Variable Inductor Design Method for Rectifiers at Railway Substations

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This paper describes a new voltage adjustment technique and its design method. In the new design, a voltage compensator, comprising a variable inductor and a controller, is connected with a transformer and a rectifier on either side in series. The authors developed a new configuration of the variable inductor suited for railway application, with a focus on six-phase AC and large current capacity. A fast simulation method for designing the inductor was developed based on the magnetic flux circuit theory and the non-linear simulation technique for ferromagnetic materials.

Keywords: DC electric traction system, rectifier, voltage adjustment, variable inductor, magnetic flux control, magnetic circuit, electrical equipment design

1. Introduction

The energy efficiency of DC feeding systems can be improved, through better regenerative electric power usage rates, by being able to adjust feeding voltage according to driving conditions, i.e. in powering or regeneration mode [1][2]. There are several types of AC/DC converter used in DC electric traction systems. The most commonly used is the diode rectifier. However, these systems are unable to actively control output voltage. The latest type of converter the PWM (Pulse Width Modulation) [3] is able to control output voltage but has a manufacturing cost about 10 times higher than the diode rectifier.

Accordingly, the authors developed a new type of voltage adjustable rectifier that can be manufactured at approximately 20% of the cost of a PWM converter. The core component of the new rectifier is a variable inductor. This paper describes the configuration and the method used to design the variable inductor used in the new rectifier.

2. AC/DC converters used in the substations

Several types of AC/DC converters (rectifiers) are utilized in DC traction substations. This section compares the features of a conventional and the new design converter.

2.1 Diode rectifier

Diode rectifiers, shown on the left in Table 1, have been common in Japan since the 1960s. The diode rectifier consists of a transformer for rectifier and a diode-bridge rectifier. The transformer for rectifier steps the voltage down from the receiving three-phase AC line, while the rectifier transforms the AC voltage/current into DC.

The voltage drop characteristic of diode rectifiers with respect to its output current, is almost entirely governed by the short impedance of the transformer for rectifier except in light-load mode. Since the diode rectifier contains no active controlled switches, it has high resilience against electric disruptions such as overloading and short circuit faults. In addition, the manufacturing cost of the diode rectifier is the lowest of all AC/DC converters used in traction substations. Diode rectifiers however, cannot actively control their output voltage.

2.2 PWM converter

The PWM converter, shown in the center of Table 1, is the latest AC/DC converter used on the Tsukuba Express line in Japan [3]. It consists of a special (multiplex) transformer for rectifier and has a semiconductor AC/DC converter.

The PWM converter can actively control its output voltage as shown in Fig. 1 (a). In addition, the PWM converter has additional functions such as a reverse transform (sending regenerated electricity to the AC line) and a power factor control (reactive power and harmonics control). It is approximately 10 times more costly to build a PWM converter than a diode rectifier, because it requires a special type of transformer, semiconducting switches (e.g. IGBTs – Insulated Gate Bipolar Transistors), computer fed controllers and filters. The semiconducting switches should have sufficient electric capacity (such as rated current and heart capacity) to deal with the type of electrical disruption mentioned above.

Thyristor rectifiers, which have similar functions but are older than PWM converters, have been utilized in traction substations in Japan. A thyristor bridge is used instead of the diode bridge in the thyristor rectifier. A DCVR (DC Voltage Regulator), which is a combination of a diode rectifier and a thyristor rectifier connected in series, is also among the technologies that have been applied over the past few years [2].

2.3 Proposed voltage adjustable rectifier

The proposed voltage adjustable rectifier shown on the right side of Table 1 has AC/DC conversion and active voltage adjustment but, in order to reduce manufacturing
costs, does not have any of the other functions of PWM converters, such as reverse transform and power factor control.

The new rectifier consists of a transformer for rectifier and a rectifier, which are components found in diode rectifiers, a variable inductor and a controller. The variable inductor is connected in series to the transformer for rectifier and the rectifier. The controller, comprising a smaller capacity semiconducting AC/DC converter, sensors and a computer, is connected to the variable inductor, and is supplied with power by the transformer for rectifier. This configuration makes it easier to use an existing diode rectifier with minimum modifications and lowers construction costs.

The output voltage of the proposed rectifier is controlled on an AC line as follows: as the variable inductor inductance is actively controlled by the controller, the voltage drop between the transformer for rectifier and the rectifier can also be actively controlled. Accordingly, the primary AC voltage of the rectifier is controlled and the output DC voltage of the rectifier is actively controlled.

Comparing voltage vs current characteristics, the output voltage control of the developed rectifier is characterized by the change in voltage drop ratio due to the change in inductance as shown in Fig. 1 (b).

3. Tohoku variable inductor

3.1 Basic technique

The proposed variable inductor used in this study uses magnetic flux control which was originally developed by the Tohoku Electric Power Company [4-8], and referred to in this paper as the “Tohoku variable inductor.” The Tohoku variable inductor applies non-linear magnetizing characteristics of ferromagnetic materials, and its basic concept is similar to that of a magnetic amplifier. However, compared to a magnetic amplifier that comprises two or more transformers with ferromagnetic cores, the variable inductor only needs one.

3.2 Phenomenon in EIE-core

The fundamental core configuration of the Tohoku variable inductor is an EIE core shown in Fig. 2, made with a ferromagnetic sheet, surrounded by two windings. AC current flows through the main winding, while the other winding with DC current flowing through it serves as a control winding. Each winding is divided into two identical parts connected in series. The magnetic flux generated by the main winding has interlinkages to the control winding, while the two divided parts of the control winding have opposite phases with respect to the flux. Therefore, there is no magnetic coupling (in other words, orthogonal) between the main winding and the control winding.

3.3 Principle of inductance control

As commonly known, ferromagnetic cores, including EIE cores, have magnetization characteristics with a non-linear relationship between the magnetic field strength H and magnetic flux density B as shown by the black curves in Fig. 3. The inductance of the main winding can be controlled by the control winding current as follows:

First, the magnetization loop without the DC control current typically has symmetric hysteresis (the blue curve in Fig. 3 (a)). Second, the center of the magnetization on the H axis is shifted by a DC bias generated by the control current as shown in Fig. 3 (b). The asymmetric red curve shows the magnetization loop shifted by the control current. Because of magnetic saturation whilst the magnetizing loop is in the positive period, the amplitude of the magnetic flux density of the loop with the control current falls below the level found without a control current. Finally, the inductance of the main winding, which is proportional to the amplitude of the magnetic flux density, is decreased.
by the control current.

The magnetization states are different across the EIE core. During the positive period of the main winding current, the left-hand side of the EIE core is saturated as shown in Fig. 4 (a). During the negative period, the right-hand side of the core is saturated, as shown in Fig. 4 (b). Accordingly, the magnetic flux distribution in the EIE core becomes symmetric across the zero cross of the AC current.

### 3.4 Double five-leg core

Two obstacles must be overcome with the EIE core: first, it is not easy to produce, because of its specific structure. Second, using an EIE core enlarges the size of the inductor, because three EIE cores are required for a three-phase inductor. Therefore, the design (double five-leg core) shown in Fig. 5 was proposed [5].

Electromagnetic phenomena of the double five-leg core are quite similar to those found in an EIE core. However, the orthogonality of magnetic fluxes generated by the main and control windings is achieved by using two independent magnetic cores. This type of variable inductor consists of a double five-leg core, three-phase main windings and a DC control winding. The control winding (inner) is divided into six parts connected in series. Each part is installed around the legs of phases U, V and W. The windings surrounding the front side core and surrounding the rear side core are wound in opposite directions to ensure no magnetic coupling occurs between the main and control windings as shown in Fig. 5. The main windings (outer) are installed around the legs sharing the front and rear side cores.

### 4. Proposed variable inductor

#### 4.1 Requirements for application to the railway

The Tohoku variable inductor was designed as a voltage regulator for high-voltage distribution systems of power companies. As such, this study aims to overcome the problems that this poses, and proposes a new design method adapted to the railways.

1. Different power source for the main winding
   - The Tohoku variable inductor is a parallel inductor whose power source should be considered as a voltage source. The main winding waveforms of the voltage and current are expected to be approximately sinusoidal. The variable inductor in this study however, is a series inductor whose power source should be regarded as a current source. The waveforms of voltage and current are non-sinusoidal with some harmonic components.

2. Different phases for main windings
   - The main windings of the Tohoku inductor carry three-phase AC. However, the proposed inductor has to have main windings suitable for six-phase AC so that it can be used on the railways, because the secondary voltage/current phase of the transformer for rectifier is six-phase to smooth ripples in output DC voltage.

3. Need to improve current capacity
   - The rated current of the Tohoku inductor is several tens of amperes. The RMS (Root Mean Square) value of the load current can be regarded as a constant for short periods such as a few seconds. However, the rated current of the proposed inductor is several thousands of amperes. The RMS value of the load current generally fluctuates widely in these short periods, depending on the operational mode (powering or regenerating) of the rolling stock. In addition, the maximum load of the proposed inductor should be much larger than the rated load in order to comply with the maximum permissible current of the diode rectifier, i.e.
three times over the rated current.

(4) The need to take into account large fault currents

The expected maximum fault current of the Tohoku inductor is several hundreds of amperes. The cause of this may be a short circuit fault, such as layer short fault in the inductor, and not an earth fault. However, the maximum fault current of the proposed inductor is 50 kA, caused by a short circuit in the electric traction system.

4.2 Structure of variable inductor

Figure 6 shows the structure of the variable inductor to be used for the voltage adjustable rectifier developed in this study. The core made of ferromagnetic sheets shown in Fig. 6 (b) is the double five-leg core, which is the same configuration as that of the Tohoku variable inductor. The windings are installed geometrically in the same manner with respect to the core.

The configuration of the windings in the proposed inductor however, differs from that in the Tohoku design. The proposed inductor has six-phase AC main windings (U1-X1, V1-Y1, W1-Z1, U2-X2, V2-Y2 and W2-Z2) and a control DC winding (F1-F2) as shown in Fig. 6 (a). Zigzag connections are used on the main winding to achieve a phase difference of 30 degrees between the series connection windings (with the suffix 1) and the zigzag connection windings (with the suffix 2).

Table 2 shows the design of the winding configuration. The number of turns in the series connection winding was set to N, and that on the zigzag was set to 2N/√3. Each main winding was divided into two parts connected in series. The numbers of turns in the control winding was set to N_c, and the winding was divided into six parts connected in series.

4.3 Magnetomotive force and inductance

Figure 7 shows the magnetomotive forces (MMFs) generated by the main windings on the complex plane. The fundamental frequency components of the MMFs are shown as vectors in the figure, where the variables from \(I_U\) through to \(I_{W2}\) are the currents in the main windings while the suffixes indicate the phases. The red vectors in Fig. 7 (b) show the resultant MMFs excited by the zigzag connection windings. As can be seen, the MMFs excited by the series connection windings and those by the zigzag ones have the same RMSs (norms) and the same phases. Therefore, only three legs of the core are required for six-phase AC by making joint use of the legs in series and zigzag connection windings.

Figure 8 shows the interlinked magnetic fluxes of the main windings indicated by blue and red vectors in the case where leakage magnetic fluxes are neglected. The variables from \(\Phi_U\) to \(\Phi_W\) are the magnetic fluxes in the legs from U to W shown in Fig. 6 (b). As can be seen, the RMSs of the interlinked fluxes by the series connection windings are the same as those by the zigzag ones, and the phase difference between these is 30 degrees. Accordingly, the positive sequence inductances of the series connection windings are the same as that of the zigzag ones (in other words, balanced). The above-mentioned results were also verified by using algebraic analysis.
5. Method for analyzing variable inductors

5.1 Magnetic circuit analysis

Numerical electromagnetic analyses, such as FEM (Finite Element Method) and BEM (Boundary Element Method), are commonly used for the design and evaluation of electromagnetic equipment, such as transformers, inductors, generators and motors. However, these methods are complicated and can be only be performed by suitably qualified individuals. In addition, conducting these analyses requires significant computation time.

O. Ichinokura, K. Nakamura, et al. therefore proposed analysis methods for variable inductors based on magnetic circuit theory (reluctance network analysis) [4, 6-8]. According to reports on their work, results using these methods agreed with experimental results. In magnetic theory, magnetic flux paths are regarded as types of electric circuit. Ohm’s law and Kirchhoff’s law are then used in the analysis based on the similarity of dominant electric current and magnetic flux equations. This theory is valid only in low-frequency ranges such as DC and power frequencies, which is not a problem for designing and evaluating the variable inductor.

By using the magnetic circuit analysis, calculations can be carried out using a general-purpose circuit simulator without the need for any expertise or special skills and in a shorter computation time. For instance, the calculation time of the magnetic circuit analysis is 1/100 or less than for FEM.

5.2 Proposed analysis model

The analytical method proposed in this study is based on a coupled analysis of electric circuits and non-linear magnetic circuits. A simplified magnetic circuit model is used to reduce the computational time required, because there are some non-linear components, such as diodes and rolling stock, which may increase computation time, in the electric traction system.

Figure 9 shows the magnetic circuit model of the front side of the double five-leg core developed in this study. The rear side of the core is modeled in the same manner. The magnetic fluxes in the iron core are approximated to be uniform: the core can then be divided into only nine components. They are the legs from U1 to W1, two vertical yokes and four horizontal yokes (the top and bottom yokes are combined with each other).

Each component of the magnetic circuit has a reluctance $R$ and a magnetic inductance $L$, of which the first letter of the suffix indicates the phase and the last digit indicates the core (1: the front side, 2: the rear side). There are MMF sources of the main and control windings on the legs which are shown as voltage sources in Fig. 9. The variable $l_{c}$ on the figure is the current in the control winding. The MMF sources on each leg are connected in series and are MMF sources of the main and control windings on the core by using a magnetic inductance [4, 8]. The method was introduced into the analysis carried out in this study, as it can easily calculate the magnetizing loop and iron loss of the core in the magnetic circuit analysis.

Magnetic inductance is obtained by the following equation,

$$L = \frac{P_{i}(B_{m})}{(\omega B_{s})^2}$$

where $P_{i}$ is the iron loss at the operating angular frequency $\omega$, expressed as a function of the steady-state amplitude of magnetic flux density $B_{m}$. The function, which is a simplified one of the methods proposed by Ichinokura et al., is not applicable to high-frequency and transient analysis, because it depends on steady-state parameters ($\omega$ and $B_{s}$). The linear interpolation is also used to form a continuous function in the same manner as in the case of reluctance.

5.3 Circuit constants

Since non-linear magnetizing characteristics of the core are applied to the developed variable inductor, non-linear phenomena have to be considered in the analysis.

(1) Reluctance

Reluctance, also known as magnetic resistance, of the core is modelled as a non-linear resistance in the analysis. The mathematical expression is given by the following equation.

$$R = \frac{H}{B_{s}(H)S}$$

where $\ell$ is the mean length of the magnetic flux path in the component of the core, and $S$ is the effective sectional area of the core. The non-linear relationship between $B$ and $H$ is obtained from the static magnetization characteristic of the core material normally given by the manufacturer. A linear interpolation is used to form a continuous function.

The blue curve in Fig. 10 shows an example of the non-linear reluctance against the magnetic flux $BS$. As it can be seen, reluctance generally monotonically and rapidly rises according to magnetic saturation.

(2) Magnetic inductance

Ichinokura, et al. proposed a simulation method to calculate the iron loss (hysteresis and eddy current losses) of the core by using a magnetic inductance [4, 8]. The method was introduced into the analysis carried out in this study, as it can easily calculate the magnetizing loop and iron loss of the core in the magnetic circuit analysis.

Magnetic inductance is obtained by the following function,

$$L = \frac{P_{i}(B_{m})}{(\omega B_{s})^2}$$

where $P_{i}$ is the iron loss at the operating angular frequency $\omega$, expressed as a function of the steady-state amplitude of magnetic flux density $B_{m}$. This function, which is a simplified one of the methods proposed by Ichinokura et al. is not applicable to high-frequency and transient analysis, because it depends on steady-state parameters ($\omega$ and $B_{s}$). The linear interpolation is also used to form a continuous function in the same manner as in the case of reluctance.
The red curve in Fig. 10 shows an example of the magnetic inductance against magnetic flux. The magnetic inductance is normally a monotonically but slowly decreasing function in relation to magnetic saturation.

5.4 Solver

The solver (electric circuit simulator) used in this study is the XTAP (eXpandable Transient Analysis Program) ver. 2.01 developed by the CRIEPI (Central Research Institute of Electric Power Industry) in Japan. Other solvers for which non-linear analyses are available, can also be used for the analysis. The computational time required for calculation ranged from about several seconds to several minutes during the ten cycles of the power frequency on a general-purpose PC (Personal Computer). FEM analysis was also carried out under the same conditions for comparison. The time required for the FEM was several days.

6. Design method of variable inductor

6.1 Fundamental policy

The inductance of the variable inductor also depends on the current of the main windings, namely the DC output current of the rectifier. The rated magnetic flux density of the core has to be reduced to decrease current dependency by improving the sectional area of the core in order to acquire the characteristics shown in Fig. 1 (b). However, this design increases the size and cost of the inductor and decreases the band of voltage control in light-load ranges.

As such, a more suitable design method was developed by increasing the rated magnetic flux density of the core by setting the DC output current corresponding to the saturation magnetic flux density at about 100 A to 1 kA. This design made it possible to maintain the control band of DC output voltage of the rectifier at the same level for a wide range of DC output currents from light-load to maximum permissible load (e.g. three times as large as the rated one), as shown in Fig. 11.

6.2 Operating modes of core

Figure 12 shows the core operating modes, where \( I_{DC} \) is the DC output current of the rectifier corresponding to the amplitude of the main winding currents; \( \lambda \), the mean length of the magnetic circuit; \( R_{SAT} \), the saturation magnetic flux density of the core. There are three operating modes corresponding to the RMS of the control current.

(1) Small control current \( (N_{DC} < N_{I_{DC}}) \) shown in Fig. 12 (a)

In this mode, the amplitude of the MMF of the control current is much smaller than in the main winding currents. The variable inductor acts like a linear inductor in the unsaturated range of the small main currents (such as <100 A). On the other hand, it acts like a constant voltage dropper in the saturated range of the normal main currents (such as >100 A).

(2) Middle control current \( (N_{DC} \approx N_{I_{DC}}) \) shown in Fig. 12 (b)

In this mode, the amplitudes of the MMFs of the control and main winding current have the same order. The inductance of the main windings becomes smaller than that of the mode of the small control current due to the magnetic saturation.

(3) Large control current \( (N_{DC} \gg N_{I_{DC}}) \) shown in Fig. 12 (c)

In this mode, the amplitude of the MMF of the control current is much larger than in the main winding currents. The variable inductor acts like an air-core inductor, which has the smallest inductance of the three modes, because the magnetizing loop is located entirely in the saturated area.
The turn \( N_C \) and the rated current \( I_C \) of the control winding are obtained by the following formula according to the equilibrium of the MMFs in the core.

\[
N_{DC}H_{SAT} = N_C I_C
\]

where \( H_{SAT} \) is the value of the magnetic field strength corresponding to \( B_{SAT} \). This relationship is similar to the equal ampere turn’s law of the magnetic amplifier.

The design process is generally an optimization process with due consideration on the realistic structure, the core material, the electromagnetic force, the electric insulation, the manufacturing process, the spatial layout in the casing and the electrical requirements of the control equipment. Finally, the detailed design process is carried out by using the magnetic circuit analysis.

7. Validation of analysis and design method

A prototype variable inductor was built for a 1.5 kV DC electric traction system. The specifications were as follows: circuit voltage 1.2 kV; rated current of the main winding 390 A; band of voltage control about 400 V; and rated control current 100 A. The prototype complies with the Japanese Electrotechnical Committee standard JEC-2210:2003 for general power inductors and technical standards of a railway operator, so that it can be used in a railway traction substation.

A verification of the design and analysis method was carried out by comparing calculated and measured results. Figure 13 shows the resulting inductance and DC output voltage of the rectifier. Figure 13 (a) shows that calculated and measured inductances agreed well when there was no control current (0 A). However, there were small differences (up to about 20%) when the control current was 50 A and 100 A, particularly in light-load ranges of the main windings. The differences are considered to have been caused by leakage magnetic fluxes which are not modeled precisely in the magnetic circuit analysis. This is not a serious problem for the equipment design, because theoretically the calculated results provide a safe-side band of control.

Figure 13 (b) shows the calculated characteristics of a voltage adjustable rectifier using the prototype variable inductor. The band of voltage control calculated through analysis agreed with the design value (about 400 V). An experiment of the voltage adjustable rectifier was carried out on a test line at the Railway Technical Research Institute. The resulting band of voltage control was 370 V, which is almost the same as the calculated one. This confirms the validity of the methods for design and analysis.

8. Conclusions

This paper described the configuration, analysis method and design method of a variable inductor to be used in a new type of voltage adjustable rectifier. The findings in this paper can be summarized as follows.

1. The voltage adjustable rectifier consists of a transformer for rectifier, a new variable inductor (including a controller) and a rectifier. The voltage control of the rectifier is achieved by adjusting the voltage drop in the variable inductor, which is connected to the transformer and the rectifier on either side.

2. The magnetic flux control technique with the use of a double five-leg core was introduced into the variable inductor. A new configuration of the inductor was developed so that it could be used in railway traction substations.

3. A new fast analysis method of the variable inductor was developed based on the magnetic circuit theory. The non-linear magnetizing property of the core of the inductor was modelled by non-linear circuit components (reluctances and magnetic inductances).

4. An suitable design method for the variable inductor was developed. The method allows an almost constant band of voltage control across a wide range of DC output current: from low loads to maximum permissible loads.

5. A prototype of the variable inductor and controller with the rated current of 390 A and the band of voltage control of about 400 V was built for a 1.5 kV DC electric traction system. The analysis and design methods were verified by comparing calculated and measured data.

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