

Loss Separation Calculation of Silicone Steel Sheet under String Excitation

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Abstract

The study of the loss characteristics of silicon steel laminates under sinusoidal excitation is the basis of studying the loss characteristics under complex harmonic excitation. The magnetic induction intensity of silicon steel sheet is also sinusoidal when sinusoidal excitation is applied on silicon steel laminated sheet. By extracting the variation law of magnetic field intensity, voltage and current, the magnetization curve and hysteresis loop of silicon steel sheet under sinusoidal excitation are obtained to characterize the loss characteristics of silicon steel sheet under sinusoidal magnetic field. This paper mainly discusses the loss experimental measurement of silicon steel sheet under sinusoidal excitation and the calculation based on loss separation.

1. Analysis of Magnetic Properties of Silicon Steel Sheets

The magnetization process of silicon steel sheet is very complex and related to many factors. For example, in the process of magnetization of silicon steel sheet changing direction many times under alternating magnetic field, some losses can be caused, which can be divided into hysteresis loss, eddy current loss and abnormal loss according to the physical reasons.

The magnetic field intensity increases gradually to the peak value and then decreases, then continues to magnetize until the reverse saturation value is reached, then increases the magnetic field intensity. A closed curve can be obtained by recording the B and H values at that time, as shown in Figure 1:

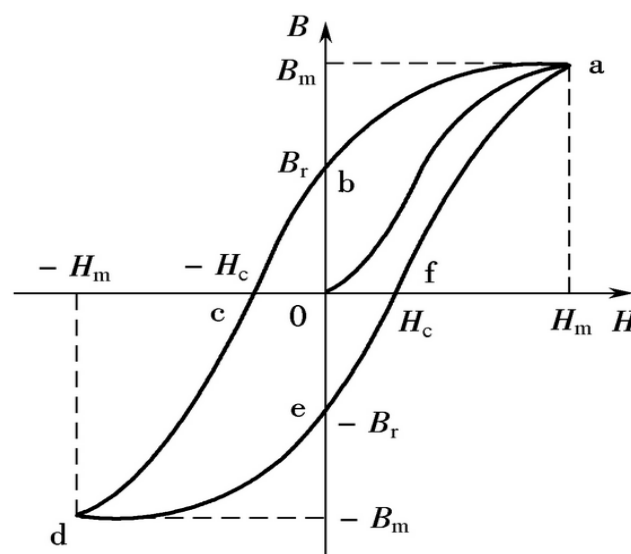


Figure 1. Hysteresis diagram

We can see from the hysteresis curve that the magnetization does not coincide with the demagnetization process. When demagnetization, the change of B always lags behind the change of H . When the H falls to 0, the B does not fall to 0 but to a certain value B_r . This phenomenon is called hysteresis. Coercivity [5] is the residual flux density and corresponding to the magnetic field intensity H_c at $B = 0$. This phenomenon is due to the fact that the magnetic domains in the silicon steel sheet will rotate repeatedly under the excitation of the external alternating magnetic field, and the magnetic domains will hinder the rotation between each other. Because of this effect, when the external magnetic field does not change repeatedly, a part of the magnetic domain with the same direction of the external magnetic field remains reversed and can not restore the original direction, thus forming the above phenomenon. Different hysteresis loops for the same ferromagnetic material at different applied excitation values and therefore different H_m are applied value can get the hysteresis loop under the corresponding value. If the inflection points of different hysteresis loops are connected in turn, the obtained curve is called basic magnetization curve or average magnetization curve. Both hysteresis loop and magnetization curve are very important curves in the magnetic properties of silicon steel sheet.

2. Construction of Experimental Platform

2.1. BROCKHAUS Epstein700 Measurement System

The first step of the loss separation calculation of silicon steel laminated sheet is to measure the loss of silicon steel sheet as the basis of the separation calculation. The equipment used to measure the magnetic properties of silicon steel sheet is Epstein square circle, single chip measuring instrument and so on. BROCKHAUS measurement system integrates Epstein square circle with different magnetic circuit length and monolithic measuring instrument of different size, and has powerful measuring function. At present, the majority of AC magnetization measurement uses Epstein square coil, this square coil has four coils, each coil has two windings, the outer layer magnetization winding is called primary winding, the inner layer inductive voltage winding is also called secondary winding. When the excitation voltage U_1 the primary coil. At the secondary coil the induced voltage will be U_2 . And primary coil also generates I_1 excitation current U_2 based on the induced voltage with magnetic induction intensity B , excitation current and magnetic field intensity H , we can get the results of magnetization curve, hysteresis loop, loss curve and so on. The principle of single chip measuring instrument is similar to Epstein square circle, air is a part of the main magnetic circuit, there is no integral magnetic circuit in the sample, there is a certain measurement error in the process of use, and the equipment price is high.

The magnetic characteristics and loss characteristics of silicon steel sheet are measured by using Epstein 700 square coil of BROCKHUAS company. As mentioned earlier, there are four coils in this square coil, each coil has two windings, one layer of electrostatic shielding can be filled between the two windings, the winding is evenly distributed on the square coil, and 700 laps are evenly distributed in the four square coils, that is, the number of each square coil is 175 laps. A mutual inductance coil is inserted into the square coil, mainly to compensate for air leakage flux. Coil arrangement on the bottom plate, and the bottom plate in order to maintain the measurement requirements, need to do a certain treatment, require no magnetic at the same time to maintain insulation. The coil is fixed to the square ring by a hard material, and the square ring has a rectangular section, about 30mm, long and about 10mm, high. The function is to load the measuring sample. the number of silicon steel laminates is a multiple of 4. In order to improve the accuracy of the measurement, the sample should be demagnetized before the measurement. This paper uses 25cm standard Epstein coils as test equipment, as shown below:

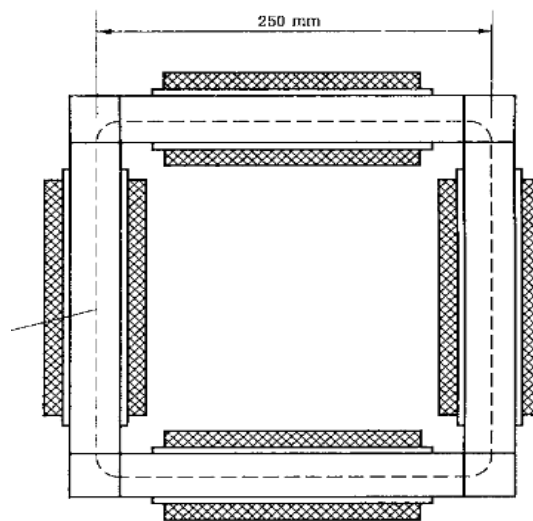


Figure 2. Schematic diagram of Epstein Circle used in the experiment

The length and width of the silicon steel sheet used in the experiment need to be measured before the measurement, and the weight of the silicon steel sheet used is measured. The silicon steel sheet that has passed the side is lapped in a double-tower mode and placed in the Epstein square ring. Open the test system used in the device in the computer, in the test, first of all, some parameters of the silicon steel sheet input, and then in the measurement coil page for the coil used for parameter setting, usually without special circumstances, the default value of the system is generally used, this default value is given by the manufacturer, for a fixed value. At last, the excitation forms of excitation signal are set up, such as sine, DC bias, harmonic and free waveform. At the same time, it is necessary to set some parameters, such as the frequency of excitation source and the frequency of demagnetization excitation source. Check that each parameter setting is correct, after confirming the correct, click on the start to measure. In the process of measurement can be viewed at any time voltage, exciting current and other magnetic characteristics. A measurement can be saved in Excel form for the surveyor to see. Each polarization or magnetic field intensity measurement consists of 1000 data points. The following diagram shows the basic information of the measured silicon steel sheet:

Table 1. Basic information of silicon steel sheet

Parameters of silicon steel sheet	Parameters
Model	30P120
Length (mm)	300
Width (mm)	30
Thickness (mm)	0.3
Density (kg/m ³)	7650
Conductivity (S/m)	2.22×10^6
Cross sectional area (mm ²)	7.2×10^{-5}

As shown in Figure 3:

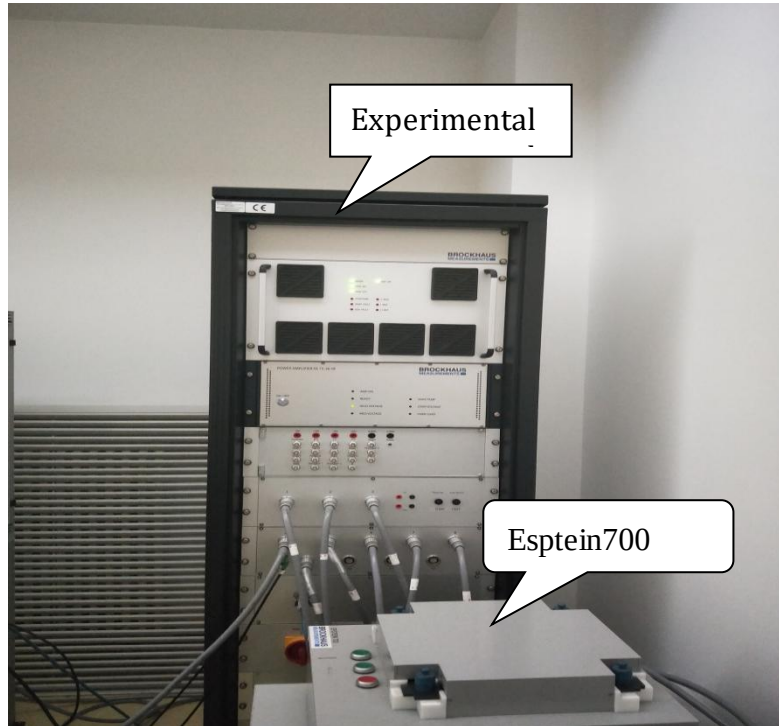


Figure 3. Measuring device diagram

2.2. Hysteresis Loss Measurement and Treatment

For the accurate measurement of hysteresis loss, it is necessary to change the excitation form in the above experiment from sinusoidal to low frequency. When the hysteresis loss is measured in this experiment, the excitation frequency is changed to 1 H z, to 2% of the above sinusoidal experimental frequency, then the total loss per cycle is calculated by formula (1) at this time:

$$W_z = W_h + k_{cl}B_m^2 f + k_{exc}B_m^{1.5} f^{0.5} \quad (1)$$

W_z here denotes total loss per cycle, unit: mJ/kg, W_h is the hysteresis loss at this time; f : frequency (Hz); B_m : flux density amplitude (T); k_{cl} and k_{exc} are the material coefficient. It can be seen from the above formula that in the magnetization process of each period, the eddy current loss produced by the silicon steel sheet is proportional to the frequency, and the abnormal loss is proportional to the 0.5th power of the frequency, while the hysteresis loss is independent of the frequency.[18]. Therefore, at this very low frequency, the eddy current loss is very small compared with the abnormal loss and hysteresis loss, which can be almost ignored. That is to say, the resulting hysteresis loop can exclude the influence of other loss terms, and the area of the curve is numerically equal to the hysteresis loop loss. As mentioned above, the hysteresis loop is used to calculate the loss at this time. The principle of hysteresis loss is described in the previous paper. It can be concluded that the magnetic domain rotation of ferromagnetic material overcomes the hindrance in the magnetization process with excitation.[19] Calculate the hysteresis loss W_h by using the integral expression.

Because the excitation signal is 50Hz ideal sine wave when measuring the loss in normal condition, we need to calculate the hysteresis loss for Hz 50 frequency, that is, the hysteresis loss value W the unit period. hand frequency f can be product. (2)

$$P_h = W_h f \quad (2)$$

P_h here which is the hysteresis loss size. The hysteresis loss calculated under the low frequency excitation can exclude the influence of frequency on the hysteresis loss coefficient. The result is stable and reliable.

3. Measurement of Silicon Steel Sheet in Sinusoidal Condition

Through the above measuring device, the magnetic characteristics of 0.1T ~1.9T are measured. Some conclusions can be concluded from the shape of each hysteresis loop in Fig 4. When the magnetic field intensity H increases slowly, the magnetic induction intensity B also increases gradually, but the growth rate is decreasing. then increase the magnetic field intensity again H , at this time we find that when the H increases, the increase B magnetic induction intensity is much smaller than the magnetic field intensity H , or even no longer increases. When the magnetic field intensity H begins to change, the magnetization process follows another trajectory. At this time, the change of magnetic induction intensity B is different from the change of magnetic field intensity H , and there is a lag situation, which we call hysteresis phenomenon. When the magnetic field intensity H decreases to zero, the magnetic induction intensity B is not zero, and the residual magnetization appears. The magnetic field must be added in the opposite direction in order to reduce the magnetic induction intensity B to zero, the magnetic induction intensity B is zero, and the corresponding magnetic field intensity is coercivity. If the reverse magnetic field intensity continues to increase, the magnetic induction intensity of the test silicon steel sheet reaches the magnetic saturation state in the opposite direction, and then the magnetic field intensity H reverse decreases to zero, and then increases in the positive direction. thus, it can be seen that during a magnetization period, the curve composed B magnetic field intensity H and magnetic induction intensity is a loop, i.e., hysteresis loop, which is symmetric about the origin. The larger the maximum magnetic induction intensity under the same frequency excitation, the more serious the hysteresis loop deformation is. At the same magnetic induction intensity B , the higher the frequency value, the larger the hysteresis loop area, which represents the greater the loss at this time.

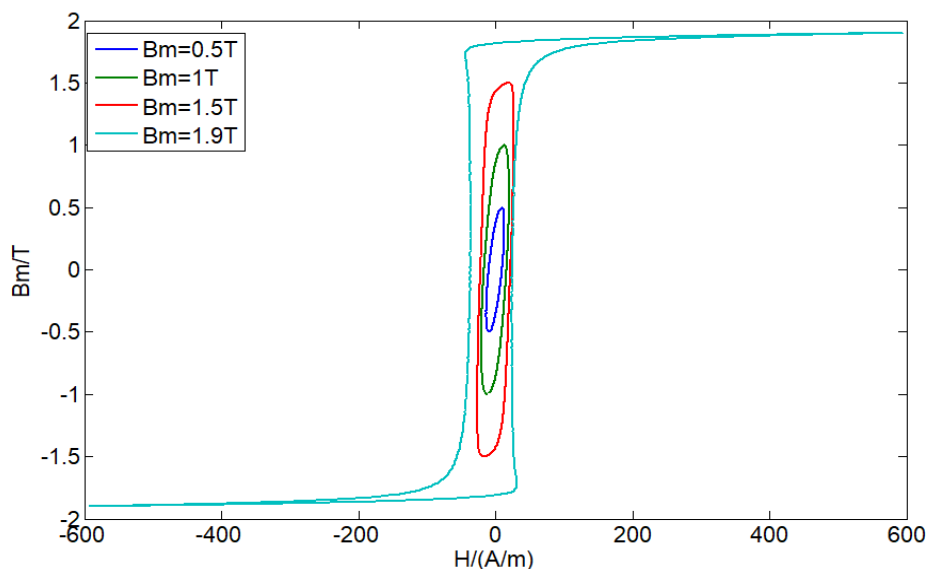


Fig 4. Schematic diagram of hysteresis loops under various magnetic induction intensities

The total loss of silicon steel laminates is shown in Figure 5:

And the loss curves of silicon steel sheets under sinusoidal 50Hz excitation are as follows, respectively. the greater the magnetic induction intensity, the greater the loss. Under the same maximum magnetic induction intensity, the higher the frequency, the greater the loss and the

greater the influence of frequency on the loss. When the maximum magnetic density is 1.9T, the loss of 150Hz is about 4 times of the loss of 50.

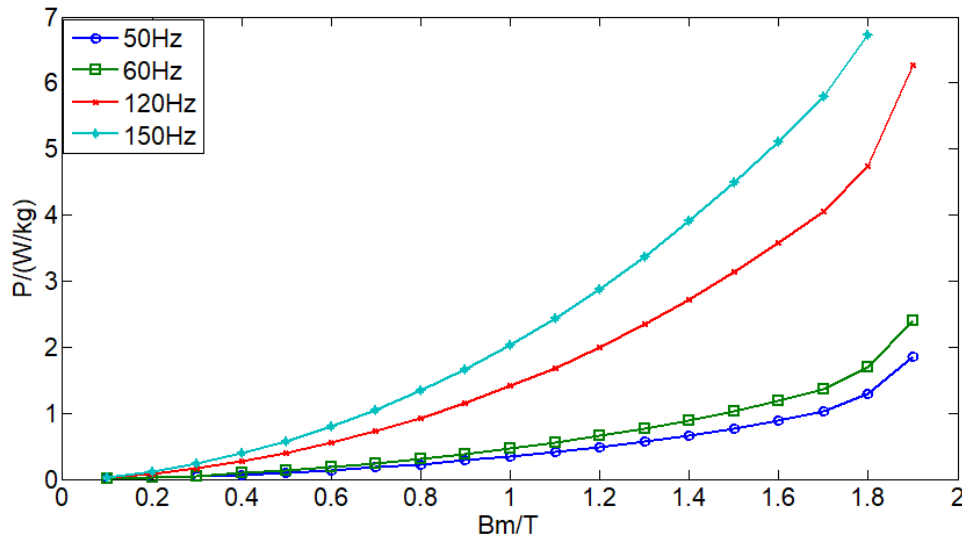


Figure 5. Comparison of losses at various frequencies

4. Calculation of Loss Separation under Sinusoidal Excitation

During the Brottei loss model, the loss of silicon steel sheet in magnetic field is divided into three parts: hysteresis loss, eddy current loss and abnormal loss. Formula as shown in formula (1-3), P_s in formula Represents total loss of silicon steel sheet, P_h For hysteresis loss, P_{cl} for eddy current loss, this section will derive the calculation of eddy current loss under sinusoidal excitation. P_{exc} unit: W/kg, this section will deduce its calculation formula and cause, hysteresis loss has been measured by low frequency magnetization experiment, the loss per unit time is proportional to the frequency f .

4.1. Calculation of Eddy Current Loss under Sinusoidal Excitation

The eddy current loss is caused by the circulation of silicon steel sheet under alternating magnetic field. The main flux direction is generally perpendicular to the cross section of silicon steel sheet, and the eddy current direction is parallel to the cross section.

$$P_{cl} = \frac{1}{12\rho} f \sigma d^2 \int_0^T \left(\frac{dB}{dt} \right)^2 dt \quad (3)$$

σ is silicon steel sheet conductivity, d is silicon steel sheet thickness, T is excitation period, B is magnetic induction strength, and ρ is silicon steel sheet density. The above parameters can be obtained in the above table of silicon steel sheet parameters. When the excitation is sinusoidal, the phase angle is assumed to be 0, that is:

$$B = B_m \cos(\omega t) \quad (4)$$

Substitute (4) into (3):

$$P_{cl} = \frac{1}{12\rho} \sigma f d^2 \omega^2 B_m^2 \int_0^T \sin^2(\omega t) dt \quad (5)$$

Formula (6):

$$P_{cl} = \frac{1}{6\rho} \sigma d^2 \pi^2 (f^2 B_m^2) \quad (6)$$

ω is angular frequency. The measured data is 1000 discrete B data points, so programming calculation using formula 1, the calculation of eddy current loss needs to consider the skin effect, skin effect refers to ferromagnetic materials in alternating magnetic field to produce Foko current, magnetic induction intensity B change lags behind the change of magnetic field intensity H, at the same time, the size of the B is inconsistent in the internal and surface, the surface B value is greater than the internal value. Depth of skin effect measured by d_s . The following expressions are commonly used (7):

$$d_s = 5030 \sqrt{\frac{\rho}{\mu f}} \quad (7)$$

For the resistivity $\rho = \frac{1}{\sigma}$, the unit is $\Omega \cdot \text{cm}$, and the f is the frequency. The skin collecting depth of the silicon steel sheet of model 30 P 120 is calculated to be 0.4 mm, greater than 0.3 mm, and the skin collecting effect can be ignored when the skin collecting depth is greater than or close to the size of the sample.

4.2. Calculation of Abnormal Loss under Sinusoidal Excitation

The abnormal loss is usually considered to be the magnetization state in the process of magnetization. In the low frequency alternating magnetic field with magnetic induction intensity, the abnormal loss is mainly due to the loss caused by magnetic after-effect or dispersion process, also known as Jordan loss. At higher frequency, the abnormal loss is mainly caused by the displacement of the magnetic domain wall.[20].

The abnormal loss is related to the derivative dB/dt of magnetic induction intensity on time according to the separation theory of Brottei iron consumption, that is, the abnormal loss per unit period is expressed as:

$$W_{exc} = \left(\int_0^T \frac{n_0 V_0}{2} \left(\sqrt{1 + \frac{4\sigma S G V_0}{n_0^2 V_0^2} \left| \frac{dB(t)}{dt} \right|} - 1 \right) \left| \frac{dB(t)}{dt} \right| dt \right) / \rho \quad (8)$$

The S of the formula is laminated cross section area, n_0 is the number of simultaneously effective magnetic objects (magnetic correlation region in the cross section of the sample) at limit $f \rightarrow 0$, V_0 is to characterize a statistical characteristic parameter, G is constant 0.1356, ρ is density. To emphasize that n_0 and V_0 are usually affect the abnormal loss of the material. Usually if the formula (9) is satisfied (generally when the inductive strength is strong).

$$\frac{4\sigma S G V_0}{n_0^2 V_0^2} \left| \frac{dB(t)}{dt} \right| \gg 1 \quad (9)$$

The above formula can be reduced to (10):

$$W_{exc} = \sqrt{\sigma GSV_0} \int_0^T \left| \frac{dB(t)}{dt} \right|^{1.5} dt / \rho \quad (10)$$

In more general cases, it can not be well judged whether (9) is satisfied. When the magnetic induction intensity is small, the formula (8) is reduced to (11):

$$W_{exc} = (\sqrt{\sigma GSV_0} \int_0^T \left| \frac{dB(t)}{dt} \right|^{1.5} dt - 2n_0 V_0 B_m) / \rho \quad (11)$$

If the magnetic induction intensity $B(t)$ changes according to the sine law, the integral formula (8) becomes the formula (12):

$$W_{exc} = (8.76 \sqrt{\sigma GSV_0 (B_m)} f^{0.5} B_m^{1.5} - 2n_0 V_0 B_m) / \rho \quad (12)$$

If the total loss minus the eddy current loss is the residual loss, it is P_{dif} . A residual loss divided by frequency is the residual loss generated by the material during a period of excitation change, which is called the unit period residual loss and is recorded as W_{dif} , i.e. (13)

$$W_{dif} = \frac{P_s - P_c}{f} \quad (13)$$

Since the value of the total loss after removing the eddy current loss is equal to the sum of the hysteresis loss and the abnormal loss, the unit period residual loss is equal to the sum of the unit period hysteresis loss and the unit period abnormal loss, such as formula (14)

$$W_{dif} = \frac{P_h + P_{exc}}{f} = W_h + W_{exc} \quad (14)$$

Among them, W_h from the area of the quasi-static hysteresis loop with an excitation frequency of 1Hz. If (14) is brought in, the formula (15) is as follows:

$$W_{dif} = (W_h + 8.76 \sqrt{\sigma GSV_0 (B_m)} f^{0.5} B_m^{1.5} - 2n_0 V_0 B_m) / \rho \quad (15)$$

Order Form (16)

$$W_{h1} = W_h - 2n_0 V_0 B_m \quad (16)$$

Form (16) to form (17)

$$W_{dif} = (W_{h1} + 8.76 \sqrt{\sigma GSV_0 (B_m)} f^{0.5} B_m^{1.5}) / \rho \quad (17)$$

As a result, the residual loss per unit period is divided into frequency independent W_{h1} and the remaining abnormal loss portion proportional to the 0.5th power of the frequency. So the loss

of silicon steel sheet at different excitation frequencies is measured and the residual loss P_{dif} calculated W_{dif} of residual losses per unit period a relationship curve varying with the 0.5th power of the f and fitted as a first function, some parameters can be determined according to the slope and the outcome, respectively.

4.3. Sinusoidal Calculation Results

Taking the above silicon steel sheet for calculation, the above conditions are substituted into the above calculation expressions, and the loss separation of the silicon steel sheet at 0.1 T-1.9T, stepped by 0.1T.

Here are 50 Hz showing the results:

Table 2. Calculation results of loss separation under 50H z

Calculation results of loss separation H z sinusoidal 50							
$B_m(T)$	$P_{cl}(W/kg)$	$P_{h1}(W/kg)$	$P_{exc}(W/kg)$	$B_m(T)$	$P_{cl}(W/kg)$	$P_{h1}(W/kg)$	$P_{exc}(W/kg)$
0.1	0.0011	0.000543	0.0037	1.1	0.13	0.087633	0.1975
0.2	0.0043	0.002506	0.0123	1.2	0.1547	0.101394	0.2347
0.3	0.0097	0.005742	0.0244	1.3	0.1815	0.112695	0.2831
0.4	0.0172	0.011055	0.0386	1.4	0.2105	0.128986	0.3303
0.5	0.0268	0.018295	0.0543	1.5	0.2417	0.150933	0.379
0.6	0.0387	0.026489	0.072	1.6	0.275	0.185829	0.4268
0.7	0.0526	0.03846	0.0891	1.7	0.3105	0.263221	0.4514
0.8	0.0687	0.051857	0.1084	1.8	0.3484	0.466867	0.473
0.9	0.087	0.063862	0.1329	1.9	0.3881	0.864259	0.5962
1.0	0.1074	0.077525	0.1597				

The loss separation (unit: W/kg) results of the 30P120 silicon steel sheet are shown in the following figure, P_{cl} in the figure for eddy loss, P_{exc} for abnormal losses, P_{h1} is the hysteresis loss at this frequency after treatment.

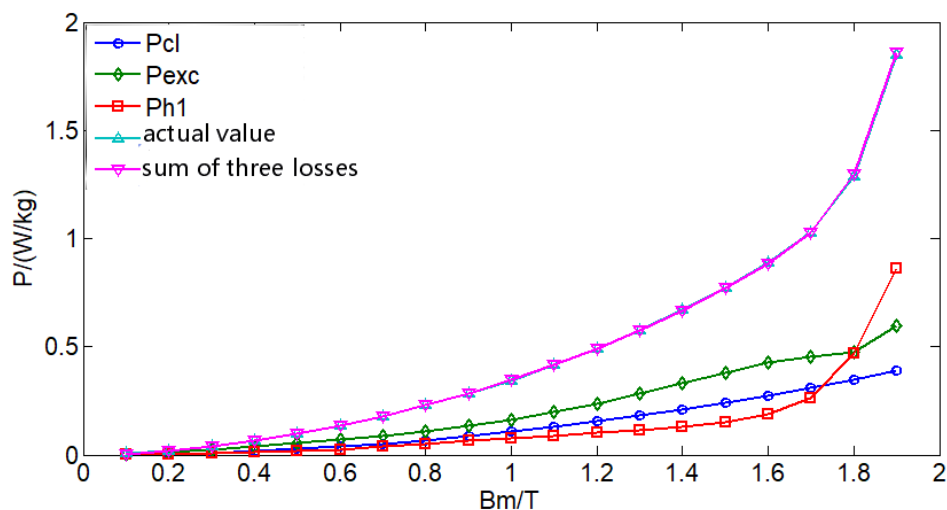


Figure 6. 50Hz sinusoidal excitation loss separation diagram

From figure 6, it can tell that the proportion of hysteresis loss, eddy current loss and abnormal loss is roughly the same at 50Hz, and in the region 1.8T—1.9T magnetic induction, the

hysteresis loss accounts for a large proportion. because the eddy current loss is proportional to the square of the frequency under sinusoidal excitation, the abnormal loss is proportional to the 1.5th power of the frequency, and the hysteresis loss is proportional to the frequency itself. As the eddy current loss of the frequency increases fastest, the abnormal loss increases faster, and the hysteresis loss increases the most slowly. It is concluded that the higher the frequency, the greater the eddy current loss ratio, and all losses increase with the increase of flux density, but the increasing speed is different. With the increase of flux density, the hysteresis loss increases gradually, and the percentage of hysteresis loss increases, and the larger the flux density, the larger the hysteresis loss ratio. The flux density is small, the increase loss of hysteresis loss is smaller than the other two losses, and the result is just the opposite when the flux density is high.

Meanwhile, the eddy current loss increases rapidly with the increase of magnetic induction intensity, but the proportion is gradually decreasing. Again, three losses at 150Hz, the eddy current loss is also verified when the flux density is the same, which is proportional to the square of the frequency, The eddy current loss of 50Hz at 1T is 0.11074W/kg. And at 150Hz eddy current loss is 0.9668W/kg, satisfies the relationship proportional to the square within the range allowed by the error. When the flux density is low, The largest percentage. When the flux density increases, And the loss is increasing, But the percentage of the total loss itself is reduced. For example, in 50Hz, the abnormal loss is 0.0543W/kg at 0.5T, 54.63%. The abnormal loss is 0.1597W/kg, at 1.0T, 45.81%; The abnormal loss is 0.473W/kg at 1.8T, accounting for 36.72%. And the magnitude of the decrease is greater than that of the eddy current loss. As you can see from the diagram. At 50Hz, there is no difference between the sum of three loss calculations and the actual loss values. The fitting has a satisfactory result.

5. Summary

Based on the Bertotti core loss model, the calculation formula and theory of the loss separation of silicon steel sheet under sinusoidal excitation, according to the national standard Epstein square circle experiment, the work is summarized as follows:

- (1) This paper first briefly introduces the Epstein square circle in the BROCKHAUS measurement system, analyzes the advantages and disadvantages of Epstein square circle, and uses the Epstein square circle to carry on the experiment after comparing with the monolithic measuring instrument. The magnetic properties of 30P120 silicon steel sheet under sinusoidal excitation frequency of 50Hz, such as hysteresis loop, loss curve and so on, were measured.
- (2) The derivation process of eddy current loss and abnormal loss under sinusoidal excitation is deduced based on Bertotti iron consumption model. At the same time, some simplified conditions are analyzed. By comparing the calculation results of each loss model with the experimental data, the hysteresis loss is based on the experimental data, and the abnormal loss and eddy current loss are analyzed and calculated emphatically. The calculation principle of different loss terms is studied and the high frequency error is found and the reason is analyzed.
- (3) The results of loss separation are analyzed to understand the effect of loss terms on the total loss and the variation law, and the results of loss separation are observed intuitively. Also for transformer or motor energy-saving and improve efficiency indirectly to provide some help.

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