# Core Loss Modeling Based on Equivalent Circuit for Switched Reluctance Motors

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# Core Loss Modeling Based on Equivalent Circuit for Switched Reluctance Motors


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***Abstract*— To estimate the core loss in SRMs, core loss estimation by equivalent circuit is preferable especially in the EV development because of its simple calculation. However, previously proposed models may limit applicable operating condition. These models refer instantaneous value, whereas hysteresis loop is a key factor to estimate core loss and the hysteresis loop directly associates with the history of magnetic flux. This paper focuses on the relation between the width of hysteresis loop and the peak to peak value of magnetic flux because the relation directly expresses the core loss. Therefore, the purpose of this paper is to propose a novel core loss model for equivalent circuit which estimates core loss in SRMs. This paper refers the peak to peak value of magnetic flux linkage and electrical angle. Along with the theoretical formulation of the model, this paper presents the model construction method. As a result, the proposed model successfully estimated core loss.**



***Keywords—core (iron) loss estimation, eddy current loss, equivalent circuit, hysteresis loss, loss modeling, switched reluctance motors***


## I. INTRODUCTION

Switched reluctance motors (SRMs) are expected as propulsion motors for electric vehicles (EVs) because the SRMs are free from permanent magnet. This feature yields many benefits such as cost-effectiveness and robust motor structure. However its nonlinearity yields unexpected behavior such as torque ripple, input current ripple, and radial force ripple, as reported in [1] [2].

To overcome these difficulties, there have been many studies as written in [3]–[7]. In these literatures, many kinds of control techniques have been reported. Almost all the literatures have verified their benefits experimentally.

On the other hand, in the case of EV development, the effect on the EV behavior is need to be evaluated. To select the most appropriate technique among infinitely existing literatures, many tests will be held. Experimental evaluation consumes a lot of time and funds. Therefore, in the early developing period, simulation is used to save the developing time and funds

As used in [4] [5], finite element method (FEM) is widely used for the development of the motor controls or motor structures because FEM simulates torque and loss accurately. In the case of EV development, FEM is sometimes not suitable because FEM needs much time even if the simulation period is a few micro seconds. In addition, if we simulate a few hours EV behavior, it takes more than a few days.

To analyze the effect of the motors or inverter circuit on EV behavior, some literatures express the electrical components as equivalent circuits instead of FEM. In many cases, core loss is expressed by equivalent core loss resistors connected in parallel to inductors as motor windings.

In the case of commercial motors, which are driven by commercial power supply and operated by constant condition, equivalent core loss resistance can be expressed as pure resistors.

In the case of other ac servo motors, the equivalent core loss resistors are determined for d-axis and q-axis circuits, respectively. Therefore core loss of their wide operating condition can be estimated. For the further accuracy, the

Table I Nomenclature

| | |
|---|---|
| $i_C$, $R_C$ | : Parameters of core loss model |
| $d$ | : Hysteresis width |
| $i_{ph}$ | : Phase current |
| $K_1$ ,$K_2$ ,$K_3$ | : Parameters of mechanical loss |
| $P_{in}$, $P_W$ | : Input energy, consumed energy of winding resistance |
| $R_W$ | : Resistance of winding |
| $T$ | : Switching period |
| $V_{DC}$, $v_L$, $v_{ph}$ | : DC bus voltage, voltage applied to inductance, voltage applied to phase winding |
| $W_C$, $W_{in}$, $W_{inv}$, $W_M$, $W_{out}$ | : Core loss, input power, inverter loss, mechanical loss, mechanical output power |
| $\theta$ | : Electrical angle |
| $\tau_e$, $\tau_L$ | : Generated torque, load torque |
| $\lambda_{P\text{-}P}$ | : Peak to peak value of magnetic flux linkage |
| $\Omega$ | : Angular velocity |

equivalent core loss resistor of each axis is expressed as a function of d-axis or q-axis current.

In the case of SRMs, due to their electrical nonlinearity, the equivalent circuit cannot be expressed with d-q equivalent circuit. Therefore, some equivalent core loss resistors [8]–[10] are expressed as a function of electrical angle.

However, in the case of EV application, SRMs are driven by various amplitude of phase current to obtain wide torque range. Therefore, the equivalent core loss resistors which depend on only electrical angle is insufficient.

Then a recent research [11] [12] have proposed derivation algorism of the equivalent core loss resistance and the resistance depends on both electrical angle and phase current. In addition, [11] [12] have also presented good performance of estimation. However, despite their good performance, the operating condition may be limited. When the SRM is operated with certain switching frequency, certain amplitude of hysteresis current control, or certain DC bus voltage, the core loss estimation must have high accuracy. However, focusing the core loss generated by every switching of inverter, keeping the accuracy of core loss estimation is difficult for below reason when the operating condition continuously changes.

When the rotor is locked and the single DC-pulse voltage is applied to phase winding like Fig. 1, a relation between phase current and magnetic flux linkage like Fig 2(a) is obtained. (The similar experiment can be shown in [13]–

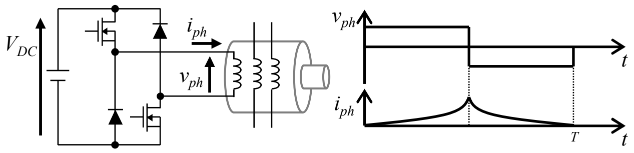



Fig. 1 DC pulse examination.

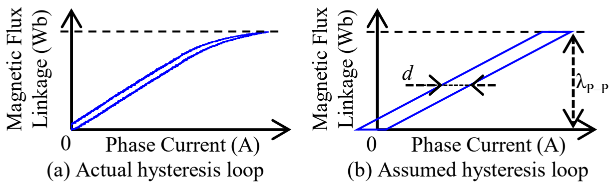



Fig. 2 Hysteresis loop obtained by DC pulse examination.

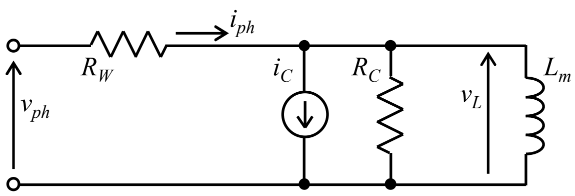



Fig. 3 Equivalent circuit for core loss.

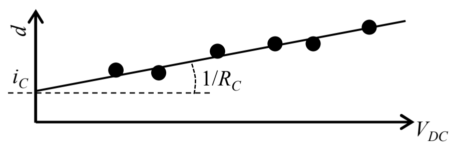



Fig. 4 Determination of $R_C$ and $i_C$.

[15].) In Fig. 2(a), the area of hysteresis loop is equal to core loss. Therefore, to estimate the core loss, the hysteresis loop should be shaped accurately. As widely known, the size of hysteresis loop depends on the operating condition. For example, the larger the injected magnetic flux is, the wider the hysteresis loop is. If only the instantaneous phase current is taken into account, the hysteresis loop cannot be shaped accurately because the relation between phase current and magnetic flux varies depending on the magnetization. Thus, the accurate estimation is difficult without the data of history of magnetic flux.

To break through above difficulties, this paper focuses on the relation between the width of hysteresis loop and the peak to peak value of magnetic flux because the relation directly expresses the core loss for above reason. Therefore, the purpose of this paper is to propose a novel core loss model for equivalent circuit which estimates core loss in SRMs.

After this section, this paper is organized by following contents. Section II explains the proposed model. Section III presents the verification of the proposed model, including the model construction. Finally, section IV gives conclusions.

## II. Proposed Core loss Model

This paper focuses on the circuit presented in Fig. 3. In Fig. 3, $R_C$ and $i_C$ express the eddy current loss and hysteresis loss. This section explains the core loss model for the parameters of $R_C$ and $i_C$. Then, this section presents the parameter extraction method from a target SRM. In addition, nomenclature in this paper is listed in Table I.

### *A. Modeling Theory*

This paper estimates the core loss, based on the area of hysteresis loop generated by single switching. Then, we assume the operation like Fig. 1. To express the area of hysteresis loop, as shown in Fig. 2(b), this paper assumes that the hysteresis loop is expressed by parallelogram and defines hysteresis width $d$, which is the difference of current at same magnetic flux linkage. (Note that the hysteresis width defined in this paper is different from the actual one.) In this case, the core loss generated in single phase by single switching of inverter is calculated by

$$W_c = \frac{d \times \lambda_{P-P}}{T} = \frac{d}{2} v_L = \frac{d}{2}\left(v_{ph} - R_W i_{ph}\right) \cong \frac{d}{2} V_{DC}, \quad (1)$$

where $T$ is the switching period, $\lambda_{\mathrm{P-P}}$ is the peak to peak value of magnetic flux linkage, $v_L$ is voltage applied to magnetizing inductance, $v_{ph}$ is output voltage of inverter, $R_W$ is resistance of phase winding, and $i_{ph}$ is output current of inverter. According to (1), core loss can be estimated by modeling hysteresis width $d$.

On the other hand, in Fig. 3, the core loss can be expressed by

$$W_c = \frac{{v_L}^2}{R_C} + \mathrm{sgn}(v_L) i_C v_L. \quad (2)$$

According to (1) and (2), the hysteresis width is expressed by

$$d = 2\frac{1}{R_C} V_{DC} + 2 i_C. \quad (3)$$

Obviously, the parameters of $R_C$ and $i_C$ can be determined by analyzing the characteristics of hysteresis width $d$.

## B. Parameter Extraction Method

The characteristics of hysteresis width $d$ can be obtained experimentally by analyzing several hysteresis loops like Fig. 2(b). Then, the parameters of $R_C$ and $i_C$ are determined, according to following procedure.

First, the hysteresis width $d$ is measured with several DC bus voltage because the hysteresis width $d$ has dependency on applied voltage, as in (3). (Note that the maximum magnetic flux linkage is constant and the rotor is locked at certain electrical angle.) The hysteresis width $d$ can be obtained by

$$d = \frac{P_{in} - P_w}{\lambda_{P-P}}, \tag{4}$$

where $P_{\mathrm{in}}$ is input power and $P_{\mathrm{W}}$ is consumed energy by experimentally measured winding DC resistance.

Then, the simple linear regression is applied to the measured data of hysteresis width $d$, as illustrated in Fig. 4. As a result, the parameters of $R_C$ and $i_C$ are extracted. The dependency of the parameters of $R_C$ and $i_C$ on the electrical angle θ is obtained by repeating above procedure at various electrical angle.

Next, to regard the parameters of $R_C$ and $i_C$ as functions of electrical angle θ, this paper applies Fourier expansion to $R_C$ and $i_C$ to determine the Fourier coefficients. The dependency of the parameters of $R_C(\theta)$and $i_C(\theta)$ on the peak to peak value of magnetic flux linkage $\lambda_{\mathrm{P\_P}}$ is obtained by repeating above procedure at various $\lambda_{\mathrm{P\_P}}$.

Finally, to regard the parameter of $R_C$ and $i_C$ as function of the peak to peak value of magnetic flux linkage, the linear regression is applied to $R_C(\theta)$ and $i_C(\theta)$. Consequently, complete database of $R_C(\theta, \lambda_{\mathrm{P\_P}})$ and $i_C(\theta, \lambda_{\mathrm{P\_P}})$ are obtained.

The parameters of $R_C(\theta, \lambda_{\mathrm{P\_P}})$ and $i_C(\theta, \lambda_{\mathrm{P\_P}})$ are depends on $\lambda_{\mathrm{P\_P}}$. As for $\lambda_{\mathrm{P\_P}}$, it means that the value of $R_C(\theta, \lambda_{\mathrm{P\_P}})$ and $i_C(\theta, \lambda_{\mathrm{P\_P}})$ change at every switching of inverter. Therefore, even if the frequency and current of switching change, the core loss can be accurately estimated. Furthermore, proposed method is based on the magnetic flux linkage, which can be directly calculated from applied voltage regardless of magnetic saturation. Therefore, the core loss can be accurately estimated even at magnetically saturated region.

# III. Experimental Verification

Experiment is carried out to verify the proposed parameter determination. First, this section constructs core loss model. Then this section evaluates the estimated core loss.

## A. Model Construction

According to above method, the core loss model for an experimental SRM is constructed. Figure 5 presents experimental motor test bench. The specification of the bench is listed in Table II. We measured hysteresis width $d$ at 5 levels of DC bus voltage in 40V–96V, 12 levels of the peak to peak value of magnetic flux linkage in 1mWb–40mWb, and 7 electrical angles in 0–180 degrees.

However, according to below reason, some data is not taken into account. As in (4), the hysteresis width $d$ is calculated based on experimentally measured DC resistance. Therefore, if the true resistance is different from the experimentally measured one, the obtained hysteresis width is wrong value. As for the aligned position, to obtain the data with large magnetic flux linkage, large current is not required due to the large inductance. As a result, copper loss is much smaller than core loss and the error of copper loss is marginable. In contrast, as for the unaligned position, due to the small inductance, large current is required and the error

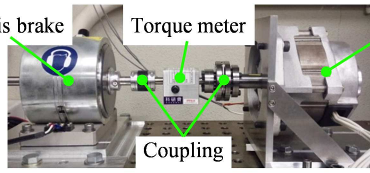



Fig. 5 Experimental motor test bench.

Table II. Specifications of motor test bench.

| Instrument | Specifications |
|---|---|
| SRM | RB165SR-96VSRM<br>(Motion System Tech. Inc.)<br>96V, 1.2kW, 6000rpm<br>Stator: 12 poles, Rotor: 8 poles<br>Number of turns: 14T/pole |
| Torque meter | UTMII-5Nm (Unipulse Corp.) |
| Hysteresis brake | AHB-6 (Magtrol Inc.) |

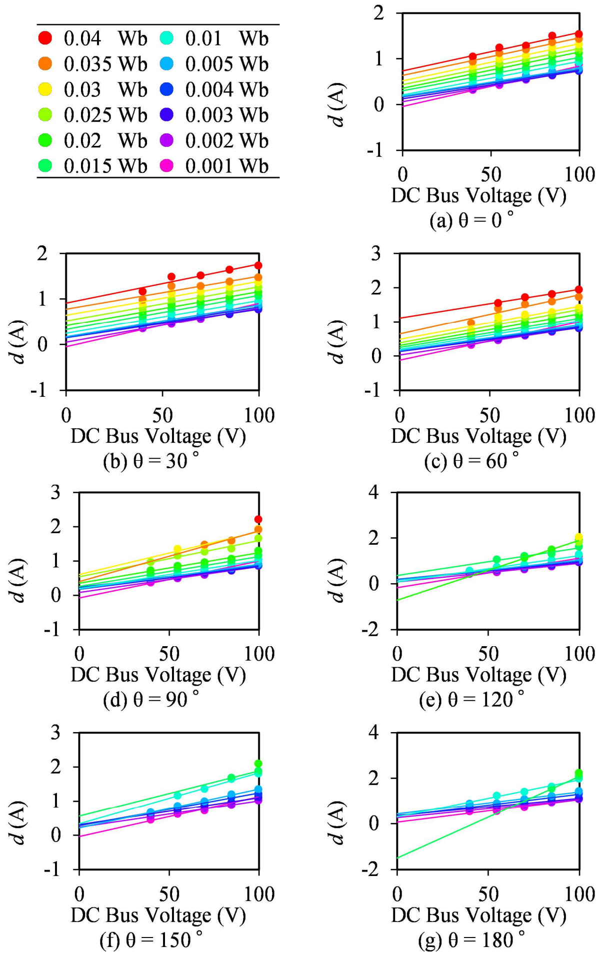
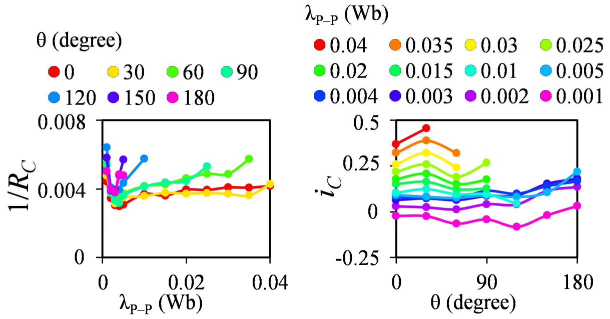
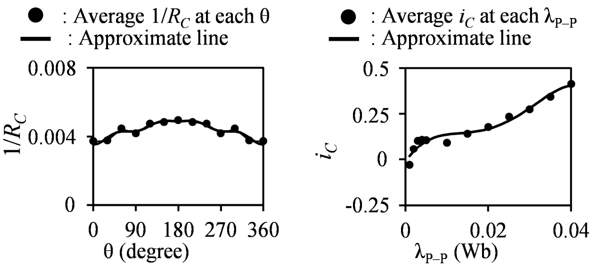



Fig. 6 Measured hysteresis width.




(a) Extracted parameter of $1/R_C$ (b) Extracted parameter of $i_C$

Fig. 7 Extracted $R_C$ and $i_C$.




(a) Simplified parameter of $1/R_C$ (b) Simplified parameter of $i_C$

Fig. 8 Simplified $R_C$ and $i_C$.

of copper loss cannot be marginable and then, the accuracy of measured core loss cannot be ensured. Therefore, this paper takes account of the data only where core loss is larger than quarter of copper loss.

Figure 6 presents the measured hysteresis width d at every electrical angle. As in (3), the every hysteresis width d increases linearly. These data was fitted by simple linear regression and the parameters of $R_C$ and $i_C$ were extracted.

Figure 7 shows the extracted parameters of $R_C$ and $i_C$. Then, this paper regard these parameter as functions of θ and $\lambda_{P\_P}$. However, due to the above reason, there is some lack of data. Therefore, this paper simplifies extracted parameters.

As for $1/R_C$, it has strong dependence on θ rather than $\lambda_{P\_P}$, focusing on the data of small value of $\lambda_{P\_P}$. Therefore, $1/R_C$ was simplified into a function of only θ, where the value of $R_C$ at each θ is the average value. Then, this paper applied linear regression of order 4 to extracted $R_C$. Consequently, this paper obtained model of $R_C$, as in Fig. 8(a). As for $i_C$, it has strong dependence on $\lambda_{P\_P}$ rather than θ, focusing on the data around aligned position. Therefore, $i_C$ was simplified into a function of only $\lambda_{P\_P}$, where the value of $i_C$ at each $\lambda_{P\_P}$ is the average value. Then, this paper applied Fourier expansion of order 4 to extracted $i_C$. Consequently, this paper obtained model of $i_C$, as in Fig. 8(b).

### *B. Evaluation of Proposed Model*

For the verification of the proposed model, this subsection evaluates the core loss estimated by the proposed model, experimentally. In the rest of this subsection, following evaluations are carried out. First, the core loss is estimated at rated power of the experimental SRM i.e. 2.9Nm, 96V, and 2000rpm. Then, to confirm the response of core loss to DC bus voltage, rotational speed, and torque, the core loss is estimated at 1Nm, 60V, and 4000rpm, respectively.

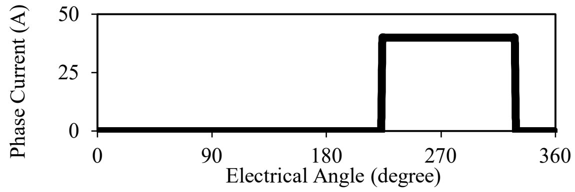



Fig. 9 Phase current profile to output 2.9Nm at 2000rpm

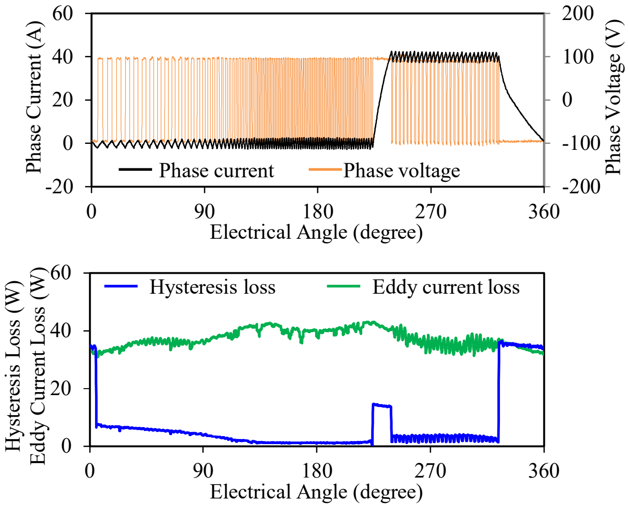



Fig. 10 Core loss estimation at 2.9Nm, 96V, and 2000rpm.

In this section, the experiment is carried out by the motor test bench in Fig. 5. In addition, the SRM is driven by the phase current waveform in Fig. 9. The phase current profile is a standard phase current profile which outputs 2.9Nm at 2000rpm and DC bus voltage of 96V.

As for the core loss model, the parameters of $\lambda_{P\_P}$ and θ are calculated based on experimentally measured phase current and phase voltage.

On the other hand, as for the experimental core loss, the core loss cannot be measured directly because the loss in the experimental system is measured as a total loss. Therefore, this paper identifies the core loss by

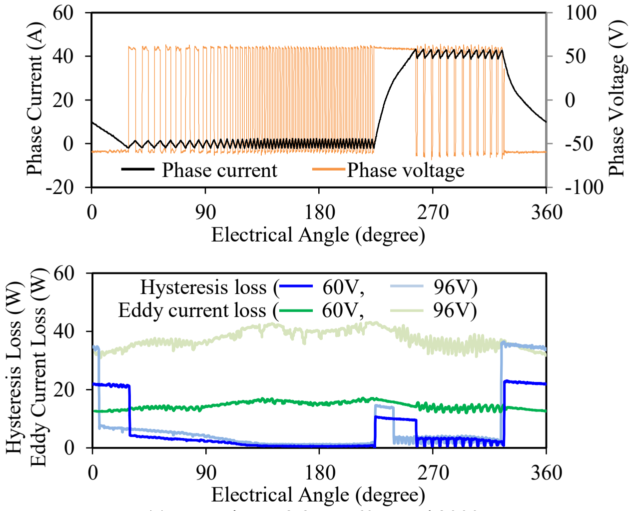
$$W_c = W_{in} - W_{out} - W_W - W_M - W_{inv}, \quad (5)$$

where $W_{in}$ is DC input power, $W_{out}$ is mechanical output power, $W_W$ is copper loss, $W_M$ is mechanical loss, and $W_{inv}$ is inverter loss. In (5), as $W_{in}$ and $W_{out}$ can be measured directly, $W_W$, $W_M$, and $W_{inv}$ are estimated by following method.

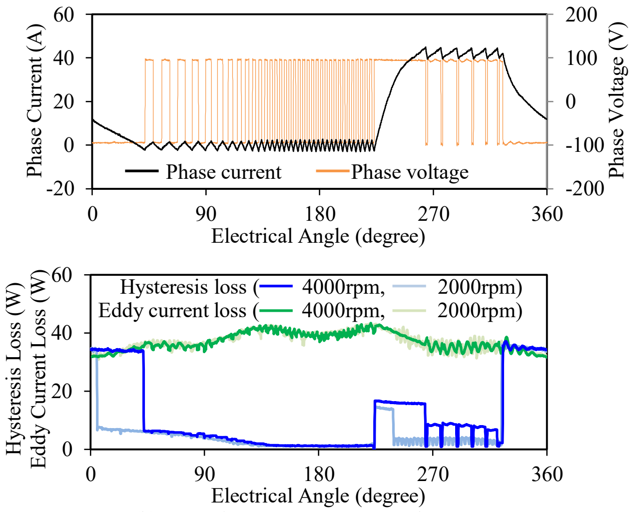
In this paper, $W_W$ is estimated based on measured DC resistance and the rms value of phase current. As for $W_{inv}$, the loss is estimated by previously measured loss map which is a function of DC output current and switching frequency. For the construction of the inverter loss map, the inverter is operated as a DC-DC converter. Then, the inverter loss is measured at various levels of DC output current and switching frequency. As for $M_M$, the loss is also estimated by previously measured mechanical loss map which is a function of rotational speed. The equation of motion of the motor test bench can be expressed by

$$\tau_L = \tau_e - K_1 \frac{\partial \Omega}{\partial t} - K_2 \Omega - K_3 \Omega^2, \quad (6)$$

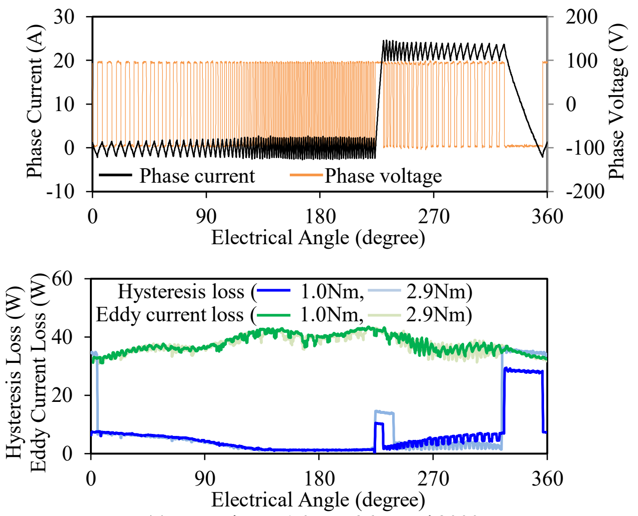
When the $\tau_e$ is zero, the motor slows down and negative




(a) Operation at 2.9Nm, 60V, and 2000rpm



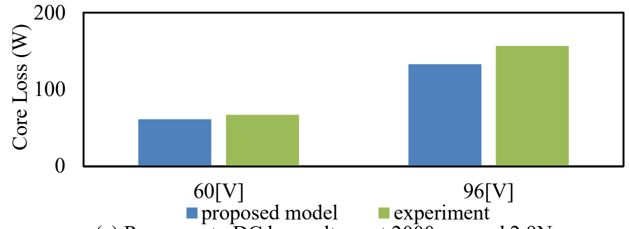

(b) Operation at 2.9Nm, 96V, and 4000rpm



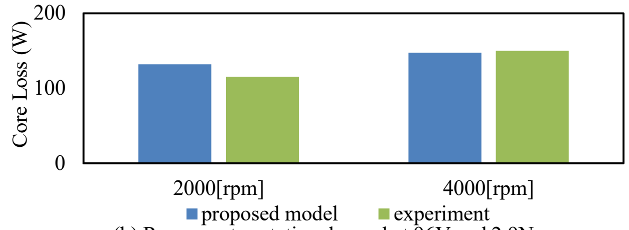

(c) Operation at 1.0Nm, 96V, and 2000rpm

Fig. 11 Evaluation data of response to DC bus voltage, rotational speed, and torque.

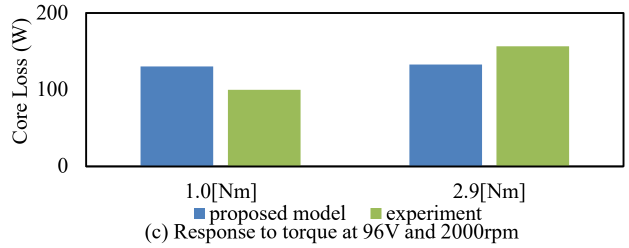
torque is detected. The negative torque is the mechanical loss. By measuring the negative torque at various rotational speed and fitting by linear regression, the mechanical loss map is constructed.




(a) Response to DC bus voltage at 2000rpm and 2.9Nm




(b) Response to rotational speed at 96V and 2.9Nm




(c) Response to torque at 96V and 2000rpm

Fig. 12 Comparison data between proposed model and experiment.

Then, we estimate the core loss by the proposed model. Figure 10 shows the core loss estimation, when the SRM is operated at 2.9Nm, 96V, and 2000rpm. In Fig. 10, estimated eddy current loss and hysteresis loss are shown which are calculated by experimental phase current and phase voltage shown in the same figure. As can be seen in Fig. 10, the proposed model can estimate the core loss dynamically.

Next, the response of core loss is evaluated. The data is shown in Fig. 11. The responses to DC bus voltage, rotational speed, and torque are evaluated, respectively.

Figure 11(a) shows the response to DC bus voltage. The reduction of core loss was confirmed as expected. Figure 11(b) shows the response to rotational speed. Due to the increment of rotational speed, the hysteresis loss was increased. Figure 11(c) shows the response to torque. Due to the large current, the hysteresis loss was increased. These data support the accurate estimation of characteristics of core loss.

Finally, the core loss estimated in Fig. 11 were compared with experimentally identified core loss. The comparison data is shown in Fig. 12.

Figure 12(a) shows the comparison data of the response to DC bus voltage. The experimental core loss increased when the DC bus voltage increased. As a result, the estimation error of was within 15%. Therefore, this evaluation revealed that the response to DC bus voltage was well expressed.

Figure 12(b) shows the comparison data of the response to rotational speed. The experimental core loss increased when the rotational speed increased. As a result, the estimation error of was within 15%. Therefore, this evaluation revealed that the response to rotational speed was well expressed.

Figure 12(c) shows the comparison data of the response to torque. The experimental core loss increased when the torque increased. As a result, the estimation error of was within 30%. Therefore, this evaluation revealed that the response to torque was well expressed. According to above evaluations, these results support appropriateness of the proposed model for core loss in SRMs.

## IV. Conclusions

To estimate the core loss in SRMs, core loss estimation by equivalent circuit is preferable especially in the EV development because of its simple calculation. To express the core loss, many core loss model for the equivalent circuit has been developed. However, previously proposed model refers only instantaneous value despite that the area of hysteresis loop depends on the history of magnetic flux. Then, these models may limit the operating condition and control method of SRMs. Therefore, to bring more flexibility in core loss analysis, a novel core loss model is required. Then, this paper proposed a novel core loss model based on the width of hysteresis loop. In the proposed model, adopted the peak to peak value of magnetic flux linkage and electrical angle which directly affect the area of hysteresis loop. As a result, the proposed core loss model successfully expressed the characteristics of core loss i.e. response to DC bus voltage, rotational speed, and torque. Consequently, the proposed model is promising for a core loss model of SRMs.

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