RAPIDLY SWITCHED ACCELERATING DEVICES FOR INDUCTION SYNCHROTRONS

J.Kishiro, K.Takayama, E.Nakamura, KEK, Tsukuba, Ibaraki, Japan
K.Horioka, M.Watanabe, Tokyo Inst. of Technology, Yokohama, Japan
A.Tokuchi, S.Niatoh, Nichikon *Co.LTD.*, Kusatsu, Shiga, Japan

Abstract

The key device in the recently proposed Induction Synchrotron (IS)[1] is a rapidly switched induction acceleration device. The first application of IS concept is the Intensity Doubler (ID)[2] which is under consideration as a major upgrade of the KEK-PS. The collaboration between KEK, Tokyo Institute of Technology, and Nichicon is developing an induction acceleration device and an all solid-state power modulator for the ID. The modulator must switch peak voltage of 10kV with pulse repetition rates of up to 880 kHz. An effective pulse duration of 1μsec is required for acceleration. Meanwhile, a shorter time-duration of 40-100nsec is required to generate the barrier bucket, achieving a long bunch, so-called super-bunch. After careful core-loss measurements for various magnetic-core materials and choice of switching elements, a prototype of induction module and modulator has been assembled and successfully operated at 100kHz with a burst of 10 pulses. In addition to the results of design studies and basic loss measurements, preliminary results observed in the switching performance are presented.

1 INTRODUCTION

In the IS, two sorts of induction pulse are required. One sort with a short time-duration and a high integrated-voltage generates the so-called barrier bucket which captures an injected bunch or stacks a super-bunch. The other with a long time-duration and a medium integrated-voltage simply accelerates the super-bunch. The required integrated-voltage, pulse-duration, and repetition rate depend on each accelerator. These parameters are determined by the momentum acceptance, ramping profile of the guiding field, and revolution period along the accelerator. Fortunately, the integrated inductive voltage linearly increase by stacking units serially in space and the required time-duration is realized by stacking units serially in time. For a while a basic specification on the single induction unit is supposed that the induced voltage is 10kV and the pulse duration is 500nsec for acceleration and 40-100nsec for the barrier bucket. Thus, the experimental demonstration of such a unit with rep-rates of MHz is crucial to discuss a feasibility of the IS. We have no sufficient information of CW high rep-rate operations of this kind of induction unit. Our main concerns are listed below,

1. (1) heat dissipation in the magnetic core and switching elements,
2. (2) jitter in the output voltage and in time,
3. (3) life of the switching element,
4. (4) charging voltage and trigger-timing control for desired acceleration.

In order to make these issues clear, a systematic study program is being conducted under the above collaboration. First of all, the loss in magnetic core has been carefully investigated, because the issue of heat dissipation is most significant. Next a prototype of induction unit employing FINEMET as a core material, which shows relatively low losses, has been assembled and operated at 100kHz with a burst of 10 pulses. Under the obtained results, the nearly final version for the ID will be designed.

2 MAGNETIC BEHAVIOUR

2.1 Core model

The design of the induction unit and switching devices are based on the following core model.

The magnetic hysteresis characteristic varies widely according to the voltage excitation shape, the rise time and the voltage swing. The minor-loop operation in the hysteresis curve is adopted to reduce the core loss to an acceptable level, unlike that of mega-watt class induction linacs, in which a nearly full-swing loop operation is usually chosen to make a whole size of device small. The magnetic hysteresis is described by,

$$B = 2B_s \tan^{-1}[\frac{H - H_c}{\alpha}]$$

where the permeability is represented as follow,

$$\mu(H) = \frac{2B_s}{\pi\mu_0}\frac{\alpha}{\alpha^2 - (H - H_c)^2}, \qquad \alpha \equiv \frac{2B_s}{\pi\mu_0\mu_r}.$$

B_s is the saturation field of the core. μ_0 and μ_r are the initial and coaresive permeability. The minor-loop is traced following these formulae and the core loss is estimated from the loop area. Figure 1 shows the estimated magnetic hysteresis curve.

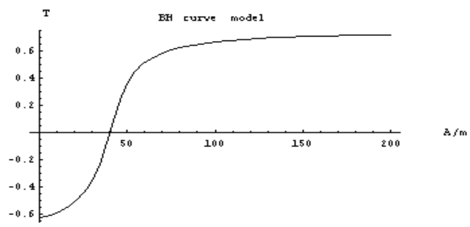

Figure 1: An estimated magnetic hysteresis curve

And also the time variation and maximum value of the magnetic current into the core is calculated. The left-hand side of figure 2 shows the estimated magnetic current flow into the core. Experimental measurement were performed to certify the minor-loop behaviour of the core and the agreement between the estimation and experimental observation(see the right-hand side of Fig.2) was obtained.

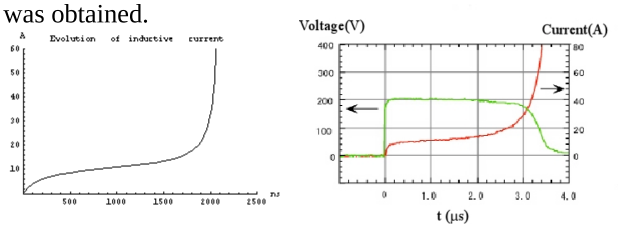

Figure 2: Magnetic current estimated and measured

2.2 Core loss measurement

The magnetic loss in the core is dependent on the core material. In addition, it strongly varies with the excitation current rise time and the maximum voltage swing. The full excitation B-H hysteresis is usually measured and some are sited on industry catalogues. However, in the IS, the induction units is excited at extremely high repetition rate. The core loss must be small, otherwise thermal degradation of the magnetic characteristics is troublesome. To mitigate the core loss as small as possible, the core operation in the minor-loop seems to be desired. However, the characteristics of the minor-loop operation have not been known well.

A test stand to measure the core magnetic performance has been set up, and the core loss variation for the different excitation rate was observed. Figure 3 presens the measured B-H curves for two sorts of core material.

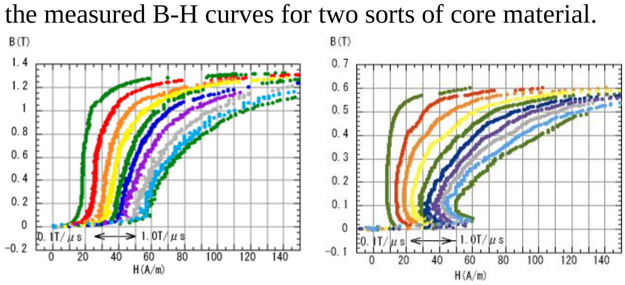

Figure 3: Measured B-H curve.
Right: Co-amorphous core,
Left: Hitachi FINEMET.

These raw data were analysed and the core loss dependence on the excitation rate was obtained. Figure 4 shows the analysed results of the core loss.

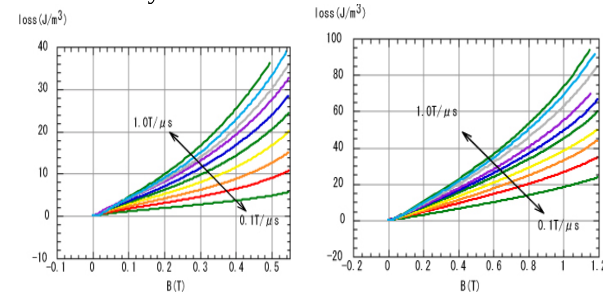

Figure 4: Measured core loss
Right: Co-amorphous core,
Left: Hitachi FINEMET.
The colour corresponds to the respective dB/dt.

2.3 Induction unit design

According to the magnetic model and measurement, the first prototype induction unit was designed, optimising the core loss and the magnetic current. The design parameters of the prototype induction unit are listed in Table 1.

Table 1: Prototype Induction design.

Voltage	V	5000
Pulse width	ns	100
Rep.rate	kHz	100
core		
Inner Radius	m	0.1
Outer Radius	m	0.2
Width	m	0.05
ΔB	T	0.2
Core loss	kW	10.4
Mag.current	A	208

3 HIGH REP. POWER SUPPLY

We are developing a high repetition rate pulsed power supply modulator, which energizes the induction units. The key issues for the modulator are,

1. High performance switching device,
2. Low inductance capacitor array,
3. High discharging rate of the capacitors.

The basic specifications on the switching device in the IS are the repetition rate of 1MHz and the pulsed voltage of 10kV. The pulse duration depends on the unit type, *i.e.*, for barrier bucket formation it is of 40-100ns and for accelerating unit it is of 500ns. At the first stage of the design, the repetition rate of 100kHz and the 100ns pulse voltage of 5kV are chosen. These are sufficiently enough to investigate the performance of the modulator in a technically attainable manner.

The modulator consists of the DC charging voltage source and switching unit, in which six FETs are connected in parallel and sixteen of those are in serial. The conceptual circuit diagram is depicted in figure 5.

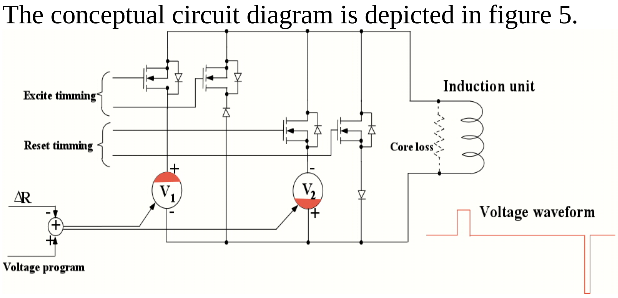

Figure 5: A conceptual design of the switching unit

Figure 6 describes a single view of the switching unit.

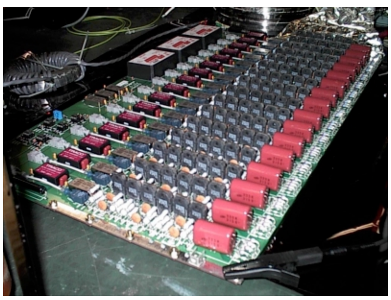

Figure 6: The FET switching array

Four FET arrays are stacked, the first one is to switch on the high voltage to the induction unit, the second one is used for holding the current prior to the following reset operation, the third one is to switch on the reset voltage and the last one is also for idling the reset current until the next excitation. All of the switching arrays are impregnated in the oil filed chassis, which takes role of insulation between the series of the FETs and simultaneously cools down the array.

Before installing into the chassis, we tried a preliminary test operation without core-reset to avoid the complexity, in which a single array was connected to the inductive core, and. A preliminary test result is shown in figure 7.

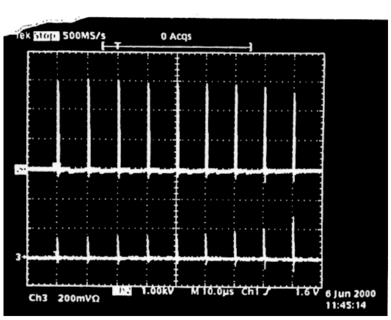

Figure 7: 100kHz continuous operation result.
Upper trace is the voltage waveform
Lower trace is the current in to the core.

The degradation of the voltage waveform comes from the fact that the core was repeatedly excited without resetting. The core goes into the saturation. However, this is not a problem, because, as mentioned previously, in the actual case the magnetic state of core is initialised every excitation by the pulse reset operation. In spite of this effect, the system demonstrates the good performance under the 100kHz operation. Figure 8 shows an expanded view.

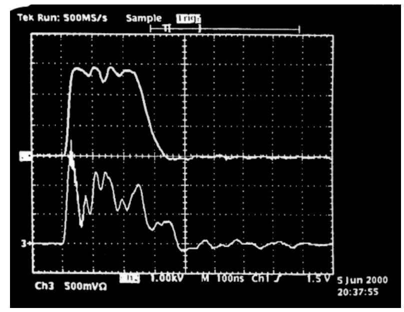

Figure 8: A single waveform under the 100kHz operation

The test operation was performed on the temporal test-bench; the ripples on the voltage and current signal might be caused from the noise. Right now, all of the switching arrays are assembled in a chassis and also the magnetic core is put into the oil filled case. And the systematic test operation is undergoing.

4 CONCLUSION

We made up the first prototype of the induction unit and switching array, and examined the performance of those at 100kHz operation. The preliminary result shows a successful operation at 100kHz. There were some noise problems as seen in Fig.8. However they are expected to be excluded by putting all of the equipments into the shielded chassis. After assembling in the chassis, we will attempt a long run examination and take data required to the final goal.

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