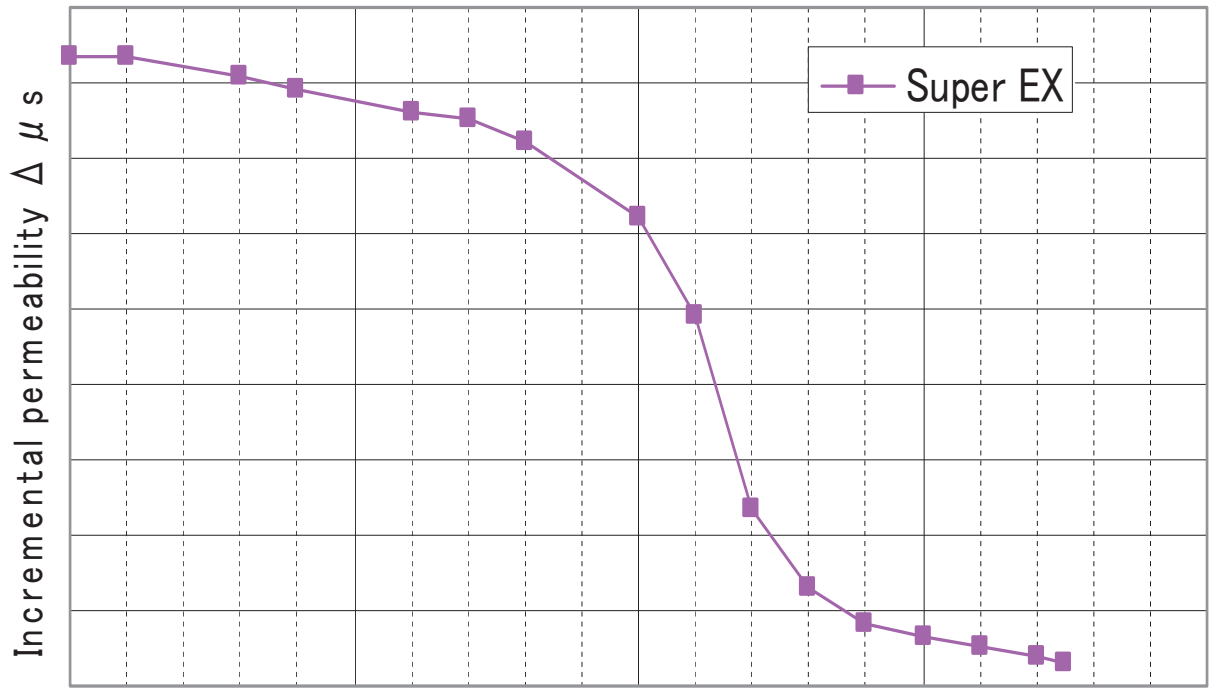
Dust core: Fe-Si series dust



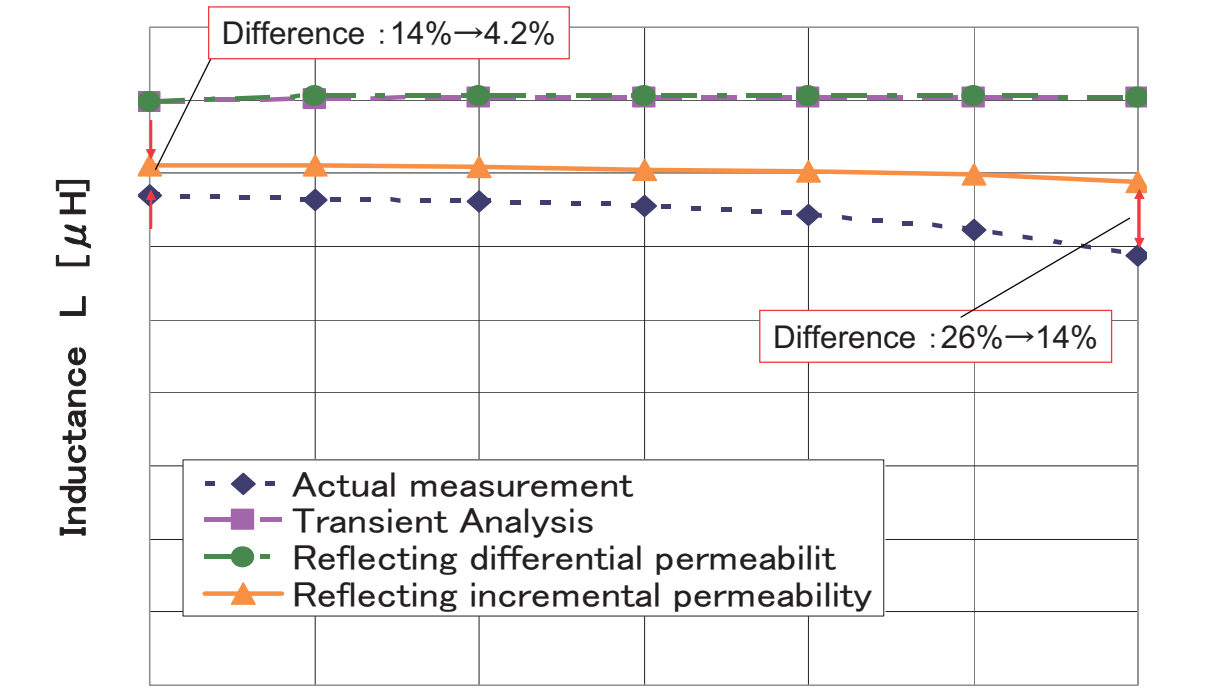
Dust core: Sendust dust



Magnetic steel sheet: B-Δμ curve



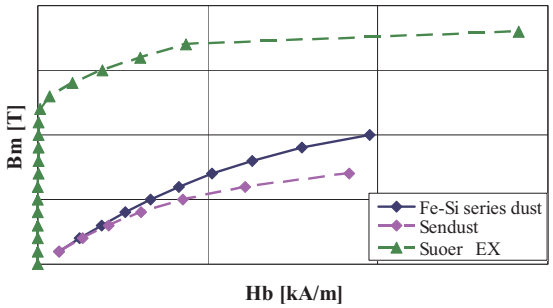
Magnetic steel sheet: Super EX



- Fe-Si series dust
  No major differences are observed with or without the employment of differential permeability.
- Sendust
  The simulation deviation from the measured result has become larger when differential permeability Is used.

- Super EX

  The simulation has become closer to measured result by the consideration of minor loop and its permeability.



It is thought that the effect of incremental permeability on the core differs by the gradient of BH curves.
.

6. In closing

Applying the frozen permeability for analysis conditions and accounting for differential or incremental permeability actualized bringing the analysis results closer to actual measurements.

Fe-Si series dust : Improvement of the result using differential or incremental permeability

Sendust : Improvement of the result using differential permeability

Super EX : Improvement of the result using incremental permeability

It is revealed that the analysis accounted for the suitable permeability results in the CAE simulation closer to actual measurements.

7. Future Challenge

- Study of the cores made from other materials.
- Study of the analysis accuracies when the reactor model is changed.

Acknowledgment

This research was made possible with the cooperation and Electrical Machinery & Apparatus Laboratory , of Doshisha University's Graduate School of Engineering, Department of Electrical Engineering.

I would like to take this opportunity to express my deep gratitude to all concerned members of Doshisha University.

Thank you very much.