Effective Magnetic Shielding in Electric Arc Furnace Transformers Using Interphase Wall Shunts

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***Abstract*—Magnetic shielding in electric arc furnace (EAF) transformers is of a great importance for stray loss reduction in different structural parts of the transformer. Conventionally, magnetic wall shunts in front of each phase or wall shunts covering the entire tank wall are used to reduce stray losses on the tank walls. In this study, interphase magnetic wall shunt configuration for effective magnetic shielding in EAF transformers is introduced. The proposed wall shunt arrangement is very effective in stray loss reduction in EAF transformers and provides a low-cost alternative for conventional magnetic wall shunt designs. A 30 MVA three-phase EAF transformer is investigated as a case study and 2D finite element analysis (FEA) is used for evaluation of stray losses in different arrangements of magnetic shunts. Also, wall shunt losses are calculated using an analytical formulation of eddy-current losses for laminated steel material. The simulation results show that the proposed wall shunt arrangement can reduce the stray losses by 48% with 33% less weight compared to conventional arrangements where wall shunts are placed exactly in front of each phase.**

***Index Terms*—finite element analysis, furnace transformer, magnetic shielding, wall shunt.**

I. Introduction

Electric arc furnace (EAF) transformers are one of the key apparatuses in smelting industries. These special type transformers are designed to deliver high currents for electric arc furnaces. Due to high levels of currents (e.g. 50 kA) they require a special design which makes them very expensive. Therefore, EAF transformers are highly protected against various types of failure. High-current busbars are one of the essential components in EAF transformers which provide high-current low-voltage connections. These busbars are designed to collect the currents from low-voltage winding disks. These output busbars are also important to establish the output heavy-duty connections which are directed to the arc furnace. In Fig. 1, a typical EAF transformer and its three-phase high-current busbars are shown. The output busbars affect the equivalent impedance of EAF transformers. Also, they have extremely high levels of short circuit forces [1]. Therefore, the design of such busbars is of a great importance and it requires extensive analysis and study of different [2]–[4].

Due to complex structure of power transformers, numerical simulations are widely used in order to evaluate their electric and magnetic design of transformers [5]–[9]. These simulations are used for the design verification and to make sure that different field parameters are within a desirable range in different operating conditions. Finite element analysis (FEA) is a well-know numerical method for analysis of power transformers [10]–[13]. This method has shown to be very effective for the evaluation of a wide range of applications including electromagnetic simulations. This method has been successfully used for design and analysis of magnetic shielding in power transformers [14]–[17]. FEA has been widely used in many studies to analyze various magnetic shielding methods in power transformers and their effectiveness in power transformers [11], [14]–[16], [18]–[20].

Since in EAF transformers a significant part of the stray losses are generated in the iron tank walls, magnetic shielding is essential for stray loss reduction on tank walls. The magnetic shields are composed of laminated steel packets which are placed on the tank walls in parallel with the busbars. These shields are called magnetic wall shunts [3], [11]. Wall shunts are used to provide a path with low magnetic reluctance for the leakage magnetic flux lines, and thereby shielding the tank walls against leakage flux. As a result, the stray loss on the tank walls is reduced significantly. Moreover, by reduction of stray losses in the transformer, the possible hotspots in the transformer tank and other structural parts are eliminated in the transformer is minimized. Proper design and placement of

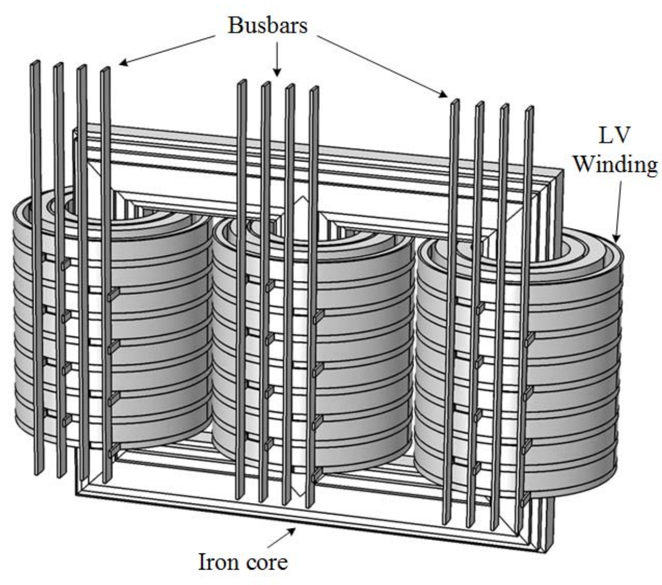

Fig. 1. A typical electric arc furnace (EAF) transformer.

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TABLE I
SPECIFICATIONS OF THE CASE STUDY TRANSFORMER.

Parameter	Value
Type	Electric Arc Furnace
Rated power	30 MVA
Voltage conversion ratio	30.5 kV /0.498 kV
LV nominal current	49.1 kA
Number of busbars	24
Busbar dimensions	$150mm \times 10mm$

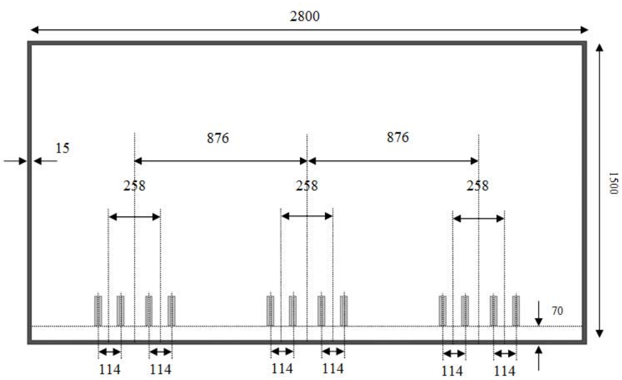

Fig. 2. The busbar configuration inside the tank walls of the case study furnace transformer.

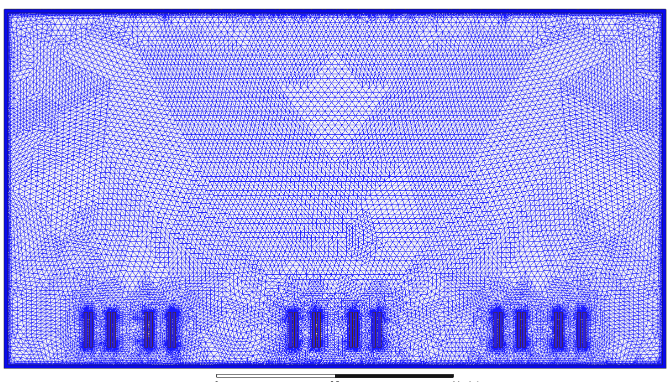

Fig. 3. The meshing of the 2D FEA model consisting of 88k elements.

wall shunts play a key role in effective stray loss reduction in tank walls.

In this paper, the use of interphase wall shunts are proposed to reduce stray losses due to high-current busbars in EAF transformers. Conventionally, wall shunts in front of each phase or wall shunts covering the entire tank wall are used to reduce stray losses on the tank walls in EAF transformers. 2D quasi-static FEA is used to calculate the losses on tank walls. Also, stray losses in the wall shunts are calculated using a numerical/analytical method based on double Fourier series of the magnetic field distribution on the wall shunts. The effectiveness of the proposed interphase shielding method is evaluated and compared with conventional wall shunt arrangements.

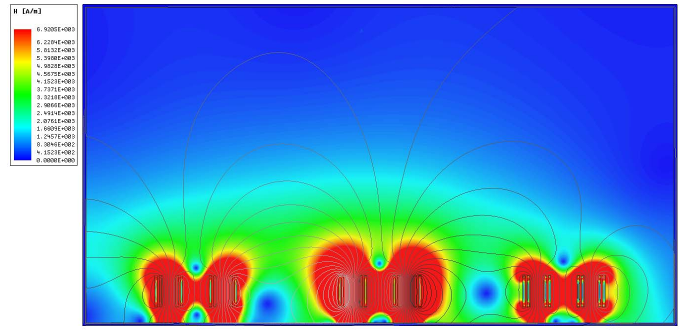

Fig. 4. The distribution of the magnetic field (H) in the 2D FEA model of the case study EAF transformer when the center phase has the maximum current.

II. 2D FINITE ELEMENT MODEL AND STRAY LOSS CALCULATION

EAF transformers with high-current low-voltage output busbars can be modeled in frequency domain using quasi-static 2D finite element analysis. In EAF transformers the LV tank walls and the windings are separated by high current busbars. Therefore, the stray losses on the LV side tank wall due to the leakage field of the windings are negligible. As a result, the stray losses on LV side tank walls are dominated by those induced by the high-current busbars. Thus, to evaluate the losses on the tank walls, the active part elements can be eliminated from the FEA model. The details of a 2D model are as follows:

A. High-Current Busbars Model

In a 2D quasi-static FEA model, the high-current busbars can be modeled as solid rectangular conductors. The three-phase current excitations with proper angular phase and direction are applied perpendicular to the modeling plane. The phase difference and the direction of current in each busbar depend on the design of the busbars. For example, in EAF transformers with double busbars (Fig. 2), adjacent busbars have the same current phase and direction, while adjacent double-busbars have the same phase with opposite current direction.

B. Tank Wall Model

The tank walls are modeled as solid steel with constant relative permeability (μ_r) and electrical conductivity (σ). The high-current busbars and their corresponding current excitations are modeled inside the tank walls. The induced current densities on the tank walls can be calculated using the quasi-static FEA and the corresponding stray losses can be calculated as follows [2]:

$$P_v = \int_{St} \frac{J^2}{2\sigma} ds \tag{1}$$

where P_v is the unit loss density (W), J is the induced current density inside the tank wall, σ is the conductivity of the busbars, and S_t is the area of the tank wall. Due to high values of relative permeability (μ_r) and electrical conductivity

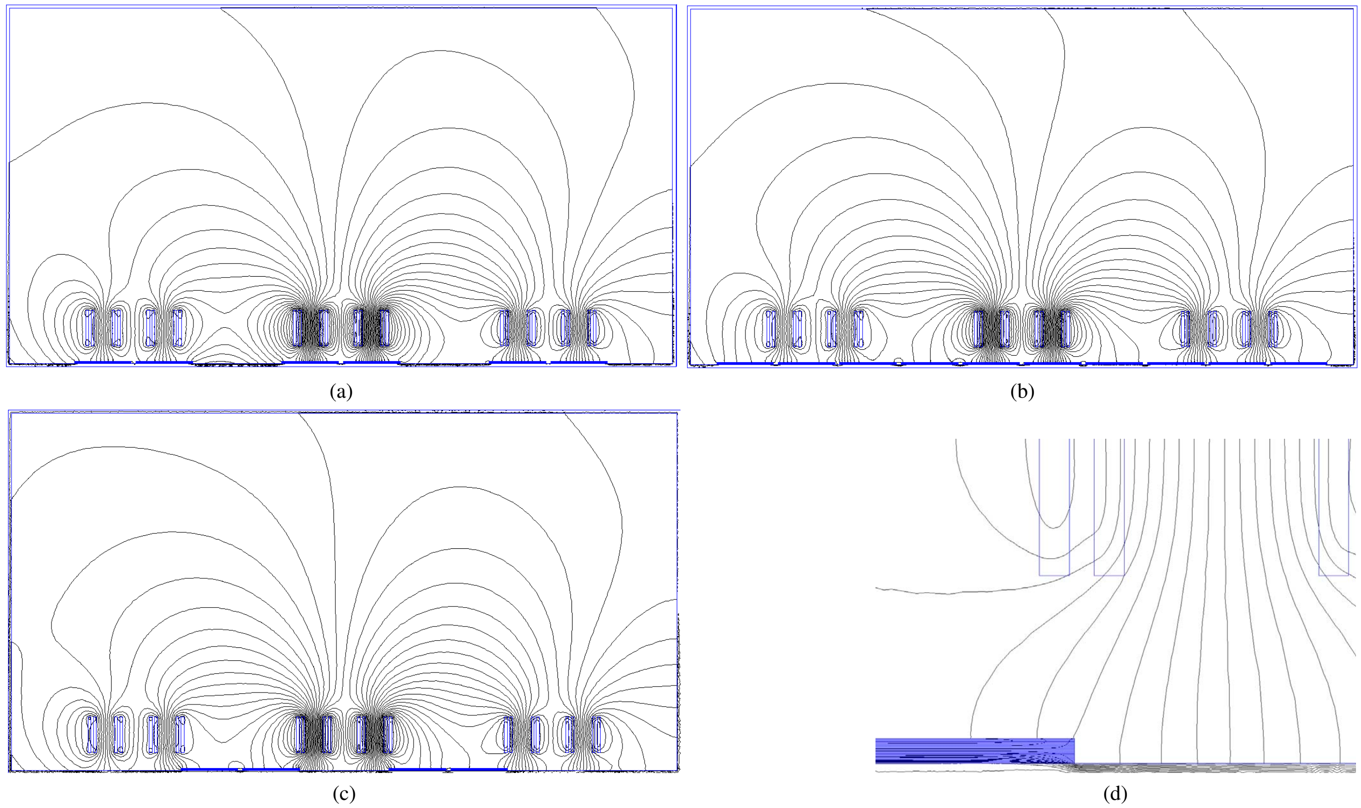

Fig. 5. Magnetic flux lines generated by the high-current busbars with different wall shunts arrangements: (a) wall shunts in front of each phase, (b) wall shunts covering the entire tank wall, (c) interphase wall shunts, (d) interphase wall shunts (closer view).

(σ) of steel, the skin depth (δ) is very low and therefore, impedance boundary condition (IBC) can be applied to the boundaries to approximately model the tank walls. However, in this study, to increase the accuracy of calculations based on 2D FEA, the tank walls are modeled as solid iron with very fine mesh elements. This also, allows the calculation of loss density distribution inside the tank walls.

C. Magnetic Wall Shunt Model

Magnetic wall shunts in power transformers are composed of laminated steel with high magnetic permeability. Therefore, magnetic wall shunts should be modeled as a nonisotropic and nonlinear material. The eddy current losses of a magnetic shunt with dimensions of $W \times 2L \times d$ can be calculated as follows [11]:

$$P = \frac{\sigma \mu^2 \omega^2}{8\pi^2} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{H_{mn}^2 L^3 W^3}{(m^2 L^2 + n^2 W^2) Real(\beta_{mn})} \tag{2}$$

where μ is the permeability (H/m), σ is the electrical conductivity (S/m), ω is the frequency (rad/s), H_{mn} are the coefficients of double Fourier series which is calculated using field distribution derived from FEA, and $\beta_{mn}^2 = j\omega\mu\sigma + \left(\frac{n\pi}{L}\right)^2 + \left(\frac{m\pi}{W}\right)^2$. The coefficients of double Fourier series H_{mn} can be calculated as follows:

$$H_{mn} = \frac{4}{WL} \int_0^H \int_0^L H_n(x,y) \cos\left(\frac{m\pi x}{W}\right) \sin\left(\frac{n\pi y}{L}\right) dxdy \tag{3}$$

where $H_n(x,y)$ is the normal magnetic field distribution on the surface of the magnetic shunts.

III. Wall Shunt Arrangements Analysis

Conventionally, in EAF transformers, magnetic wall shunts are placed in front of each phase to minimize the losses on the tank walls and structural parts. In order to analyze the effectiveness of different magnetic wall shunt arrangements in stray loss reduction, 2D quasi-static FEA is carried out on different shunt arrangements and corresponding losses are evaluated using (1) and (2). The specifications of the case study EAF transformer is given in Table I and the busbar configuration is shown in Fig. 2. In Fig. 3, the mesh elements of the case study transformers without magnetic shielding is shown. Also, in Fig. 4, the distribution of the magnetic field (H) of the case study EAF transformer when the center phase has the maximum current.

A. Tank Walls without Wall Shunts

In order to evaluate the effectiveness of different wall shunt arrangements in stray loss reduction, it is important to evaluate the stray losses without magnetic shunts. FEA is performed on

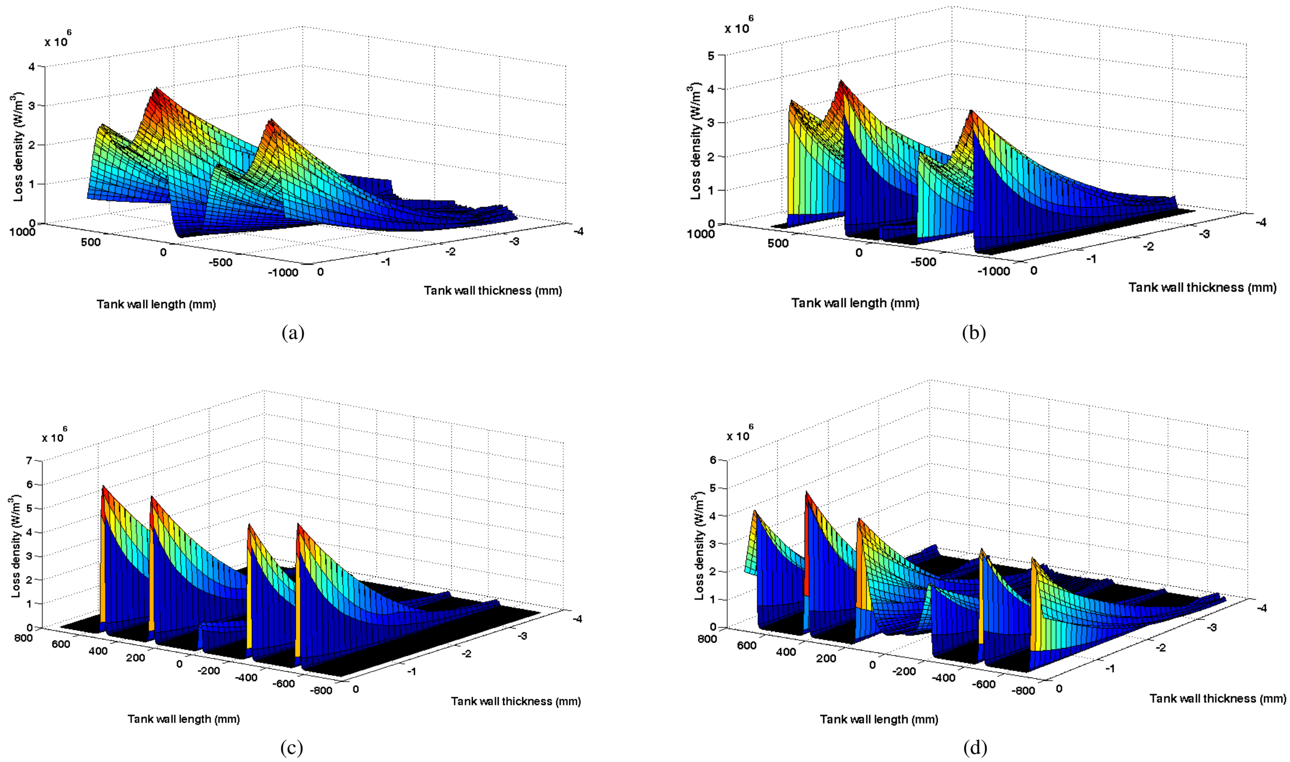

Fig. 6. Power loss density inside the tank wall with different wall shunt arrangements: (a) no wall shunts are used, (b) wall shunts in front of each phase, (c) wall shunts covering the entire tank wall, (d) interphase wall shunts.

the case study EAF transformer and the stray loss on tank walls and magnetic wall shunts are calculated. The calculations show that the stray loss on tank wall without wall shunts is 7.51 kW. Also, the distribution of power loss density inside the tank wall on LV side is presented in Fig. 6(a). This figure shows that the losses in the areas between phases are maximum and in the areas in front of each phase is minimum. This is due to the fact that the total current in each phase is zero, the flux densities in the area in front of phases would low, and as a result, the corresponding stray losses on the tank wall would be low.

B. Wall Shunts in Front of Phases

Typically, in large power transformers magnetic wall shunts are placed in front of each phase to reduce the stray losses due to leakage flux of the windings. The case study transformer with 6 wall shunts in front of each phase is modeled using FEA. In Fig. 5(a), the magnetic flux lines produced by the high-current busbars with wall shunts in front of each phase in the 30 MVA case study transformer are shown. Also, the corresponding stray losses and shunt losses are presented in Table II. Fig. 5(a) shows that the flux lines enter normally to the magnetic wall shunts' surfaces and exit from the edges parallel direction. The normal component of flux density on shunt surfaces induces current densities normal to the model plane which leads to an increased the loss in the shunts. Also, this arrangement of wall shunts does not effectively divert the flux lines from entering to the tank walls, and thus loss reduction in tank walls would not be significant. Table II shows that using this wall shunt arrangement the stray losses are reduced by 17.34%. The corresponding power loss density distribution inside the tank wall on LV side is shown in Fig. 6(b). By comparing Figs. 6(a) and 6(b) it can be seen, the magnetic shunts in front of phases are not effective in loss reduction. This is due to the fact that the tank wall losses in the areas in front of phases are minimum.

C. Wall Shunts on the Entire Tank Wall

One of the arrangements which can be used to shield tanks walls against stray fluxes is to cover the entire tank wall with magnetic shunts. Although this arrangement minimizes the tank wall losses, it may not be a cost-effective solution as it requires quite a few number of shunts. In Fig. 5(b), the flux lines generated by the high-current busbars with 10 magnetic wall shunts covering the entire tank wall of the case study 30 MVA EAF transformer are shown. Also, the corresponding stray losses are presented in Table II. This table shows that using this wall shunt arrangement with 10 shunts the stray losses are reduced by 66.97%. Therefore, wall shunt arrangements covering the entire tank wall are about 3.9 times more effective than wall shunts in front of phases. The corresponding power loss density distribution inside the tank wall on LV side is shown in Fig. 6(c). By comparing Figs. 6(a) and 6(c) it can be seen that the magnetic shunts covering

TABLE II
COMPARISON OF STRAY LOSSES IN DIFFERENT WALL SHUNT ARRANGEMENTS.

Wall shunt arrangement	No. of shunts	Tank wall loss (W)	Shunt loss (W)	Total loss reduction (%)
No shunts	—	7536.1	—	—
In front of phases	6	5617.8	611.5	17.34
Entire tank wall	10	1789.5	700.0	66.97
Interphase	4	3740.4	139.6	48.51

the entire tank wall have effectively reduced the losses and the losses are limited only to the gaps between wall shunts. However, this arrangement requires 66.7% more shielding material compared to the arrangement with wall shunts in front of phases.

D. Interphase Wall Shunts

As discussed in Section III.A, in the case that the tank wall is not shielded the area between phases has higher losses. Therefore, magnetic shielding of the area between phases and diverting the magnetic flux path from tank walls into magnetic wall shunts can be an effective method for stray loss reduction. Based on this idea, the interphase wall shunts are introduced in this research to effectively reduce the stray losses as well as shunt losses in a cost-efficient way. In this wall shunt arrangement, magnetic shunts are placed between phases. This arrangement can effectively reduce the stray loss due to leakage flux generated by the high-current busbars. In Fig. 5(c), the flux lines due to the high-current busbars with wall shunts between phases in the case study 30 MVA EAF transformer is shown. Fig. 5(d) shows the flux lines path in front of busbars where the magnetic flux penetrates into the tank wall and then is diverted by the interphase magnetic shunts. The calculated power loss density distribution inside the tank wall on LV side is shown in Fig. 6(d). By comparing Figs. 6(a) and 6(c) it can be seen, the interphase magnetic shunts have effectively reduced the losses on the tank wall and the losses are limited only to the gaps between wall shunts.

The corresponding stray losses are presented in Table II. This table shows that by placing the interphase shunts the stray loss is reduced by 48.51% with only 4 shunts. In other words, compared to the arrangements with wall shunts in front of phases, the proposed interphase shunt arrangement is about 2.8 times more effective in stray loss reduction with 33% less material. Therefore, the proposed interphase shunt arrangement is the most efficient method for stray loss reduction in EAF transformers with high-current busbars, and can be used as an alternative for conventional wall shunt arrangements.

IV. CONCLUSION

The use of interphase wall shunts as a cost-effective alternative for conventional magnetic shielding arrangements in EAF transformers are introduced. The proposed interphase arrangement of wall shunts provides a very efficient and cost-effective method for stray loss reduction in EAF transformers with high-current busbars. The effectiveness of the shunts are evaluated using 2D FEA and its benefits over conventional arrangements are verified. The loss density distributions on the tank walls of a case study transformer with different wall shunt arrangements are calculated. The loss distributions show that the losses in the area between phases form a major part of the total stray losses and therefore, interphase wall shunts are very effective in stray loss reduction. The calculations show that compared to the arrangement with wall shunts in front of phases, interphase wall shunts are about 2.8 times more effective in stray loss reduction while they require 33% less laminated steel material.

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